New constraints on the Slate Islands impact structure, Ontario, Canada

Virgil L. Sharpton, Burkhard O. Dressler, Robert R. Herrick — Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, Texas 77058

Bernie Schnieders, John Scott — Ontario Geological Survey, 435 South James Street, Thunder Bay, Ontario, P7E 6E3, Canada

ABSTRACT

The Slate Islands in northern Lake Superior represent the eroded remains of a complex impact crater, originally ~32 km in diameter. New field studies there reveal allogenic crater fill deposits along the eastern and northern portions of the islands indicating that this 500–800 Ma impact structure is not as heavily eroded as previously thought. Near the crater center, on the western side of Patterson Island, massive blocks of target rocks, enclosed within a matrix of fine-grained polymict breccia, record the extensive deformation associated with the central uplift. Shatter cones are a common structural feature on the islands and range from <3 cm to over 10 m in length. Although shatter cones are powerful tools for recognizing and analyzing eroded impact craters, their origin remains poorly constrained.

INTRODUCTION

The Slate Islands are an ~7-km-wide archipelago located in northern Lake Superior ~10 km south of Terrace Bay, Ontario (Fig. 1). Numerous shatter cones (observed first by R. Sage during field mapping in 1973; Halls and Grieve, 1976; Sage, 1978, 1991), microscopic evidence of shock metamorphism (Grieve and Robertson, 1976; Sage, 1978, 1991), and polymict breccia dikes provide clear indications that these islands represent the heavily eroded central portion of a complex impact crater. Bathymetric data suggest an original crater diameter of ~32 km.

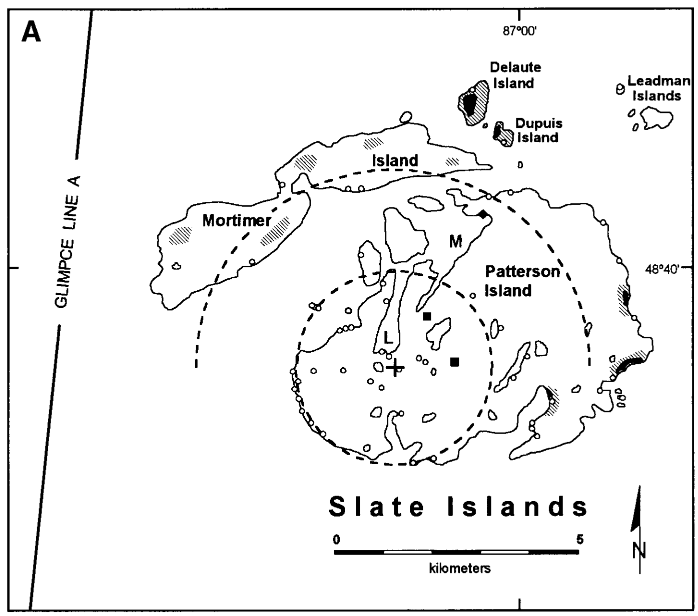
With the exception of a detailed investigation of Slate Islands shatter cones (Stesky and Halls, 1983), the islands have received little scrutiny in the past 15 yr. Commonly rough and unpredictable weather conditions, combined with difficult access, have hindered detailed investigations of the islands' excellent rock exposures along the shores cleaned by wave action of Lake Superior. Exploration of island interiors is further encumbered by dense vegetation and rugged terrain. Our work over the past two summers took advantage of the generous logistical support of the Ontario Geological Survey, which allowed us safe, extended access to these islands.

Here we present a brief, updated overview of the islands' geology, including a revised structural interpretation, and report on new shatter cone observations that serve to illustrate the severe deficiencies in theoretical models of how these features form.

GEOLOGICAL SETTING AND AGE CONSTRAINTS

A wide variety of Archean and Proterozoic country rocks are present on the islands (Sage, 1991). Archean rocks of the Wawa Subprovince of the Superior Province, making up the bulk of the exposed rock units, are greenschist facies, felsic to mafic pyroclastic volcanic rocks, pillowed and variolitic basalt flows, and feldspar porphyries. These supracrustal rocks are interbedded with minor mudstones, siltstones, and ironstones. Archean felsic and mafic igneous rocks intrude the supracrustal sequences. Laminated argillite and chert-carbonate-hematite ironstone of the Gunflint Formation and argillite of the Rove Formation, both belonging to the Proterozoic Animikie Group, and Keweenawan metabasalts, diabases, and interflow siliciclastic sediments are of limited spatial extent. The northern part of the north-south–trending Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) reflection seismic line A (Mariano and Hinze, 1994) traverses the crater, ~7 km to the west of the center. These data reveal a thick layered sequence in the vicinity of the crater indicating that Keweenawan rocks probably dominated the upper target stratigraphy at the time of impact.

