Physical and chemical evidence of the 1850 Ma Sudbury impact event in the Baraga Group, Michigan

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ABSTRACT

An ejecta layer produced by the Sudbury impact event ca. 1850 Ma occurs within the Baraga Group of northern Michigan and provides an excellent record of impact-related depositional processes. This newly discovered, ~2–4-m-thick horizon accumulated in a peritidal environment during a minor sea-level lowstand that punctuated a period of marine transgression. Common ejecta clasts include shock-metamorphosed quartz grains, splash-form melt spherules and tektites, accretionary lapilli, and glassy shards, suggesting sedimentation near the terminus of the continuous ejecta blanket. Sedimentologic and geochemical data indicate that primary fallout from a turbulent ejecta cloud was reworked to varying degrees by an impact-generated tsunami wave train. Observed platinum group element anomalies (Ir, Rh, and Ru) within the Sudbury ejecta horizon are sufficient to suggest that the impactor was a meteorite. Documenting and interpreting the detailed characteristics of the Sudbury ejecta horizon in Michigan have yielded a fingerprint to identify this chronostratigraphic marker in other Paleoproterozoic basins. For the first time a foundation exists to assess the consequences of the Sudbury impact on Precambrian ocean chemistry and early life.

Keywords: bolide, impact, meteorite, ejecta, sedimentology, platinum group elements, Sudbury, Michigan.

INTRODUCTION

The Sudbury structure of Ontario, Canada (Fig. 1; cf. Spray et al., 2004), is interpreted to be the product of a bolide impact 1850 Ma (Krogh et al., 1984; Corfu and Lightfoot, 1996), based on well-documented shock-induced macroscopic and microscopic deformation structures (e.g., Dietz, 1964; French, 1967). The best evidence for an impact origin is the presence of shatter cones in autochthonous footwall rocks (Dietz, 1964) and planar traces of fluid inclusions in autochthonous and redeposited quartz grains that represent former planar deformation features (PDFs; French, 1967, 1998). Other evidence includes the presence of fullerenes (Becker et al., 1994) and relict basal-oriented Brazil twin lamellae in quartz (Joreau et al., 1996) within the Sudbury structure, together with the discovery of ejecta in northwestern Ontario, Minnesota (Addison et al., 2005), Michigan (Cannon et al., 2006; Kring et al., 2006; Pufahl et al., 2006), and possibly South Greenland (Fig. 1; Chadwick et al., 2001).

The Sudbury structure consists of the Sudbury Basin filled with sedimentary rocks of the Whitewater Group, the Sudbury Igneous Complex that surrounds the basin, and a brecciated crater (Spray et al., 2004). The crater's original diameter is estimated to be 200–280 km (Mungall et al., 2004), the second largest known impact site on Earth (Spray et al., 2004). Although much is known about the Sudbury structure, largely because of its economic importance as a major nickel deposit, little is known about the related ejecta blanket. These deposits contain important information regarding impact-generated depositional processes far from the impact site (Pope et al., 1999). Virtually no data of this type exist for large Precambrian impacts such as Sudbury. Ejecta chemistry can often reveal bolide type (cf. Kyte, 2002; Tagle and Claeys, 2005), which is unresolved for the Sudbury structure. The purpose of this paper is to understand the accumulation of Sudbury ejecta and elucidate impactor type by documenting and interpreting the sedimentology and platinum group element (PGE) chemistry of the Sudbury ejecta horizon in two drill cores from northern Michigan (Fig. 1). Such information provides a fingerprint with which to identify this layer in other Paleoproterozoic basins around the world, making it possible to more fully assess consequences of the Sudbury impact on Precambrian ocean chemistry and early life.

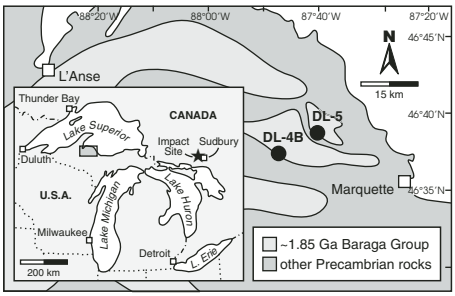

Figure 1. Map showing locations of drill cores DL-4B and DL-5 within the Baraga Group, northern Michigan.

