

NOTE

Small Rimmed Depression in Lake Ontario: An Impact Crater?

Troy L. Holcombe^{1,4,*}, John S. Warren², David F. Reid³, William T. Virden⁴, and David L. Divins¹

¹*National Oceanic and Atmospheric Administration
National Geophysical Data Center
325 Broadway
Boulder, Colorado 80305*

²*Canadian Hydrographic Service (retired),
10 Larose St., PO Box 1094
Almonte, Ontario K0A 1A0*

³*National Oceanic and Atmospheric Administration
Great Lakes Environmental Research Laboratory
2205 Commonwealth Blvd.
Ann Arbor, Michigan 48105-2945*

⁴*National Oceanic and Atmospheric Administration
Cooperative Institute for Research in Environmental Sciences
University of Colorado
Campus Box 216
Boulder, Colorado 80309*

ABSTRACT. Detailed bathymetry of Lake Ontario reveals a small circular feature and adjoining SW-trending ridge associated with a small topographic high identified as Charity Shoal on nautical charts. The feature consists of a circular basin 1,000 m in diameter and 19+ m deep, completely surrounded by a low-relief rim that rises to within 5 m of the water surface over much of its extent. A N53E tapering ridge is contiguous with the feature and extends southwestward. Bedrock consists of middle Ordovician limestones 100-150 m thick overlying rocks of Precambrian age. The limited information available suggests that the feature may be an extraterrestrial impact crater, but other origins such as sinkhole, volcanic cone, or kettle, are not ruled out. Time of formation is not known, but likely times include the Pleistocene when the area was exposed by glacial erosion, the middle Ordovician near the time of deposition of limestones, or the Cambro-Ordovician or Precambrian when erosion surfaces of this age were exposed. A subtle negative magnetic anomaly coincides with the feature and is consistent with an impact origin, though not positively diagnostic. Relief of the feature is low compared to that typical of an impact crater of this size. Glaciation may have diminished relief by eroding the rim and filling the central basin with drift. Verification as an impact crater will require detailed geophysical surveys and collection and analyses of samples from in and around the structure.

INDEX WORDS: Bathymetry, impact crater, Lake Ontario, Charity Shoal, geophysics.

INTRODUCTION

Charity Shoal in Lake Ontario consists of a small circular feature and adjoining ridge, occurring at

latitude 44° 02' N and longitude 76° 29' W about 12 km SW of Wolfe Island, Ontario (Fig. 1). Detailed morphology of this feature emerged from new Lake Ontario bathymetry completed and published under the auspices of a joint project con-