Dikes of clastic-matrix breccia were noted by Halls and Grieve



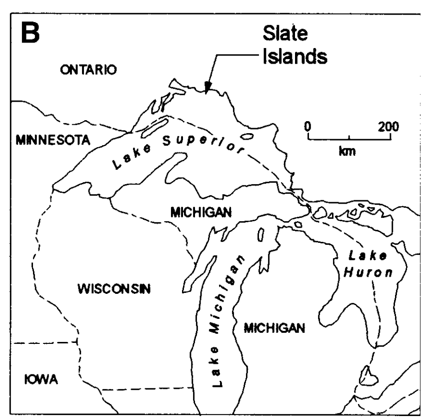


Figure 1. A: Sketch map of Slate Islands impact structure, located in northern Lake Superior (see B). Dashed lines show concentric trends of coast lines and structural elements indicating crater center on western side of Patterson Island (approximate location is shown by +). Previous estimates of crater center, based on shatter cone orientations (Stesky and Halls, 1983) or shock isobars deduced from planar deformation features in quartz (Grieve and Robertson, 1976), are shown as filled squares. Shatter-coned outcrops are shown as small unfilled circles. Location of large shatter cone discussed in text is shown as filled diamond. M signifies McGreevey Harbour. Diagonal pattern indicates generalized locations of some larger autoclastic and allogenic breccia deposits. Map is adapted from Sharpton et al. (1996).

(1976) and Sage (1978, 1991). In addition to these features we have identified pseudotachylites, polymict allogenic breccias (including glass-bearing "suevite"; e.g., von Engelhardt, 1990), and monomict autoclastic breccias related to the impact event. On Slate Islands, allogenic and autoclastic breccias are concentrated along the eastern side of Patterson Island, as well as on Mortimer, Dupuis, and Delaute islands (Fig. 1).

Available constraints on the age of the impact are not robust. Grieve et al. (1995) listed the age as <350 Ma because the level of erosion at Slate Islands is similar to that of the ~350 Ma Charlevoix structure in Quebec. The sandstone of the 800 Ma Jacobsville Formation, however, appears to be the youngest target unit observed in the polymict breccias or otherwise deformed by the Slate Islands impact event. Carbonate units probably were deposited throughout the region between the Michigan and Hudson Bay Lowland basins during the Ordovician and Devonian (Norris and Sanford, 1968) but these rocks have not been observed as clasts within the polymict breccias. This leads us to conclude that the age of the Slate Islands impact event is most likely 500–800 Ma.

REVISED STRUCTURAL INTERPRETATION

Previously the whole island group was interpreted as uplifted and deformed parautochthonous basement eroded so deeply that the only breccias remaining were those injected during impact into the crater subfloor ~0.5 to 1.5 km beneath the crater's central peak (Halls and Grieve, 1976; Grieve and Robertson, 1976). Allogenic and autoclastic breccias, however, on the northern and eastern flanks of the central uplift indicate that the present exposure depth does not greatly exceed the original crater depth (a few hundred metres below the original ground surface). This is verified by the reprocessed GLIMPCE data, which clearly show offsets and rotations of shallow layers consistent with the intensely deformed structural trough and the outlying rim zone of this complex crater (Sharpton and Dressler, 1996).

On the basis of shatter cone orientations (Stesky and Halls, 1983) and shock barometry (Grieve and Robertson, 1976), previous studies placed the crater center approximately coincident with the islands' center (Fig. 1). Concentric topographic and structural trends, coupled with the concentration of crater fill deposits on the northern and eastern parts of the islands, however, suggest that the crater center lies in the western Patterson Island, near the southern end of Lawrence Bay (Fig. 1). This region is characterized by networks of 0.5- to >4-m-thick linear bodies of polymict breccia (Fig. 2) previously interpreted as clastic injection dikes (Halls and Grieve, 1976; Grieve and Robertson, 1976). Nonconformal structural and lithological relationships across these enclosed breccia bodies, however, indicate that most represent the fine-grained matrix surrounding blocks of uplifted and rotated deep crustal rocks ranging from a few metres to perhaps hundreds of metres across. This impact-generated melange provides crucial insight into the style and intensity of the deformation associated with central peak formation.

