Figure 1. Regional geologic map of northeastern Minnesota showing the location of Gunflint Trail (modified from Jirsa and Miller, 2005). Field trip area lies near the northwestern end of the trail at the junction of Neoarchean, Paleoproterozoic, and Mesoproterozoic terranes.
INTRODUCTION

The Paleoproterozoic Gunflint Iron Formation is the eastern extension of the Biwabik Iron Formation, which was bisected by intrusions of the Mesoproterozoic Duluth Complex. The Gunflint lies unconformably on deformed Archean greenstone-granite terrane of the Wawa subprovince of Superior Province, and Paleoproterozoic diabasic dikes that cut the Archean rocks locally. The stratigraphic top of the iron-formation is marked by a major unconformity and ejecta that resulted from a meteorite impact near Sudbury Ontario ca. 1850Ma (Krogh, 1984; Davis, 2008). Of the 176 known and scientifically verified terrestrial impacts, the Sudbury event was the second largest and forth oldest (TUwww.unb.ca/passc/ImpactDatabaseUT). The resulting ejecta blanket has been identified in Ontario, Michigan, and here in Minnesota near Gunflint Lake and in drill core along the Mesabi Iron Range. The overlying Rove Formation—a mudstone and turbiditic sandstone unit—was deposited directly on the ejecta. 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). 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. 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, macroscopic sedimentary textures are well preserved in most outcrops. Metamorphism adjacent to the Logan Intrusions was minor. The formations are depicted on Figures 2 and 3, and are described below:

Figure 2. Geologic map and schematic cross-section (A-A’), showing approximate location and stratigraphic position of some field trip stops. Geology modified from Morey and others, 1981. 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 resulting from contrasting resistance to erosion.
Figure 3. Schematic stratigraphic section of Gunflint Iron Formation and adjacent rocks, comparing older stratigraphic nomenclature with that used informally here. Approximate stratigraphic positions of field trip stops are shown in boxes.
GENERAL DESCRIPTION OF UNITS

Gunflint Iron Formation

As on the Mesabi Iron Range, the Gunflint Iron Formation has historically been subdivided into so-called cherty (granular) and slaty (argillaceous) informal subunits or members. The members are 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, depicted in Figure 3, the lower cherty and lower slaty members represent deposition during a single marine transgression. We infer that this was followed by a regression that deposited the lower part of the upper cherty member—the resulting sedimentary strata are collectively and informally termed lower sequence here. 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. The contact between the two sequences is a diastem inferred to represent a period of maximum regression. The initial stages of the 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 are variably brecciated and/or chaotically folded, carbonate-bearing, and capped by granular ejecta from the ca. 1850 Ma Sudbury meteorite impact event, collectively termed Sudbury impact layer here.

**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 upper sequence.

**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).

**Sudbury impact layer** (SEE Discussion below)—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, 2010a). 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).
Rove Formation

The Rove Formation consists of 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.

DISCUSSION OF SUDBURY IMPACTITE LAYER

(Field Trip stops 5, 6, and 7)

The Gunflint Lake exposures lie some 480 miles (770 km) west of Sudbury, making this one of the most distant sites known to contain what is considered “proximal ejecta” from the ca. 1850 Ma Sudbury meteorite impact event. Similar deposits have been discovered in Thunder Bay, Ontario and Michigan that are well documented by Addison and others (2005), Cannon and Addison (2007), and Pufahl and others, (2007). Deposits near Gunflint Lake appear to be consistently thicker than in other areas, even though these sites are more distal than those in Michigan and Ontario. The impact deposits at sites further away from the crater than Gunflint Lake are much thinner and lapilli are only rarely present. This has led Addison et al. (2010) to hypothesize that the Gunflint Lake deposits may represent thick ramparts, as described for end-of-flow Martian base-surge deposits (Kenkmann and Schonian, 2006; Osinski, 2006; Mouginis-Mark and Garbeil, 2007). It should be noted at the onset, that only a small portion of the material described here can be considered true ejecta; that is, material that was air-borne. The great majority of the 7 meter-thick deposit is breccia that consists of thoroughly disheveled fragments that appear to have been derived from subjacent iron-formation. Like the deposits near Thunder Bay, the breccia is sandwiched between Gunflint Iron Formation and sedimentary strata of the Rove Formation. Unlike deposits near Thunder Bay, the breccia lies within the metamorphic aureole of the Tuscarora and Poplar Lake Intrusions of the Duluth Complex (ca. 1100 Ma), and is intruded by diabasic sills of the Logan Intrusions (ca. 1115 Ma; Heaman and Easton, 2005). Pervasive carbonate mineralization and metamorphism has overprinted and obscured much of the original, delicate mineralogic features, but macroscopic textures and geochemical content that convey information about protolith and depositional mechanisms are preserved.

