INSTITUTE ON LAKE SUPERIOR GEOLOGY
SPECIAL PUBLICATION #1

FIELD TRIP GUIDEBOOK FOR THE SLATE ISLANDS, ONTARIO

PETE HOLLINGS, MARK SMYK,
BILL ADDISON & PHIL FRALICK

Institute on Lake Superior Geology
www.lakesuperiorgeology.org

INSTITUTE ON LAKE SUPERIOR GEOLOGY
SPECIAL PUBLICATION #1

FIELD TRIP GUIDEBOOK FOR THE SLATE ISLANDS, ONTARIO

PETE HOLLINGS

Department of Geology, Lakehead University, Thunder Bay, Ontario, P7B 5E1, Canada

MARK SMYK

Resident Geologist's Office, Ontario Geological Survey, Ministry of Northern Development and Mines, Thunder Bay, Ontario, P7E 6S7, Canada

BILL ADDISON

R.R. 2, Kakabeka Falls, Ontario, P0T 1W0, Canada

PHIL FRALICK

Department of Geology, Lakehead University, Thunder Bay, Ontario, P7B 5E1, Canada

Cover Photos: Top - Shatter cone clast in impact breccia; Middle - Interflow sandstone unit in Paleoproterozoic basalts; Bottom - West coast of Patterson Island.

Institute on Lake Superior Geology
Special Publication #1

Field Trip Guidebook for the Slate Islands, Ontario

Reference to material in this volume should follow the example below:

Hollings, P., Smyk, M., Addison, B. and Fralick, P., 2006. Field trip guidebook for the Slate Islands. Institute on Lake Superior Geology, Special Publication 1, p. 21.

Published by the Institute on Lake Superior Geology and distributed by the ILSG Secretary:

Pete Hollings - ILSG Secretary
Department of Geology
Lakehead University
955 Oliver Road
Thunder Bay, ON P7B 5E1
Canada
Email: peter.hollings@lakeheadu.ca

ILSG website: www.lakesuperiorgeology.org

ISSN 1042-9964

Table of Contents

Introduction

This volume is intended to serve not only as a guide for participants during the August 2006 field trip to the Slate Islands, but also as a reference for those planning to revisit the area at a later date. Consequently we have included UTM coordinates (NAD 83 datum) for stops. The Slate Islands are covered by southern boreal forest with some shoreline arctic-alpine disjunct flora and is protected as a Natural Environment Provincial Park with no visitor facilities. Rock collecting and sampling is prohibited throughout the entire archipelago unless a permit is first obtained from the Ministry of Natural Resources:

Slate Islands Provincial Park
Ministry of Natural Resources
P.O. Box 970
Nipigon, ON P0T 2J0

Phone: (807) 825-3403

This is the first time a publication has been produced for a field trip that is not directly associated with an ILSG Annual Meeting. However, the location of the Slate Islands dictates that field trips to the islands are best made later in the summer when weather and lake conditions are more conducive to travel.

Safety Considerations

A field trip to the Slate Islands creates a number of unique safety issues. Please exercise caution when getting in and out of the boats, as the outcrops are often sharp and extremely slippery. Personal flotation devices should be worn in the boats at all times. If you are planning to revisit these sites please be very careful. Lake Superior is a cold, dangerous lake; waves can often be metres high and even in mid-summer fog can appear very quickly. A GPS system, compass and maps should be utilized. We strongly encourage you to charter a large boat from the mainland rather than trying to make the trip to the islands yourself.

Acknowledgements

We would like to thank all those who provided comments on this guide and assisted with the running of the field trips, particularly Doug Caldwell and John Scott.

Woodland Caribou on the Slate Islands

Regional Geology

The Slate Islands comprise a 7 km-wide archipelago of 17 islands located in northern Lake Superior approximately 12 km southeast of Terrace Bay (Fig. 1). The geology of the islands has been mapped by Coleman (1901), Parsons (1918) and by Sage (1975, 1991). The islands comprise both Archean and Proterozoic rocks. The Archean rocks are part of the Schreiber-Hemlo greenstone belt (Wawa Subprovince). Paleoproterozoic sequences include the Gunflint and Rove Formations of the Animikie Group. Mesoproterozoic Keweenawan basalts are interpreted to be an extension of the Osler Group of the Midcontinent Rift (Sage, 1991).

Sage (1978, 1991) mapped greenschist facies Archean metavolcanic rocks and subvolcanic intrusive rocks ranging in composition from calc-alkaline dacite to tholeiitic basalt. The Archean supracrustal rocks consist of coarse felsic pyroclastic units, felsic to mafic tuffs, feldspar-phyric flows and amygdaloidal, pillowed and variolitic mafic flows with thin interbeds of argillite and siltstone (Fig. 2; Sage, 1991). On the basis of pillow facing directions Sage proposed that an antlicinal structure crosses the centre of Mortimer Island. The pillowed flows are most common on Mortimer and Delaute islands (Fig. 2); pillows are typically bun- to mattress-shaped and up to 2m across (Sage, 1991). In places on Mortimer Island the massive and pillowed basalts grade into flow breccias. Volcanic and intrusive rocks of more felsic compositions are found on Patterson, Dupuis, Spar and Leadman islands (Fig. 2) and have been interpreted by Sage (1991) to be highly sheared, amygdaloidal and porphyritic carbonatised sequences. Archean metasedimentary rocks are relatively rare and are predominantly volcaniclastic as they appear to interfinger with the volcanic flows (Sage, 1991).

The Archean mafic volcanic rocks from the Slate Islands are can be subdivided into two distinct geochemical suites. One suite is characterized by flat primitive mantle-normalized patterns typical of tholeiitic rocks found in modern oceanic plateaus whereas the second, more abundant, suite is characterized by weakly LREE-enriched patterns with minor negative Nb anomalies, characteristic of rocks formed in an island arc setting (Fig. 3; P. Hollings, unpublished data). Similar assemblages have been reported in the Schreiber-Hemlo greenstone belt (Polat et al., 1998).

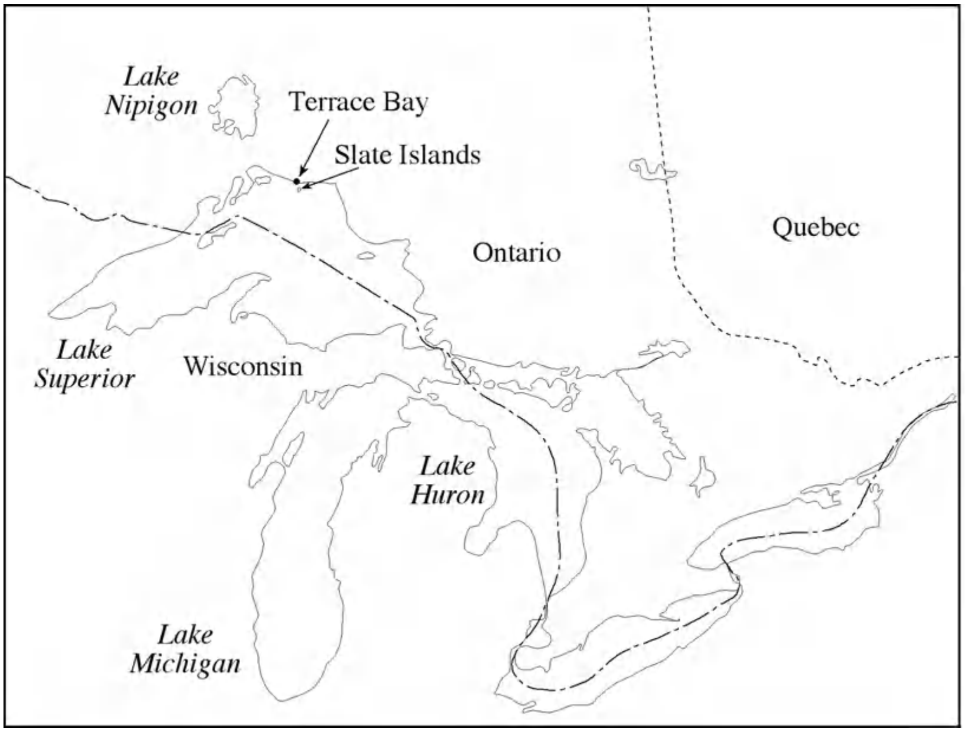


Figure 1. Map showing the location of the Slate Islands.

