9-1-2012

Using Microstratigraphy and Stromatolite Clastic Behavior to Characterize the Emplacement of the Sudbury Impact Layer in Ontario and Minnesota

Melissa Maslowski
Winona State University

James Reed
Winona State University

Thomas Stromback
Winona State University

Candace Kairies-Beatty
Winona State University

Nancy Peterson
Grants and Sponsored Projects Office

Re: Student Research Reports for
Melissa Maslowski
James Reed
Thomas Stromback

May 7, 2013

Dear Ms. Peterson –

Please find attached the undergraduate research report documents for Melissa Maslowski, James Reed, and Thomas Stromback. These three students worked on the Sudbury Impact Layer deposits in northern Minnesota and Thunder Bay, Ontario, over this past year with Drs. Candace L. Kairies Beatty, W. Lee Beatty, and Jennifer L. B. Anderson in the Geoscience Department.

These three students (along with Mallery Navis and Christina Slowinski for a total of $3000) were awarded undergraduate research funds to support their impact-cratering related projects in February 2012. These funds were used to support their field work in May 2013 at their outcrops in northern Minnesota and Thunder Bay, Ontario.

In addition, these three students were awarded a total of $1000 to support their travel to Houston, TX, to present their work at the Lunar & Planetary Science Conference in March 2013.

Please find attached a Research Project Abstract and Summary form for each of the three students along with their co-authored LPSC abstract and the poster they presented at that conference. They also presented their poster at the Ramaley Research Celebration and gave a talk as a part of the Geoscience Department's Earth Talks Series in April 2013.

If you have any further questions, please feel free to contact one of us.

Thank you for your continued support of undergraduate research at WSU!

Sincerely,
Jennifer L. B. Anderson
Candace L. Kairies Beatty
W. Lee Beatty

RESEARCH / CREATIVE PROJECT ABSTRACT / EXECUTIVE SUMMARY
FINAL REPORT FORM

Title of Project
Stratigraphic characterization of Sudbury Ejecta - Outcrop Suite A

Student Name Melissa Maslowski

Faculty Sponsor W. Lee Beatty, Jennifer L.B. Anderson, and Candace L. Kairies Beatty

Department Geoscience

Abstract
Melissa completed field work at the Sudbury Impact Layer deposits in Thunder Bay, Ontario, in May 2012. She spent the fall semester examining her photos and rock samples in hand sample and thin section. In addition, she continued her background research into stromatolites and ejecta deposition.

Melissa submitted a co-authored abstract about her work and that of James Reed and Thomas Stromback at the Sudbury Impact Layer to the Lunar & Planetary Science Conference in January 2013. She attended the LPSC in March 2013 and presented as part of that conference as well as the Undergraduate Research conference held the Sunday prior to LPSC.

Melissa, Jim, and Tom presented their poster at the Ramaley Research Celebration in April 2013. Melissa, Jim, and Tom also gave a combined talk about their research as part of the Geoscience Department's Earth Talks series in April 2013.

Melissa's Earth Talks slides, LPSC abstract, and poster are attached.

Thank you for supporting undergraduate research!

The end product of this project in electronic format has been submitted to the Provost/Vice President for Academic Affairs via the Office of Grants & Sponsored Projects Officer (Maxwell 161, npeterson@winona.edu).

Student Signature ______________________ Date ______________

Faculty Sponsor Signature ______________________ Date ______________

RESEARCH / CREATIVE PROJECT ABSTRACT / EXECUTIVE SUMMARY
FINAL REPORT FORM

Title of Project
Stratigraphic Characterization of Sudbury Ejecta -- Outcrop Suite B

Student Name James Reed

Faculty Sponsor Jennifer L.B. Anderson, W. Lee Beatty, and Candace L. Kairies Beatty

Department Geoscience

Abstract
Jim completed field work at the Sudbury Impact Layer deposits in the Gunflint Lake area of Northern MN in May 2012. He spent the fall semester examining his photos and rock samples in hand sample and thin section and creating a stratigraphic column of his outcrop. In addition, he continued his background research into ejecta deposition.

Jim submitted a co-authored abstract about his work as well as that of Melissa Maslowski and Thomas Stromback at the Sudbury Impact Layer to the Lunar & Planetary Science Conference in January 2013. He attended the LPSC in March 2013 and presented as part of that conference as well as the Undergraduate Research conference held the Sunday prior to LPSC.

Jim, Melissa and Tom presented their poster at the Ramaley Research Celebration in April 2013. Jim, Melissa, and Tom also gave a combined talk about their research as part of the Geoscience Department's Earth Talks series in April 2013.

Jim's Earth Talks slides, LPSC abstract, and poster are attached.

Thank you for supporting undergraduate research!

The end product of this project in electronic format has been submitted to the Provost/Vice President for Academic Affairs via the Office of Grants & Sponsored Projects Officer (Maxwell 161, npeterson@winona.edu).

Student Signature ______________________ Date ______________

Faculty Sponsor Signature ______________________ Date ______________

Appendix C

RESEARCH / CREATIVE PROJECT ABSTRACT / EXECUTIVE SUMMARY
FINAL REPORT FORM

Title of Project
Stratigraphic Characterization and Visualizing the Sudbury Ejecta Deposits in Northern Minnesota -- Outcrop Suite C

Student Name Thomas Stromback

Faculty Sponsor Candace L. Kairies Beatty, Jennifer L.B. Anderson, and W. Lee Beatty,

Department Geoscience

Abstract
Tom completed field work at the Sudbury Impact Layer deposits in the Gunflint Lake area of Northern MN in May 2012. He spent the fall semester examining his photos and rock samples in hand sample and thin section and creating a stratigraphic column of his outcrop. In addition, he continued his background research into ejecta deposition.

Tom submitted a co-authored abstract about his work as well as that of Melissa Maslowski and James Reed at the Sudbury Impact Layer to the Lunar & Planetary Science Conference in January 2013. He attended the LPSC in March 2013 and presented as part of that conference as well as the Undergraduate Research conference held the Sunday prior to LPSC.

Tom, Jim, and Melissa presented their poster at the Ramaley Research Celebration in April 2013. Tom, Jim, and Melissa also gave a combined talk about their research as part of the Geoscience Department's Earth Talks series in April 2013.

Tom's Earth Talks slides, LPSC abstract, and poster are attached.

Thank you for supporting undergraduate research!

The end product of this project in electronic format has been submitted to the Provost/Vice President for Academic Affairs via the Office of Grants & Sponsored Projects Officer (Maxwell 161, npeterson@winona.edu).

