Discovery of distal ejecta from the 1850 Ma Sudbury impact event

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ABSTRACT

A 25–70-cm-thick, laterally correlative layer near the contact between the Paleoproterozoic sedimentary Gunflint Iron Formation and overlying Rove Formation and between the Biwabik Iron Formation and overlying Virginia Formation, western Lake Superior region, contains shocked quartz and feldspar grains found within accretionary lapilli, accreted grain clusters, and spherule masses, demonstrating that the layer contains hypervelocity impact ejecta. Zircon geochronologic data from tuffaceous horizons bracketing the layer reveal that it formed between ca. 1878 Ma and 1836 Ma. The Sudbury impact event, which occurred 650–875 km to the east at 1850 ± 1 Ma, is therefore the likely ejecta source, making these the oldest ejecta linked to a specific impact. Shock features, particularly planar deformation features, are remarkably well preserved in localized zones within the ejecta, whereas in other zones, mineral replacement, primarily carbonate, has significantly altered or destroyed ejecta features.

Keywords: Sudbury impactite, distal ejecta, precise U-Pb dates, Gunflint and Biwabik Formations, Ontario, Minnesota.

INTRODUCTION

Robert Dietz (Dietz, 1964) first proposed that the Sudbury structure, Canada, was generated by a hypervelocity impact; it is currently listed as the second-largest (diameter ~260 km) known Earth impact site (Spray et al, 2004) and, at 1850 ± 1 Ma (Krogh et al., 1984), likely the third oldest (Earth Impact Database, 2004). Still, a key question remains: Where are the distal ejecta? An impact of this size should have generated an ejecta layer over much of Earth, but it has not been located, except perhaps in Greenland (Chadwick et al., 2001).

The southern part of western Ontario, Canada, and northern Minnesota, Wisconsin, and Michigan, United States, ca. 1878 Ma (Fralick et al., 2002), constituted a broad south-facing continental shelf (the Animikie Shelf) on which the Gunflint Iron Formation of Ontario and Minnesota and the Biwabik Iron Formation of Minnesota formed (Fralick et al., 2002; Ojakangas et al., 2001; Morey and Southwick, 1995) (Fig. 1). Shales of the Rove and Virginia Formations overlie the Gunflint and Biwabik Formations, respectively (Ojakangas et al., 2001; Morey and Southwick, 1995).

North of Lake Superior, most Animikie sedimentary rocks form a homocline dipping ~5° southeast (Floran and Papike, 1975). They have been subject to burial temperatures <150 °C (Stille and Clauer, 1986). The age, location, and depositional environment make the Animikie Shelf a promising area to look for Sudbury ejecta. A search resulted in the discovery of impact-related features present near the probable Gunflint-Rove boundary in the sedimentary succession recovered in three diamond drill cores (PR98-1, BP99-2, MC95-1) in Ontario and two drill cores from near the probable Biwabik-Virginia boundary in Minnesota (LWN99-2, VHB00-1). The Ontario drill holes are ~650 km west-northwest of the center of the Sudbury structure (Fig. 1); the Minnesota holes are ~875 km west of the Sudbury structure. The Minnesota sites are ~260 km southwest of the Ontario sites.

EJECTA BEDS AND FEATURES

The proposed impact-related bed is in the uppermost Gunflint and Biwabik Formations and occurs in a recrystallized and silicified carbonate sequence with alteration possibly related to subaerial exposure (Fig. 2A, 2B). Carbonate layers ~2 m thick occur above the ejecta horizons, which are overlain by Rove Formation or Virginia Formation shales. Specimens from this horizon were examined by using binocular, petrographic, and scanning electron microscopes.

The proposed ejecta layer ranges from ~43 cm to ~70 cm thick in the Ontario drill cores (Fig. 2C). Except for core BP99-2, lower or upper boundaries are poorly defined owing to replacement of ejecta features by carbonate. In the Minnesota cores, the lower boundaries of the layer are better defined, whereas the upper boundaries are less clear, giving ejecta thicknesses from ~25 to ~58 cm.

