Welcome to the Ontario Geological Survey Virtual Field Trip exploring the **Geology of the Sudbury Impact Structure**.

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This field trip is based on the Sudbury Structure field trips that have been given for over 20 years by the Sudbury District Office of the Ontario Geological Survey, Resident Geologist Program, and recent work in the southwest Sudbury Structure by Gordon et al. We lean heavily on the Sudbury geology field guides by Rousell and Brown (2009), Bleeker et al. (2022), and references therein. Many other works are used, and these will be listed in the references at the end of the trip.

The Sudbury Structure, a remnant of a 1.85 billion year old impact crater, is located in northern Ontario, Canada, 400 kilometres north of Toronto. It is one of the oldest, largest and best-preserved impact structures on Earth. Although not the focus of this virtual field trip, Sudbury is host to one of the largest magmatic nickel-copper-platinum group element mining camps in the world.

The Sudbury impact occurred 1.85 billion years ago. The impact area consisted of Archean rocks of the Superior Province's Levack Gneiss and Ramsey–Algoma Granitoid complexes overlain by Proterozoic rocks of the supracrustal Huronian Supergroup of the Southern Province.

Numerous mafic intrusive suites intrude the basement and/or Huronian Supergroup rocks, the most voluminous of the area being the Matachewan dike swarm, Nipissing Intrusive Suite and East Bull Lake Suite.

On impact, the crater formed, a large volume of rock melted and large volumes of solid and melted rock were ejected.

The shock waves continued to impact the target rocks. The pseudotachylite or Sudbury Breccia, footwall breccias and Sublayer were formed.

In mere minutes, rebound and rim collapse began.

Uplift and rim collapse slowed. Impact-related features in the footwall continued to form. Initial injection of impact melt dikes into the footwall occurred.

The crater and melt sheet stabilized. Crater walls slumped. Fall-back breccias formed.

Local readjustments, cooling and fall back continued. The cooling melt sheet began to differentiate. Subsequent injection of impact melt dikes into the footwall occurred.

1.85 billion years later, this is a schema of the cross section of the remnant impact crater.

On surface, the remnant impact crater is 60 kilometres long and 30 kilometres wide. It has been deformed (folded and faulted) and eroded over the past 1.85 billion years to give an ovoid shape.

Bleeker et al. (2022) have made an approximate determination on the location of ground zero of the impact based on their work and the impact ring structures defined by Butler (1994). Ground zero is outside and south of the current configuration of the Sudbury Igneous Complex. The final crater diameter is postulated to be approximately 300 kilometres.

The remnant crater is visible on satellite imagery and has a distinct magnetic signature.

In a simplified stratigraphic section, the footwall rocks are overlain by the Main Mass of the Sudbury Igneous Complex. The footwall contains rock types associated with the impact, such as footwall breccias and pseudotachylite called Sudbury Breccia, and exhibits evidence of the impact.

The Sudbury Igneous Complex consists of the Sublayer and the Main Mass. The Sublayer occurs as breccias at the contact between the footwall and the Main Mass, and as quartz diorite dikes called Offset dikes. These are the impact melt dikes. The Main Mass consists of, from bottom to top, norite, quartz gabbro and granophyre.

The Sudbury Igneous Complex is overlain by the Whitewater Group. The basal formation being the Onaping Formation: impact fallback, debris flows and crater wall slump. The overlying formations are crater-fill sediments unrelated to the actual impact.

We will be visiting a cross section of the impact-related rocks, from the impact evidence in the footwall, through the units of the Sublayer and the Main Mass, ending with the Onaping Formation.

**Effects of the Sudbury Impact Event on the Footwall Rocks of the Sudbury Structure.**

Footwall rocks of the Sudbury Structure are defined as rock units affected by deformational and metamorphic features related to the Sudbury impact event. Based on this classification, the footwall extends from 9 up to 80 kilometres from the contact of the Main Mass of the Sudbury Igneous Complex.

The passage of high-pressure, high-velocity shock waves from impacting meteorites causes permanent changes in the footwall rocks. This is known as shock metamorphism.

Effects of shock metamorphism include planar crystal deformation features in minerals and unique fracture patterns called shatter cones. These features are critical to the identification of impact structures because of their uniqueness, wide distribution and ease of identification.

Shatter cones were first identified in the Sudbury area in the 1960s. They are conical fracture surfaces that formed from the impact-related high-pressure shock waves passing through the rock. The distinct cone shape is defined by striations and ridges radiating outward from an apex.