Student Signature ______________________ Date ______________

Faculty Sponsor Signature ______________________ Date ______________

Using Microstratigraphy and Stromatolite Clastic Behavior to Characterize the Emplacement of the Sudbury Impact Layer in Ontario and Minnesota. J.P. Reed, M.L. Maslowski, T.J. Stromback, W.L. Beatty, C.L. Kairies Beatty, and J.L.B. Anderson, Department of Geoscience, Winona State University, Winona, MN. (corresponding author: JLAnderson@winona.edu)

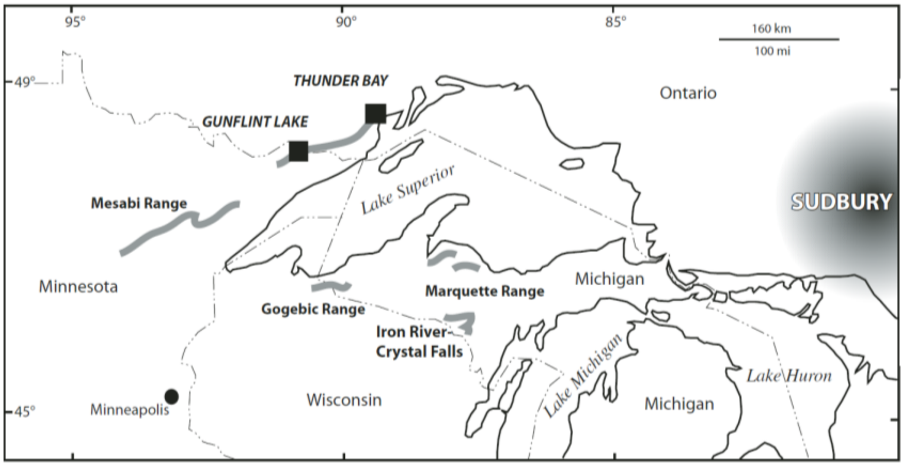


Figure 1. Location of Sudbury Impact Layer (SIL) deposits discussed in this paper (black squares) relative to the Sudbury impact site. (From [1])

Introduction: The Sudbury Impact Layer (SIL) was deposited 1.85 Ga as ejecta from the Sudbury impact event in Sudbury, Ontario, was deposited over the upper Midwest and Canada [2]. The SIL has been identified in outcrop and core samples up to 950 km away from the Sudbury crater in southern Ontario [2], northern Minnesota [2,3], and the upper peninsula of Michigan [4,5] (Figure 1). Following the general description of [1], a typical SIL sequence includes a shocked mega- and meso-breccia at its base comprised of deformed country rock (in the outcrops we observed, banded iron formations sometimes including stromatolites), a gritstone boundary layer, and a thinner ejecta layer with larger lapillistones (Figure 2) beneath smaller spherules (Figure 3). The SIL is unique in that the unit (up to 30 m thick in some places) formed in less than one day and preserves an incredibly detailed record of distal ejecta emplacement from one of the largest known impact events on Earth.

We are currently working on two lines of research at the SIL outcrops in Thunder Bay, Ontario, and near Gunflint Lake in northern Minnesota. First, we are examining the behavior of lithofied stromatolites as “quasi-clasts” during the deformation, brecciation, and mixing of local banded iron formations as the shock wave passed and ejecta was deposited. Second, we are analyzing the microstratigraphy of the lapilli-bearing ejecta layers at two outcrops near Gunflint Lake, MN, to better define the processes at work when the ejecta was deposited.

Figure 2. Example of larger lapilli found near Gunflint Lake, MN, some with concentric zoning. These are generally observed above the breccia and below the spherules (Figure 3).

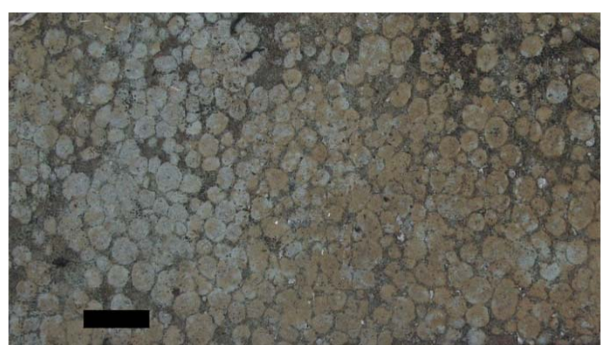


Figure 3. Example of spherules found near Gunflint Lake, MN. Scale bar is 1 cm.

Methods – Stromatolites: Stromatolite-bearing SIL deposits in the Thunder Bay, Ontario area were noted by previous researchers[1,2], but the stromatolites in these outcrops were not examined in detail. For this investigation, stromatolites at three outcrops were cataloged. High-resolution panoramas of two of the outcrops were captured using a GigaPan Epic robotic camera mount. Samples were collected from float at two of the outcrops.

Methods – Microstratigraphy: Two outcrops near Gunflint Lake, MN, showing the transition from ejecta-absent to ejecta-bearing layers within the SIL were selected for this study. Each outcrop was carefully measured and described in detail. Representative samples from the transition and ejecta-bearing layers were collected. A high-resolution panorama of each outcrop was captured using a GigaPan Epic robotic camera mount. Hand samples were cut and scanned at high resolution to observe the structural characteristics of the transition from ejecta-absent to ejecta-bearing units as well as the number, size and shape distribution of lapilli (Figure 4). Petrographic thin sections of these samples are also being prepared.

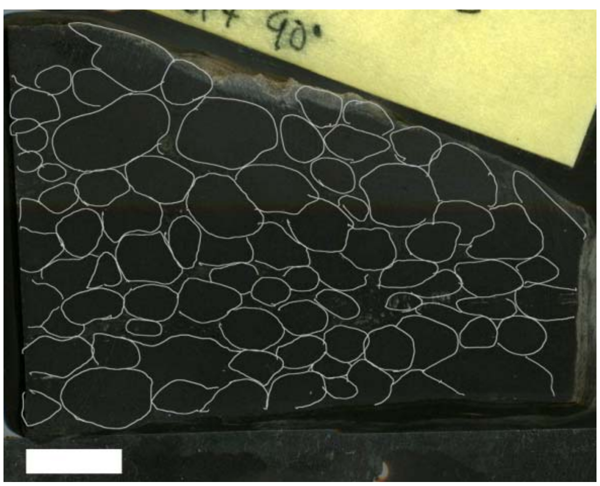


Figure 4. Cross-section of a lapilli-bearing sample (Gunflint Lake, MN) with outlined lapilli. Scale bar is 1 cm.

Preliminary Results – Stromatolites: We observed two types of stromatolite growth forms: laterally linked hemispheroids (LLH) and stacked hemispheroids (SH), after [6]. At two of the outcrops we observed stromatolites *in situ* showing evidence of truncation. A hemispheroidal stromatolite in one of the hand samples appears to have been truncated abruptly and covered with a mix of lapilli and mm-scale breccia (Figure 5). Other stromatolites of both morphologies appear to have been entrained in the ejecta curtain and deposited as clasts in the SIL.

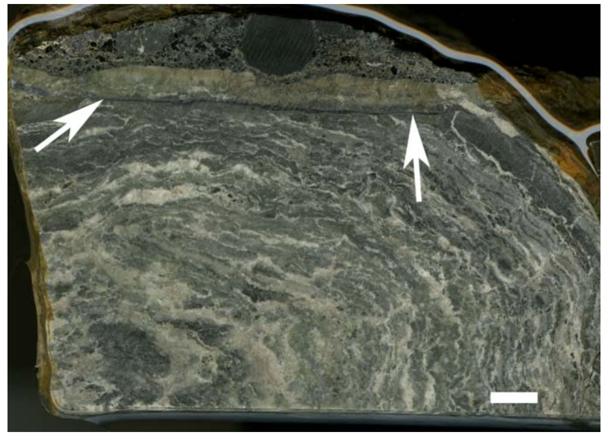


Figure 5. Cross-section of a hemispheroidal stromatolite from the SIL (Thunder Bay, Ontario) showing sharp truncation (arrows). Note large lapilli and breccia above truncation. Scale bar is 1 cm.

Preliminary Results – Microstratigraphy: Most lapilli observed in hand samples appear to be oval-shaped rather than spherical (Figure 4). Lapilli in some hand samples also appear to be somewhat imbricated.

Future work – Stromatolites: We will examine petrographic thin sections of the stromatolite shown in Figure 5 to better characterize the planed boundary and ejecta deposit. We will also investigate the distribution of stromatolites within the SIL breccia to discern possible patterns of deposition based on clast size and morphology.

Future Work – Microstratigraphy: We will complete an analysis of the size and shape distribution of lapilli and spherules in thin section. We will also prepare large- and small-scale stratigraphic sections of the SIL outcrops and attempt to correlate the two.