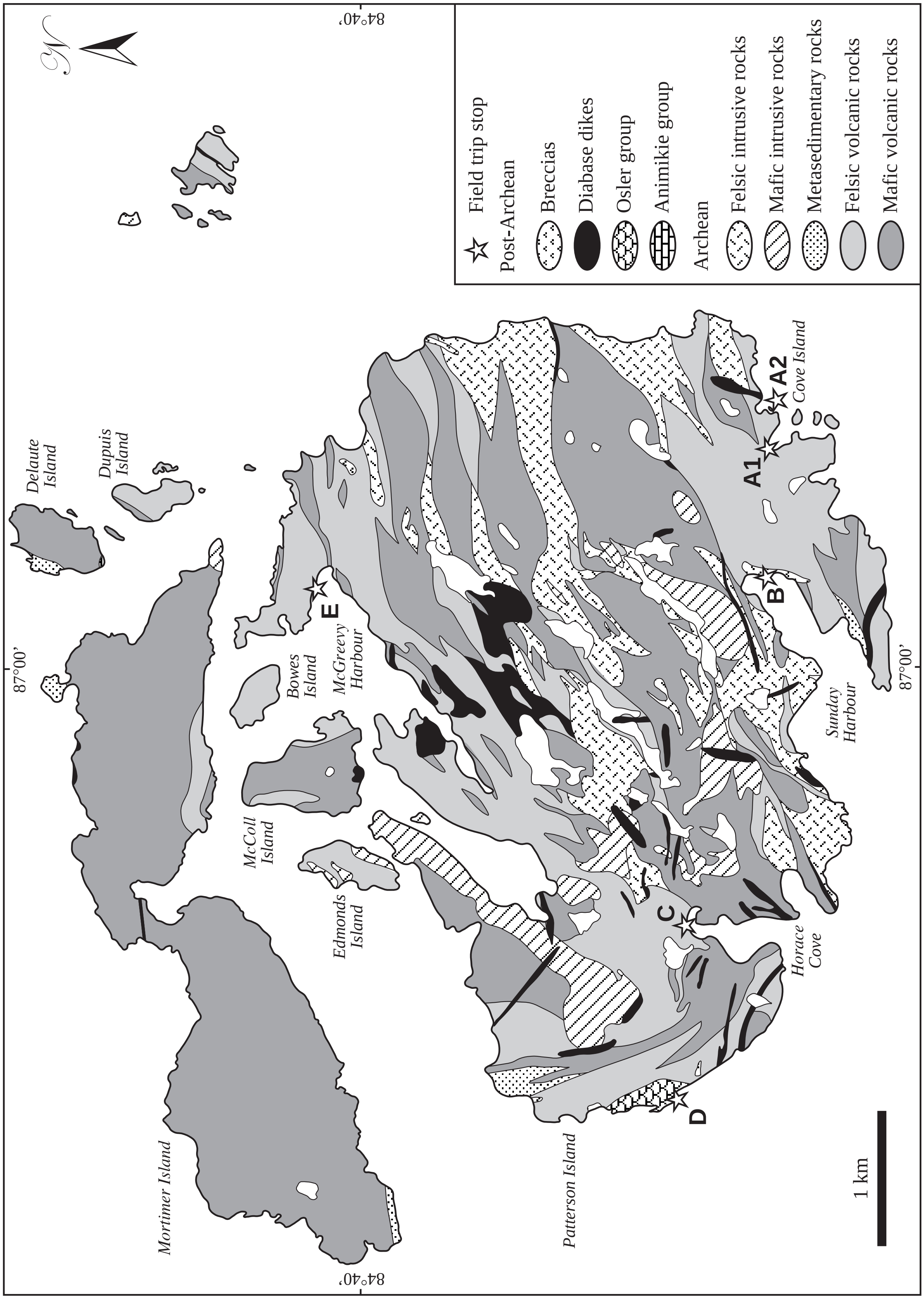


Figure 2. Geological map of the Slate Islands. Modified after Sage (1991).

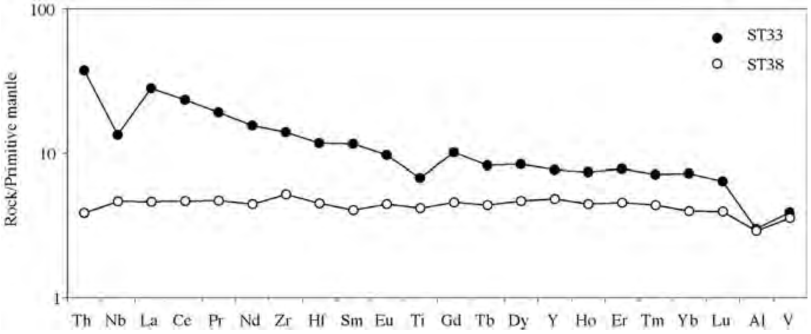


Figure 3. Primitive mantle normalised diagram showing representative samples of the two geochemical suites recognised amongst the Archean mafic volcanic rocks of the Slate Islands. ST33 = arc-type, ST38 = plateau-type. Normalising values from Sun and McDonough (1989).

On the western shore of Patterson Island, Sage (1991) reported an ~20m thickness of iron formation of the Gunflint Formation lying unconformably on the Archean basement and below Mesoproterozoic Keweenawan basalts (Fig. 2). The lowermost three metres of the sequence consists of interbedded jaspilitic chert, hematite and carbonate overlain by a sequence of hematitic chert. The argillites are generally massive and only locally display well-developed bedding. Recent re-examination of outcrops on eastern Mortimer Island and Delaute Island mapped as Paleoproterozoic Rove Formation clastic sedimentary rocks, has resulted in them being reinterpreted as Archean metasedimentary rocks analogous to the McKellar Harbour turbidite sequence on the mainland and this is now reflected on Figure 2.

Keweenawan basalts unconformably overlie the Gunflint rocks (Fig. 2) and form an ~120m thick flow sequence that dips ~80° at its base and diminishing to ~25° towards its top (Sage, 1991). This implies some degree of block rotation. Twenty-two individual flows can be recognized within the upper portion of the sequence. Interflow contacts are typically sharp and often marked by thin interflow sedimentary units (Sage, 1991). The basalts are typically vesicular and amygdaloidal, and in places show poorly developed ropy flow tops. The feldspar and pyroxene-phyric basalt flows are incipiently to completely altered, to sericite, carbonate and calcite (P. Hollings, unpublished data). However, even the relatively unaltered samples are significantly more altered than Osler basalts in the vicinity of Rossport (Hollings et al., 2006). Red, medium-grained, well-sorted, arkosic sandstone interflow units consist of sub-rounded to sub-angular grains of predominantly quartz, plagioclase, K-feldspar, volcanic rock fragments and amphibole. The feldspars, especially the K-feldspar, are commonly intensely weathered (seriticised). Most grains have very fine-grained hematitic coatings. The sandstone is relatively matrix-poor with an earlier phase of radiating chalcedony and quartz fans to drusy cement overgrown by a later stage of blocky carbonate, void-filling cements. Halls (1974) proposed that the paleomagnetic signature of the basalts was comparable to the lower portions of the Osler volcanic group in northwestern Lake Superior. The aforementioned rocks are also intruded by a number of Keweenawan dikes and breccia bodies which commonly occupy and obscure lithologic contacts (Sage, 1991).

Hinze et al. (1966), on the basis of aeromagnetic data, interpreted the presence of two major faults, which intersected to the south of the Slate Islands (Fig. 4). Sage (1991) has proposed that the onshore extension of the

Figure 4. Faults of eastern Lake Superior with inferred directions of movement from Sage (1991). Modified from Hinze et al. (1966).

northeast-trending Big Bay-Ashburton Bay Fault may be related to northeast-trending structures associated with the Mesoproterozoic Midcontinent Rift-related alkalic carbonatitic complexes at Deadhorse Creek and Prairie Lake.

Sage (1991) reported that, in the vicinity of Patterson Island, breccia dikes cut and enclose blocks of lamprophyre with carbonatite affinity that have yielded a K-Ar age of ~300 Ma. Recently this unit has been dated using the U-Pb method, yielding a Keweenawan age of ~1100 Ma (L. Heaman, University of Alberta, personal communication, 1994, referenced in Dressler et al., 1999) suggesting the young K-Ar ages are likely the result of resetting. The breccias have been used to both argue for and against a meteor impact theory for the Slate Islands and are discussed further below.

One Archipelago, Two Possible Origins

In addition to the complex bedrock geology, the islands have also been the focus of interest and debate because they are considered by some to represent the “best-preserved, medium-sized, meteor impact structure on Earth” (V. Sharpton, Lunar and Planetary Institute, NASA, pers. comm. 1995). However, this theory is not universally accepted and Sage (1991, 1999) has proposed an endogenous cryptoexplosion process for formation of the islands.

The Case for an Extraterrestrial Impact Origin for the Slate Islands Structure

Before discussing the evidence for an impact, it is worth outlining the basic dynamics of a hypervelocity extraterrestrial impact. The continuous process that occurs during an impact is more readily understood if it is dealt with in stages (summarized by French, 1998, and outlined in particular for the Slate Islands by Dressler et al., 1998).

1) *Contact/Compression Phase*. As the impactor hits, hypervelocity shock waves are generated in both the impactor and the target rocks which forces the bedrock downwards and outwards, instantaneously vapourizing the impactor and the target rock near the point of impact, while further away the target melts as the shock pressures attenuate.

2) *Decompression/Excavation Phase*. The shock wave is immediately followed by a rarefaction or tensional wave, decompressing the remaining rock and allowing it to relax, opening fractures large and small, driving material downward, outward and upward, excavating an extremely short-lived, steep-sided, unstable transient crater.

3) *Central Peak Formation*. If the impactor and consequent forces are large enough, the unloading of deep bedrock by the removal of overlying rock plus the decompression following the shock wave, results in material in the bottom of the crater rebounding upward into a central peak within the transient crater (as when a drop of water hits the calm surface of a pond).

4) *Transient Crater Collapse and Formation of the Final Crater*. As the transient crater reaches its maximum size, the fractured and faulted oversteepened walls begin collapsing into the crater in a rush, meeting and mixing with the likewise collapsing central uplift, before settling into an approximation of the final crater form. The entire process from first contact by the impactor to this stage has not lasted much more than 5-10 minutes in most craters, perhaps 15 minutes in the very largest craters a couple of hundred of kilometres in diameter.