Shatter cones, shown here as circles, are abundant in the Sudbury area and have been identified up to 17 kilometres away from the contact of the Sudbury Igneous Complex. The trend of the axes, shown with black arrows, exhibit various orientations. Different orientations are attributed to the interference of a series of shock fronts during initial formation and with post-impact folding and faulting of the footwall rocks.

Shatter cones can occur in all rocks around the Sudbury Igneous Complex that predate the impact event, but form best in structurally isotropic lithologies. They are most commonly observed in quartzites of the Mississagi Formation of the Huronian Supergroup shown here.

Shatter cones range from a few centimetres to several metres in size. In the Sudbury area, shatter cones up to 3 metres long have been observed.

Here is an example of shatter cones that formed in diamictites of the Ramsay Lake Formation of the Huronian Supergroup. They exhibit different orientations within the same outcrop.

Shatter cones provided some of the earliest evidence supporting a meteorite impact origin for the Sudbury Structure.

**Breccias in the Footwall Rocks of the Sudbury Structure.**

There are 2 types of impact-related breccias that occur within the footwall of the Sudbury Structure. These are locally known as Sudbury Breccia and Footwall Breccia.

Sudbury Breccia formed through shock-induced melting or cataclasis of footwall rocks during cratering. All rock types in the Sudbury area that are older than the impact event contain various amounts of Sudbury Breccia. Sudbury Breccia is abundant within 15 kilometres of the Sudbury Igneous Complex contact and present as scattered and isolated exposures up to 80 kilometres from the contact. Sudbury Breccia is typically localized along lithological contacts and structural weaknesses within the footwall rocks.

Sudbury Breccia has an aphanitic to microcrystalline matrix that is fragmental or pseudotachylitic and variably recrystallized. It contains millimetre- to metre-sized clasts that are generally locally derived, with some exotic material.

This is an example of pseudotachylitic Sudbury Breccia that intruded the Creighton Pluton. Clasts are commonly equant with subrounded to subangular shapes. The contact between matrix and clasts is very sharp.

The colour of the matrix can be very dark, almost black, to green and even greenish yellow as seen here.

This is an example of a clastic Sudbury Breccia vein in quartzites of the Mississagi Formation of the Huronian Supergroup. The breccia matrix exhibits flow-surface patterns that resemble sheath folds.

Sudbury Breccia occurs as discontinuous veins or irregular shaped bodies within the footwall rocks.

Size ranges from millimetre-scale veinlets to breccia belts that are hundreds of metres thick and tens of kilometres in length.

Sudbury Breccia can be matrix or clast supported and contain monolithic, bilithic and heterolitihic clasts mainly derived from local footwall rocks. Sudbury Breccia is interpreted to be the earliest impact breccia as it is crosscut by all other impact-related lithologies.

There is field evidence for at least 2 generations of Sudbury Breccia.

At this outcrop, earlier, clast-poor Sudbury Breccia veinlets within quartzites of the Stobie Formation of the Huronian Supergroup are crosscut by a second generation of Sudbury Breccia that is clast rich.

Sudbury Breccia is of great economic importance in the Sudbury area as it is host to several significant nickel-copper-PGE* deposits.

The second type of impact-related breccia that occurs within the footwall of the Sudbury Structure is known as Footwall Breccia.

Footwall Breccia has many names, it has been referred to as “leucocratic breccia”, “late granite breccia” and “metabreccia”. Footwall Breccia is one of the most puzzling rock types in the Sudbury area. How it formed is not fully understood, but has been attributed to metamorphic recrystallization, partial melting and deformation of target rocks.

Footwall Breccia occurs in discontinuous lenses and sheets at the base of the Main Mass of the Sudbury Igneous Complex and along Offset dikes.

It is a heterolithic breccia and contains fragments mainly of local footwall rocks with some exotic inclusions. Clasts of Sudbury Breccia have been identified locally supporting the interpretation that Footwall Breccia formed afterwards.

*PGE = platinum group elements

Footwall Breccia has a crystalline matrix that varies greatly in grain size, composition and texture. It is highly dependent on the proximity to the Sudbury Igneous Complex contact and what the local footwall rocks are. The matrix is sub-igneous at the contact with the Sudbury Igneous Complex and has a metamorphic character with increased distance from the contact.

Here is an example of Footwall Breccia from the North Range. It has a pink, recrystallized granitic matrix. It contains angular to subrounded clasts of local footwall from the Levack Gneiss Complex. It ranges from matrix to clast supported.

In the South Range, Footwall Breccia developed in rocks of the Huronian Supergroup and is very different from that seen in the North Range.

Here is an example of Footwall Breccia from the Crean Hill area where metavolcanic and metasedimentary rocks of the Stobie Formation are crosscut by dikes and pods of Footwall Breccia.