SHATTER CONES AT THE SLATE ISLANDS STRUCTURE

Shatter cones are a specific type of rock fracturing produced by the passage of a high-pressure shock wave (Dietz, 1964). Their surface is decorated with linear ridges and grooves, referred to as "horsetail striations" that radiate from the cone's apex (Fig. 3). Complete cones are rarely observed. Parasitic, partial cones commonly lie on the surfaces of larger ones (Dietz, 1968). Their distinctive appearance makes them an invaluable field tool for discriminating impact (e.g., Dietz, 1947, 1961, 1964, 1968). In addition, shattercones provide important directional information useful in identifying the crater center and measuring rotations associated with late-stage crater collapse (Sharpton and Grieve, 1990, and references therein). Numerous recent publications deal with the distribution and/or the orientation of shatter cones in a number of terrestrial impact structures (e.g., Dressler, 1984, 1990; Manton, 1965; Simpson, 1981; Milton et al., 1972; and Murtaugh, 1976).

Shatter cones are present in practically all target rocks of the Slate Islands, and we also recognized them in breccia fragments (Fig. 4). They are especially well developed in Keweenawan metabasalts and interflow sediments. In Figure 1, northern Mortimer Island and sections of Patterson Island appear to be devoid of shatter cones; however, this mainly reflects the lack of field investigations in these areas.

At the Slate Islands structure, shatter cones typically range in size from ~2–3 cm to ~1 m long. The smallest shatter cones are most common in fine-grained metasediments. Keweenawan metabasalts commonly exhibit somewhat larger, but equally well-developed cones, 10–30 cm long (Fig. 3).

We identified an outcrop of Archean felsic metavolcanic rock (Fig. 5) in McGreevy Harbour (Fig. 1) exhibiting one confirmed shatter cone, located closest to the shoreline, that is at least 10 m long. Several other large, conical features are obvious on the near-vertical walls of the outcrop, but steep slopes and thick scree prohibited our reaching these features to confirm their origin. Nonetheless, these features appear identical to the confirmed shatter cone in terms of scale, morphology, and orientation, and a similar genesis seems probable. We are aware of no reports of similarly large shatter cones from other impact craters; however, this does not mean such megacones are unique to the Slate Islands. The exceptional exposures along the wave-battered shores of the Slate Islands impact structure provide two- and three-dimensional views of many features and rock units related to impact that in most other terrestrial craters can be explored only on relatively small outcrops or through expensive drilling.

At its exposed base, one of the megacones is at least 7 m wide. This exposure represents ~25° of the cone's basal perimeter; therefore, the true width of this feature may exceed 20 m at its base. Horsetail striations and parasitic cones cover all the exposed surface of the megacones. For the confirmed megacone, surface attitudes were used to derive the apical orientation, assuming a full cone angle of 90°. The megacone points ~60° above the horizontal toward the southwest, at an azimuth of 230°. This orientation is consistent with the widely observed characteristic of shatter cones pointing toward the impact point. This cone is located ~2–4 km from the point of impact, so even though the effective blast point was above the original pre-impact level of the shatter-coned unit (the parautochthonous rocks of the crater subfloor), upward and outward block rotation of ~30° seems to be required to account for its steep inclination. This sense of rotation is an expected structural response to uplift at the crater center.

UNDERSTANDING SHATTER CONE FORMATION

Shatter cones were first described by Branco and Fraas (1905) from the Steinheim crater in Germany. Now, after almost a century of controversy, these features are almost universally accepted as diagnostic evidence of meteorite impact (Sharpton and Grieve, 1990). Nonetheless, only two theoretical models of shatter cone formation appear in the literature (Johnson and Talbot, 1964; Gash, 1971). According to Johnson and Talbot (1964), shatter cones form where the elastic precursor of a shock wave is refracted by some inhomogeneity in the target medium. The elastic precursor, direct wave, and the scattered wave then interact to produce stresses above the target's elastic limit within a double-conical structure whose axis is normal to the shock front. Outside this conical structure the stress does not reach values above the elastic limit. Strain is focused along the boundary between the cone and its surroundings, where material

FIGURE 2

Figure 2. Westward view from shoreline of southwestern Patterson Island illustrating (submerged) polymict breccia bodies (dark dike-like bodies) that enclose large, rotated blocks of Archean to Proterozoic rocks. This melange was formed as crater floor near ground zero rebounded during impact to form central peak.

undergoes a transition from elastic to plastic behavior; brittle rupture along this boundary thus results in a typical ridged and grooved shatter cone surface. In most cases, only one half of the double cone develops. In Gash's model (1971), shatter cones are produced by the interaction of an incident compressive wave and a tensile wave reflected from a highly reflective source, such as the target surface.