5) *Long Term Adjustment*. Then begins a long process of adjustment, lasting decades to many millennia, depending on many things, but primarily crater size. During this final stage, loose debris continues settling, aided by tremors as stresses are released, hydrothermal activity begins in medium-sized to large craters, cooling continues, and finally, consolidation and lithification of breccias takes place.

A number of authors have proposed that the Slate Islands have preserved the site of a meteor impact (Halls, 1975, 1976; Robertson and Grieve, 1976; Halls and Grieve, 1976; Halls and Stesky, 1978; Dressler et al., 1995, 1998, 1999). The islands themselves have been identified as the central uplift of a medium-sized impact structure, which, bathymetry suggests, is surrounded by a submerged annular trough ringed by a ridge 30 to 32 km in diameter (Halls and Grieve, 1976; Dressler et al., 1995), representing the suggested final crater diameter. A crater this size implies an ~1.5 km diameter impactor with an arrival velocity of ~ 15 km/s. This circular feature was also transected and confirmed by the Great Lakes International Multidisciplinary Program of Crustal Evolution (GLIMPCE) seismic reflection line (Fig. 5; Mariano and Hinze, 1994).

According to Dressler et al. (1998) almost all the rocks of the archipelago are somewhat brecciated and

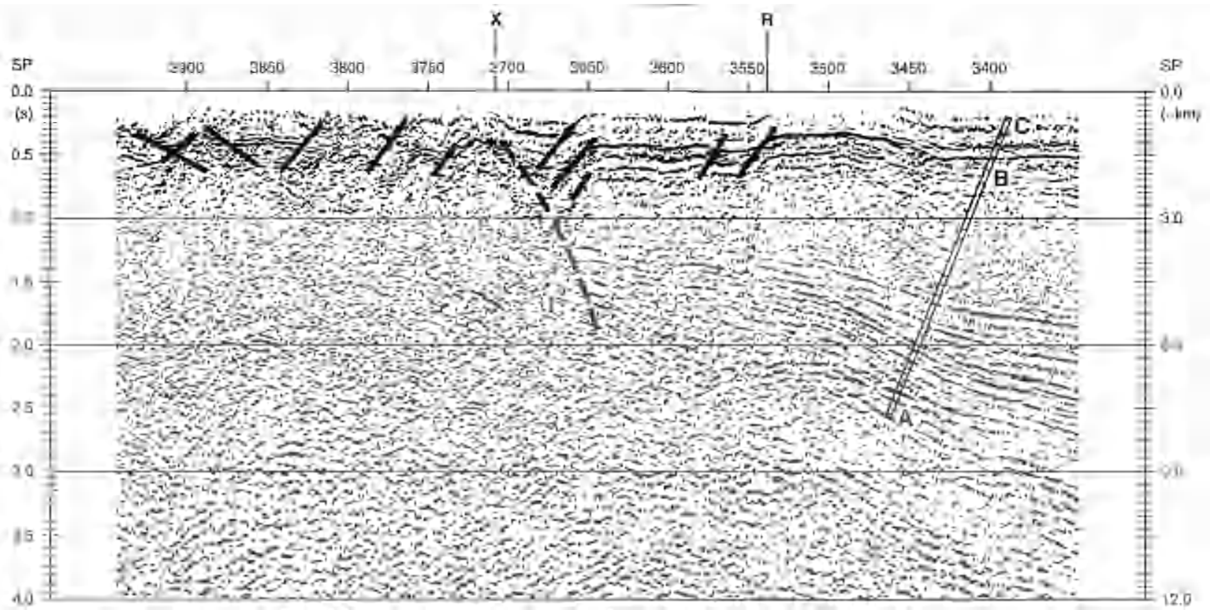


Figure 5. Reprocessed northern part of GLIMPCE Line A (courtesy of B. Milkereit, Geological Survey of Canada, 1994, published in Dressler et al., 1999). Left vertical axis is seconds of two-way time, right vertical axis is approximate depth in kiometres and horizontal axis shows shot points. X is the westward projection of the approximate centre of the central uplift. The distance from the centre of the central uplift (approximate geographic centre of the archipelago) to R is 15-16 km. R lies approximately where the rim of the structure is placed based on bathymetry. The strong reflections at 0.5 s may represent arenites of the Jacobsville Formation and not multiple reflections of the lake bottom which is at relatively shallow depth in the area investigated here. AB: Keweenawan basalt; BC: Jacobsville Formation. From Dressler et al. (1999).

they propose that the bedrock can be considered a megabreccia, although the detailed mapping of Sage (1991) showed good structural coherence across the islands. For Sage (1999) this structural coherence between the blocks and with rocks on the mainland argues for an endogenous origin for the breccias on the islands. All local rocks have been intruded by a network of anastamosing breccia bodies ranging in colour from brick-red to greenish grey. The breccias consist of sharply angular to sub-rounded fragments up to four metres across derived from local Precambrian rocks. The breccias have been ascribed to both endogenous intrusive activity (e.g., Sage, 1991) and meteor impact (e.g., Sharpton et al., 1996) and have been used to argue both for and against the impact theory on the Slate Islands.

The age of the Slate Islands structures and breccia bodies is poorly constrained (Table 1). Grieve et al. (1995) proposed an age of <350 Ma based on similarities in the erosional level between the Slate Islands and the ~350 Ma Charlevoix structure in Quebec. Sharpton et al. (1996) have proposed an age of 500-800 Ma based on the presence of clasts of the Mesoproterozoic Jacobsville sandstone (southern shore of Lake Superior, Michigan) and absence of any Devonian or Ordovician carbonates. However, the Slate Islands sandstone clasts are similar to sandstone interflow units found within the Osler basalts on the western shore of Patterson Island and, thus, may not be Jacobsville sandstone. More recent Ar-Ar age determinations on impact-generated pseudotachylites have yielded spectra consistent with an age of ~450 Ma (Fig. 6; Sharpton et al., 1997; Dressler et al., 1999). Features that have been used in support of an impact event include dikes of clastic-matrix breccia

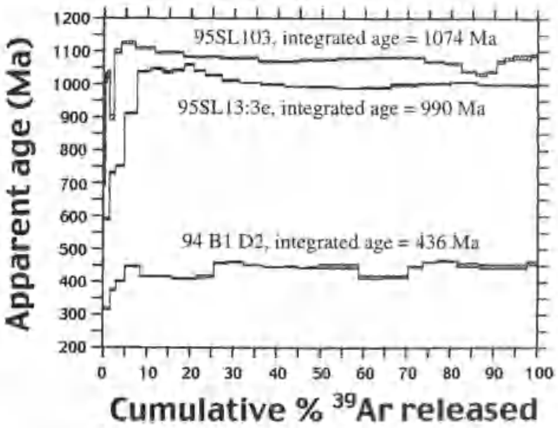


Figure 6. ^{40}Ar-^{39}Ar release spectra. Samples 95SL103 and 95SL13:3e: dark gray, inclusion bearing "impact melts" (Keweenawan basalt). Sample 94B1D2, inclusion-poor pseudotachylite. From Dressler et al. (1999).

Table 1. Stratigraphic age constraints on the Slate Islands impact. The age of the Jacobsville is ~1100 Ma, however these clasts may be interflow sandstones from within the Osler-like volcanic flows (see text). From Dressler et al. (1999).

Observation	Age Constraint	Comment	Reference*
Brecciated Keweenawan	<1.1 Ga		1, 2
Shock-deformed and brecciated lamprophyre			
K-Ar (antigorite and phlogopite)	<282 to 310 Ma	U-Pb determinations more reliable	3
U-Pb (perovskite)	<1.1 Ga		4
Brecciated sandstone of the Jacobsville Formation	<800 Ma		5
Apparent absence of Ordovician/Devonian rock fragments in impact breccias	>350 Ma	Hudsons Bay Lowlands and Michigan basins were almost certainly connected during Ordovician/Devonian	6, 7
Similarity of Slate Islands erosion level with that of 357 Ma Charlevoix impact structure.	<350 Ma	Erosion levels are variable in various parts of the Canadian Shield	8

*1 = Halls and Grieve, 1976; 2 = Dressler and Sharpton, 1997; 3 = Sage, 1991; 4 = L. Heaman, U. of Alberta; 5 = Card et al., 1994; 6 = Norris and Sanford, 1968; 7 = Sharpton et al., 1996; 8 = Grieve et al., 1995.

(Halls and Grieve, 1976; Sage, 1991), which include; pseudotachylites, polymictic allogenic breccias and monomictic autoclastic breccias (Sharpton et al., 1996) concentrated on the eastern shore of Patterson Island as well as Mortimer, Dupuis and Delaute islands.