*Corresponding author: E-mail: tholcombe@ocean.tamu.edu

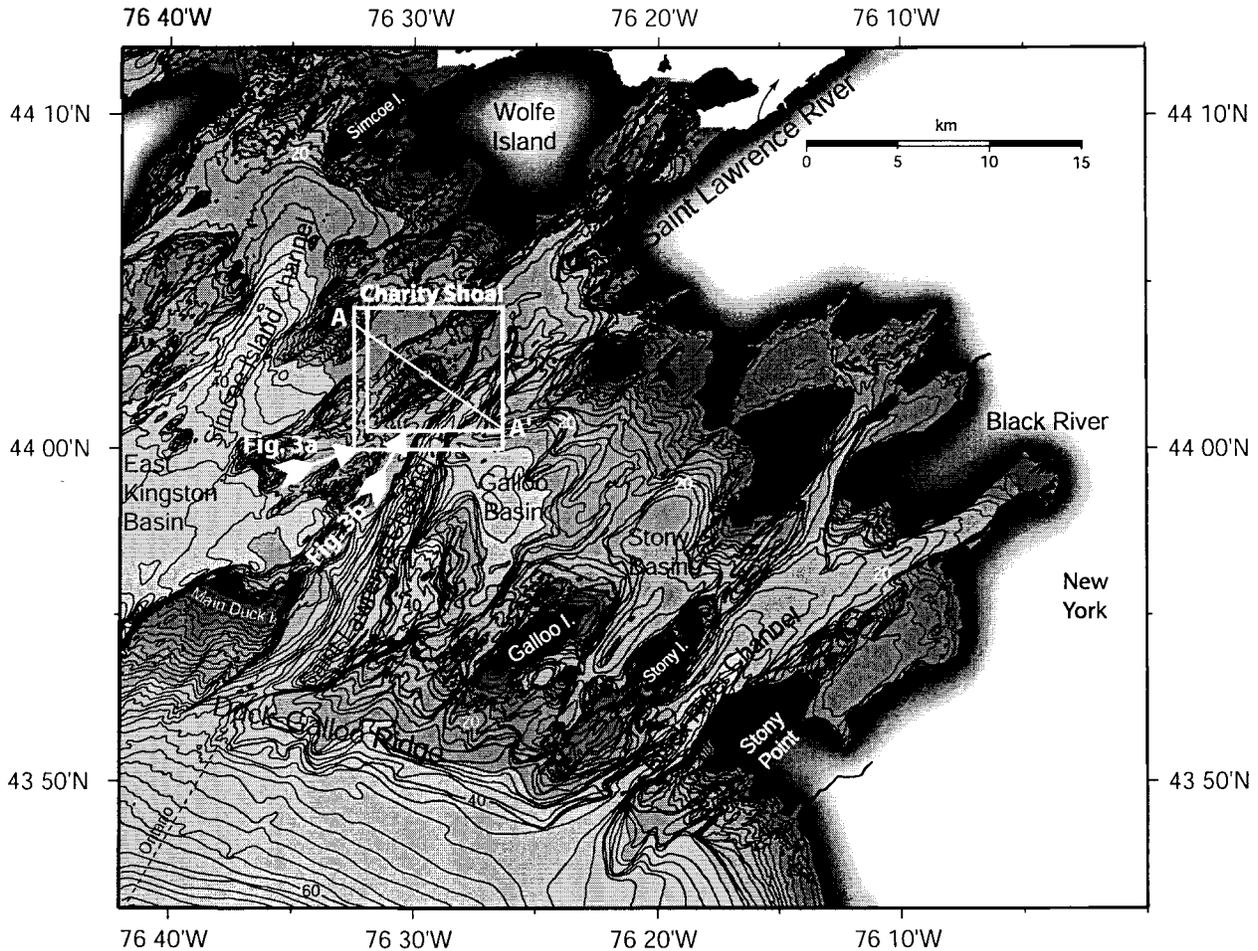


FIG. 1. Index map showing bathymetry of northeastern Lake Ontario and location of Charity Shoal. Locations of bathymetry map and three-dimensional views (Fig. 3) are shown, as well as the location (A-A') of the cross-sections shown in Figure 4. Depths are in meters.

ducted by the National Oceanic and Atmospheric Administration's (NOAA) National Geophysical Data Center, the NOAA Great Lakes Environmental Research Laboratory, and the Canadian Hydrographic Service (Viriden *et al.* 1999). This new bathymetry was compiled from historic data sets collected for more than 100 years in support of nautical charting and navigation safety by the U. S. Coast Survey, the U. S. Army Corps of Engineers, and the Canadian Hydrographic Service. Figure 2 shows the density of the sounding data covering the Charity Shoal feature. More information on source bathymetry and methods of construction is available (Holcombe *et al.* 1997). The new lakefloor bathymetry (Viriden *et al.* 1999) makes possible (1) detailed physiographic description of Charity Shoal and its surrounding area, (2) consideration of the

geologic setting, and (3) speculation concerning its origin.

RESULTS AND DISCUSSION

Physiography

As seen in Figure 3, Charity Shoal is comprised of a raised rim around a small circular basin approximately 1,000 m in diameter and slightly over 19 m deep at its deepest point. The rim rises to minimum depths of 2 to 5 meters at two locations on the NW and E side, and at one point on the NW shoal it rises almost to the surface, where nautical charts show a depth of 0.3 m. Most of the rim crests at minimum depths between 5 and 10 meters. Slopes on the outside face of the rim are less steep than the slopes on the inside face of the rim.