GENERAL GEOLOGY

In northern Michigan the Sudbury ejecta horizon occurs in the Paleoproterozoic Baraga Group (Cannon et al., 2006; Kring et al., 2006; Pufahl et al., 2006), an ~1200-m-thick sedimentary succession of marine clastic, iron formation, and phosphatic sedimentary rocks deposited on the Nuna continental margin. Sedimentation was influenced by the Penokean orogeny to the south (Ojakangas et al., 2001), which began ca. 1875 Ma and ended by 1835 Ma (Schneider et al., 2002). The age of the Baraga Group is based on a U-Pb zircon date of 1852 ± 6 Ma (Sims et al., 1989), which may represent the maximum age for sedimentation (Ojakangas et al., 2001).

In drill cores DL-4B and DL-5 the ejecta horizon occurs 30–40 m above the unconformity with the Archean basement (Fig. 2A), where it is intercalated with flaser bedded intertidal sandstone and dessicated supratidal chert containing numerous subaerial exposure surfaces (Fig. 2A; Pufahl et al., 2006). These deposits accumulated during a minor sea-level lowstand within an overall marine transgression that culminated with deposition of subtidal siltstone and prograding deltaic sandstone complexes (Pufahl et al., 2006). The ejecta horizon can be correlated across Lake Superior to northwestern Ontario and Minnesota, where it is associated with similar peritidal sedimentary rocks (Addison et al., 2005). It thins westward, away from the impact site, from a thickness of ~300 cm in Michigan to ~50 cm in Minnesota ~100 km northwest of Duluth, where its thickness is less variable (Fig. 1; Addison et al., 2005).

EJECTA HORIZON DESCRIPTION

In DL-4B the ejecta horizon occurs above supratidal chert and is interbedded with intertidal sandstone (Fig. 2B). It consists of two distinct coarse-tail graded beds with an upward decrease

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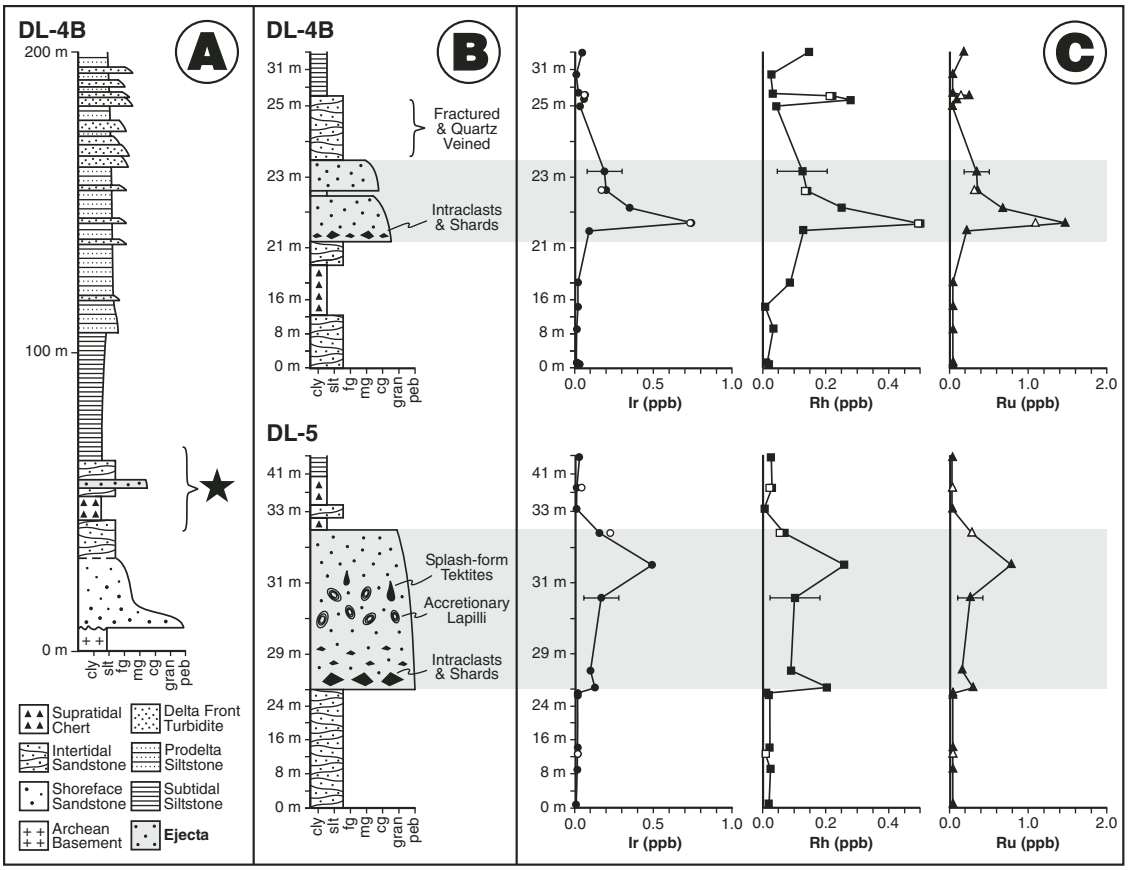