Shatter cones occur throughout the islands but are most obvious in the Keweenawan basalts. They are interpreted to have formed from the passage of a high-pressure shock wave (Dietz, 1964). They are characterized by a surface decorated with linear ridges and grooves (horsetail striations) that radiate from the apex of the cone. On the Slate Islands most shatter cones range from 2cm to ~30cm long; those in the Keweenawan rocks are 10 to 30 cm long (Sharpton et al., 1996). In addition Sharpton et al. (1996) reported a number of "mega cones" at least 10m long (and possibly up to 20m) in McGreevy Harbour (Fig. 2). As with the breccias the origin of the cones themselves remains controversial (Sharpton et al., 1996). Dressler et al. (1999) has suggested that the shatter cones formed during the compressional phase of the impact (Fig. 7) and indicate a minimum shock pressure in the target rocks of 3 GPa. Sage (1991) observed that shatter cones were most extensive close to breccia outcrops and used this to argue that the explosive emplacement of diatreme dikes was responsible for their formation. However, more detailed work (Sharpton et al., 1996) indicated that the shatter cones are ubiquitous on the islands. Dressler et al. (1995, 1999) have reinterpreted

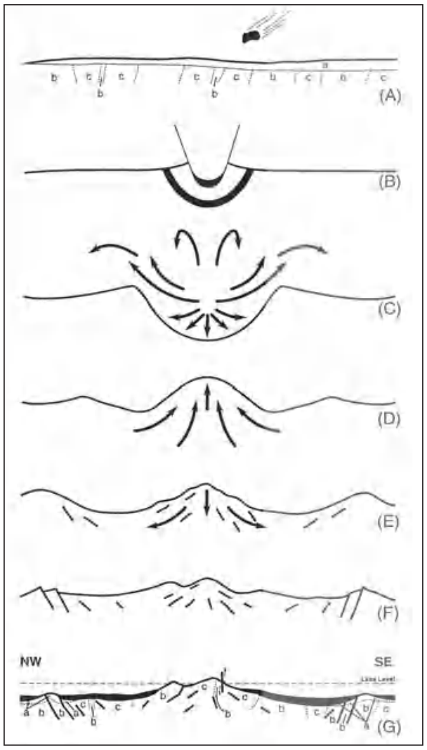


Figure 7. Formation of the Slate Islands impact structure. A) preimpact target; B) contact and compression; C) excavation; D) central uplift; E) central uplift collapse and modification; F) final structure; G) present structure, black areas indicate impact melt overlain by allogenic breccias (assumed, not shown in D-F). a, Proterozoic and younger supracrustal rocks: Deformed Archean greenstone assemblage (assumed in annular trough); b, Mafic metavolcanics, minor metasediments and intrusive rocks; c, Intermediate and felsic metavolcanics, minor metasediments and intrusive rocks. From Dressler et al. (1999).

Sage's diatremes as impact breccia bodies (e.g., Bunte breccia, suevite).

Microscopic planar deformation features (PDFs) in quartz and feldspar have been observed in rocks from the Slate Islands by Halls and Grieve (1976), Sage (1991) and Dressler et al. (1994). These planar lamellae are shock induced micro-melt zones <2-3 µm wide along crystallographic axes. They first appear in quartz at pressures of ~8 GPa along the {0001} and {1011} axes and at ~10 GPa they begin to appear along the {1013} axis (French, 1998). PDFs are considered diagnostic of the extremely intense shock waves produced during hypervelocity impacts. However, a single set of PDFs can easily be confused with Bohm lamellae and other planar features, and thus, two or more criss-crossing sets of PDFs along different measured crystallographic axes are the preferred diagnostic features. Criss-crossing sets of PDFs are seen both in the Slate Islands host rocks and in breccia components. In a detailed study of these features Dressler et al. (1998) showed a zone of maximum shock intensity on Patterson Island (Fig. 8), suggesting the location of the impact was slightly west of the center of Patterson Island.

A detailed study of the breccias on the Slate Islands has been undertaken by Dressler and Sharpton (1997) who have estimated that breccias make up ~15 to 25% of the Islands' rocks. Interpretation of which breccia types cross-cut other breccias, plus features such as PDFs, allowed them to hypothesize when various features formed during the impact process. It is within this context that Dressler and Sharpton (1997) place their interpretations of the breccias (Figs. 7, 8 & 9; Table 2). The breccias identified by the authors include:

- ***Pseudotachylites*** which are thought to have formed as a result of brittle-or brittle-ductile seismic faulting and instantaneous melting due to the passage of the hypersonic shock wave during the compressional phase of the impact event. Pseudotachylites are relatively rare in the archipelago and occur as small veins and dikes. The early formation of these pseudotachylites is supported by the presence of clasts of pseudotachylite in the breccias.
- ***Polymictic clastic matrix breccias*** are the most abundant breccia type on the islands but are more common on Patterson Island than on the outlying islands. The breccias contain a wide variety of clasts from all host lithologies, that are angular to sub-rounded, and range in size from <1mm to several metres. These are interpreted to have formed when decompression allowed opening of fractures within the crater walls and floor (Dressler et al., 1999) excavating the crater to a depth of ~1.5 km in approximately 1 minute.

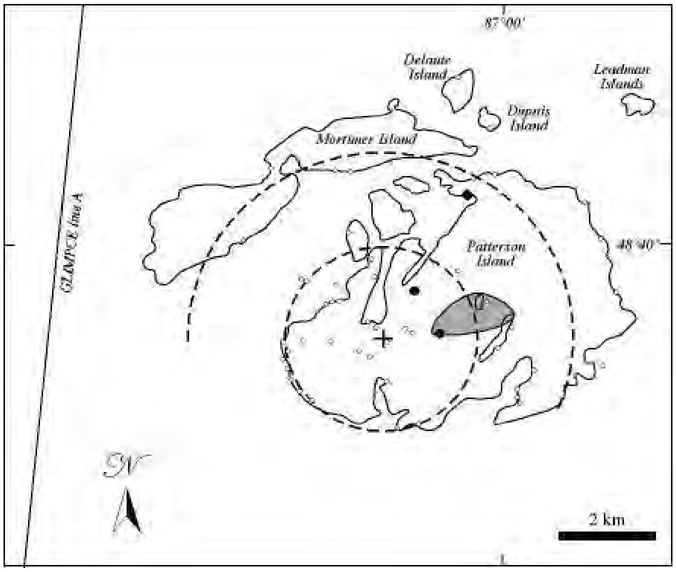
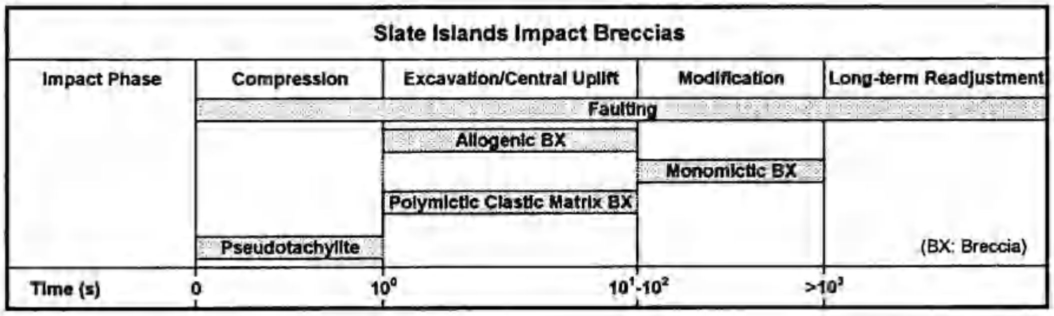


Figure 8. Sketch map of Slate Islands impact structure, located in northern Lake Superior. Dashed lines show concentric trends of coast lines and structural elements indicating crater center on western side of Patterson Island (approximate location is shown by cross). Previous estimates of crater center, 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 circles. Shatter-coned outcrops are shown as small unfilled circles. Filled diamond shows location of >10m shatter cone. Map is adapted from Sharpton et al. (1996). Shaded field is the area of highest shock values from Dressler et al. (1998).

Table 2. Slate Islands impact breccias. From Dressler and Sharpton (1997).



Breccia type	Diagnostic observations	Impact stage
Breccias in target rocks		
Pseudotachylite	Fluidal melt texture; thin dikelets and anastomosing veins; sharp contacts with host rocks; few clasts, some with shock features. Relatively scarce, observed on Patterson and Mortimer islands.	Compression
'Cryptic breccia'	Homogeneous rock that breaks into small, angular fragments when struck with a rock hammer. Central Patterson Island only.	Compression
Polymictic clastic matrix breccia	Wide variety of clasts of various shapes and sizes; shock metamorphic features; altered glass in places; fragments of pseudotachylite in places; forms dikes and irregularly shaped bodies with sharp contacts with host rocks; cuts across pseudotachylite. All islands, but mainly on Patterson Island.	Central uplift and excavation; possibly also somewhat later.
Monomictic breccia	Monomictic, angular fragments in clastic matrix; transitional contacts with host rocks; contains fragmented, polymictic, clastic matrix breccia dikes. Mortimer Island and outlying islands only. Very scarce on Patterson Island.	Crater modification
Allogenic breccias		
Suevite	Shock metamorphic clasts and altered glass fragments in clastic matrix. Glass fragments have no aerodynamic shapes. South and east Patterson Island and Dupuis Island only.	Excavation
'Bunte Breccia'	Polymictic, glass-free breccia. No features indicative of strong shock. South Patterson and Delaute islands.	Excavation