FIG. 2. Sounding data coverage for the Charity Shoal area, illustrating the distribution of data employed in construction of the detailed bathymetry. Spot depths are in meters and tenths. Both U. S. and Canadian bathymetric soundings are shown. Five-meter contours delineate the basic features of Charity Shoal and adjacent topography.

An elongated tapering ridge with a minimum depth less than 6 m extends away from the feature toward the southwest (Fig. 3), making this the tail of a crag-and-tail feature, a common occurrence in some drumlin fields. Smaller SW-trending ridges

lie northwest of and parallel to the main ridge. The most prominent of these smaller ridges, its crest tapering to the SW, extends away from, and is continuous with, the NW shoal of the rim. Within the interior basin are two separate small depressions,

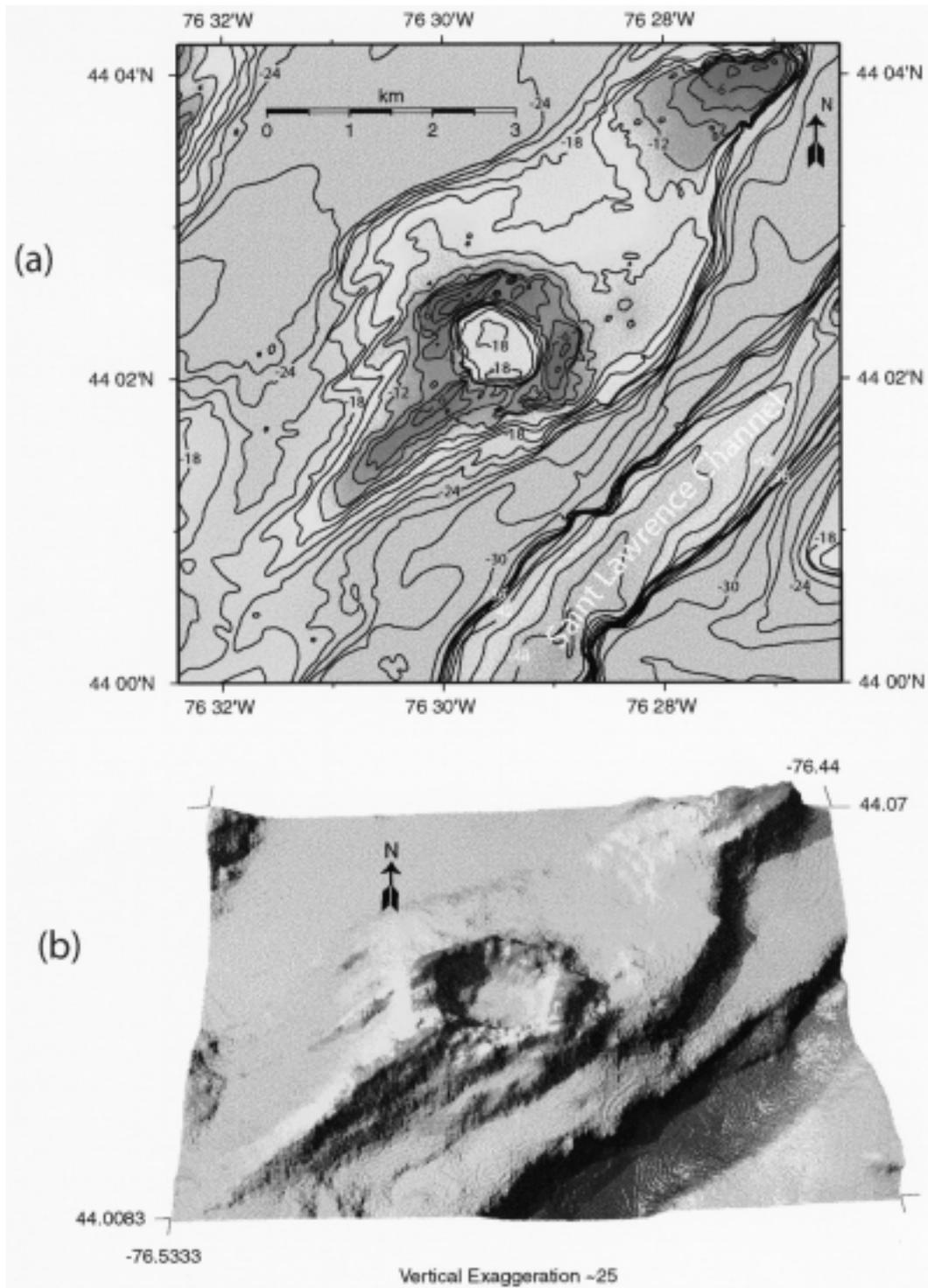


FIG. 3. (a) Map view close-up of the detailed bathymetry of Charity Shoal area. Depths are in meters and the contour interval is 2 m. (b) Three-dimensional perspective of Charity Shoal area showing distinct bowl-shaped depression and rim (both images courtesy of Virden et al. 1999).

one on the NW which is 18+ m deep, and one on the SE which is 19+ m deep.

The rim of Charity Shoal rises from a broader flat-topped ridge cresting at 12 to 14 m north, east, and west of the rim (Figs. 1 and 3). This larger broader ridge forms one of several ridge segments that extend N23E between Main Duck and Wolfe Islands, and lie just NW of the 30 to 50 m deep Saint Lawrence Channel. On either side of this ridge, and on the southeast flank of the rim facing the Saint Lawrence Channel, depth falls to 20 to 26 m. The Saint Lawrence Channel, also oriented at about N23E, leads from the main basin of Lake Ontario northeastward for about 50 km to the present outflow channel of the lake. To the northwest of Charity Shoal lies the Simcoe Island Channel, parallel to but shallower and wider than the Saint Lawrence Channel. Smaller scale linear topography oriented consistently at about N53E extends over Charity Shoal and throughout the NE area of the lake; these features probably were formed by intense subglacial erosion during the last glaciation. These N53E lineations, which include the Charity Shoal SW ridge and the several adjacent smaller ridges, are superimposed on the trend of the main ridge and form the *en echelon* topography (Fig. 3).