References: [1] Jirsa, MA, et al. (2011) *GSA Field Guide 24*, p. 147-169, doi:10.1130/2011.0024(08). [2] Addison, WD, et al. (2005) *Geology, v. 33*, doi:10.1130/G21048.1. [3] Jirsa, MA (2010) *Inst. of Lake Superior Geology: 56th Annual Meeting, v. 56*. [4] Pufahl, PK, et al. (2007) *Geology, v. 35*, p. 827-830. [5] Cannon, WF, et al. (2010) *GSA Bull., v. 122*, doi:10.1130/B26517.1. [6] Logan. BW, et al. (1964) *The Journal of Geology*, p. 68-83.

Acknowledgements: We would like to give special thanks to Dr. Mark Jirsa and Dr. Paul Weiblen of the MN Geological Survey and Dr. Phillip Frahlick of Lakehead University, Thunder Bay, Ontario. This project is funded by a WSU Undergraduate Student Research Award as well as WSU Faculty Professional Improvement Funds.

WINONA STATE UNIVERSITY

Using Microstratigraphy and Stromatolite Clastic Behavior to Characterize the Emplacement of the Sudbury Impact Layer in Ontario and Minnesota.

J.P. Reed, M.L. Maslowski, T.J. Stromback, W.L. Beatty, C.L. Kairies Beatty, and J.L.B. Anderson,
Department of Geoscience, Winona State University, Winona, MN. (corresponding author: JLAnderson@winona.edu)

WINONA STATE UNIVERSITY GEOSCIENCE

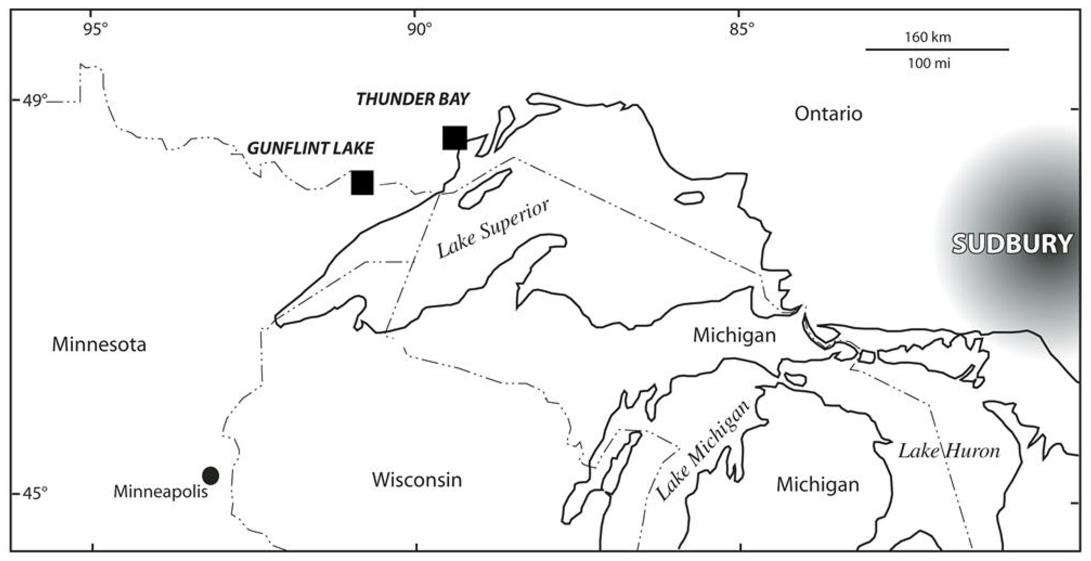


Figure 1. Location of Sudbury Impact Layer (SIL) deposits discussed here (black squares) relative to the Sudbury impact site. (Adapted from [1])

Introduction

Ejecta from the Sudbury impact event in Sudbury, Ontario (1.85 Ga) was recently identified in outcrop in the upper Midwest [2,3] and Canada [2] (Figure 1). These deposits, known as the Sudbury Impact Layer (SIL), are unique in that the unit formed in less than one day and preserves an incredibly detailed record of distal ejecta emplacement from one of the largest known impact events on Earth. We present here two ongoing lines of research at the SIL deposits: (1) Deformation of local banded-iron formations containing lithified stromatolites that occurred as the initial shock wave passed and (2) microstratigraphy of the transition from non-ejecta-bearing to ejecta-bearing layers to better define their emplacement.

Discussion — Potential Deposition Scenario

Our observations at these two field areas support previous interpretations of the deposition of the SIL in Jirsa *et al.* [1], Branney & Brown [4], and Addison *et al.* [5]. Two minutes after the impact at Sudbury, the seismic wave arrived in Ontario and northern Minnesota [3], brecciating the local Gunflint Iron Formation. An advancing base surge preceded the ejecta cloud, planing the bedrock and truncating stromatolites in the process (Figures 2, 3). Large Iron Formation clasts were entrained in the surge and randomly redeposited (Figure 4).

Evidence suggests that the ejecta cloud did not behave in a ballistic fashion, but was similar to a wall of debris, entrained clasts and ash. Turbulence within the cloud provided the conditions under which concentrically zoned lapilli were formed [4] (Figures 3B, 5B, 6B, 6C, 7C). As this mass moved across the surface, ash, lapilli and bedrock clasts were deposited on the sheared bedrock, as observed in Thunder Bay (Figures 2B, 3) and northern Minnesota (Figures 7A, 7C, 7D, 7E, 7F).

The nature of the deposits varied from outcrop to outcrop. The five outcrops discussed here display evidence of at least four different depositional scenarios, some within a few kilometers of each other. Larger "lapilli" are present in Thunder Bay and in Gunflint Lake (Figures 3, 7C), while smaller "spherules" are observed only at Gunflint Lake (Figures 7D, 7E). At some outcrops, lapilli are deposited directly on breccia (Figures 2B, 7). At others, layers of fine-grained ignimbrite lie below lapilli (Figure 7F). Some lapilli-bearing layers are clast-supported (Figure 5B, 7C), while other spherule-bearing layers are thinly interbedded with ignimbrite (Figure 7D). These differences make correlation difficult and suggest that the emplacement mechanism(s) were more complex than those responsible for most sedimentary and volcaniclastic deposits.

Interpretation of the SIL deposits at Gunflint Lake is further complicated by contact metamorphism from the overlying Logan Intrusions (1.115 Ga). Metamorphism at Gunflint Lake appears to have resulted in lapilli that are compacted when compared to lapilli from unmetamorphosed Thunder Bay deposits (Table 1). It may also be the cause of pressure-solution features that appear in Gunflint Lake rocks (Figure 5).

Table 1. Lapilli size and flattening in Gunflint Lake and Thunder Bay deposits.

Location:	Gunflint	Thunder Bay
Avg. Lapilli Grain Size:	4.61 +/- 1.42 mm	7.37 +/- 3.15 mm
Avg. Flattening:	43 +/- 15 %	19 +/- 13 %

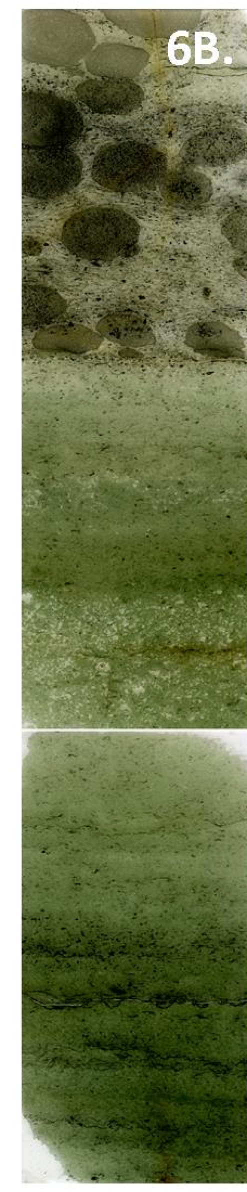
Acknowledgements: We would like to give special thanks to Dr. Mark Jirsa and Dr. Paul Weiblen of the MN Geological Survey and Dr. Phillip Frahlick of Lakehead University, Thunder Bay, Ontario. This project is funded by a WSU Undergraduate Student Research Award, Undergraduate Student Travel Award, and Faculty Professional Improvement Funds. Partial funding for LPSC was provided by NASA's Science Mission Directorate through the YSS Undergraduate Conference.