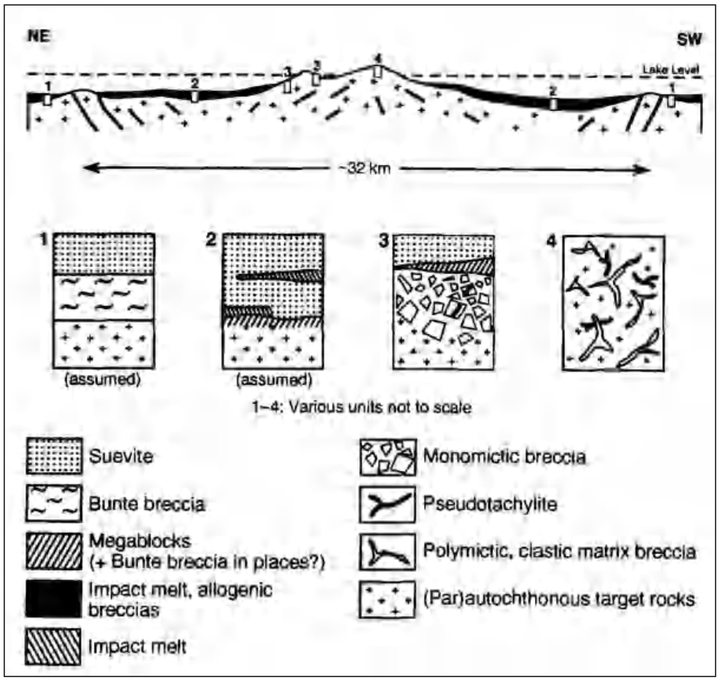


Figure 9. Section across the Slate Islands complex impact structure showing distribution of breccias investigated. Minor polymictic clastic matrix breccias are also present further away from the centre of the structure than shown here. Profile is based on bathymetric information from around the archipelago and on topographic maps of the islands. From Dressler and Sharpton (1997).

The presence of Proterozoic clasts in breccias dominated by Archean material has been used to argue for downward movement and mixing of clasts over distances possibly as much as 5 km (Dressler and Sharpton, 1997).

- ***Allogenic breccia*** deposits containing altered glass fragments (suevites) or with no glass fragments (Bunte breccia) are present on Dupuis and Patterson islands and have been used to argue for a shallower erosion level for the archipelago (Sharpton and Dressler, 1996). The Bunte breccias are interpreted to have formed either as fall-back deposits in the crater or as ground-surge deposits. The breccias contain mainly Proterozoic clasts, supporting their origin as fall-back deposits (Dressler et al., 1999). Dressler et al. (1999) have also reported the presence of suevite breccias and use the absence of aerodynamically shaped glass fragments to argue that they are also fall-back breccias.
- ***Monomictic, autochthonous breccias*** are found on Mortimer Island and a number of the small outlying islands. The breccias comprise angular, densely packed fragments typically up to 20 cm in size within a matrix of similar clastic rock powder. These are interpreted to have formed late in the impact process during the crater modification phase (Fig. 7) as huge blocks of rock slumping off the transient crater walls ground together during their slide into the crater over several minutes (Dressler et al., 1999). The breccias are often autoclastic with transitional borders with their host rocks (Dressler and Sharpton, 1997).

Halls and Grieve (1976) and Grieve and Robertson (1976) proposed that the Slate Islands represented uplifted basement that preserved breccias injected during impact into the crater subfloor (~0.5 to 1.5 km below the central peak). However, Sharpton et al. (1996) have suggested that the allogenic and autoclastic breccias indicate that the present exposure surface is only a few hundred metres below the original ground surface. This issue is not without controversy and is discussed further in Halls (1997), Grieve and Robertson (1997) and Sharpton and Dressler (1997).

Current interpretations based on topographic and structural trends place the crater center in the west-central part of Patterson Island (Fig. 8; Sharpton et al., 1996) whereas earlier interpretations based on shatter cone orientations and shock barometry (Stesky and Halls, 1983; Grieve and Roberston, 1976) suggested that it was closer to the center of Patterson Island (Fig. 8). However, given that both locations are within 1.5 km of each other and given that the impacting body was estimated to have a diameter of ~1.5 km, none of the proposed locations should be considered definitive (Sharpton et al., 1997).

The Case for a Cryptoexplosion Origin for the Slate Islands Structure

The title of Sage's (1999) paper clearly stated his case: "The Slate Islands: A Uniquely Sited Cryptoexplosion Structure". He noted that the Slate Islands are situated on or near the Proterozoic-Archean boundary and at the intersection of two major inferred faults, the Big Bay-Ashburton Bay Fault (or accommodation zone) and the Michipicoten Fault. He also noted that the Slate Islands lie on the flank of the Midcontinent Rift where crustal thickness reaches 50 km or more, and on a topographic ridge, extending southwest to Superior Shoals and northeast to the mainland, which bisects this thick crust. Perhaps most importantly to Sage, the Slate Islands are close to the Port Coldwell Alkalic Rock Complex, the Kilalla Lake Alkalic Rock Complex, Prairie Lake Carbonatite, Deadhorse Creek Diatremes and McKellar Creek Diatremes (Sage, 1999), all of Keweenawan age.

Sage (1991) argued that "the possibility of a meteorite impact at this precise location – on a ridge traversing the Lake Superior Basin, on the nose of an Archean fold structure, at the precise location of the Proterozoic-Archean contact, at the precise location of two intersecting regional faults, and at the precise location of highly volatile alkalic magmatism – is too incredible to accept (Sage, 1991, p.56)". Sage (1978) presented a number of geological observations favouring a non-impact origin many of which were elaborated upon in Sage (1991). These included:

- Clast size sorting in the diatremes from fine-grained at the margins to coarse-grained at the center is typical of laminar flow (Sage, 1978) and more likely to occur in a diatreme than by downward intrusion.
- Orientation of shatter cones was not consistent with a central impact structure.
- Contact metamorphic effects between the breccia and alkalic diabase indicates that hydrothermal

activity accompanied breccia emplacement.

- The presence or absence of an igneous matrix in breccia dikes on the islands and the mainland does not preclude an igneous origin.

The Debate

The debate – cryptoexplosion vs impact – over the origin of the Slate Islands structure largely mirrors (in a more genteel way) the vigorous debate which began when Dietz (1964) proposed that the Sudbury Structure was due to an impact. When Alvarez et al. (1980) proposed that the K/T extinction was caused by an impact, the debate became a nasty scientific controversy. Now, some 26 years later, the debates over Sudbury and the Chicxulub-K/T extinction crater are resolved in favour of an impact origin for both. The debate is summarized by Powell (1998) in an interesting, very readable popular book, "Night Comes to the Cretaceous".

To reiterate Sage's statement, "the possibility of a meteorite impact at this precise location – on a ridge traversing the Lake Superior Basin, on the nose of an Archean fold structure, at the precise location of the Proterozoic-Archean contact, at the precise location of two intersecting regional faults, and at the precise location of highly volatile alkalic magmatism – is too incredible to accept" (Sage, 1991, p.56). Halls (1979) counters that the absence of complex overlapping shatter cone sets argues against the multiple emplacement events proposed by Sage (1978). On a larger scale Halls (1978) argued that the regional faults proposed by Sage (1978) are only inferred from geophysical data and the magnetic anomalies may also delineate the unfaulted margin of the Keweenawan basin. Halls (1979) also provided alternative explanations for the apparent coincidences suggested by Sage, observing that the lower and upper Precambrian contact predates the shock event and cannot be used to argue either for or against.

The Slate Islands debate centres mainly on the interpretation of three sets of features: the breccias, shatter cones, and planar deformation features (PDFs). Sage (1991) has proposed that the breccias originated from the forcible emplacement of volatile-rich magmas formed at depths > 35 km which have risen to a shallower level and exsolved a gas phase. The higher volatile contents of clasts and matrix have been argued to support this model. However, arguing against an origin at depths of ~35 km is the absence of deep-seated or magmatic material in the breccias (Robertson and Grieve, 1979). Another breccia problem is explaining how dikes containing upper level Paleoproterozoic fragments were emplaced into lower level Archean rock. Halls and Grieve (1976) were the first to suggest a downward injection of breccias into fractures (during the crater modification stage following the passage of the initial shock wave) as a result of an impact event (Robertson and Grieve, 1979). However, Sage (1991) has countered that the presence of stratigraphically high level clasts at depth could also be explained by collapsing fluid columns after the emplacement of diatremes. Today, the various breccia types (pseudotachylites, polymictic, allogenic, and monomictic autochthonous), their relationships within each other, and their locations within the Slate Islands structure seem to be best explained by their production during various phases of the impact process (Sharpton and Dressler, 1997; Dressler and Sharpton, 1997; Dressler et al., 1999).

Sage (1991) has also advocated that the forceful emplacement of diatremes formed at depths > 35 km could account for the shock features – shatter cones and PDFs – preserved on the islands. Sage (1999) provides a number of examples of other occurrences of planar deformation lamellae and shock textures that may have been produced by kimberlite emplacement, however, he acknowledges that these features have also been interpreted as having been formed by impact events.