The most obvious impact feature within this stratum in the Ontario cores is an 11-cm-thick layer of scattered, dark gray, 0.4–2.5-cm-diameter accretionary lapilli near the middle of the layer, making it a useful ejecta marker (Fig. 2C). Accretionary lapilli have central cores

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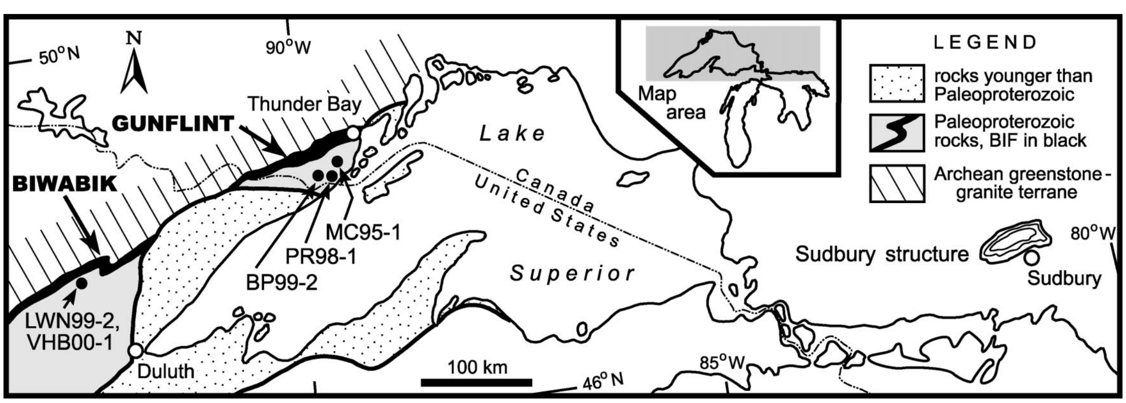

Figure 1. Location of Sudbury structure in relation to Ontario and Minnesota diamond drill holes (Appendix DR1 [see footnote 1 in text] gives sources and coordinates). BIF—banded iron formation.

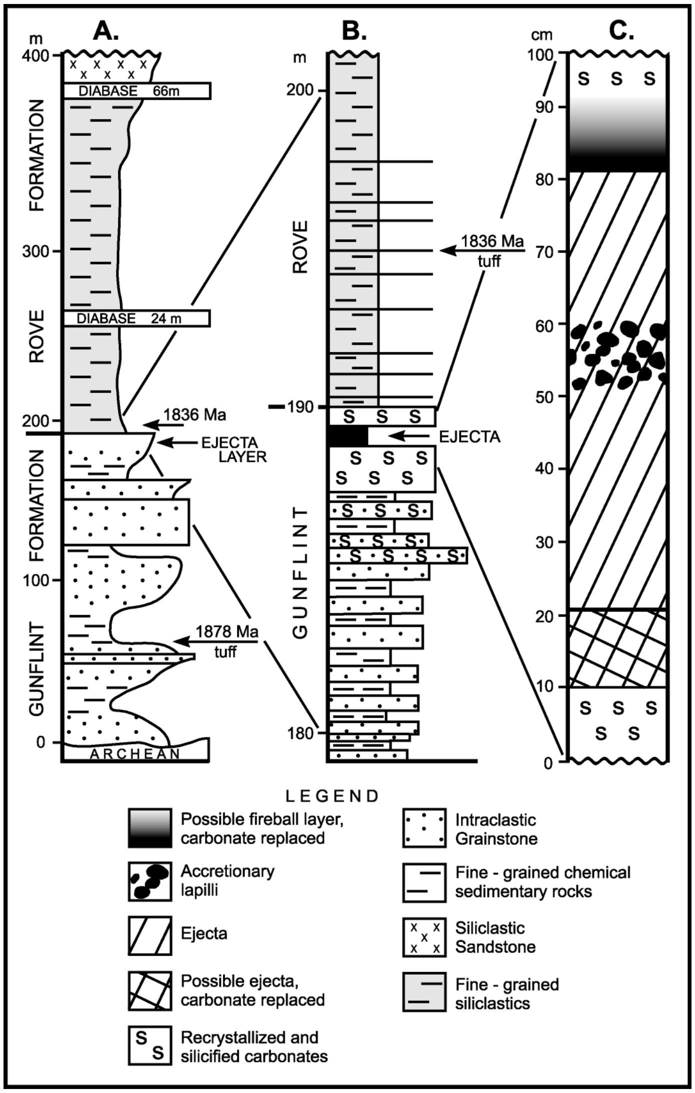

Figure 2. A: Overview of Gunflint and Rove Formations based on drill core 89MC-1. Tuff age of 1878 Ma is from Fralick et al. (2002). B: Detail from column A showing Gunflint-Rove boundary zone and relationship of ejecta to dated Rove tuff. Minnesota cores and other Ontario cores show similar features in this zone. C: Detail of ejecta layer in drill core BP99-2, most complete and least-altered ejecta section in all cores. Possible carbonate-replaced fireball layer fades into overlying carbonate. Minnesota ejecta layers are thinner and lack accretionary lapilli.