References: [1] Jirsa, MA, et al. (2011) *GSA Field Guide 24*, p. 147-169, doi:10.1130/2011.0024(08). [2] Addison, WD, et al. (2005) *Geology, v. 33*, doi:10.1130/G21048.1. [3] Jirsa, MA (2010) *Inst. of Lake Superior Geology: 56th Annual Meeting, v. 56*. [4] Branney, MJ & Brown, RJ (2011) J. Geology, v. 119, p. 275-292. [5] Addison, WD et al. (2010) in GSA Special Paper 465, p. 245-268. [6] Logan, BW, et al. (1964) *The Journal of Geology*, p. 68-83.

DEPOSITION OF FRACTURED BEDROCK, ASH, LAPILLI AND SPHERULES

Lapilli

4.5—12 cm outcrop thickness
(Figures 6B, 6C)
Dark gray lapilli (0.5-1.5 cm diameter) in a light gray/green ignimbrite matrix. Some lapilli display concentric zoning and are shortened vertically. This bed sharply contacts the underlying facies.



Ignimbrite

11.5-37 cm outcrop thickness
(lower part of Figure 6B)

A light green-gray silty deposit containing numerous dark green laminar beds ranging from 0.5-35mm thick. The laminar beds consist of very fine, angular, crystalline grains. Locally, the middle of the section displays minor upward thickening of these beds. This unit sharply contacts the overlying lapilli. A rip-up clast of bedded ignimbrite can be found in overlying lapilli. A green, well-sorted, sub-rounded to rounded medium to coarse sand, 0.5cm thick is found locally at the top of this bed.

Mesobreccia

23-33 cm outcrop thickness
(Figure 6A)
A matrix-supported breccia with 0.2-3 cm, sub-rounded to sub-angular clasts in an ironstone matrix. Matrix and clast orientation display semi-ductile horizontal flow features. Contact with underlying megabreccia is not consistently sharp, and is derived from clast size and prominence of flow features.

Megabreccia

8-14 cm outcrop thickness
(Figure 7, at outcrop GF005)
A heavily weathered, matrix-supported breccia with unsorted, angular chert clasts (4-25 cm) in an ironstone matrix that appears to be deformed in a ductile manner. Much larger clasts (up to 5 m), have been found in this unit [1].

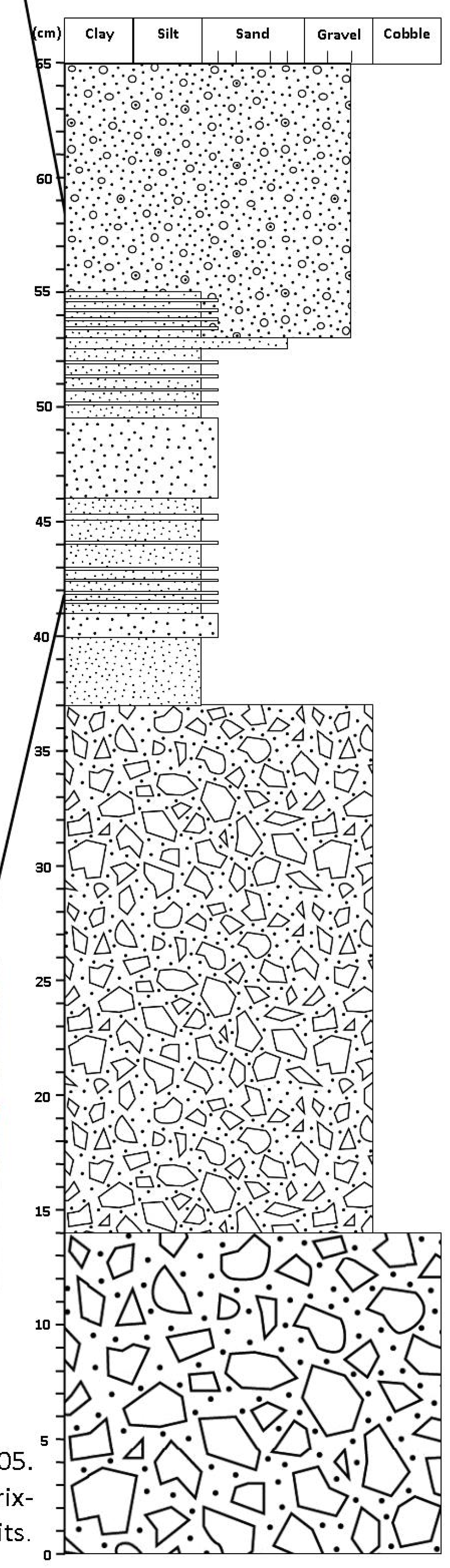


Figure 6. Stratigraphy of Outcrop GF005. Grain size based on size of clasts in matrix-supported units.

UPPER UNIT — Gunflint Lake

← GF005 is 1.6 km West of GF003 →

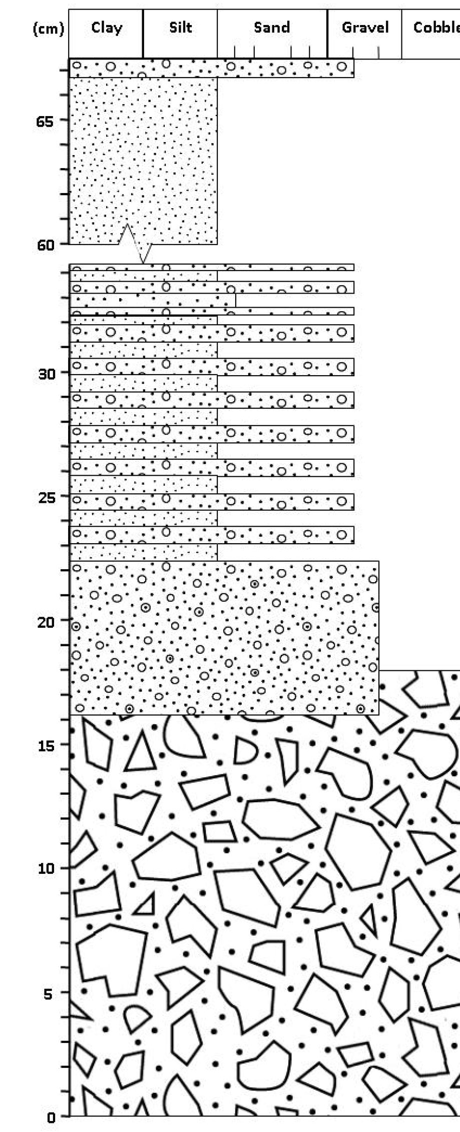
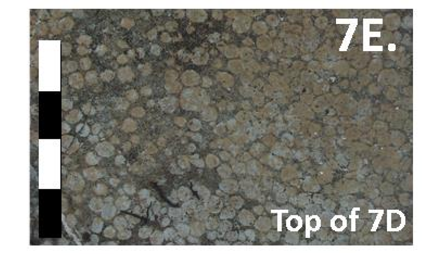
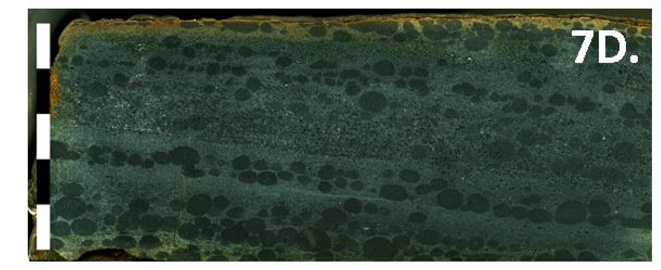


Figure 7. Stratigraphy of Outcrop GF005. Grain size based on size of clasts in matrix-supported units.