Geologic Setting

Stratigraphy of the bedrock underlying Charity Shoal is not known from *in situ* bedrock samples but is extrapolated into the area using geological maps and descriptions of adjacent land areas in New York and Ontario (McFall 1993, Johnsen 1971), together with the new bathymetry. Two possible geological cross-sections through the feature has been constructed (Fig. 4, a or b). Bedrock consists of middle Ordovician (470 to 500 ma) limestones with minor horizons of shale, and dolostone, 100 to 150 m thick, overlying lithologically diverse late Precambrian (900 to 1200 ma) metamorphic and metasedimentary rocks, and possibly a few meters of upper Cambrian (500 to 510 ma) dolostone, sandstone, and siltstone. Charity Shoal is on strike with lower Trenton Group limestone (Sanford and Baer 1981), at about the level of the lowermost Shoreham Limestone or upper Kirkfield Limestone in New York (Johnsen 1971), and the Verulam Formation in Canada (McFall 1993). These strata are characterized by bed-to-bed and area-to-area variability in resistance to erosion, but they are generally less resistant than limestones of the uppermost Trenton Group (Cobourg Limestone in NY, Lindsay

Limestone in Canada), which form cuestas to the south. The strata dip gently southwestward.

Surficial bottom character around Charity Shoal is described in a report by Edsall *et al.* (1992), based on side-looking sonar imagery, photographs, surface sediment samples, and direct observations from a remotely operated submersible vehicle. Bottom types were characterized as 1) hard stratified bedrock over the area of the Charity Shoal feature that was identified as the elevated rim and adjacent tail; 2) rubble, broken bedrock, and bedrock on the side slopes and away from the rim; and 3) stiff, varved lake clays covered with a thin layer of coarse sand on the floor within the basin. Overall, bedrock is described as exposed or lying beneath thin sediments or rubble. Side-scanning sonar mosaics (Edsall *et al.* 1992) show areas of exposed stratified bedrock on the rim of the Charity Shoal feature, described as having been eroded.