The breccia matrix ranges from felsic to mafic in composition with intermingled combinations present as well.

In general, the Footwall Breccia matrix is fine to medium grained and has a granoblastic texture.

Here is an example of felsic breccia in contact with a mafic breccia with abundant felsic clasts in sharp contact with metabasalt of the Stobie Formation.

Here is another example of a felsic breccia dike in sharp contact with metabasalt of the Stobie Formation.

The breccias range from clast poor to clast rich. They contain rounded to irregularly shaped clasts of basalt, dacite and arenite. This Footwall Breccia has a mafic matrix and contains abundant clasts of basalt and arenite.

The contact relationships between the different breccias is complicated. They are frequently sharp and crosscut each other as well as the brecciated footwall rocks, but can be gradational.

Sulphide mineralization is associated with specific breccia compositions.

Another possible variation of Footwall Breccia is present in the South Range where the Sudbury Igneous Complex is in contact with the Drury Township intrusion of the East Bull Lake Suite.

This breccia has a recrystallized anorthositic matrix which contains sulphide mineralization.

It is matrix supported and hosts abundant centimetre-sized mafic clasts.

Footwall Breccia is another very important economic unit as it hosts many of Sudbury's nickel-copper-platinum group element deposits.

Moving into the Sudbury Igneous Complex. The Sublayer is below the melt sheet and consists of the Contact Sublayer and the Offset quartz diorite dikes. The Contact Sublayer is at the contact between the footwall rocks and the melt sheet. That is to say, on the crater floor. The Offset quartz diorite dikes, as the name implies, intrude into the footwall.

We'll look at the Contact Sublayer first.

The contacts of the Contact Sublayer can be sharp or gradational. It's an inclusion- or xenolith-bearing igneous-textured gabbronorite. The inclusions or xenoliths can be norite, or lithologies from the footwall. It forms discontinuous lenses or sheets along the contact, preferentially occurring in troughs and embayments. The Sublayer hosts the contact nickel deposits in Sudbury, but not all Sublayer is mineralized. This is an example of unmineralized norite breccia Sublayer. Here, dark norite fragments are in a slightly more felsic gabbronorite matrix.

This is an example of the mineralized norite breccia Sublayer. This outcrop is the Discovery Outcrop for the Sudbury nickel camp. The true discovery outcrop has been mined out (of course), but this outcrop is near that site and is a protected historic site. The rusty weathering, or gossaning, from the oxidation of the sulphides masks the fragmental nature of the rock.

Up close and on a fresh surface, the igneous texture is visible. As is the sulphide mineralization. Here, we can see the sulphides forming the matrix of the breccia, enveloping the fragments.

Now let's look at the Offset dikes which are the impact melt-bearing dikes that extend into the footwall.

Offset dikes form thin, subvertical intrusions that extend up to 20 kilometres into the underlying footwall rocks of the Sudbury Structure. They can be radial, concentric or discontinuous.

The radial Offset dikes extend outwards from the contact of the Sudbury Igneous Complex. The concentric Offset dikes are oriented subparallel to, but away from, the contact of the Sudbury Igneous Complex. The discontinuous Offset dikes are radial or concentric and hosted within Sudbury Breccia.

The following photos and videos are of the Whistle, Parkin, Worthington, Copper Cliff and Trill Offset dikes.

Offset dikes are composite intrusions consisting of a central core of inclusion- and sulphide-bearing quartz diorite, locally referred to as "IQD", flanked by sulphide-poor and inclusion-poor quartz diorite, locally referred to as “QD”. These 2 phases were emplaced through multiple injections. The initial phase of inclusion-poor QD was followed by injection of the sulphide-enriched IQD.

Here is an example of the two phases as seen at the Worthington Offset dike.

The contacts between the QD[*] and IQD[*] phases are sharp, but can be gradational.

The contact between Offset dikes and footwall rocks is typically sharp.

Here the quartz diorite of the Copper Cliff Offset dike is in contact with rhyolite of the Copper Cliff Formation of the Huronian Supergroup. The contact is sharp and abundant fragments of the Copper Cliff rhyolite are entrained within the quartz diorite.

Quartz diorite in the QD phase of Offset dikes is overall medium grained and homogeneous. It locally exhibits spherulites indicative of quench textures formed during the cooling of the superheated melt. Here is an example of spherulitic amphiboles after pyroxene from the Whistle Offset.

This is the heterolithic, sulphide-bearing IQD at the Parkin Offset.

IQD is heterolithic and contains inclusions of angular to subrounded clasts derived mainly from local country rock. Inclusions are enclosed in a massive, medium-grained quartz diorite matrix.

