Meteoritics & Planetary Science 40, Nr 12, 1887–1899 (2005)
Abstract available online at http://meteoritics.org

Intra-crater sedimentary deposits at the Haughton impact structure, Devon Island, Canadian High Arctic

Gordon R. OSINSKI[1†*] and Pascal LEE[2]

[1]Mars Institute, 980 Seymour Street, Suite 1306, Vancouver, British Columbia V6B 1B5, Canada
[2]Mars Institute, SETI Institute, and NASA Ames Research Center, Moffett Field, California 94035–1000, USA
[†]Present address: Canadian Space Agency, 6767 Route de l'Aeroport, Saint-Hubert, Québec, J3Y 8Y9, Canada
[*]Corresponding author. E-mail: osinski@lycos.com

(Received 30 June 2005; revision accepted 04 October 2005)

Abstract–Detailed field mapping has revealed the presence of a series of intra-crater sedimentary deposits within the interior of the Haughton impact structure, Devon Island, Canadian High Arctic. Coarse-grained, well-sorted, pale gray lithic sandstones (reworked impact melt breccias) unconformably overlie pristine impact melt breccias and attest to an episode of erosion, during which time significant quantities of impact melt breccias were removed. The reworked impact melt breccias are, in turn, unconformably overlain by paleolacustrine sediments of the Miocene Haughton Formation. Sediments of the Haughton Formation were clearly derived from pre-impact lower Paleozoic target rocks of the Allen Bay Formation, which form the crater rim in the northern, western, and southern regions of the Haughton structure. Collectively, these field relationships indicate that the Haughton Formation was deposited up to several million years after the formation of the Haughton crater and that they do not, therefore, represent an immediate, post-impact crater lake deposit. This is consistent with new isotopic dating of impactites from Haughton that indicate an Eocene age for the impact event (Sherlock et al. 2005). In addition, isolated deposits of post-Miocene intra-crater glacigenic and fluvioglacial sediments were found lying unconformably over remnants of the Haughton Formation, impact melt breccias, and other pre-impact target rock formations. These deposits provide clear evidence for glaciation at the Haughton crater. The wealth and complexity of geological and climatological information preserved as intra-crater deposits at Haughton suggests that craters on Mars with intra-crater sedimentary records might present us with similar opportunities, but also possibly significant challenges.

INTRODUCTION

The Haughton impact structure, which is approximately 39 Ma old, and the surrounding terrain on Devon Island in the Canadian High Arctic present a wide variety of geological traits that offer various analogues for Mars (e.g., Lee 1997; Lee et al. 1998; Zent et al. 1998; Lee et al. 1999; Lee and Osinski 2005). Of particular interest at Haughton is the existence of well-preserved sedimentary deposits inside the crater, the Miocene-age Haughton Formation (Hickey et al. 1988), that provide a unique record of post-impact lacustrine activity. Over the past 39 million years, glacial and fluvial processes have substantially modified the landscape, although the amount of erosion and sedimentary record left by these processes is not well established. This is a problem not unique to Haughton, as the post-impact sedimentary evolution within impact craters has not generally been well-studied and is not considered to be an important process associated with impact events. As a result, the few previous studies of intra-crater sedimentary deposits have typically focused on understanding the paleoenvironmental and paleobiological record they contain (e.g., Lozej and Beals 1975; Hall 1978; Gronland et al. 1990; Arp 1995).