Stratigraphic and sedimentological characteristics of the Sudbury impact layer are extremely varied from outcrop to outcrop, not surprising given the apparent chaos of impact processes. Nevertheless, a generalized stratigraphic description can be made. Most of the deposit at Gunflint Lake is made up of disorganized-bedded boulder “megabreccia”, with clasts composed of lithologies present in rocks of the underlying Gunflint Formation. The boulder breccia is commonly overlain by a decimeters-thick, matrix-supported pebble “mesobreccia” to massive, pebbly sandstone. Rare, scattered accretionary lapilli occur in this unit. The mesobreccia is overlain in some sections by accretionary lapilli beds with clast-supported textures (lapillistone). These fill shallow scours in the top of the mesobreccia, or deeper scours that remove strata all the way down to megabreccia. The base of the scours is commonly overlain by a one-centimeter-thick wisp of coarse-grained sandstone, followed vertically by the accretionary lapilli. In other locations, in an area covering a few square kilometers, layers of parallel laminated, medium-grained sandstone separate the breccia from the accretionary lapilli-rich beds. In places cross-stratified lapillistone fills scours into the underlying sandstone, giving a paleocurrent direction of 260 degrees. The bearing from Sudbury to Gunflint Lake is 280 degrees. At other locations, where individual smaller scours at the base of the lapillistone are not present, the basal, clast-
supported lapillistone bed drapes a shallow erosive scour. The lowermost accretionary lapillistone is massive-textured, as are overlying accretionary lapilli-rich beds, except where rare, small-scale, low-angle cross-stratification dipping towards 060 degrees is visible. The basal bed is generally less than 15 cm thick and succeeded upwards by 1 to 5 cm thick accretionary lapilli beds alternating with coarse- and medium-grained sandstone beds. The sandstones are parallel laminated and composed of a mixture of locally derived grains, more far traveled mineral grains, and devitrified glass. Accretionary lapilli in the bed at the base of the lapilli-rich interval average 0.7 to 0.8 cm and those higher in the section and interbedded with sandstone 0.2 to 0.4 cm. The sandstone beds become more dominant in the next few decimeters. Here they are medium- to fine-grained with stringers and patches of small accretionary lapilli. Some beds are massive with abundant, isolated lapilli. Parallel lamination to undulating parallel lamination is common in the non-massive beds. Approximately 10 cm of thinly laminated siltstone caps the impact deposit.

In the following discussion, the term “impactite” has been applied informally to include all facies of sedimentary rocks inferred to have been formed or deformed in response to the ca. 1850 Ma Sudbury meteorite impact. By that definition, it includes autochthonous material interpreted to be seismically folded and shattered iron-formation (ejecta-absent), and overlying strata composed largely of allochthonous material derived from the impact site (ejecta-bearing). Figure 4 depicts the apparent stratigraphic relationships. In no single outcrop are all facies present; however, an approximation of temporal relationships can be inferred from the juxtaposition of two or more facies in individual outcrops.

**Figure 4.** Stratigraphic framework derived from 8 exposures along a 2 mile strike-length near Gunflint Lake; hung from the contact between ejecta-bearing and ejecta-absent facies of the impactite horizon (bold dashed line) (from Jirsa, 2010a).

In the following section, facies are described in apparent stratigraphic order from oldest to youngest:

**Ejecta-Absent**

Contorted iron-formation facies: The uppermost layers of iron-formation are chaotically folded and exhibit both ductile and brittle behavior in close proximity at the scale of individual outcrops. The rheologic response depends on the apparent rigidity of material at the time of deformation. Silica-rich layers display brittle, shattered to semi-ductile, boudinage-like textures. By contrast, much of the iron-silicate mudstone layers behaved in a ductile fashion,
locally showing evidence of fluidization and injection into superjacent strata. Folds are non-systematic in trend and style, and multiple hinge detachments occur. These attributes counter-indicate a regional tectonic origin, and instead are best viewed in the context of impact as the result of impact-generated seismicity imposed on semi-lithified substrate.