Figure 2. A: Lower Baraga Group stratigraphy, drill core DL-4B, showing position of Sudbury ejecta horizon (star). B: Detailed ejecta stratigraphy in drill cores DL-4B and DL-5 (cly—clay; slt—silt; fg—fine grain; mg—medium grain; cg—coarse grain; gran—granule; peb—pebble). C: Ir, Rh, and Ru geochemical profiles across ejecta intervals (shaded), including anomalies discussed in text. Anomalies are statistically significant based on one tailed, two sample, equal variance Student's *t*-tests at the 1.5%, 7.3%, and 0.3% confidence levels, respectively. Open circle, square, and triangle indicate duplicate sample.

in bed thickness and grain size. The beds are 150 and 80 cm thick and separated by 6 cm of wavy laminated siltstone. Each is sharp based and indistinctly stratified with diffuse, 1–2-cm-thick stratification bands composed of slightly coarser, granule-size (2–4 mm) shards and intraclasts. The lower 25 cm of the thicker bottom bed contains pebble- and cobble-sized siltstone rip-ups derived from underlying sediments.

The ejecta stratigraphy is different ~15 km to the east in DL-5 (Fig. 1), where it consists of a single 440-cm-thick, coarse-tail graded bed between a unit of intertidal sandstone below and supratidal chert above (Fig. 2B). The base of the bed is erosive and contains more rip-ups than the lowermost bed in DL-4B. From this intraclast-rich bottom it grades into a 2.0-m-thick zone containing abundant 0.5–1.0-cm-diameter accretionary lapilli and 1.0–2.0-cm-long clasts interpreted as splash-form tektites (Figs. 3A, 3B). The abundance of these clasts decreases from this zone to the bed top.

In both drill cores the ejecta horizon has been pervasively altered during greenschist facies metamorphism to a mixture of dolomite, actinolite, and tremolite. In spite of this alteration, however, ejecta clasts are well preserved. Granule- and pebble-size, glass- or melt-like shards with abundant vesicle wall fragments (Fig. 3C) are common, as well as rare ~0.60-mm-long, bedding-parallel carbonate grains interpreted as dolomite-replaced, splash-form melt spherules or microtektites (Fig. 3D; cf. Chadwick et al., 2001). Very fine sand- and silt-size, subrounded quartz grains with single and multiple sets of fluid-inclusion-array–defined planar microstructures (PMs) after probable annealed PDFs are also very common, especially in DL-4B (Figs. 4A, 4B). Similar spherules and shock-metamorphosed quartz grains occur within suevitic breccias of the Whitewater Group filling the Sudbury structure (French, 1967; Stevenson, 1972) and within ejecta around Thunder Bay (Fig. 1; Addison et al., 2005). Primary differences in Michigan ejecta include the lack of shocked granitic clasts and abundance of high-index PMs within subrounded quartz grains (Fig. 4C).

EJECTA HORIZON CHEMISTRY

We collected 29 10–15-cm-long pieces of drill core from holes DL-4B and DL-5 for geochemical analysis. These samples were crushed, pulverized, and analyzed for PGEs (Pt, Pd, Ir, Rh, Ru; see GSA Data Repository Table DR1[1]) and Au using a NiS fire assay, acid digestion, and Te coprecipitation with inductively coupled plasma–mass spectroscopy at Geoscience Laboratories, Sudbury, Ontario. Sample duplicates and reference materials were also analyzed to assess sampling and analytical error (cf. Bettenay and Stanley, 2001).

Au, Pt, and Pd concentrations do not exhibit discernable trends or spatial relationships within the ejecta horizon, probably because they are less refractory and were mobilized during metamorphism. The more refractory Ir, Rh, and Ru, however, exhibit anomalous concentrations (<2 ppb) that are ~11, 3, and 8 times higher than background levels, respectively (Fig. 2C).

Mass ratios of Rh and Ru to Ir are highest at the base of the ejecta horizon (~1.5 and ~2.4, respectively) and decrease to near chondritic levels higher within the layer in each drill core (Appendix 1; see footnote 1). In DL-4B this decrease occurs through both coarse-tail graded beds.