Origin

The Charity Shoal feature, with its circular rim surrounding a central basin (Fig. 3), is unusual for the area; no similar feature has been found elsewhere on the floors of the Great Lakes. It resembles a simple impact crater as defined by Pilkington and Grieve (1992), though this origin cannot be proven with the limited information available. Other possibilities include a volcanic cone, a sinkhole, or a kettle hole. Sinkholes are unusual in the area even though the bedrock is mostly limestone. Intense glacial erosion in this area would likely have stripped away limestones weakened by solution action, leaving a bedrock surface less affected by solution action. A kettle origin would suggest that the rim was formed from glacial drift, whereas intensely eroded bedrock has been observed on the Charity Shoal rim (Edsall *et al.* 1992). A sinkhole would not be expected to have a rim that is of higher elevation than the surrounding topography.

A scale 1:50,000 aeromagnetic map of the area (Geological Survey of Canada 1987) reveals a subtle (250 nanoteslas) negative magnetic anomaly, circular in shape and about 300 to 500 m in diameter, centered over the western part of the central Charity Shoal depression. Such a low-relief negative magnetic anomaly is characteristic of many simple impact craters (Pilkington and Grieve 1992). However, a magnetic anomaly might also be detected over a volcanic feature, or over an inhomogeneity in magnetic susceptibility in the underlying Precambrian rock strata whose location is coinci-