Robertson and Grieve (1979) observed that shatter cone formation is a function of lithology as well as shock pressure and the fissile Archean metavolcanics would display more poorly developed cones than the structurally isotropic Keweenawan flows. The distribution of microscopic shock effects has been recorded by Grieve and Robertson (1976) who showed that the intensity of these features increase in a consistent fashion from the coast inward to the proposed impact centre (see Fig. 8). Roberston and Grieve (1979) also argued that diatreme emplacement is normally considered to be a process of "drilling and venting by gas streaming" rather than by violent explosions and that the pressures induced by this process are unlikely to exceed 1.5 GPa, whereas pressures of 2-6 GPa are required to generate shatter cones (French, 1998). Halls (1979) took issue with Sage's measurements of shatter cones suggesting that he did not use the correct measurement procedure and did not properly correct his data and that stated that there is no convincing spatial correlation between shatter cones and breccia dikes, and furthermore, the breccias contain shatter-coned clasts (Halls and Grieve, 1976).

PDFs seem beyond debate, so long as they are really PDFs (and not Böhm lamellae), based upon measured widths and spacing of lines and particularly based upon their alignment along measured crystallographic axes. French (1998) has summarized a large body of laboratory experimental evidence and field evidence on PDFs, as do Dressler et al. (1998). Dressler et al. (1998) measured a large number of PDF orientations in Slate Islands quartz crystals. They found PDFs aligned along many different axes, notably the {1013} and {1012} axes, indicative of shock pressures as high as 18 GPa, pressures equivalent to those many hundreds of kilometers depth within Earth. Such observations cannot be explained by diatremes.

A little discussed problem for the impact hypothesis is the apparent absence of evidence for an impact on the mainland north shore of Lake Superior, only 15 km from the proposed impact centre, which supposedly produced a crater ~15-16 km in radius.

Thus, on both side of the debate, problems still have to be resolved, but the majority of the evidence described from the Slate Islands Structure is best explained by an impact.

Economic Geology

A synopsis of the mineral exploration history and mineralization is provided by Sage (1991). Two styles of mineralization in the Archean metavolcanic rocks have garnered the most exploration interest: 1) lode gold; and 2) volcanogenic massive sulphide copper-zinc.

Gold is associated with quartz-carbonate veins in deformed and altered (Fe-carbonate, sericite, chlorite, tourmaline) rocks. More than 20 occurrences of visible gold in float boulders of quartz vein material have been recorded on the islands (Resident Geologist's Files, Thunder Bay South District, Thunder Bay). Visible gold has also been noted in-situ near Horace Cove (aka St. Mary's Bay).

Massive sulphides occur in felsic metavolcanic rocks or as fragments in pyroclastic rocks. Massive pyrite sampled by Sage (1991) returned 0.11% Cu and 0.28% Zn. A sulphide-facies banded iron formation sampled by Resident Geologist staff in 1995 near Cove Island returned 604 ppm Zn, <100 ppm Cu and 157 ppm Pb (Resident Geologist's Files, Thunder Bay South District, Thunder Bay).

Stops

The field trip stops are labeled with letters rather than numbered in sequence as access to all stops, particularly on the outer shores of the islands, is weather-dependent. Many of the stops require some wading in order to reach all the outcrops so a change of footwear is recommended. Please take care when getting in and out of boats as outcrops are usually extremely slippery.

Stop A – "Honeymoon Bay" near Cove Island

UTM coordinates – 0502004E 5386377N

This small bay near Cove Island (Fig. 2) provides exposures of strongly sheared Archean felsic metavolcanic rocks at its northeast end (Stop A1). These metavolcanic rocks are phyllitic, displaying a pronounced west-trending, steeply dipping foliation with minor folds and kink bands. They are intruded by a 1 m wide, Paleoproterozoic diabase dike that zigzags across the outcrop (Fig. 10). A small (50 cm) wide breccia dike crosscuts the metavolcanic rocks. Metavolcanic rocks along the western shore of the bay are cut by a number of grey, heterolithic breccia dikes with 0.5 to 5 cm, angular to sub-rounded clasts (Figs. 11 & 12). Narrow (<1 cm) dikelets may extend into the wall rock from the parent breccia dike.

Figure 10. Diabase dyke intruding Archean felsic metavolcanic rocks at Stop A1.

Figure 11. Breccia dyke intruding Archean felsic metavolcanic rocks at Stop A1. Dykelets marked by arrows.

Figure 12. Heterolithic breccia dyke at Stop A1.

From this point groups will be shuttled out to a small island to the east of Honeymoon Bay (Stop A2; Fig. 2; *UTM coordinates 0502426E 5386437N*). This island consists of heterolithic breccia with clasts over 2 m across (Fig. 13). From the top of the island it is possible to look down upon a series of anastamosing dark grey breccia dikes under the water in the bay (Fig.

Figure 13. Typical breccia exposed on the breccia island at Stop A2.

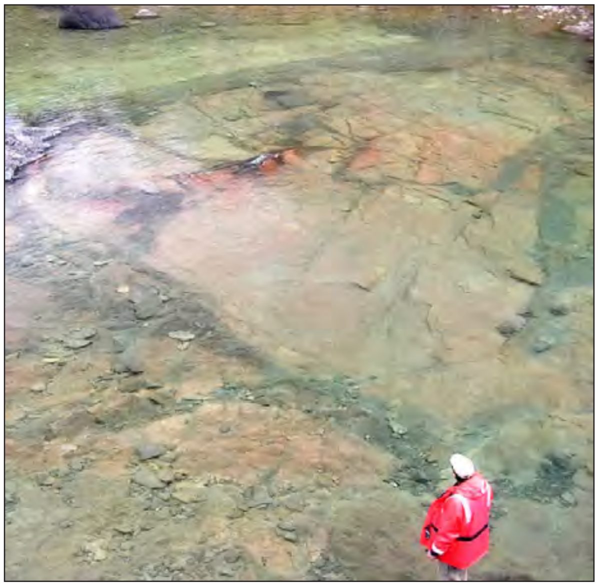


Figure 14. Anastamosing breccia dykes at Stop A2.

14) and across to a second island where an ~2 m wide, recessively weathered clast of reddish metavolcanic rock is clearly visible. You will need to get your feet wet to fully appreciate this outcrop. The majority of clasts typically range between <1 to 10 cm in size. They are derived from Archean metavolcanic rocks, Mesoproterozoic diabase and a variety of nondescript, fine-grained, variably altered rocks of indeterminate origin. Ragged, injected bodies of breccia may extend from larger, parent dikes.

Figure 15. Omars from the beach at Sunday Harbour (Stop B).

Stop B – Sunday Harbour

UTM coordinates – 0500801E 5386425N

The beach consists of reworked glaciofluvial sediments characterized by a variety of locally derived and exotic rounded cobbles and boulders. Most of these are felsic plutonic and mafic metavolcanic rocks of the Schreiber-Hemlo greenstone belt. The exotic clasts are best exemplified by what have been termed "omars" (Prest, 1990), glacial erratics of massive, dark siliceous greywacke that contain light-toned (generally buff-weathering) calcareous concretions which are typically subspherical and weather recessively (Fig. 15). Omars, which commonly occur in and on eskers and outwash, but which also may be found in till and lacustrine deposits, are inferred to have been derived from the Omarolluk Formation of the Belcher Group in southeastern Hudson Bay (Prest et al., 2000). Most of the erratics were dispersed northwestward and westward across the Hudson Bay Paleozoic Basin by Labrador Sector ice, followed by westward and southwestward movement of ice across the Paleozoic and Archean terrain of northern Ontario, northern Manitoba and the upper Midwestern United States.

A series of breccias are exposed on the eastern shore of Sunday Harbour. Dressler et al. (1999) reported the presence of two allogenic breccias at this outcrop: a Bunte Breccia is reported from the southern portion of the outcrop and a suevite breccia to the north. The southern end of the outcrop is a heterolithic grey breccia with clasts up to 50cm wide. It also contains clasts with well-developed shatter cones (Fig. 16).

The grey breccia contains conspicuous reddish metavolcanic clasts and rare mafic to ultramafic clasts up to 50 cm across. At this location, the breccia is quite friable and easily dislodged from outcrop faces. Narrow diabase dikes with quartz-filled tension gashes intrude the metavolcanic rocks and are exposed just offshore in shallow water. Foliation orientations in the metavolcanic rocks are variable, suggesting either large-scale folding or rotation of large blocks of country rocks. Reddish alteration zones appear as dike-like bodies, cutting the grey breccia in places.

Figure 16. Shatter cone clast in breccia at Sunday Harbour (Stop B).

Stop C – Horace Cove

UTM coordinates – 0497386E 5387206N

Shoreline outcrops at this location expose pervasively Fe-carbonatized and sericitized, schistose Archean metavolcanic rocks (Fig. 17). A strong, west-trending and steeply dipping foliation has resulted in the development of fissile, phyllitic rocks that also contain quartz, chlorite, green mica (chromian muscovite) and pyrite. Hydrothermal alteration and deformation preclude definitive recognition of the protolith. Sage (1991) has noted schistose basaltic to andesitic rocks, as well as dacitic to rhyolitic flows in the vicinity. Quartz- and feldspar-phyric units and sections containing quartz blebs (amygdules?) are also noted. Thin section analysis of this quartz-sericite schist by Nichols (1963) revealed a fine-grained groundmass of quartz blebs and scaly intergrowths of sericite that hosts siderite euhedra, altered albite and prochlorite and quartz amygdules.