**Parautochthonous breccia facies:** At several locations, straight-bedded iron-formation passes laterally along strike into irregular zones in which the silica-rich layers have been broken and disheveled, while still retaining some semblance of jigsaw-puzzle fit.

**Megabreccia facies:** This term is used for breccia composed of unsorted slabs (as large as 5 m), blocks, and smaller fragments of iron-formation. The fragments are angular and in most places have random orientations. Fragments of green, iron-silicate mudstone typically show some evidence of semi-ductile behavior, and locally this material was fluidized to form irregular matrix and clastic (muddy) dikes.

**Ejecta-Bearing**

**Mesobreccia facies:** This is fragmental rock containing angular, subrounded, and amoeboid clasts (up to 5 cm long) of dark green material and scattered accretionary lapilli. Petrography shows that much of the original structure of the clasts has been metamorphically recrystallized and annealed; however, relics of amygdaloidal and fluid-looking textures remain—implying a glassy protolith.

**Lapillistone-gritstone facies:** Accretionary lapilli as large as 1.5 cm occur as irregular masses and layers interbedded with sandy to silty gritstone. In areas least affected by metamorphism, several grains of shocked quartz with planar deformation features have been identified in thin section.

**Spherule, pellet, small lapilli facies:** The upper parts of ejecta horizons locally contain layers, lenses, and interbeds of accretionary or relict glass grains that are smaller than typical lapilli and generally lack concentric zonation. These apparently accreted particles may represent waning ejecta plume deposition.

**Ejecta-bearing conglomerate facies:** In a few localities, the uppermost part of impactite deposits consist of conglomerate containing subrounded fragments of iron-formation (in contrast to angular fragments typical in breccias described above), and matrices containing variably abraded lapilli.

**Interpretation**

The arrangement of facies described above and depicted on Figure 4 can be interpreted in the context of experimental evidence and observations from Lunar and smaller terrestrial impacts. Using calculations from Collins and others (2005), one can predict arrival times for various effects of the impact here, some 480 miles from the impact site, as follows:

- **EVENT** ~APPROXIMATE ARRIVAL TIME
  1) Fireball ~13 seconds (the modern equivalent of 3rd degree burns)
  2) Earthquake ~2-3 minutes (>10.9 at epicenter)
  3) Ejecta Ground Surge ~5-10 minutes (predicts ejecta 1-3 meters thick, grain sizes ~1cm)
  4) Air blast ~40 minutes (sonic boom)
  5) Tsunami ~1-3 hours (speculation—arrival and affects dependant on basin bathymetry and pre-impact position relative to strand line, which are difficult to establish)

Nearly all contacts between individual facies are gradational, with one very important exception—in all exposures, the boundary between ejecta-absent and ejecta-bearing facies is extremely sharp. This is inferred to reflect a fundamental shift in geologic processes from intense seismic perturbation of uppermost iron-formation represented by the ejecta-absent facies, to deposition by the passing ejecta plume. The uppermost conglomerate facies represents mixing of local and exotic detritus, presumably by tsunamis or post-impact fluvial or marine processes.
Stop Descriptions
NOTE: All UTM coordinates are given in NAD 83; Zone 15.

STOP 1 - Contact zone of Neoarchean Saganaga Tonalite and metabasalt; unconformably overlain by Paleoproterozoic (Kakabeka) conglomerate and basal Gunflint Iron Formation.

**Location:** UTM: 661,965E/5,329,062N, Bush path off Gunflint Trail (County Highway 12)

**Description:** Conglomerate developed at the gently southward dipping unconformity between Neoarchean intrusive and metavolcanic rocks and the overlying basal part of the Paleoproterozoic Animikie Group. The unit, regionally known as the Kakabeka Conglomerate, is present only locally on the western end of the Gunflint range. In most places, granular iron-formation lies directly on eroded Archean surfaces. This small outcrop is one of the few places where the conglomerate is exposed and easily accessible along the contact. The conglomerate is greenish gray, poorly bedded, and contains subangular to subrounded fragments of Saganaga Tonalite and related granitoid rocks, metabasalt, diabase, and quartz, in a granular siliceous matrix (Fig. 5). The underlying Archean metavolcanic rocks contain abundant granitic sheets and dikes, presumably related to border phases of Saganaga Tonalite. The pronounced foliation in the Saganaga Tonalite was interpreted by Grout (1933) as a primary flow fabric (trachytoid). The tonalite is inferred to have been emplaced into Archean metavolcanic rocks shortly after early (DB1B) deformation, based a U-Pb date of 2689±1 in Canadian exposures (Corfu and Stott, 1998). As such, it experienced major regional metamorphism and transpression associated with DB2B deformation. As with many large plutons in such terranes, the debate remains unresolved about whether the fabrics are wholly magmatic, wholly tectonic, or some hybrid of the two.