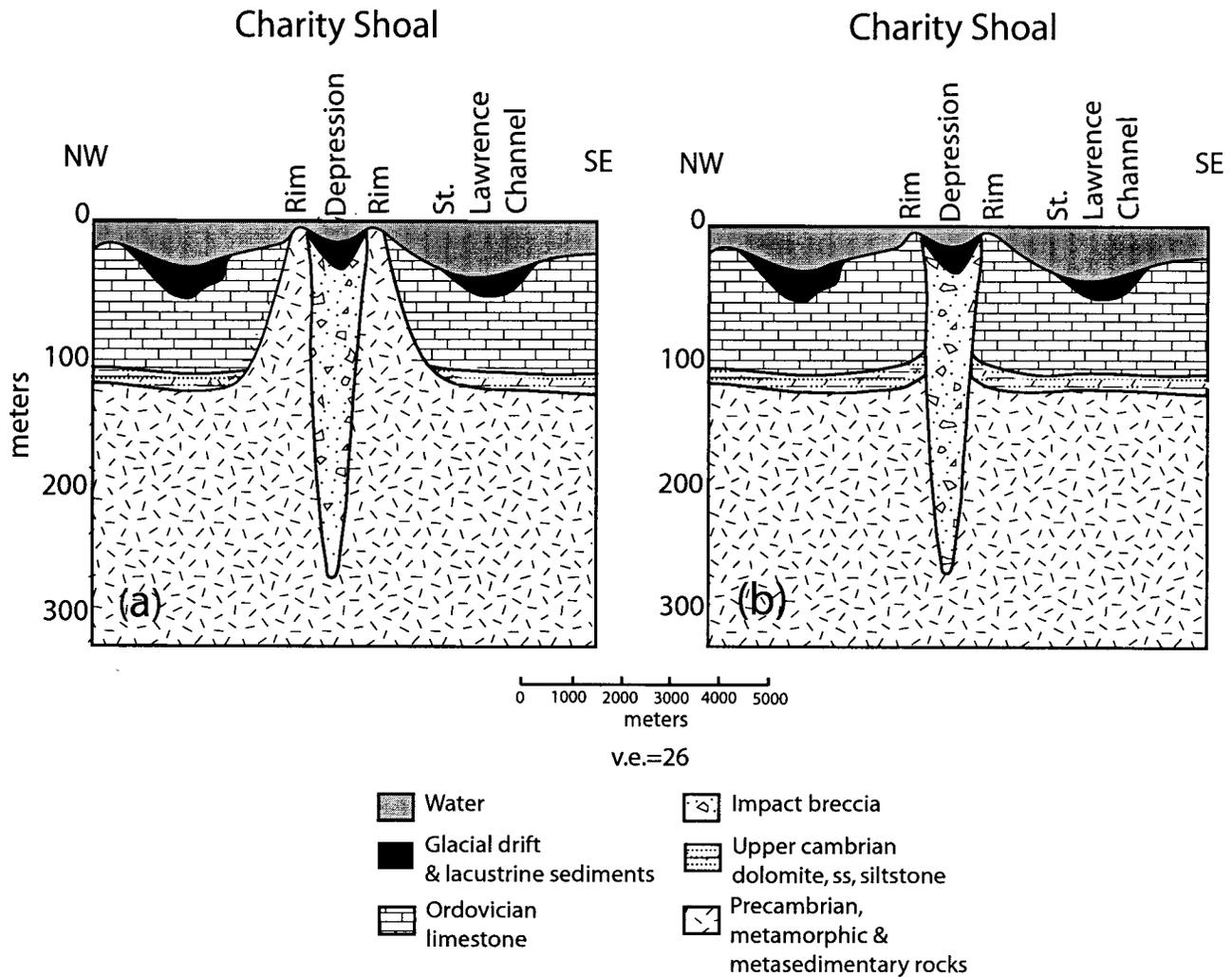


FIG. 4. NW-SE (A-A' in Fig. 1) cross-sections through Charity Shoal showing a reconstruction of 1) water column, 2) topography of Charity Shoal, 3) glacial drift and postglacial sediments in low-lying areas, 4) bedrock of Ordovician limestone underlain by Cambrian sedimentary rocks and pre-Cambrian metamorphic and metasedimentary rocks, and 5) inferred location of Breccia lens and sediment infilling. Figure 4a hypothesizes an extraterrestrial impact event that formed a crater on the Precambrian erosion surface and was subsequently buried beneath Ordovician limestones. Figure 4b hypothesizes a much more recent extraterrestrial event that formed a crater on an erosion surface of Ordovician limestone, probably in the Pleistocene after exposure by glacial erosion.

dental with respect to Charity Shoal. A magnetic anomaly seems unlikely over a kettle, or over a sinkhole formed in limestone strata having low magnetic susceptibility.

Time of Origin

The question arises as to when this feature was formed. The exact time of formation is uncertain, but there are several scenarios to consider:

1. The feature, including its upraised rim, was formed on the Precambrian or Cambro-Ordovician erosion surface and subsequently buried beneath late Cambrian or middle Ordovician strata, where it was preserved until finally unearthed by intense glacial erosion in the Pleistocene.
2. The feature was formed during deposition of middle Ordovician limestone host rocks (~ 500 ma). This scenario would require

formation beneath water, because the host rocks are marine limestones; the resulting feature probably would have been filled in with additional marine limestones.

3. The feature formed much later in pre-existing limestone host rocks, probably in the Pleistocene, but preceding the last retreat of the glaciers.
4. The feature formed during the early Holocene. Charity Shoal area was apparently exposed subaerially in the early Holocene when lake levels were lower (Sly and Prior 1984, Anderson and Lewis 1985). Later the area became water-covered.

Charity Shoal as an Extraterrestrial Impact Crater

Charity Shoal may have had a possible extraterrestrial impact origin. French (1998) describes a two-part process for recognizing and confirming impact structures. First, an anomalous circular or near-circular physical signature, such as a circular topographic, physiographic, or geophysical (gravity and magnetic anomalies) surface pattern, must be recognized (e.g., Charity Shoal's circular morphology). Steeper inward-facing than outward-facing slopes on the crater rim are often observed, as are observed on Charity Shoal. Confirmation of the impact origin requires discovery of unique shock metamorphic effects in the associated rocks, such as shatter cones, siderophile-element anomalies (iridium content, osmium isotopes), high-pressure mineral phases, or high-temperature melting effects in rock fragments.

There are nearly 160 known terrestrial impact structures on earth (Grieve and Shoemaker 1994), with more being found every decade. There are two classes of impact craters: simple and complex. Simple impact craters are formed by smaller extraterrestrial objects and are generally less than 2,000 m diameter in sedimentary host rocks. In well-preserved form they consist of a bowl-shaped depression surrounded by a structurally uplifted and locally overturned rim (Pilkington and Grieve 1992, Grieve 1997). The Charity Shoal feature fits this description quite well. One of the most well-known and best-studied examples of a simple impact crater on earth is the Barringer Meteorite Crater in Arizona, which is about the same diameter (1,100 m) as the Charity Shoal feature (1,000 m).