However, intra-crater sedimentary deposits may also hold valuable clues to the pace of recovery of the environment and post-impact biological succession following large impact events (Cockell and Lee 2002). Moreover, due to the requirement of liquid H_2O for life as we know it, intra-crater sedimentary deposits have long been suggested as important candidate targets in the search for evidence of past life on Mars (e.g., Cabrol and Grin 1995, 1999; Newsom et al. 1996; Grin and Cabrol 1997; Cabrol et al. 1999, 2001). Lacustrine sediments are known to provide favorable environments for the preservation of fossils (e.g., slow decay rates; fine sediment grain size; quiet conditions during sedimentation). Impact crater lakes also provide confined and protected sedimentary basins that can preserve detailed paleoenvironmental records, often in areas where limited data exists. For example, the lacustrine sediments of the Haughton Formation provide the only record of Miocene sedimentation in the Canadian Arctic (Hickey et al. 1988). A further important aspect of impact crater lakes is the possibility of a thermal input from post-impact hydrothermal activity (e.g., Newsom et al. 1996). This may have important astrobiological implications, as hydrothermal systems in general might have provided habitats or “cradles” for the origin and evolution of early life on Earth and possibly on Mars (e.g., Shock 1996; Farmer 2000; Kring 2000; Cockell and Lee 2002). Importantly, there is abundant evidence for impact-induced hydrothermal activity at Haughton (Osinski et al. 2001, 2005a). An understanding of intra-crater sedimentary deposits at Haughton will therefore advance our understanding of the post-impact modification of impact structures, the evolution of the Arctic environment through time, and how similar intra-crater sedimentary settings may be explored on Mars.

GEOLOGICAL SETTING OF THE HAUGHTON IMPACT STRUCTURE

Haughton is a well-preserved complex impact structure 23 km in diameter that is situated on Devon Island in the Canadian Arctic archipelago (75°22′N, 89°41′W) (Fig. 1). New ^{40}Ar-^{39}Ar dating of potassic glasses within strongly shocked basement gneisses yields a formation age of ~39 Ma for Haughton (Sherlock et al. 2005), making this structure substantially older than previously thought (23.4 ± 1.0 Ma) (Jessburger 1988). The target rocks at Haughton comprise a series of Lower Paleozoic sedimentary rocks of the Arctic Platform ~1880 m thick (Frisch and Thorsteinsson 1978; Osinski et al. 2005b), which overlies the Precambrian metamorphic basement of the Canadian Shield (Fig. 1). The unmetamorphosed sedimentary succession consists of thick units of dolomite and limestone, with subordinate evaporite horizons and minor shales and sandstones (Thorsteinsson and Mayr 1987).

Allochthonous crater-fill deposits form a virtually continuous unit of ~54 km^2 that covers the central area of the structure (Fig. 1) (Osinski et al. 2005c). Recent field studies and analytical scanning electron microscopy indicate that these rocks are carbonate-rich impact melt breccias, comprising variably shocked mineral and lithic clasts set within a melt groundmass of calcite + silicate glass ± anhydrite (Osinski and Spray 2001, 2003; Osinski et al. 2005c). The lithic clasts are typically angular and are predominantly limestone and dolomite, with subordinate lithologies from the Paleozoic cover sequence and the crystalline basement (Metzler et al. 1988). The impact melt breccias have a maximum current thickness of ~125 m, although the presence of this unit up to ~140 m above the central topographic low area suggests that the original thickness exceeded 200 m (Osinski et al. 2005c). Isolated outcrops up to ~6 km in radius further suggest that, originally, the crater-fill completely occupied the central area of the crater (Osinski et al. 2005b). The crater-fill impact melt breccias provided a heat source that drove a hydrothermal system within the crater following the impact event (Osinski et al. 2001, 2005a). Hydrothermal circulation resulted in the deposition of a series of alteration products (carbonates, sulfates, sulfides, and quartz) within cavities and fractures in the impact melt breccias, central uplift lithologies, and around the faulted crater rim (Osinski et al. 2001, 2005a).