![Figure 5](image-url). Outcrop photograph of Kakabeka conglomerate lying unconformably on vertically foliated and eroded Archean Saganaga Tonalite (uniform light gray area on right side of photo). Note diversity of fragment types, including Archean metabasalt (dark) and tonalite (light), quartz pebbles (light, subrounded), and Paleoproterozoic diabase (dark gray).
STOP 2 - Lower Sequence of Gunflint Iron Formation.

Location: UTM: 661,844E/5,328,896N, Road cut on Gunflint Trail (Highway 12)

Description: Gently southward-dipping, thinly interbedded granular and argillaceous iron-formation typical of the lower sequence. In earlier terminology, this stratigraphic position is the lower part of the Upper Cherty member of the Gunflint Iron Formation.

STOP 3 - Stromatolitic grainstone at the diastem separating lower and upper sequences of Gunflint Iron Formation.

Location: Three exposures—specific locations given below, Magnetic Rock Hiking Trail

CAUTION and ADVICE: This is a fairly long hike, approximately 1 mile round-trip; please be prepared with water and other field needs. Although this is not in the BWCAW, it does lie within Superior National Forest and is frequented by hikers. For this reason, and to preserve scientific value, please be respectful in matters of hammering and sampling.

Description:

3a [UTM: 662,034E/5,328,885N] Thin-bedded, fine-grained, chert-amphibole-magnetite-bearing strata assigned to the upper part of the lower sequence of Gunflint Iron Formation (“Lower slaty member”). Beds strike ENE and dip generally less than 8 degrees southward.

3b [UTM: 662,401E/5,329,093N] Stromatolites lie within and just above a major regression-transgression boundary that is marked by intraformational conglomerate containing fragments of the underlying granular chert that appear to have been cohesive at the time of incorporation, and in-situ and dislodged stromatolites. Irregular domal and laminar stromatolite forms are present. Note the presence of granules, intraclasts, and oncoliths—the latter consist of intraclasts coated with what likely was biogenic material, now composed largely of silica.

3c [UTM: 662,583E/5,329,257N] Crest of ridge exposes the same boundary described above, here with abundant 3-dimensional views of stromatolites, intraformational conglomerate, and stromatolite "hash," all in a peloidal to ooidal, siliceous grainstone matrix. Given the apparent mineralogic replacement and moderate metamorphic grade, little of the original carbon-based material is likely present. Despite this, examples of nearly all morphological forms of stromatolites can be found, including columnar-digitate, domal, and laminar (Fig. 6).
STOP 4 - **Uppermost, largely argillaceous, Gunflint Iron Formation**

**Location:** UTM: 663,754E/5,328,212N, Gravel pit north of Gunflint Trail.

**Description:** This dip-slope exposure consists of interbedded granular (cherty) and laminated (slaty) strata of the uppermost Gunflint Iron Formation. The slope defines the southern limb of a large, shallowly east-plunging anticline. The gentle dip of this limb illustrates the observation that open folding and moderate-relief topography are responsible for the complex map pattern.

The bedding surface is marked by what have been referred to in earlier literature as “syneresis cracks”. The cracks, now filled with quartz, occur both concentrically and radially around a central, apparently raised core within a single granular layer of siliceous iron-formation (Fig. 7). Syneresis cracks are defined generally as shrinkage cracks formed by dewatering in a gel or colloidal suspension. They differ from septarian cracks that may develop in a similar way, in that the latter typically occur in concretions. Surprisingly diverse interpretations can be found in the literature about syneresis cracks (summarized in Pratt, 2001). There is, however, general agreement that they represent localized tensional failure during sediment dewatering. The explanation for localized semi-brittle response to what likely were formation-wide stresses—caused by compaction or vibration due to syn-sedimentary earthquakes—is more contentious. It has been ascribed variously to the localization of cements, locally increased pore pressure, or zones of granular sediment made coherent by "microbial glue." It is interesting to note that syneresis structures are more prevalent in Precambrian and Cambrian rocks than younger ones.
This may be due in part to more uniform organic bonding of clays in younger strata, which reduced the occurrence of stress-localization.