Simple impact craters typically are partially filled by an allochthonous breccia lens, approximately parabolic in cross section, that is formed by slump-

ing of the wall material during crater formation (Pilkington and Grieve 1992). According to Grieve (1997), for a simple impact crater, the depth to the true floor of the actual crater from the top of the rim (true depth), and the depth to the top of the breccia lens from the top of the rim (apparent depth), follow simple depth:diameter relationships:

$$d_a = 0.13D^{1.06} \text{ and } d_t = 0.28D^{1.02} \quad (1)$$

where D is the final rim diameter in km, and d_a and d_t are the apparent and true depths, respectively.

Applying these equations to the Charity Shoal feature, where $D \sim 1$ km, yield $d_a = 130$ m and $d_t = 280$ m. The present maximum depth in the floor of the depression is just over 19 m from the water surface and about 17 m below the highest part of the rim. Consequently, if the Charity Shoal feature is an impact crater that follows Grieve's (1997) relationships, the crater has been filled almost to its rim (by a combination of impact breccia (~150m thick based on $d_t - d_a$), and/or Ordovician limestone, and/or glacial drift and lake sediments), and/or the rim has been considerably eroded.

If extraterrestrial impact is confirmed, time of origin scenarios (1) and (3) warrant further consideration. Under scenario (1), illustrated in Figure 4a, the feature could have formed as early as Precambrian, prior to deposition of the late Cambrian and/or middle Ordovician strata, anytime in the 500 to 1,000 ma time frame, but probably toward the end of this period. This scenario suggests that the rim, formed of uplifted Precambrian strata, was not completely eroded prior to burial and preservation beneath younger rocks. Much later, in the Pleistocene, glacial erosion would have again exposed the rim.

Under scenario (3), illustrated in Figure 4b, impact would have occurred much later, after the target bedrock was exposed by removal of overlying strata. Impact may have occurred during the Pleistocene, with glacial erosion as the agent of exposure, and impact occurring during an interglacial period when ice cover had retreated. Since the estimated thickness of Ordovician limestones is 100 to 150 m in this area, a 1,000 m-diameter impact crater at this location should penetrate the Ordovician limestone deposits and extend downward at least 130 meters into the underlying Precambrian igneous, metamorphic, and metasedimentary rocks (see Fig. 4b). Consequently, the breccia and ejecta in the crater should include Precambrian rocks as

well as Ordovician limestone. Glaciation may have scraped away the ejecta outside the rim, and also covered or diluted the original ejecta in the crater with a thick layer of glacial drift.

Existence and continuity of many N53E topographic lineations over Charity Shoal and adjacent areas (see Fig. 1) suggests that the feature predates the last glacial advance. Also suggesting subglacial erosion of an earlier-formed feature is the occurrence of stratified bedrock exposed at or near the surface over the Charity Shoal rim and adjacent areas (Sly and Prior 1984, Edsall *et al.* 1992). Additional circumstantial evidence that the feature existed prior to the last glacial advance includes the low profile of the rim, and the apparent sediment layer inside and nearly filling the basin. For comparison, rim height of the Barringer Meteorite Crater is about 45 m above the surrounding topography. If one assumes approximately the same rim height immediately after formation of the Charity Shoal feature, the only conclusion is that a strong erosional agent, such as glaciation, has decreased rim height by 80 to 90 percent, from 45 m to 5 to 10 m.

CONCLUSIONS

Charity Shoal's circular shape, with an elevated rim around a central crater-like basin, renders explanations other than an impact crater less likely. However, other modes of origin, such as glacial erosion or carbonate solution (sinkhole), cannot be ruled out unless impact-produced features are confirmed with rock and sediment samples obtained on-site. Verification of Charity Shoal as an impact crater will require detailed geophysical surveys and collection and analyses of samples from in and around the structure.

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