Shatter cones clearly form during an early phase of the impact process because shatter-coned clasts occur in melts and allogenic breccias from the Slate Islands and other impact structures. Yet neither of the two hypotheses (Johnson and Talbot, 1964; Gash, 1971) accounts for all observed features associated with shatter cones (Table 1). For instance, it is difficult to reconcile either model with the observation that shatter cones of diverse size occur at a single location; shatter cones within the same outcrop at Slate Islands can range in axial length from $<$10 cm to $>$10 m.

We have never observed antithetic point-to-point shatter cones as predicted in the model of Johnson and Talbot (1964) and know of no reports of this relationship from elsewhere. Furthermore, although inhomogeneities, such as shale chips or fossils, have been reported to lie at the apices of cones in other impact structures (Milton, 1977), most cones we have observed do not have any obvious point-source inhomogeneity at their apices. In contrast, the presence of vesicles and amygdules in the Keweenawan basalts neither nucleated shatter cones nor affected their size or abundance. Gash's model does not require the interaction of the shock wave with an inhomogeneity, but because shock wave interactions with free surface reflections are needed, shatter cone formation throughout the central portions of the crater floor, where most are observed, seems problematic.

FIGURE 5

Figure 5. Location of large shatter cones, McGreevy Harbour, Patterson Island.

Both models fail to account for the occurrence of shatter cones over a wide range of shock pressure. Roddy and Davis (1977) deduced from their investigations of shatter cone formation in experimental explosions that, in crystalline rocks, the conical features require a formational stress range of ~4 ± 2 GPa. In the Manicouagan impact structure in Quebec (Dressler, 1970, 1990; Murtaugh, 1976), shatter cones occur in rocks that contain shock-produced glasses of quartz, plagioclase, and scapolite, indicating that peak pressures exceeded 30–45 GPa (Stöffler, 1971, 1972) in shatter-coned rocks. At the Slate Islands, shatter cones are found in rocks that contain microscopic planar deformation features in quartz grains indicative of shock pressures in excess of 12 GPa. Because the Hugoniot elastic limit for most rock-forming materials ranges from 2 to 4 GPa, these observations are contrary to the Johnson and Talbot prediction that pressures in the medium surrounding the cone do not exceed the elastic limit.

Shatter cones are easily recognized products of the high-pressure conditions associated with meteorite impact and have become one of the most expedient and useful tools for identifying and studying terrestrial impact craters. Yet, as the observations presented

FIGURE 3

Figure 3. Shatter cone in Keweenawan basalt showing typical surface characteristics.

FIGURE 4

Figure 4. Shatter-coned fragment in impact breccia. Lens cap is 5.5 cm in diameter.

TABLE 1. CHARACTERISTICS OF SHATTER CONES

Property	Range	Comments
Rock types	Shatter cones are best developed in fine-grained, homogeneous rocks; less well developed in coarse, heterogeneous rocks.	However, grain size and homogeneity are not the only factors. In the Sudbury impact structure, shatter cones are developed in fine-grained metasediments, whereas fine-grained metabasalts are practically devoid of shatter cones.
Occurrence	At Slate Islands, in parautochthonous rocks of the central uplift and in shatter-coned clasts in impact melt rocks and breccias.	Common in many terrestrial impact structures and large-scale explosion cratering experiments (Roddy and Davis, 1977).
Pressure range	4 ± 2 to 30 - 45 GPa	This estimate is based on Roddy and Davis (1977) and the observation of shatter cones in shock metamorphosed rocks in the Manicouagan impact structure that show diaplectic isotropization of plagioclase, scapolite, and quartz (Dressler, 1970, 1990; Murtaugh, 1976).
Orientation	Preferred orientation toward ground zero; in places antithetic; rarely more random.	Antithetic orientation compatible with hypothesis of Johnson and Talbot (1964). Random orientations probably the result of interaction of shock wave with reflections from inhomogeneities.
Size	1-2 cm to >10 m	Very large shatter cones may be more common than previously thought. Limited exposure may hinder recognition.
Apical angle	66° - 122° (Milton, 1977)	Do small shatter cones have larger apical angles than large ones, or is the angle a reflection of shock pressure or rock type?

above illustrate, to date, there is no satisfactory model for how these features are formed.

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