Finally, a series of post-impact Neogene to Quaternary sediments occupy the central part of the structure (Fig. 1; map insert). The paleolacustrine sediments of the Haughton Formation have received little attention since they were first classified by Hickey et al. (1988). Several cores of the Haughton Formation were obtained as part of the DRILLEX drilling experiment, which was carried out during the 1998 field season of the Haughton Mars Project (J. Schutt, personal communication). The Quaternary sediments have not been studied in detail before. Here we present the results of detailed field and petrographical studies carried out over several field seasons of the Haughton-Mars Project, which reveal important new information about the nature, distribution, and origin of intra-crater sedimentary deposits at Haughton. This data will be synthesized with the new work on impactites (Osinski and Spray 2001; 2003; Osinski et al. 2005c) and radiometric age data (Sherlock et al. 2005) for Haughton.

SAMPLES AND ANALYTICAL TECHNIQUES

Fieldwork and sampling were carried out over the course of seven field seasons of the Haughton-Mars Project. Thin sections were made from four samples of reworked impact melt breccias and five nodules from the Haughton Formation. These were investigated using standard optical microscopy techniques. Two polished thin sections of reworked impact melt breccias were investigated using a JEOL 6400 digital scanning electron microscope (SEM), equipped with a Link Analytical eXL energy dispersive spectrometer (EDS) and Si(Li) LZ-4 Pentafet detector. Beam operating conditions were 15 kV and 2.5 nA at a working distance of 37 mm, and count times of 100 sec. Representative samples of the unconsolidated Haughton Formation were washed in dilute acid to remove the carbonate. The residues were investigated for shock metamorphic indicators using optical microscopy. X-ray diffraction (XRD) was performed on powdered samples of the various intra-crater sediments using a Philips 1710 diffractometer and generator, with operating conditions of 40 kV and 20 mA.