of randomly oriented, coarser grains, including quartz and feldspar (as large as 0.8 mm maximum dimension) plus finer material obscured by carbonate replacement. The central cores are surrounded by concentric layers of finer material composed of secondary replacement carbonate and silicate minerals. Accretionary lapilli are also reported from Chicxulub ejecta deposits (Salge et al., 2000). Two or three sets of alternating coarse- and fine-grained layers are present in some accretionary lapilli (Fig. 3A), suggesting multiple accretionary episodes. The Minnesota cores lack accretionary lapilli.

A larger number of accreted grain clusters are also present; their outlines range from smooth to jagged, and their largest dimensions range from 0.3 to 4 mm (Fig. 3B). Accreted grain clusters have randomly oriented grains and grain sizes similar to accretionary lapilli centers, but lack the fine, concentric outer layers. Accreted grain clusters probably fell from the debris cloud before they could accrete the finer, outer material found around accretionary lapilli.

Planar deformation features (PDFs) in shocked quartz and feldspar grains are considered a reliable indicator of hypervelocity impact (French, 1998). Quartz and feldspar grains are, numerically, the most or second-most common ejecta component in the Ontario layers. The following well-preserved planar features were found within the top 60%–70% of the ejecta stratum: single-set and crossed multiple-set decorated PDFs (Fig. 3C); laddered PDFs in feldspar (Fig. 3D); and planar fractures (Fig. 3E) (French, 1998). Most grains with PDFs are located within accretionary lapilli and accreted clusters. Lacking accretionary lapilli, the Minnesota cores contain significantly fewer shocked grains. PDFs are the primary basis for proposing that this layer is ejecta from an impact event.

Another distinctive feature of younger impact ejecta is glassy material, most commonly spherules, and less commonly sphere-within-sphere features (Walkden et al., 2002), also called bubbly spherules (Smit et al., 1996) or vesicular spherules (Stinnesbeck et al., 2001) (Fig. 3F). All probable glass in these ejecta has devitrified, leaving the original structures as smectite or smectite-illite replaced features. These features, in turn, are commonly replaced by carbonate (primarily dolomite, secondarily calcite, rarely ankerite) or, less commonly, silica in the form of chert, chalcedony, and recrystallized quartz. Carbonate replacement of smectite-illite replaced features either destroys features or leaves only outlines or partial outlines of original features (Fig. 3F). Similar carbonate-replaced spherule and microtektite features are reported from Chicxulub ejecta (Smit et al., 2000). Carbonate also replaces silicified features. However, given this material's age, the ejecta features are remarkably well preserved in localized zones not heavily altered by carbonate replacement.

GEOCHRONOLOGICAL CONSTRAINTS

Zircons were not observed in the proposed ejecta layer. However, zircon grains were extracted from a Rove Formation tuffaceous layer at 688.24 m depth in Ontario core PR98-1, ~5.8 m above the probable topmost ejecta. These were dated by using both sensitive high-resolution ion microprobe (SHRIMP) and isotope-dilution thermal-ionization mass spectrometer (ID-TIMS) methods (described in Appendix DR1[1]). Fragile, needle-like zircons and larger euhedral zircons yielded 15 SHRIMP analyses that are $<5\%$ discordant and have $<0.25\%$ common Pb, giving a single age population with a mean of 1827 ± 8 Ma (mean square of weighted deviates, MSWD of 0.82, Fig. 4A; Appendix DR1 [see footnote 1]). We handpicked ~20 euhedral zircon grains from another sample of the same tuffaceous layer and air abraded them for ID-TIMS analyses. Four single-grain analyses of the most undamaged crystals produced one concordant datum and a consistent Pb-loss line (MSWD of 0.3) with a primary crystallization age of 1836 ± 5 Ma (Fig. 4C).