Spherules interbedded with Ignimbrite

> 27 cm outcrop thickness
(Figures 7D, 7E and 7F)
Lenses of dark green/gray semi-spherical to oval spherules interbedded with ignimbrite at semi-regular intervals. Spherules are distinguished from lapilli by their small size (0.2-1.0 cm) and lack of zoning.



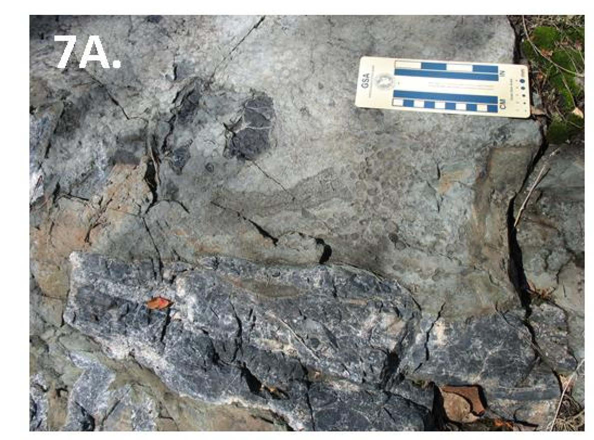


Lapilli

6 cm outcrop thickness (Figure 7C)
Dark gray/green lapilli (0.4-1.5 cm) supported by a weathered light gray/green ignimbrite. The lapilli are oval to spherical. The largest of the lapilli display concentric zoning (up to 2 rings).

Megabreccia

(Figures 7A and 7B)
Brittle deformation of bedrock and ductile or flow features are particularly evident at this outcrop. Approximately one meter thickness of the top of the megabreccia is exposed here. Chert clasts range from 5-72 cm.



Gunflint Lake Pressure Solution Features

Lapilli and ignimbrite facies in samples of the SIL from Gunflint Lake show evidence of what appear to be pressure solution features, including stylolites (Figures 5A, 5B, 5D), concave-convex grain contacts (Figure 5B, 5D) and volume loss (Figure 5C, 5D).

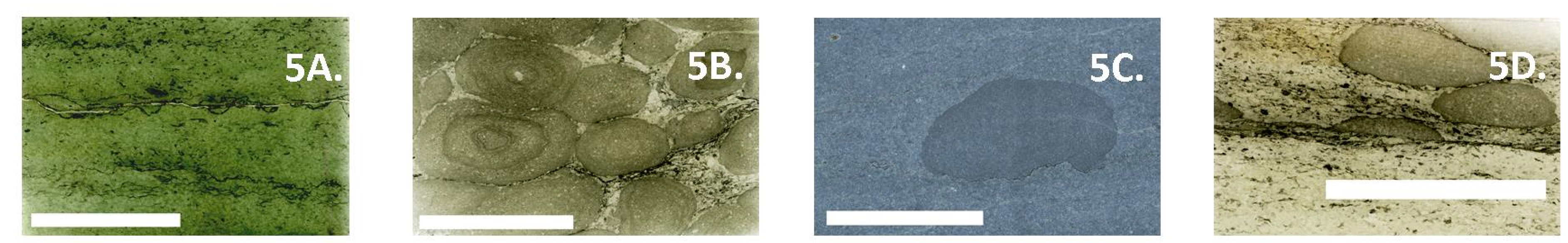
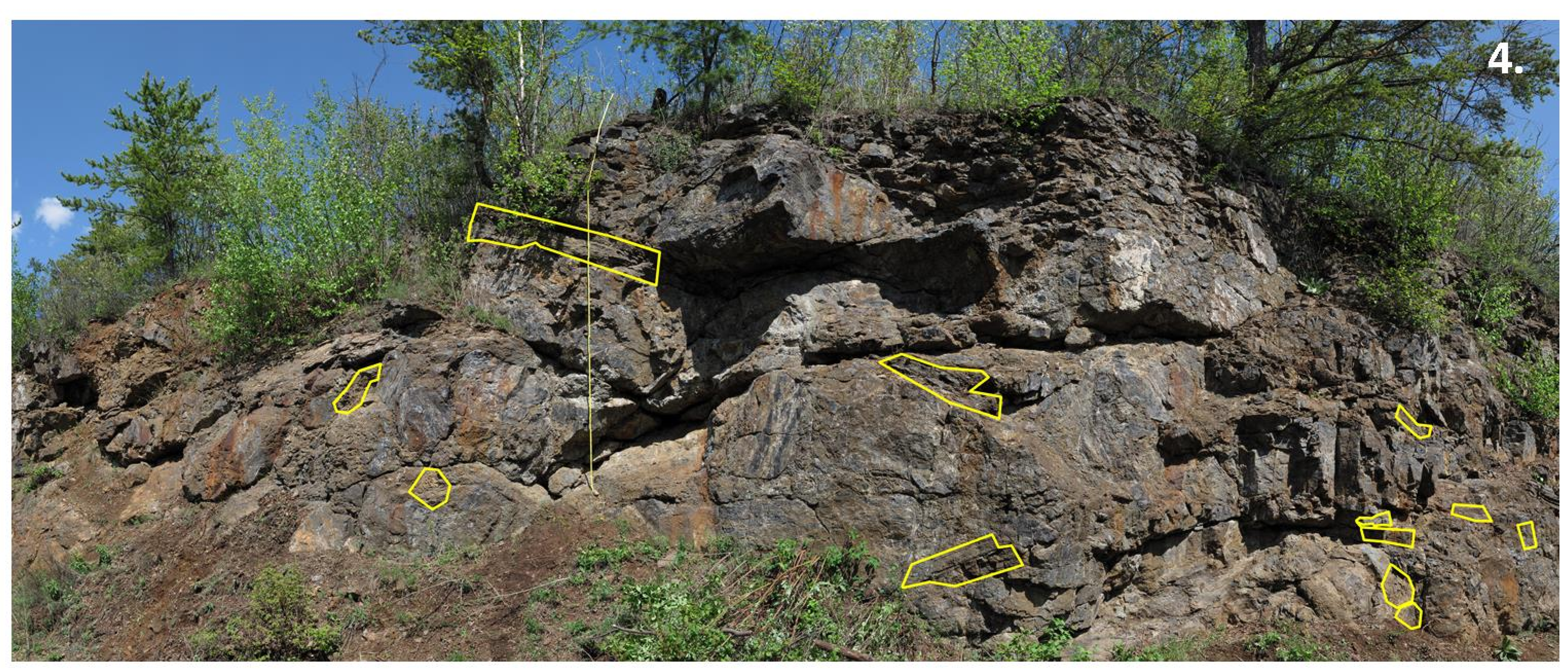


Figure 5. Apparent pressure solution features in Gunflint Lake SIL rocks. **A.** Stylolites in ignimbrite, Outcrop GF005. **B.** Stylolites and concave-convex grain contacts in lapilli-bearing unit, Outcrop GF005. **C.** Volume loss in lapilli-bearing unit, Outcrop GF003. **D.** Stylolites, concave-convex grain contacts and volume loss in lapilli-bearing unit, Outcrop GF005. All scale bars equal 1 cm.