DISCUSSION AND CONCLUSIONS

Despite significant dilution, the observed PGE anomalies (Ir, Rh, and Ru) in the Sudbury ejecta horizon (Fig. 2C) have distinctly higher concen-

[1]GSA Data Repository item 2007201, Table 1 (Platinum Group Element data from the Sudbury ejecta horizon in northern Michigan) and Appendix 1 (changes in Rh/Ir and Ru/Ir ratios through this layer in drill cores DL-4B and DL-5), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

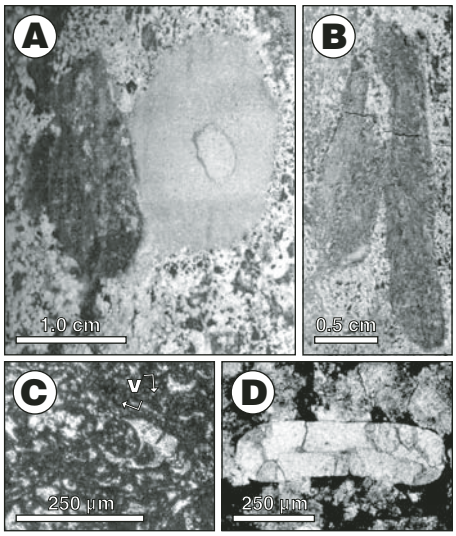

Figure 3. A: Possible splash-form tektite with partially dolomite-replaced rim (left) and probable accretionary lapillus. Core DL-5. B: Teardrop-shaped clasts interpreted as splash-form tektites. Core DL-5. C: Glass- or melt-like shard containing vesicle wall fragments (v). Core DL-4B. D: Oval carbonate grain interpreted to be dolomite-replaced, dumbbell-shaped melt spherule (cf. Figure 4a in Chadwick et al., 2001). Core DL-4B.

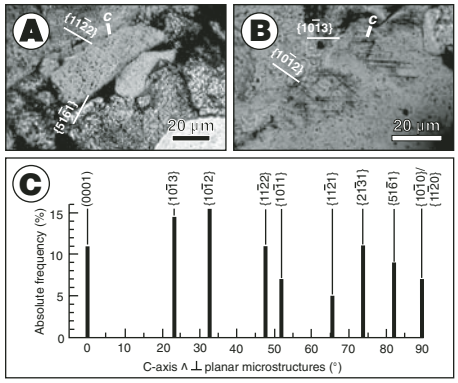

Figure 4. A: Photomicrograph of two sets of highly annealed, decorated planar microstructures (PMs) defined by concentrations of micrometer- to submicrometer-scale fluid-inclusion arrays. Crystallographic orientations of planes and quartz c-axis are indicated. Plane-polarized light, universal-stage microscope view. Core DL-4B. B: Photomicrograph of two sets of relatively well preserved decorated PMs, ~2–3 µm thick and spaced ~3–8 µm apart, that strongly resemble shock-produced planar deformation features. Crystallographic orientations of planes and quartz c-axis are indicated. Plane-polarized light, flat-stage microscope view. Core DL-4B. C: Histogram of absolute frequency percent of indexed PMs in quartz, plotted relative to angle between pole to plane and quartz c-axis, from Sudbury ejecta layers, drill cores DL-4B and DL-5. Based on universal-stage measurement of 109 sets of planes in 59 grains, with 9% of planes unindexed. Representative Miller crystallographic indices are shown. Indexing and plotting methods are after Engelhardt and Bertsch (1969), Stöffler and Langenhorst (1994), and Grieve et al. (1996).

trations than in ejecta ascribed to mafic volcanism (Sawlowicz, 1993; Schmitz and Asaro, 1996; Schmitz et al., 2004), and exhibit geochemical contrasts sufficient to suggest that the impactor was a meteorite (Sawlowicz, 1993; Schmitz et al., 2004), and not a comet as previously proposed (Pope et al., 2004). Nickel-normalized cross-plots of PGEs typically used to discriminate bolide type (cf. Kyte, 2002) are not effective in these samples because Ni appears to have been mobilized during metamorphism. Dilution by intense carbonate alteration also explains why observed anomalies are nearly an order of magnitude lower than those at the Cretaceous-Tertiary boundary (Montanari et al., 1983; Alvarez et al., 1992), if a meteoritic impactor is assumed.