A similar tuffaceous layer from the lower Virginia Formation, ~260 km southwest of the Ontario drill holes, and ~5.1 m above the probable top of the ejecta in Minnesota drill hole VHB00-1, yielded fragile needle-like zircons and larger euhedral zircons that were dated by SHRIMP: 23 analyses are $<5\%$ discordant and give a single age population with a mean of 1832 ± 3 Ma (MSWD of 0.98, Fig. 4B).

The zircon morphologies in both tuff layers suggest in situ magmatic crystallization, and their ages are interpreted to represent eruption and deposition of the tuff layers.

DISCUSSION AND CONCLUSIONS

The Rove and Virginia Formations and the Gunflint and Biwabik Iron Formations are considered correlative (Tanton, 1931; Morey and Southwick, 1995; Ojakangas et al., 2001) because of their stratigraphic similarities and their occurrence on-strike with each other (Fig. 1). However, precise ages to support this correlation have been unavailable

[1]GSA Data Repository item 2005036, Appendix DR1, sample locations, impact-feature photomicrographs, sensitive high-resolution ion microprobe (SHRIMP) procedures and data, zircon photomicrographs, isotope-dilution thermal-ionization mass spectrometer data, and scanning electron microscope data and methodology, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

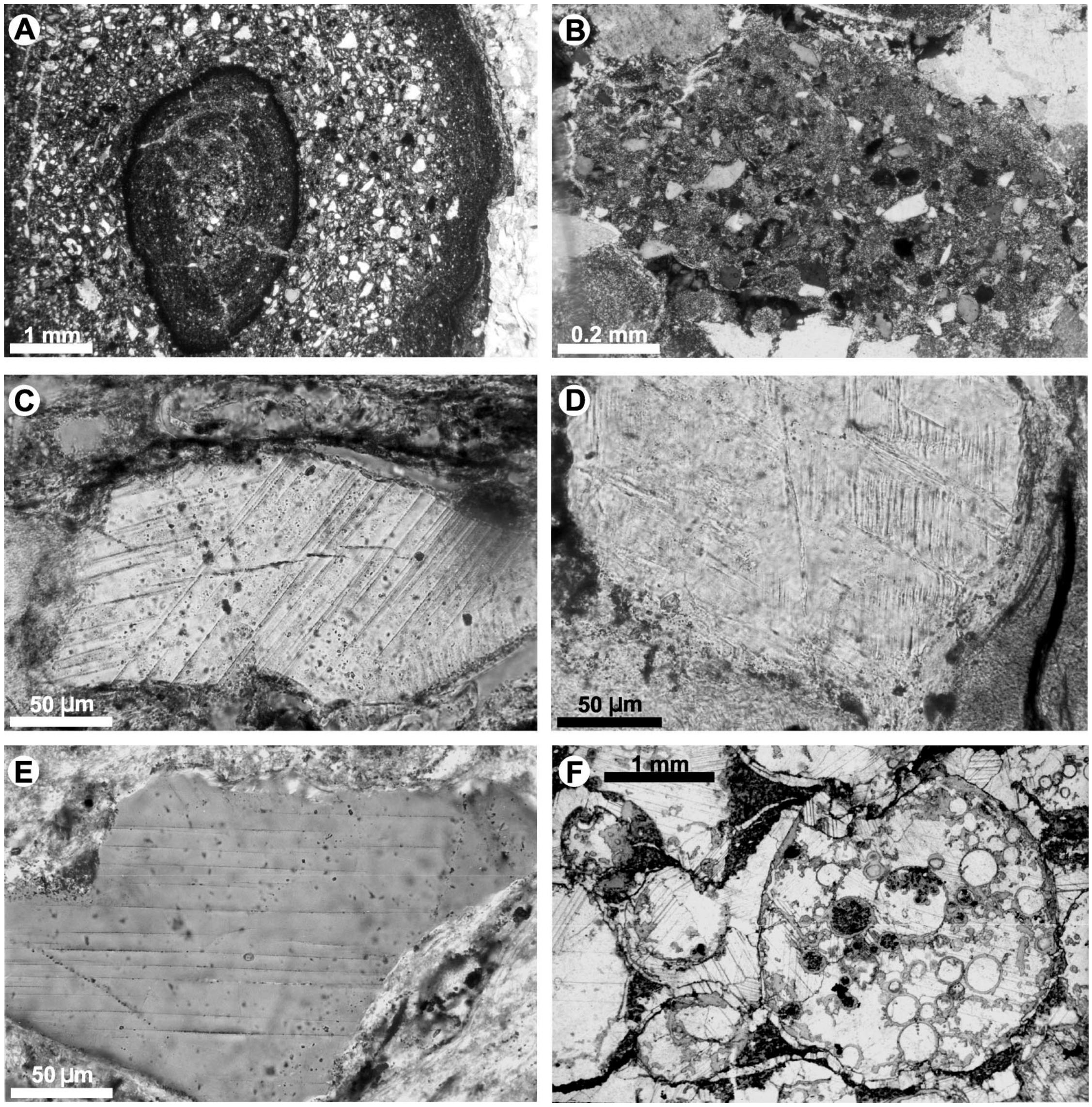

Figure 3. A: Accretionary lapillus having dark core with lighter, coarser quartz and feldspar grains and dark, finer-grained concentric outer accreted layers of secondary replacement carbonate and silicate minerals (core BP99-2, slide JN29A). B: Accreted grain cluster