BEDROCK PLANING AND ENTRAINMENT



BASAL UNIT — Thunder Bay

Stromatolites (sedimentary structures built by photosynthesizing bacteria) are common in several outcrops of the Gunflint Formation in Thunder Bay, Ontario. Many display laterally-linked hemispheroidal (LLH) and stacked hemispheroidal (SH) morphologies that are useful in determining their original orientation [6]. Examination of stromatolite orientations at three outcrops in the Thunder Bay area suggests two primary mechanisms of bedrock deformation related to the Sudbury impact: (1) Truncation or planing of the upper layers of bedrock (Figures 2, 3) and (2) entrainment and deposition of bedrock clasts (Figure 4). These imply that the base surge and lower portion of the ejecta cloud was energetic enough to plane off the country rock and turbulent enough to entrain large (> 1 m) blocks and redeposit them.

◄ **Figure 4.** LLH-SH stromatolite-bearing boulders at the Grand Trunk Pacific Railroad site [5]. Major stromatolite-bearing blocks outlined in yellow show the random orientation of clasts in this deposit. Outcrop height is approximately 6 m.

View the GigaPan panorama of this outcrop at www.gigapan.com/gigapans/114729

Figure 2. ◄ **A.** Map view of the Private Drive outcrop [5] showing truncated LLH-SH stromatolites. ▲**B.** Same outcrop in cross-section, truncated in situ LLH-SH stromatolites overlain by ejecta.

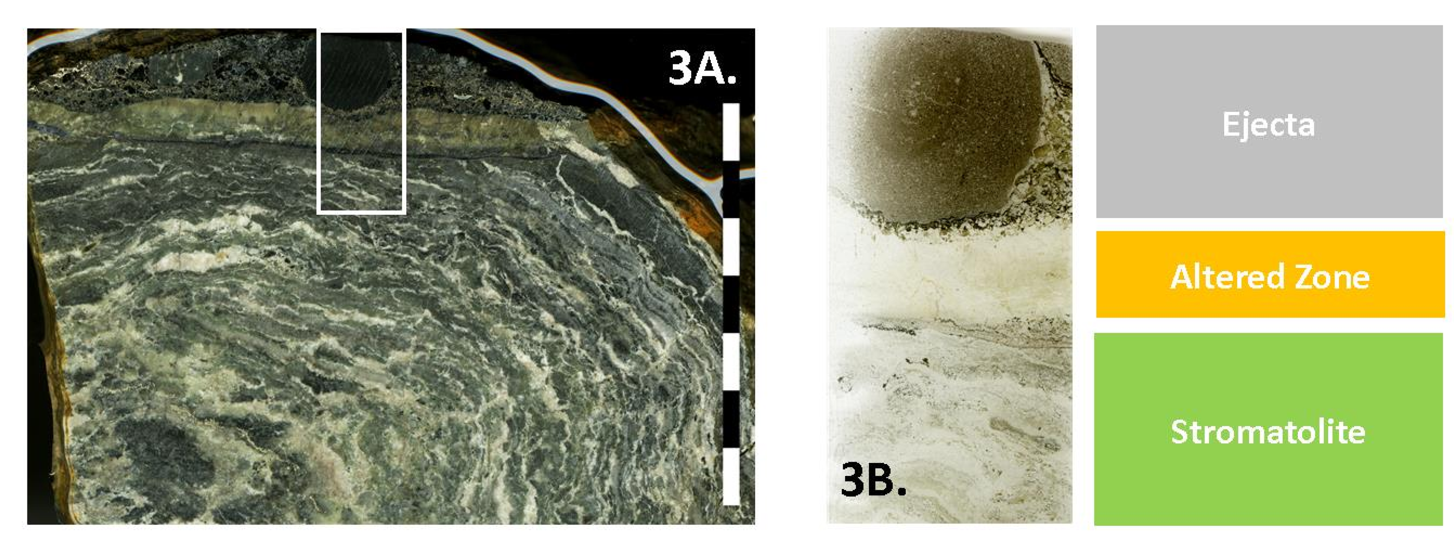


Figure 3. A. Cross-section of truncated SH stromatolite from Highway 588 outcrop [5]. B. Inset of A. showing the contact between truncated cherty stromatolite and overlying ejecta deposit. Note the zone of alteration and the large concentrically-zoned lapilli resting unconformably on the planed stromatolite.

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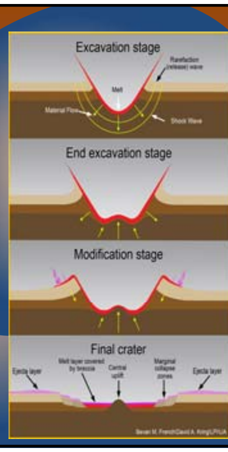
J.P. Reed, M.L. Maslowski, T.J. Stromback,
W.L. Beatty, C.L. Kairies Beatty, and J.L.B. Anderson

Introduction

- Impact Cratering Introduction
- What is Sudbury?
- Thunder Bay Work
- Gunflint Work
- Summary and Interpretations

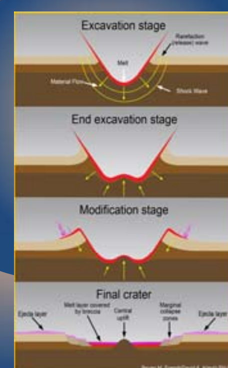
What is Impact Cratering?

- Dominant geologic process in our solar system
- Formed when a meteor or comet strikes a planetary body
- High velocities cause a pit, or crater, while also fracturing the surrounding rock.



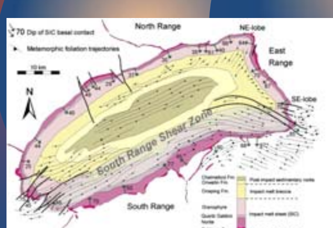
Ejecta Blanket Formation

- The impact strikes the Earth. Fireball occurs 13 seconds in.
- Melting & vaporization. A shock wave is generated throughout (2-3 minutes, 10.9-13 at epicenter).
- Target material is pushed down and out. Flow direction is bent up. (5-10 minutes).
- Highly shocked, fast moving material leaves the surface near the impact point (Sonic boom 40 minutes).
- As the crater grows, material velocity slows.



What is the Sudbury Impact?

- 1.85 Ga
- One of the largest, and one of the oldest
- Meteor diameter ~10-15km
- Shallow sea
- Anoxic Earth



Why Study Sudbury?

- Large
- Well preserved crater
- Well-preserved ejecta blanket (SIL)
  - Atmosphere?

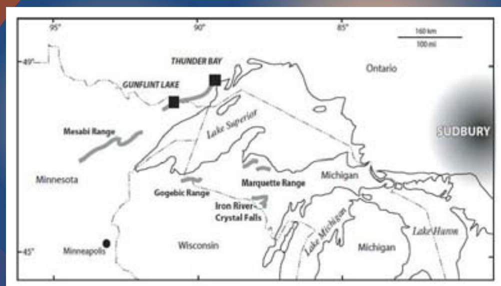
Ejecta Breccia

The Sudbury Impact Layer (SIL) is characterized by:

- Chaotically folded and brecciated Iron Formation
- Exotic material that has been fragmented, liquefied, and/or vaporized.

Lapilli/Spherules

Field Sites



Location of SIL deposits relative to the Sudbury Impact Layer (SIL).