The accumulation of ejecta in northern Michigan is interpreted to reflect a combination of impact-generated subaerial and subaqueous depositional processes. In drill core DL-4B the repetition of coarse, normally graded, erosive beds (Fig. 2B) containing replaced spherules and granule-sized, glass- or melt-like shards (Figs. 3C, 3D) within an otherwise muddy peritidal environment is consistent with reworking of ejecta by an impact-generated tsunami (cf. Schnyder et al., 2005; Moore et al., 2006). Graded beds are interpreted to have been produced by two successive tsunami waves that swept landward, eroding and reworking supratidal and shallow subtidal sediments, followed by a steady-state flow that slowly decelerated and eventually moved seaward. The thinner, finer character of the second bed indicates a decrease in energy typical of tsunami wave trains (Schnyder et al., 2005). The indistinct stratification bands within ejecta beds suggests subaqueous deposition from an aggrading traction carpet (cf. Sohn, 1997) that likely developed as a consequence of sustained flow during tsunami run-up and back flow. Wave reworking of rapidly deposited suspended sediment that accumulated between successive tsunami waves is interpreted to have produced the wavy laminated siltstone between graded beds.

In drill core DL-5 the stratigraphic position of the ejecta horizon below supratidal chert, as opposed to above in DL-4B (Fig. 2B), suggests deposition in a slightly deeper water peritidal setting. Ejecta material is interpreted to have infilled topographic lows, causing rapid aggradation and development of an expansive supratidal environment. The presence of a single ~400-cm-thick graded bed containing abundant glass- or melt-like clasts indicates that rapid fallout from the ejecta cloud was the primary depositional process. The tektite- and/or accretionary lapilli–rich zone in the middle of the bed and finer sediment above likely record collapse of a turbulent ejecta cloud (Pope et al., 1999) and eventual rainout of material that was expelled high above the Earth as a vapor plume. The bed's erosive base is interpreted to be tsunami generated, having formed by mixing underlying flaser-bedded sandstone with initial deposits of the ejecta curtain. The absence of a second tsunami-produced bed implies that accumulation from the ejecta cloud overwhelmed the depositional system at this location, thus overprinting other sedimentary processes. Changes in Rh/Ir and Ru/Ir ratios through the ejecta horizon (Appendix 1; see footnote 1) from relatively high values reflecting mixing with marine sediments to ones approaching carbonaceous chondrite values support the interpretation of energetic mixing followed by quiescence and rainout.

Sedimentologic data indicate that DL-4B and DL-5 are near the terminus of the continuous ejecta blanket. The absence of splash-form tektites and the finer, thinner nature of the horizon in DL-4 relative to DL-5 indicate that DL-4 is close to the boundary between proximal and distal ejecta. This transition is ~500 km from the Sudbury structure, which is in agreement with other impact deposits where this change occurs at approximately five crater radii from the crater center (cf. French, 1998).

The limit of the turbulent ejecta cloud is interpreted to have extended as far as Thunder Bay (Fig. 1), a radial distance of ~650 km from the impact site, which suggests that the cloud covered an area of at least ~1.33×10^6 km^2. This estimate is based on the presence of a 10-cm-thick layer of accretionary lapilli in the middle of the ejecta horizon near Ontario and absence of such clasts in Minnesota (Addison et al., 2005). The patchy distribution of accretionary lapilli in northern Michigan also suggests that cloud circulation was erratic, possibly reflecting interaction with the Penokean mountains to the south. The abundance of high-index PMs, including rhombohedral-form planes within subrounded quartz grains (Fig. 4C), and the absence of granitic clasts in ejecta imply further that over Michigan this cloud contained highly shocked material primarily from the upper, central portion of the target, which probably consisted of abundant quartz sand–bearing sediment or rock (cf. Grieve et al., 1996; Trepmann and Spray, 2006).

Documenting and interpreting the detailed characteristics of the Sudbury ejecta horizon have yielded a fingerprint to identify this chronostratigraphic marker in other Paleoproterozoic basins from around the world. This provides a foundation on which to assess consequences of the Sudbury impact on Precambrian ocean chemistry and evolution of early life. The Sudbury impact occurred during onset of sulfidic ocean conditions, a dramatic change in ocean chemistry that lasted for nearly 1 b.y. (e.g., Poulton

et al., 2004). This oceanic event is interpreted to have been driven by initial oxygenation of the atmosphere and marks the beginning of a long period of stasis in eukaryote evolution (Anbar and Knoll, 2002). Although ostensibly coupled (Anbar and Knoll, 2002), the effects of a bolide impact during this critical stage in Earth history have not been addressed.

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