in carbonate matrix showing randomly oriented quartz and feldspar grains similar to those in accretionary lapilli cores (core BP99-2, slide JN24). Note absence of fine-grained outer concentric layers typical of accretionary lapilli (cf. A). C: Quartz grain with two decorated planar deformation feature (PDF) sets, surrounded by carbonate (primarily dolomite) replacement matrix (core BP99-2, slide JN32). D: Laddered PDFs in feldspar (core PR98-1, slide 10). E: Quartz grain with possible planar fractures, some weakly decorated with bubbles and some almost without decoration. Planar fractures are distinguished by their width, typically (5–10 μm) and spacing between fractures (15–20 μm), whereas PDFs typically have widths of <2–3 μm and spacings of 2–10 μm (French, 1998). Widths of features here are typical of PDFs, whereas spacings are typical of both PDFs and planar fractures (core PR98-1, slide 10). F: Spheres-within-sphere feature, likely originally glass, now devitrified and replaced by carbonate (primarily dolomite), which has destroyed most interior detail. Matrix is also carbonate (core LWN99-2, slide H1-3-8). Other photomicrographs are available in Appendix DR1 (see footnote 1 in text).

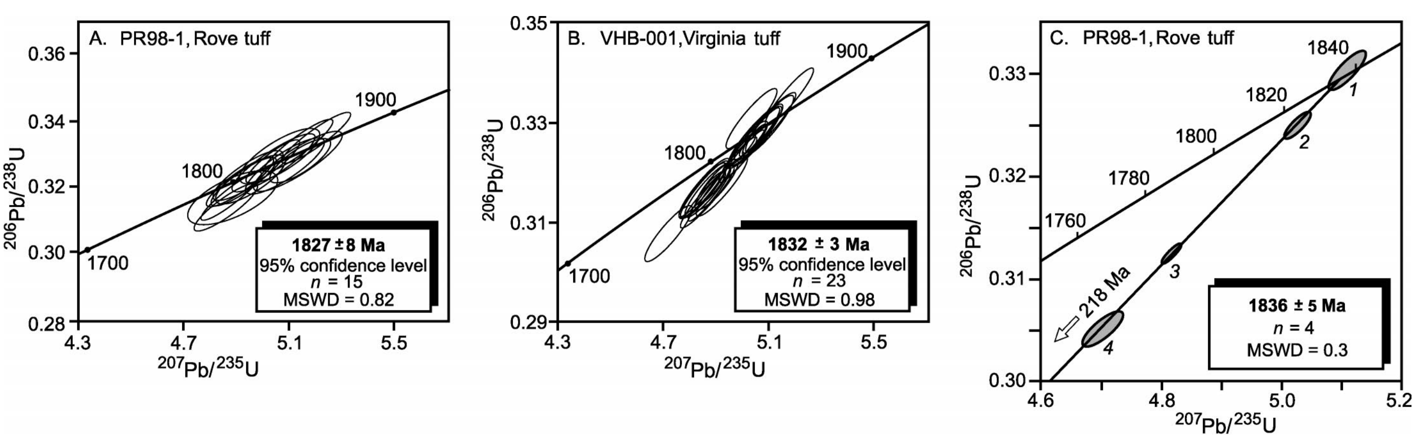

Figure 4. A–B: Concordia diagrams, showing age of Rove Formation tuff (core PR98-1) and Virginia Formation tuff (core VHB00-1), derived from sensitive high-resolution ion-microprobe data. C: Concordia diagram showing age of Rove Formation tuff (core PR98-1) derived from isotope-dilution–thermal-ionization mass spectrometry data. MSWD—mean square of weighted deviates.