What is a Stromatolite?

- Accretionary structures
- Formed by blue-green algae mats
- Earliest non-microscopic fossils identified

Why are stromatolites important?

- Four common growth forms, two seen in Thunder Bay
  - Laterally-linked hemispheroidal (LLH) and stacked hemispheroidal (SH)
- Stromatolites are useful indicators
  - Environment at time of deposition
  - Orientation (way up)

Thunder Bay Work

Private Drive & Highway 588 outcrops:

- Stratigraphically lowest outcrops
- Show evidence of truncation

Thunder Bay Work

Grand Trunk Pacific Railroad outcrop:

- Show evidence of entrainment and deposition of bedrock clasts.

Gigapan showing LLH-SH stromatolite-bearing boulders at the Grand Trunk Pacific Railroad site. Yellow outlines show random orientation of clasts in this deposit. Outcrop height is approximately 6 m.

Gigapan image can be viewed at www.gigapan.com/gigapans/114729

Gunflint Site

- 750 km West of the Sudbury Impact
- Around 150 km SW from The Thunder Bay Outcrop
- Looked at two different outcrops within the Gunflint Lake Region
  - GF-003 "Tom's outcrop"
  - GF-005 "Jim's outcrop"
  - 1.6 km apart

General Geology

- This area is part of the Gunflint Iron Formation
- The upper portion of the Gunflint Iron Formation has been incorporated within the SIL (Sudbury Impact Layer)
  - SIL ranges up to 30m thick
  - Composed of shocked mega and meso-breccia of the deformed country rock
    - (Ironstone matrix and chert clast)
  - Overlain by the Sudbury ejecta cloud
  - Entire area has been contact metamorphosed by the Logan Intrusions (1.115 Ga).

SIL units

- Non-Ejecta Bearing
  - Mega-Breccia
  - Meso-Breccia
- Ejecta Bearing
  - Ignimbrite
  - Lapilli
  - Spherules

Mega-Breccia

- Large disorganized, broken up pieces of rock that is cemented together by a finer grained material.

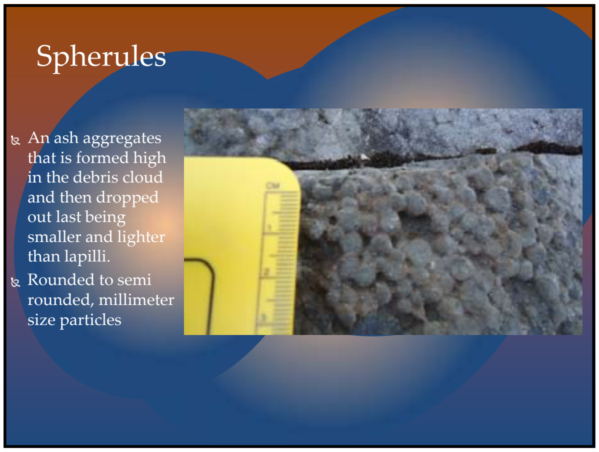
Meso-Breccia

Ignimbrite (Ash)

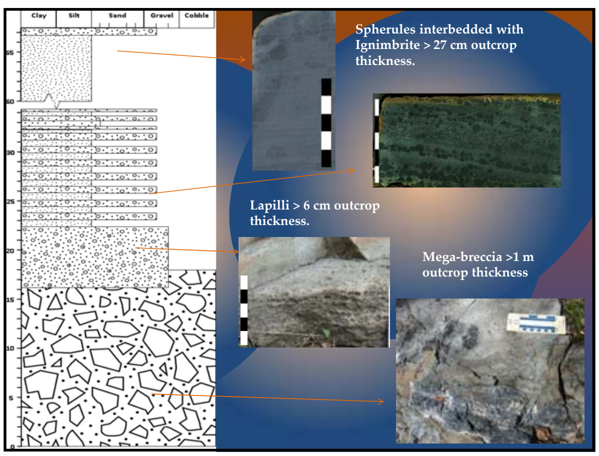
- Volcanic term for a consolidated rock from a pyroclastic flow
- In our case from the debris cloud that is similar to a pyroclastic flow but on orders of magnitude larger

Lapilli

- Partially solidified ash aggregates that accumulate more ash particles as it's picked up in the debris cloud
- Millimeters to centimeters in size with concentric laminations around an ash core
- Usually rounded to semi-rounded in shape

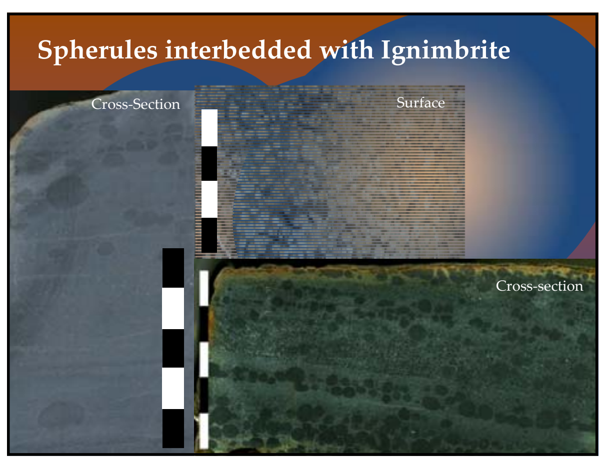

Spherules
An ash aggregates that is formed high in the debris cloud and then dropped out last being smaller and lighter than lapilli.
Rounded to semi rounded, millimeter size particles


Spherules
Lapilli
Mega-Breccia


Clay
Silt
Sand
Gravel
Cobble
Spherules interbedded with Ignimbrite > 27 cm outcrop thickness.
Lapilli > 6 cm outcrop thickness.
Mega-breccia >1 m outcrop thickness


Mega-Breccia


Lapilli


Spherules interbedded with Ignimbrite
Cross-Section
Surface
Cross-section

Gunflint Outcrop 005

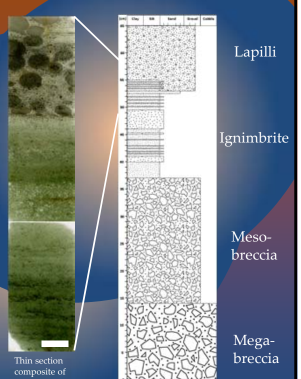
- Non-ejecta & ejecta bearing units
- Lateral variation of all units at outcrop scale

Non-Ejecta bearing units

Stratigraphic Column of GF-005

Ejecta bearing units

- Lapilli absent from lower ignimbrite unit.
- Spherules found up-section near outcrop.
- Grain size of ash aggregates (spherules & lapilli) grade normally, decreasing up-section.



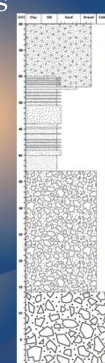
Thin section composite of ignimbrite and lapilli. *Scale bar is 1 cm.

Stratigraphic Column of GF-005

Comparison of Gunflint Outcrops

- Upper and lower members present
- Varying unit thicknesses
- Discontinuous units
- Lapilli distribution in ignimbrite unit varies

Stratigraphic Column of GF-003



Stratigraphic Column of GF-005

Post-Impact Events

1.) Fireball
2.) Shockwave
3.) Base Surge (Density Current)
4.) Air Blast

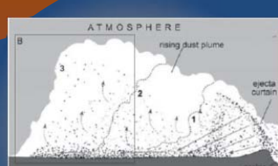


Diagram of stages of base surge and ejecta entrainment in ensuing debris cloud.