Along the shoreline, quartz-carbonate veins, with which most of the gold is associated, occupy a 050°-trending fracture set. They range up to approximately 8 cm in width and are locally folded. Visible gold, pyrite, chalcopyrite and hematite are noted. Grab sampling of vein material by Resident Geologist's Program staff returned up to 3.95 ounces Au per ton and 0.2 ounce Ag per ton (Resident Geologist's Files, Thunder Bay South District). The style of mineralization, alteration and deformation resembles that at Heron Bay, on the mainland shore of Lake Superior, approximately 50 km east of this location.

The following synopsis of gold exploration at Horace Cove (aka St. Mary's Bay) was modified from that of Sage (1991). Parsons (1918) concluded that the gold showing on the northwest corner of Horace Cove was the most promising of the known gold occurrences. From 1960 to 1963 Kimberly-Clark Pulp and Paper Company Limited conducted a mineral exploration program of the islands to test two gold showings. The main gold showing (St. Mary's Bay occurrence) is on the northwestern corner of Horace Cove and the second occurrence (Cosen's Showing) lies 240 m to the northeast.

In 1960 Kimberly-Clark contracted an aeromagnetic and electromagnetic survey of the island. In 1961 and 1962 trenching, bulldozing, stripping, sampling and geologic mapping was done by the company over both the St. Mary's Bay zone and Cosen's showing. At St. Mary's Bay bulldozer stripping to depths of 1.6 to 2.0 m exposed an area of approximately 18,900 m^2; at Cosen's showing 240 m to the north, approximately 5350 m^2 of similar stripping was completed (G.E. Parsons, consulting geologist, personal communication, 1976). In 1963, Kimberly-Clark formed the Slate Island Mining Company Limited (The Northern Miner, September 19, 1963). Kimberly-Clark held a 50% interest, Junior Frood Mines Limited 25%, Upper Canada Mines Limited 12.5% and Cadamet Mines Limited 12.5% in

Figure 17. Intensely sheared Archean metavolcanic rocks and folded quartz-carbonate vein at Horace Cove (Stop C).

this new company (Financial Post Survey of Mines, 1964, p.169). In 1963, this company completed 20 diamond drill holes, totalling an estimated 1974 m on the St. Mary's Bay zone (G.L. Puttock, personal communication, 1974). This work disclosed variable, but locally very high-grade, gold mineralization in quartz veins of short strike length and over narrow widths of 2 to 10 cm. Mineral exploration of the islands ceased with the termination of the efforts of Kimberly-Clark. In April 1973, finding the islands of no further use to them, Kimberly-Clark transferred its rights to the islands back to the Crown. Subsequently, in September 1973 the islands were removed from staking.

The gold-bearing, quartz-carbonate veins of St. Mary's Bay zone and Cosen's showing display a strong southwesterly strike. Since the host rocks of the veins are folded into a northwest-trending sequence, these veins are approximately normal to stratigraphy as was observed in several places along the eastern shore of Patterson Island. Some evidence for shear folding of the quartz veins is indicated at the St. Mary's Bay zone by the irregular "sawtooth" pattern of some of the veins. Nichols (1963) suggested that gold-bearing quartz veins on Patterson Island occurred in the nose of a fold and occupied shear and tension fractures. Based on samples and descriptions by G.E. Parsons (consulting geologist for Kimberly-Clark Pulp and Paper Company Limited, personal communication, 1974), gold locally occurs in three ways. These are:

(1) in association with pyrite within the quartz-carbonate veins;

(2) as flakes and thin sheets along the flanks of the quartz-carbonate veins; and

(3) as thin sheets or flakes along schistosity planes of the rocks enclosing the quartz-carbonate veins.

Sampling by Sage (1991) of various quartz veins returned nil to insignificant gold values except for the St. Mary's Bay zone, where assays of 0.5 ounce Au per ton over widths of 2 to 3 cm were obtained. The quartz veins vary from tabular, lensoid, clearly defined veins to irregular anastomosing structures with no clearly discernible attitude. An average of 98 clearly defined veins gave an average width of 10.7 cm and a length of 5.5 m (Sage, 1991). Reddish-brown, coarse-grained carbonate is an ubiquitous, accessory to dominant mineral and pyrite is common to abundant. Rarely, black needle-like crystals of tourmaline were noted. A contoured stereonet plot of 167 quartz vein attitudes indicated a rather broad spread of attitudes with one and possibly two maxima. The strongest maximum defines a 070°-trending vein set dipping approximately 60° southeast. The second maximum defines a 035°-trending, vertically dipping vein set. The intersection of these two trends would define a lineation striking 210°, plunging about 14° southwest.

Brummer (1962) delineated an area of sericite schist and shearing extending for 300 m north-south and 570 m east-west at the northern end of Horace Cove. Pyroclastic rocks, diorites and porphyritic metavolcanic rocks were also noted. Three steeply dipping to vertical vein sets were identified: a major set at 035°; and minor sets at 063° and 050° to 060°. The 40 veins that had been discovered at that point ranged in strike length between 16 and 60 m and in width from 0.5 to 20 cm, averaging 5 cm. Brummer (1962) noted that approximately 80% of the gold occurred as this films along the outer vein margins. The altered wall rock was not sampled for assay; Nichols (1963) noted an absence of gold in wallrock.

Stop D – Western shore of Patterson Island

UTM coordinates – ca. 495965E 5387400N

This location on the western shore of Patterson Island (Fig. 2) is a microcosm of Slate Islands geology, in that a variety of rock types and geologic features are exposed. The southernmost outcrops (*UTM coordinates - 495965E 5387324N*) are sheared Archean metavolcanic rocks which are unconformably overlain by hematite-jasper banded iron formation and ferruginous shales of the Paleoproterozoic Gunflint Formation (Fig. 18).

Figure 18. Unconformable contact between Keweenawan basalts (left) and Animikie Gunflint Formation (right).

The base of the Gunflint outcrop consists, very approximately, of 20m of interlayered grainstone and slaty iron formation. Diabase and red breccia dikes have obscured the lower contact of the Gunflint Formation. The grainstone layers are 1 to 30 cm thick and are composed of intraclasts of chert and jasper. Clast sizes range up to that of small pebbles but are dominated by medium-to coarse-grained sand. The rock has a pervasive quartz cement. The slaty iron formation layers form bundles less than one to several centimetrers thick. Individual layers are millimeter to sub-millimeter in thickness. They are composed of magnetite mixed with what is probably siliciclastic clay and silt. This unit is overlain by approximately 7 m of just the slaty iron formation. This denotes a rapid change from shallower, storm-dominated, bottom to deeper, more quiescent conditions, a trend similar to the Gogebic iron formation successions described from Wisconsin (Pufahl and Fralick, 2004). The exposed upper part of the Gunflint section dips approximately 20° to 30° to the north. The upper contact of the Gunflint with overlying Mesoproterozoic (Keweenawan) flood basalts is also obscured by diabase and breccia bodies. Small, delicate shatter cones (< 5 cm long) are developed in the argillaceous portions of the sedimentary rocks (*UTM coordinates - 495964E 5387369N;* Fig. 19).

A series of north-striking basalt flows ranging from 1 to 2 m thick outcrop along the shoreline. Sage (1991) has noted 22 separate flows in this section. The basalts are vesicular and amygdaloidal and dip approximately 20° to 60° to the west. Pipe amygdules occur near flow bases; coalescing amygdules may form flow-parallel lenses and bands (Fig. 20). Ropy flow tops, characteristic of pahoehoe lava, are locally preserved (Fig. 21). An approximately 1m thick interflow sandstone unit can be accessed by wading across the small bay. Medium-grained, interflow red sandstones form successions up to a couple of metres thick. Bed thicknesses vary from a few centimeters to approximately 1 m. The sandstones are massive; sedimentary structures, aside from upper flow regime parallel laminations, are not well preserved. This may be the result of fluid escape, especially during heating by overlying basalt flows. Trough-like structures in the top of one bed overlain by basalt flows may represent gouge marks where blocks of solidified lava caught up in the overriding basalt flow has been dragged through the unlithified sand in a manner analogous to glacial striae (Figs. 22 & 23). The channels are oriented in an east-west direction, perpendicular to the strike of the flows. The interflow sandstone is thicker than interflow sedimentary rocks in Osler basalts on Wilson Island (Hollings and Fralick, 2005). In addition to the thick interflow unit, thin layers of baked interflow mudstone can be seen within and

Figure 19. Shatter cones in the Gunflint Formation at Stop D on Patterson Island.

Figure 20. Amygdaloidal Keweenawan basalt. Stop D on Patterson Island.

Figure 21. Pahoehoe texture developed on basalt flow tops at Stop D on Patterson Island.

Figure 22. Keel marks left in the upper surface of an interflow sandstone unit at Stop D, Patterson Island. Flow direction is parallel to black arrows.

Figure 23. Close-up of keel marks left in the upper surface of an interflow sandstone unit at Stop D, Patterson Island.

Figure 24. Shattercones in Keweenawan diabase, Stop D Patterson Island.

between the basalt flows. Shatter cones are particularly well-developed in the basalt flows and in the boulders and blocks that litter the beach (Fig. 24). In places the shatter cones exceed 20 cm in length.

Stop E – McGreevy Harbour

UTM coordinates – 500825E 5390752 N

Dressler et al. (1999) have interpreted the structures preserved in the Archean felsic volcanic rocks at this site as large shatter cones, the largest being ~10m high (Fig. 25). To the west of the larger shatter cone a partial cone may be preserved that would imply a total length on the order of 20m. It is difficult to disembark at this site and equally hard to clamber on the steep talus cascading into the water. The scale of these large features is better appreciated from 15 to 20 m offshore.