until now. These age data, based on zircons from comparable stratigraphic positions in the Rove and Virginia Formations, strongly support the correlation of the Rove and Virginia Formations and, by stratigraphic inference, the Gunflint and Biwabik Formations.

The similar ejecta features and stratigraphic positions of the proposed ejecta layers in Ontario and Minnesota, plus the correlative ages for the Rove and Virginia Formations just 5–6 m above the layers, all indicate that the ejecta layers are derived from the same event. The layer thicknesses also imply that ejecta blanketed an area much greater than the 260-km-wide zone between the Ontario and Minnesota drill cores. These ejecta are from a large impact.

The oldest previously reported shocked quartz and feldspar in distal ejecta linked to a specific large impact site are for the ca. 590 Ma (Earth Impact Database, 2004) Acraman Crater, Australia (Gostin et al., 1986). These Sudbury ejecta are ~1260 m.y. older.

The Sudbury ejecta layer is ~105 m above the 1878 Ma upper Gunflint tuff, ~5.8 m below the 1836–1827 Ma Rove volcanic ash, and ~5.1 m below the correlative 1832 Ma Virginia ash. Thus, this layer is found between strata straddling the time of the Sudbury impact (1850 ± 1 Ma). If it did not originate from the Sudbury impact, another significant ejecta layer should exist in the Gunflint-Rove stratigraphic column between the dated tuffaceous layers, given the proximity of the area to Sudbury, the location of all areas on the same craton, and the fact that this part has been stable for >1878 m.y. No second ejecta layer has been found, although it could have been removed by erosion. However, no other impact event is known to have occurred anywhere on Earth between 1878 Ma and 1827 Ma (Earth Impact Database, 2004). The abundance of quartz and feldspar in the layer indicates that the ejecta are from a continental source. Because the Minnesota ejecta layers are thinner than those in Ontario, the impact site likely is to the east, toward Sudbury. The Sudbury impact is the only known impact location close enough to have produced a craton-sourced, westward-thinning ejecta layer this thick, in these locations, given the time constraints established by zircon dating.

Currently, the Cretaceous-Tertiary boundary Chicxulub impact provides evidence of distal ejecta features and its consequences for life on Earth. Now, with evidence from the 1850 Ma Sudbury impact, it is possible to compare ejecta evidence from two large impacts. Both show similar distal ejecta features, including planar features in quartz and feldspar grains, accretionary lapilli, spherules, and sphere-within-sphere features.

The Gunflint Formation's fossil-rich record of microbial biota is overlain by the fossil-absent Rove Formation. Is this an impact-induced extinction? It is difficult to judge how the impact affected the biological communities. Evidence in these drill cores suggests an interval of subareal diagenesis near the end of Gunflint sedimentation, likely induced by Penokean orogenic uplift from the south. More work is needed to show this. Then, ~14 m.y. after the impact, the Rove sea transgressed onto the area, initiating deposition of fine-grained siliciclastic debris off the postorogenic hinterland. Rove Formation sediment geochemistry indicates increasing sulfidation of the ocean (Poulton et al., 2004). While the trend increases upward from the ejecta layer, and therefore was not solely caused by it, the ejecta may have been a factor that helped push a delicately balanced oceanic chemical system toward an increasingly sulfidic state. The carbon-rich Rove Formation suggests that life was flourishing by this time, while its lack of fossil evidence could be due to a lack of silica required to preserve fossils.

Discovery of these ejecta will stimulate further study comparing the Sudbury and Chicxulub ejecta, which may shed light on the consequences of large impacts for life and ocean chemistry at very different times in Earth's history.