Recent mapping by the author (Jirsa, 2010b) indicates that these quartz-filled cracks occur only in some granular siliceous layers that lie near the stratigraphic top of the iron-formation. This stratigraphic position, and their enigmatic structural attributes, may indicate an origin by impact-induced seismic wave passage through cohesive, semi-rigid chert during the Sudbury meteorite impact event.

Figure 7. Polygonal quartz veining on eroded bedding surface of thinly bedded Gunflint Iron Formation.

STOP 5 - Paleoproterozoic ejecta and breccia from the Sudbury meteorite impact, intruded by sill and dikes of the Mesoproterozoic Logan Intrusions.

Location: UTM: 664,785E/5,329,200N

Description: This traverse provides a cross-section through diabase of the Logan Intrusions and underlying deposits of iron-formation, breccia, and ejecta. The diabase is medium- to coarse-grained in its core to the south, and grades to finer grained and more porphyritic near its base to the north. The northernmost outcrops lie along a steep cliff that exposes basal Gunflint Iron Formation, a thick sequence of breccia (Fig. 8), localized pods of bedded lapillistone and mesobreccia (Fig. 9), and likely reworked breccia containing rounded fragments of iron-formation in a matrix composed largely of accretionary lapilli. The precise stratigraphic position of the latter two facies is not entirely clear, though the strata containing accretionary lapilli (true ejecta) appear to lie near the top of the deposit.
Figure 8. Large-fragment breccia

Figure 9. Bedded lapillistone and mesobreccia.
STOP 6 - Folded and brecciated Paleoproterozoic iron-formation overlain by ejecta-Sudbury impact layer.

**Location:** Several localities within small area; UTM given below.

**Descriptions:**

6a [UTM: 663700E/5328967N] Folded iron-formation overlain by ejecta. The chaotic fold style (Fig. 10) indicates soft-sediment deformation just prior to deposition of ejecta, which implies iron-formation was not yet lithified at the time of impact.

![Figure 10](image)

**Figure 10.** Folded siliceous iron-formation, overlain by thin skin of ejecta containing accretionary lapilli (Bill Addison and Bevan French for scale).

6b Traverse from UTM: 663,664E/5,329,107N, northwest to 663,628E/5,329,186

This traverse crosses folded and brecciated iron-formation in ductilly deformed and locally highly metamorphosed green iron carbonate mudstone. At the northern-most UTM location, a cliff and ridge-top exposure includes a 7m-thick breccia abruptly overlain by mesobreccia, capped by small (2-5mm) accretionary pellets and slightly larger concentrically zoned lapilli (Fig. 11). Some of these small particles may be relict glass spherules; however, metamorphism precludes definitive identification.
Figure 11. Megabreccia sharply overlain by mesobreccia and other ejecta.

6e [UTM: 663,535E/5,329,100] Gray lapillistone and sandstone (Fig. 12).

Figure 12. Graphic sedimentological analysis of interbedded lapillistone and sandstone outcrop (Fralick).
STOP 7 - Paleoproterozoic Sudbury impact layer, basal Rove Formation, and Mesoproterozoic Logan Intrusion.

Location: UTM: 665,200E/5,329,300N

Description: This outcrop affords a great number and variety of views of the ejecta and breccia (Fig. 13) because the exposed surface is nearly parallel with strike and dip of formations. The stratigraphic sequence is similar to that at Stop 5; however, this site lies along the top of the deposit, showing the relationship between ejecta and breccia more clearly. Just to the south is the Logan sill that was traversed at Stop 5, underlain by about 10 feet of slate and graywacke inferred to be the basal section of the Rove Formation.

Figure 13. Breccia irregularly overlain by a “skin” of lapillistone.

REFERENCES


Davis, D.W., 2008, Sub-million-year age resolution of Precambrian igneous events by thermal extraction-thermal ionization mass spectrometer Pb dating of zircon: Application to crystallization of the Sudbury impact melt sheet: Geology, 36:383-396.


www.unb.ca/passc/ImpactDatabase (and references therein) Website describing 176 meteorite impact structures world-wide. Developed and maintained by Planetary and Space Science Centre, University of New Brunswick, Fredericton, New Brunswick, Canada.