Figure 25. Large shatter cone visible in the cliff side in McGreevy Harbour (Stop E).

References

Alvarez, L.W., Alvarez< W., Asaro, F., andMichel, H.V. 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. Science, 269, 1095-1108.

Brummer, J.J. 1962. Gold-bearing veins, St. Mary's Bay, Patterson Island, Lake Superior, Ontario; unpublished report, Resident Geologist's Files, Thunder Bay South District, 5p.

Cannon, W.F., Green, A.G., Hutchinson, D.R., Lee, M., Milkereit, B., Behrendt, J.C., Halls, H.C., Green, J.C., Dickas, A.B., Morey, G.B., Sutcliffe, R. and Spencer, C., 1989. The North American Midcontinent Rift Beneath Lake Superior from GLIMPCE Seismic Reflection Profiling; Tectonics, v. 8, n. 2, p. 305-332.

Card, K.D., Sanford, B., and Davidson, A., 1994. Bedrock geology, Lake Superior, Ontario, USA. Natural Resources Canada, Map NL-16/17-G.

Coleman, A.P., 1901. The Slate Islands in Iron Ranges of Northwestern Ontario, Ontario Bureau of Mines, v. 11, 552-555.

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

Dressler, B.O. and Sharpton, V.L., 1997. Breccia formation at a complex impact crater: Slate Islands, Lake Superior, Ontario, Canada. Tectonophysics, 275, 285-311.

Dressler, B.O., Sharpton, V.L., Schuraytz, B. and Scott, J., 1994. Bunte breccia, impact melt and suevite at teh SLate Islands impact structure, Ontario. Ontario Geological Survey, Miscellaneous Paper 163, 59-61.

Dressler, B.O., Sharpton, V.L., Schnieders, B. and Scott, J., 1995. New observations at the Slate Islands impact structure, Lake Superior. Ontario Geological Survey, Miscellaneous Publication 164: 53-61.

Dressler, B.O., Sharpton, V.L. and Schuraytz, B.C., 1998. Shock metamorphism and shock barometry at a complex impact structure: Slate Islands, Canada. Contributions to Mineralogy and Petrology, 130, 275-287.

Dressler, B.O., Sharpton, V.L. and Copeland, P., 1999. Slate Islands, Lake Superior, Canada: A mid-size, complex impact structure. Geological Society of America, Special Paper 339, 109-124.

French, B.M., 1998. Traces of catastrophe. Lunar and Planetary Institute, Contrib. 954, 120 pp.

Grieve, R. A. F., and Robertson, P. B., 1976, Variations in shock deformation at the Slate Islands impact structure, Lake Superior, Canada: Contributions to Mineralogy and Petrology, v. 58, p. 37–49.

Grieve, R. A. F., and Robertson, P. B., 1997. New constraints on the Slate Islands impact structure: Comments and Reply. Geology, 25, 666-667.

Grieve, R. A. F., Rupert, J., Smith, J., and Therriault, A., 1995, The record of terrestrial impact cratering: GSA Today, v. 5, p. 189, 194–196.

Halls, H.C., 1974. A Keweenawan sequence from the Slate Islands, Northern Lake Superior. Institute on Lake Superior Geology, 20th Annual Meeting, Sault Ste. Marie, Ontario, p.14.

Halls, H.C., 1975. Shock-induced remanent magnetization in Late Precambrian rocks from Lake Superior. Nature, 255, 692-695.

Halls, H.C., 1976. The Slate Islands: The Central Uplift of a meteorite impact crater. Institute on Lake Superior Geology, 22nd Annual Meeting, St Paul, Minnesota, p.27

Halls, H.C., 1979. Diatremes and shock features in Precambrian rocks of the Slate Islands, northeastern Lake Superior: Discussion. Geological Society of America Bulletin, 90, 1084-1086.

Halls, H.C., 1997. New constraints on the Slate Islands impact structure: Comments and Reply. Geology, 25, 666.

Halls, H. C., and Grieve, R. A. F., 1976, The Slate Islands: A probable complex meteorite impact structure in Lake Superior: Canadian Journal of Earth Sciences, v. 13, p. 1301–1309.

Halls, H. C., and Stesky, R.M., 1978. Paleomagnetic and shatter cone measurements from the Slate Islands, Northern Lake Superior. Canadian Geophysical Union, 5th Annual Meeting, London, Ontario, p.34.

Hinze, W.J., O'Hara, W.N., Trow, J.W. and Secor, G.B., 1966. Aeromagnetic studies of eastern Lake Superior, in Steinhart, J.S., ed., The earth beneath the continents. American Geophysical Union, Geophysical Monograph, 10, 95-110.

Hollings, P., and Fralick, P., 2005. A stratigraphic transect across the northern flank of the Midcontinent Rift near Rossport. In; Hollings, P. (Ed.), Institute on Lake Superior Geology Proceedings, 51st Annual Meeting, Nipigon, Ontario, Part 2 - Field trip guidebook, v.51, part 2, 57-70.

Hollings, P., Fralick, P. and Cousens, B., 2006. Geochemistry and sedimentology of the Osler Formation: Evaluating rifting in the Proterozoic. Canadian Journal of Earth Sciences, in press.

Mariano, J., and Hinze, W. J., 1994, Structural interpretation of the Midcontinental rift in eastern Lake Superior from seismic reflection and potential-field studies: Canadian Journal of Earth Sciences, v. 31, p. 619–628.

Nichols, L.C. 1963. Gold occurrences on the Slate Islands of Lake Superior; unpublished B.Sc. thesis, Queen's University, Kingston, Ontario, 61p.

Norris, A.W. and Sanford, B.V., 1969. Paleozoic and

Mesozoic geology of the Hudson Bay lowlands. *In* Hood, P.J., ed., Earth science symposium on the Hudson Bay. Geological Survey of Canada, Paper 68-53, 169-205.

Parsons, A.L., 1918. Slate Islands, Lake Superior. Ontario Bureau of Mines, Annual Report, 27, 155-167.

Polat, A., Kerrich, R., and Wyman, D., 1998. The late Archean Schreiber-Hemlo and White River-Dayohessarah greenstone belts, Superior Provnce: Collages of oceanic plateaus, oceanic arcs, and subduction-accretion complexes. Tectonophysics, 289, 295-326.

Powell, J.L.,. 1998. Night comes to the Cretaceous. Harcourt Brace and Company, New York, 250 pp.

Prest, V.K. 1990. Laurentide ice-flow patterns: A historical review, and implications of the dispersal of Belcher Island erratics; Géographie physique et Quaternaire, v.44, p.113-136.

Prest, V.K., Donaldson, J.A. and Mooers, H.D. 2000. The Omar story: The role of Omars in assessing glacial history of west-central North America; Géographie physique et Quaternaire, v.54, no.3, p.257-270.

Pufahl, P., and Fralick, P., 2004. Depositional controls on Paleoproterozoic iron formation accumulation, Gogebic Range, Lake Superior Region, USA. Sedimentology, 51, 791-808.

Roberston, P.B. and Grieve, R.A.E., 1976. Comparison of the distribution of shock metamorphism at Charlevoix, P.Q., and Slate Islands, Ontario. Geological Association of Canada – Mineralogical Association of Canada, Annual Meeting, Program with Abstracts, v. 1, p.42.

Roberston, P.B. and Grieve, R.A.E., 1979. Diatremes and shock features in Precambrian rocks of the Slate Islands, northeastern Lake Superior: Discussion. Geological Society of America Bulletin, 90, 1087-1088.

Sage, R.P., 1975. Slate Islands. Ontario Division of Mines, Ministry of Natural Resources, Map P. 997, scale 1” to 0.25 miles.

Sage, R.P., 1978. Diatremes and shock features in Precambrian rocks of the Slate Islands, northeastern Lake Superior. Geological Society of America Bulletin, 89, 1529-1540.

Sage, R. P., 1991, Precambrian geology, Slate Islands: Ontario Geological Survey Report 264, 111 p.

Sage, R.P., 1999. The Slate Islands: A uniquely sited cryptoexplosion structure. In Summary of Field work and other activities 1999, Ontario Geological Survey, Open File Report 6000, 28-1 to 28-13.

Sharpton, V. and Dressler, B., 1997. New constraints on the Slate Islands impact structure: Comments and Reply. Geology, 25, 668-669.

Sharpton, V., Dressler, B., Herrick, R., Schnieders, B., Scott, J., 1996. New constraints on the Slate Islands impact structure, Ontrio Canada. Geology, 24, 851-854.

Sharpton, V.L., Copeland, P., Dressler, B.O. and Spell, T.L., 1997. New age constraints on the Slate Islands impact structure, Lake Superior, Canada. Lunar and Planetary Science Conference XXVIII, 1287-1288.

Stesky, R. M., and Halls, H. C., 1983, Structural analysis of shatter cones from the Slate Islands, northern Lake Superior: Canadian Journal of Earth Sciences, v. 20, p. 1–18.

Sun S. S., and McDonough., W.F., 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. *In* Magmatism in the ocean basins. *Edited by* A.D. Saunders, and M.J. Norry. Geological Society Special Publication. 42: 313-345.