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REFERENCES CITED

Chadwick, B., Claeys, P., and Simonson, B., 2001, New evidence for a large Paleoproterozoic impact: Spherules in a dolomite layer in the Ketilidian orogen, South Greenland: Geological Society [London] Journal, v. 158, p. 331–340.

Dietz, R.S., 1964, Sudbury structure as an astrobleme: Journal of Geology, v. 72, p. 412–434.

Earth Impact Database, 2004, Earth impact database: www.unb.ca/passc/ImpactDatabase (accessed October 2004).

Floran, R.J., and Papike, J.J., 1975, Petrology of the low-grade rocks of the Gunflint Iron-Formation, Ontario–Minnesota: Geological Society of America Bulletin, v. 86, p. 1169–1190.

Fralick, P., Davis, D.W., and Kissin, S.A., 2002, The age of the Gunflint Formation, Ontario, Canada: Single zircon U-Pb age determinations from reworked volcanic ash: Canadian Journal of Earth Sciences, v. 39, p. 1085–1091.

French, B.M., 1998, Traces of catastrophe: Lunar and Planetary Institute Contribution 954, 120 p.

Gostin, V.A., Haines, P.W., Jenkins, R.J.F., Compton, W., and Williams, I.S., 1986, Impact ejecta horizon within late Precambrian shales, Adelaide geosyncline, South Australia: Science, v. 233, p. 198–200.

Krogh, T.E., Davis, D.W., and Corfu, F., 1984, Precise U-Pb zircon and baddeleyite ages for the Sudbury area, *in* Pye, E.G., et al., eds., The geology and ore deposits of the Sudbury structure: Ontario Geological Survey Special Volume 1, p. 431–446.

Morey, G.B., and Southwick, D.L., 1995, Allostratigraphic sequence relationships of Early Proterozoic iron-formations in the Lake Superior region: Economic Geology, v. 90, p. 1983–1993.

Ojakangas, R.W., Morey, G.B., and Southwick, D.L., 2001, Paleoproterozoic basin development and sedimentation in the Lake Superior region, North America: Sedimentary Geology, v. 141–142, p. 319–341.

Poulton, S.W., Fralick, P.W., and Canfield, D.E., 2004, The transition to a sulphidic ocean ~1.84 billion years ago: Nature, v. 431, p. 173–177.

Salge, T., Tagle, R., and Claeys, P., 2000, Accretionary lapilli from the Cretaceous-Tertiary boundary site of Guayal, Mexico: Preliminary insights into expansion plume formation: Meteoritics & Planetary Science, v. 35, p. A140–A141.

Smit, J., Roep, T.B., Alvarez, W., Montanari, A., Claeys, P., Grajales-Nishimura, J.M., and Bermudez, J., 1996, Coarse-grained, clastic sandstone complex at the K-T boundary around the Gulf of Mexico: Deposition by tsunami waves induced by the Chicxulub impact?, *in* Ryder, G., et al., eds., The Cretaceous-Tertiary event and other catastrophes in Earth history: Geological Society of America Special Paper 307, p. 151–182.

Spray, J.G., Butler, H.R., and Thompson, L.M., 2004, Tectonic influences on the morphometry of the Sudbury impact structure: Implications for terrestrial cratering and modeling: Meteoritics & Planetary Science, v. 39, p. 287–301.

Stille, P., and Clauer, N., 1986, Sm-Nd isochron-age and provenance of the argillites of the Gunflint Iron Formation in Ontario, Canada: Geochimica et Cosmochimica Acta, v. 50, p. 1141–1146.

Stinnesbeck, W., Schulte, P., Lindenmaier, F., Adatte, T., Affolter, M., Schilli, L., Keller, G., Stuben, D., Berner, Z., Kramar, U., Burns, S.J., and Lopez-Oliva, J.G., 2001, Late Maastrichtian age of spherule deposits in northeastern Mexico: Implications for Chicxulub scenario: Canadian Journal of Earth Sciences, v. 38, p. 229–238.

Tanton, T.L., 1931, Fort William and Port Arthur, and Thunder Cape map-areas, Thunder Bay District, Ontario: Geological Survey of Canada Memoir 167, 222 p.

Walkden, G., Parker, J., and Kelly, S., 2002, A Late Triassic impact ejecta layer in southwestern Britain: Science, v. 298, p. 2185–2188.

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