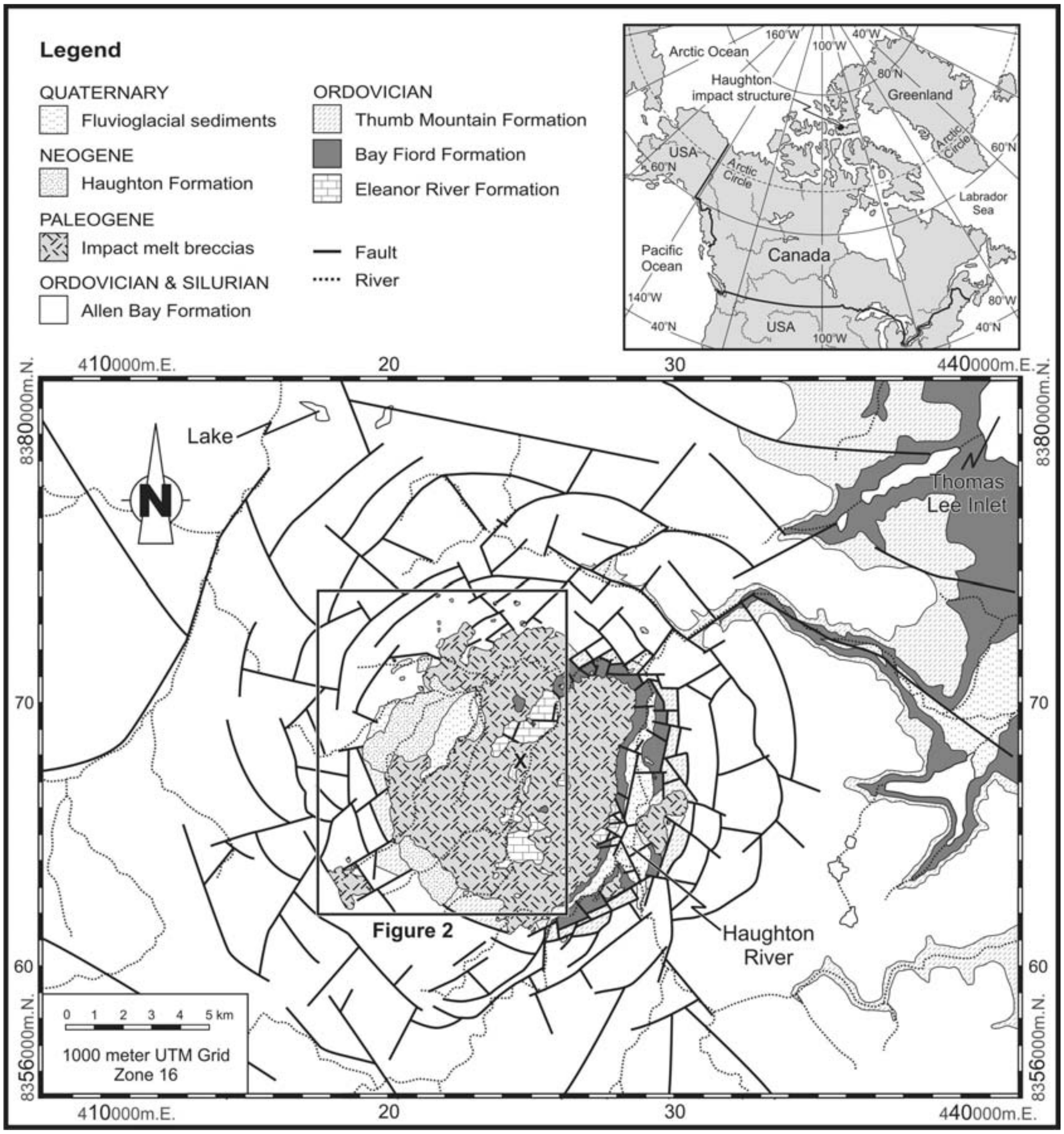

Fig. 1. A simplified geological map of the Haughton impact structure, Devon Island, Canadian High Arctic (insert). See the map insert associated with this issue for a more detailed version.

INTRA-CRATER SEDIMENTARY DEPOSITS

Detailed mapping as part of this study reveals that several different types of intra-crater sedimentary deposits are present within the Haughton impact structure (Figs. 1–3; map insert). These units are outlined below in chronological order.

Reworked Impact Melt Breccias

At several localities and in drill holes AH98-5 and AH98-6, the crater-fill impact melt breccias are unconformably overlain by a layer of pale gray sandstone ~10 cm to ~1.5 m thick (Figs. 2–4). This unit is well-sorted, coarse-grained (~1–2 mm grain size), and contains occasional shocked quartz grains displaying planar deformation features (PDFs). The preponderance of carbonate lithic and mineral fragments classifies this lithology as a litharenite or lithic sandstone, which is clearly derived from the underlying impact melt breccias (Fig. 4). It is notable that these reworked impact melt breccias are only preserved where they are overlain by sediments of the Haughton Formation. This suggests that this unit was once more widespread, but has since been eroded away from on top of the crater-fill impact melt breccias.

Haughton Formation

Paleolacustrine sediments of the Haughton Formation are intermittently exposed over an area of 8.62 km^2 in the west-central area of the structure (Figs. 1 and 2). This unit is