Clasts of QD are commonly present within the IQD phase as seen here at the Worthington Offset dike. This is an important piece of evidence for the relative timing of the 2 phases.

Here is the contact between QD and sulphide-poor IQD at the Trill Offset.

Clasts of QD are abundant within the IQD phase.

The matrix of IQD is mineralogically similar to the QD phase, but, overall, finer grained and more granular in texture.

Clasts in the IQD vary in size from less than 1 millimetre to tens of metres.

Offset dikes host some of the largest and richest ore deposits in Sudbury.

We’re now going to visit the Main Mass or melt sheet of the Sudbury Igneous Complex. It is a gradational sequence of igneous rocks ranging from 2.5 to 5 kilometres thick. At the base is the Norite unit, a medium- to coarse-grained, cumulate-textured, two-pyroxene gabbronorite with variable amounts of quartz (up to 15%). The intermediate unit is a two-pyroxene quartz gabbro with quartz ranging from 15 to 60%, generally

[*]QD = sulphide-poor and inclusion-poor quartz diorite;
IQD = inclusion- and sulphide-bearing quartz diorite.

increasing upward, but not in a constant manner. Both lower and upper contacts are gradational. The upper unit of the Sudbury Igneous Complex is the granophyre. Granophyric intergrowth of quartz-plagioclase-potassium feldspar are modally predominant in the unit. The general ratio of norite to gabbro to granophyre is 25 to 15 to 60.

Starting with the norite.

Where the Sublayer is mineralized, the norite above it will contain sulphides as we see here. This outcrop is immediately above the Discovery Outcrop.

As we move farther from the Sublayer, the norite loses most of the sulphides. There are variations and complexities in the norite unit, but it can also be massive and homogenous, as in this example.

The norite exhibits typical mafic intrusive textures in outcrop. As mentioned earlier, it is a medium- to coarse-grained, cumulate-textured, two-pyroxene gabbronorite with up to 15% quartz.

Up-section, we move into the quartz gabbro.

The transition from norite to gabbro is gradational. The gabbro unit is a two-pyroxene quartz-gabbro with quartz ranging from 15 to 60%. It forms a thin section of the Sudbury Igneous Complex. Remember the norite–gabbro–granophyre ratio is 25:15:60.

The uppermost unit of the Sudbury Igneous Complex is the granophyre. So named because of its dominant granophyric texture.

But before we look at the common granophyre, the gabbro–granophyre transition exhibits spectacular dendritic and acicular amphibole crystals. The amphibole crystals can range from 1 to 50 centimetres in length. This unit is included in the granophyre, and the term Crow’s Foot Granophyre has been coined for this subunit.

The more common granophyre, however, is more equigranular. There are variations in grain size and mineral proportions within the unit, but sometimes it’s homogeneous as seen here.

The granophyre generally has about 60% quartz or quartz–plagioclase–potassium feldspar intergrowths. Of course, the granophyric texture that gives rise to the name of the unit is not visible on outcrop.

The Onaping Formation of the Whitewater Group was deposited on top of the Sudbury Igneous Complex or melt sheet. It consists of fall-back breccia and debris flows emplaced shortly after the impact. The fall-back breccia is the material that was ejected by the force of the impact, both solid target rock fragments and melted material. The Onaping Formation has an estimated thickness of 1.6 to 1.8 kilometres.

The Onaping Formation fall-back breccia is a chaotic fragmental rock.

Originally, it was interpreted as volcanic in origin, because of the presence of shards, glassy-rimmed fragments and lithic-cored bombs. However, a few features in this unit identify it as of impact origin. The most compelling evidence is geochemical or microscopic: the presence of an iridium anomaly, the presence of “impact diamonds” and fragments containing shock metamorphosed quartz. On outcrop, we observe the glassy-rimmed, often angular, fragments and a lithic cored “bomb”.

We’ve come to the end of our Virtual Field Trip of the Sudbury Impact Structure.

We hope you enjoyed viewing these unique and complex rocks that were created, or modified, by the Sudbury impact.

As we said in the beginning, this field trip and the information presented is based on the work of many talented researchers.

The selected references shown here is available as a downloadable PDF from the GeologyOntario Web site along with this video.

At this point, we would like to thank everyone who has helped us pull together this virtual field trip. In particular, we’d like to thank our field assistants and colleagues at the Ontario Geological Survey.

And we have an extra special shout out to our silent co-author, Patrick Gervais. You didn’t hear his actual voice, but his “voice” is in every still shot, video and musical interlude.

It has been our pleasure to take you on this journey, and we hope you have enjoyed the experience.