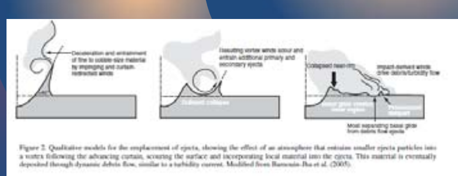


Diagram of ejecta curtain and base surge formation.

Shockwave

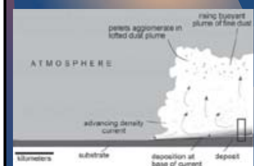
- 10.9 – 13 magnitude earthquake at epicenter in Sudbury Ontario.
- Brittle deformation of bedrock in both Thunder Bay and then Gunflint Lake.

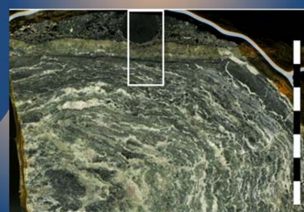
Uppermost section of shocked mega-breccia at oblique outcrop 003 in Gunflint Lake. Approx. outcrop width is 5 m.

Basal unit of shocked mega-breccia containing outlined stomatolites in Thunder Bay, Ontario. *Approx.outcrop height is 6 m.

Base Surge

- Leading edge of base surge planes bedrock and brecciated stromatolites in Thunder Bay.
- Initial base surge eventually forms drop out deposits of accretionary lapilli and ignimbrite over sheared bedrock.

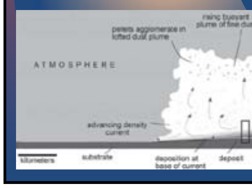


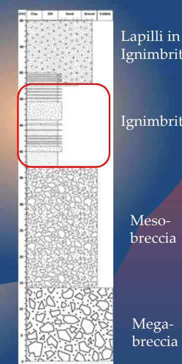


Cross section and thin section of sheared stromatolite. *Scale in cm.

Base Surge

- Formation of stratified debris cloud:
  - Lower, stronger currents promote accretion of ash (accretionary lapilli).
  - Upper, weaker currents form smaller ash aggregates (spherules).
- Initially, ignimbrite (ash), is continuously deposited.





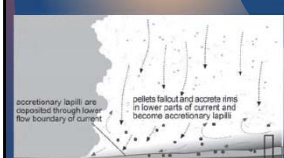
Stratigraphic Column of GF-005

Base Surge

- Some accretionary lapilli accumulate in lower currents, depositing above and with ash.
- Absence of lapilli in lower ignimbrite unit.

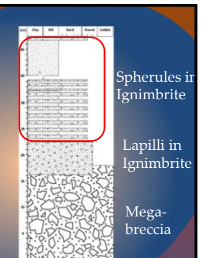
Thin section composite of ignimbrite and lapilli. *Scale bar is 1 cm.

Stratigraphic Column of GF-005

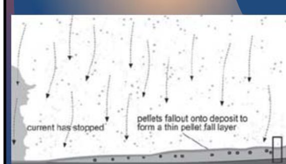


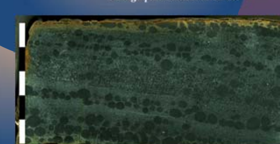
Debris Cloud Fallout

- Base surge has passed.
- Ash deposition continues from debris cloud.
- Spherules deposit last, above lapilli.



Stratigraphic Column of GF-003





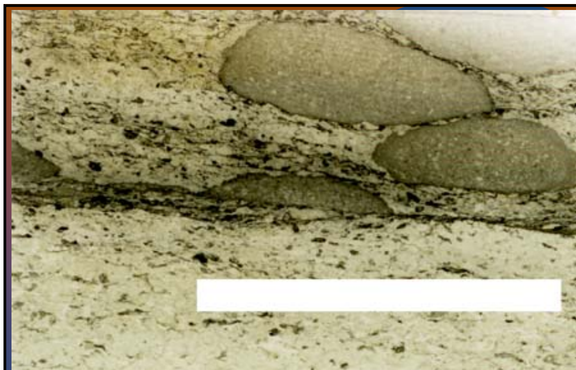
Spherule lenses in ignimbrite at GF-003. *Scale is in cm.

Pressure Solution Features

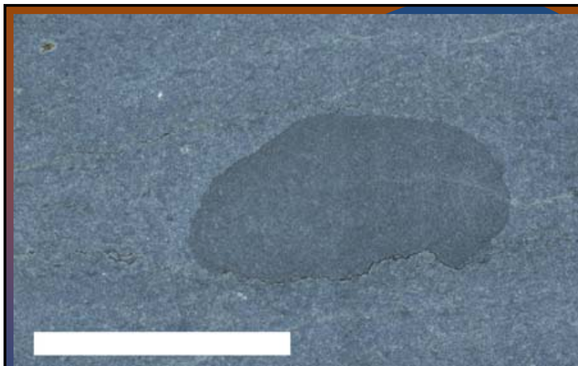
- Under great pressure, grains undergo dissolution where they can contact other grains, resulting in:
  - Stylolites: Jagged, irregular seams perpendicular to direction of pressure.
  - Concave/convex relationships: Grains press into one another.
  - Missing mass: Grains can be dissolved along stylolite seams.

Thin section of stylolites in ignimbrite.
*Scale bar is 1 cm.

Thin section of convex/concave contacts in concentrically zoned accretionary lapilli.
*Scale bar is 1 cm.

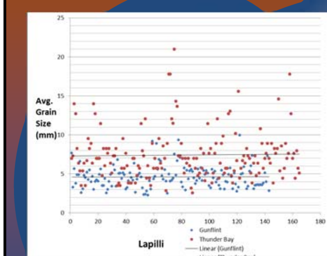


Thin section of lapilli missing mass, cut by stylolite.
*Scale bar is 1 cm.



Thin section of ash pellet (spherule), missing mass, cut by stylolite.
*Scale bar is 1 cm.

Lapilli Variation Between G.F. and T.B.



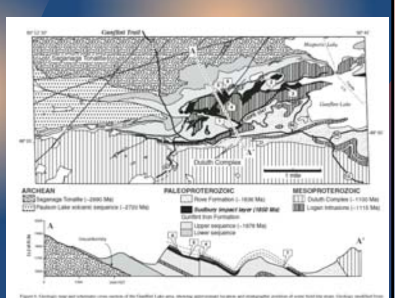
Graph 1: Average lapilli grain size between Gunflint and Thunder Bay.

Location:	Gunflint	Thunder Bay
Avg. Lapilli Grain Size:	4.61 +/- 1.42 mm	7.37 +/- 3.15 mm
Avg. Flattening:	43 +/- 15 %	19 +/- 13 %

Table 1: Lapilli size and flattening in Gunflint Lake and Thunder Bay Deposits.

Post-Depositional Events

- Burial
  - Rove Formation 1.836 Ga
- Contact metamorphism
  - Logan Intrusions 1.115 Ga



Conclusions

- Ejecta-bearing SIL deposits consistent with those from other large impacts and volcaniclastic processes associated with deposition mechanisms for a base surge/debris flow.
- No evidence for ballistic emplacement of ejecta is present.
- Topography may have influenced distribution of debris flow deposits.
- Contact metamorphism and burial has altered deposits at Gunflint Lake to a certain extent.

Acknowledgements

We would like to give special thanks to:

Dr. Anderson, Dr. Beatty, Dr. Kairies Beatty
Luke Zwiefelhofer
Dr. Mark Jirsa and Dr. Paul Weiblen of the MN Geological Survey
Dr. Phillip Frahlick of Lakehead University, Thunder Bay, Ontario
Emily CoBabe-Amman – NASA Education and Outreach

This project is funded by a WSU Undergraduate Student Research Award as well as WSU Faculty Professional Improvement Funds.