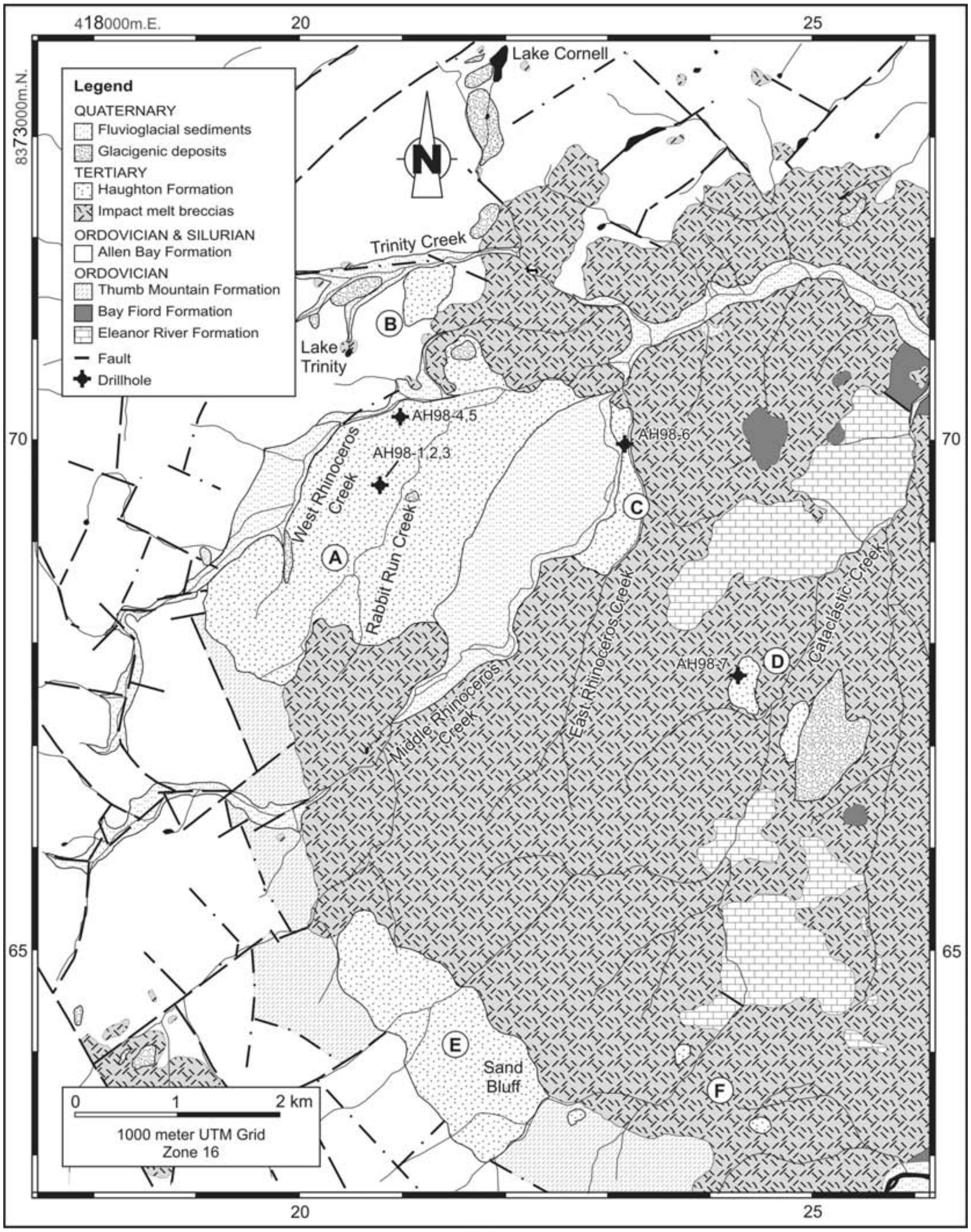

Fig. 2. A detailed geological map showing the location of post-impact intra-crater sedimentary deposits in the western half of the Haughton impact structure (see Fig. 1 for context). This represents the region where such sediments are most common, although an expansive series of fluvioglacial and fluvial sediments exists in the Haughton River valley to the east of this map (see Fig. 1 and map insert). The location of shallow drill holes obtained as part of the DRILLEX experiment, carried out during the 1998 field season of the Haughton-Mars Project, are shown on this map.

therefore more widely distributed than previously thought (cf. ~7 km^2 in Hickey et al. 1988). Sediments of the Haughton formation are preserved in six geographically separate areas (see Fig. 2 for localities):

A. The main expanse of Haughton Formation strata centered on West Rhinoceros Creek and Rabbit Run Creek. Hickey et al. (1988) estimate a thickness of ~48 m for the Haughton Formation. However, this assumes that the upper boundary of the formation is the present-day erosion surface. Given the unconsolidated nature of the Haughton Formation and the ongoing erosion, a value of 48 m must be viewed as a minimum.

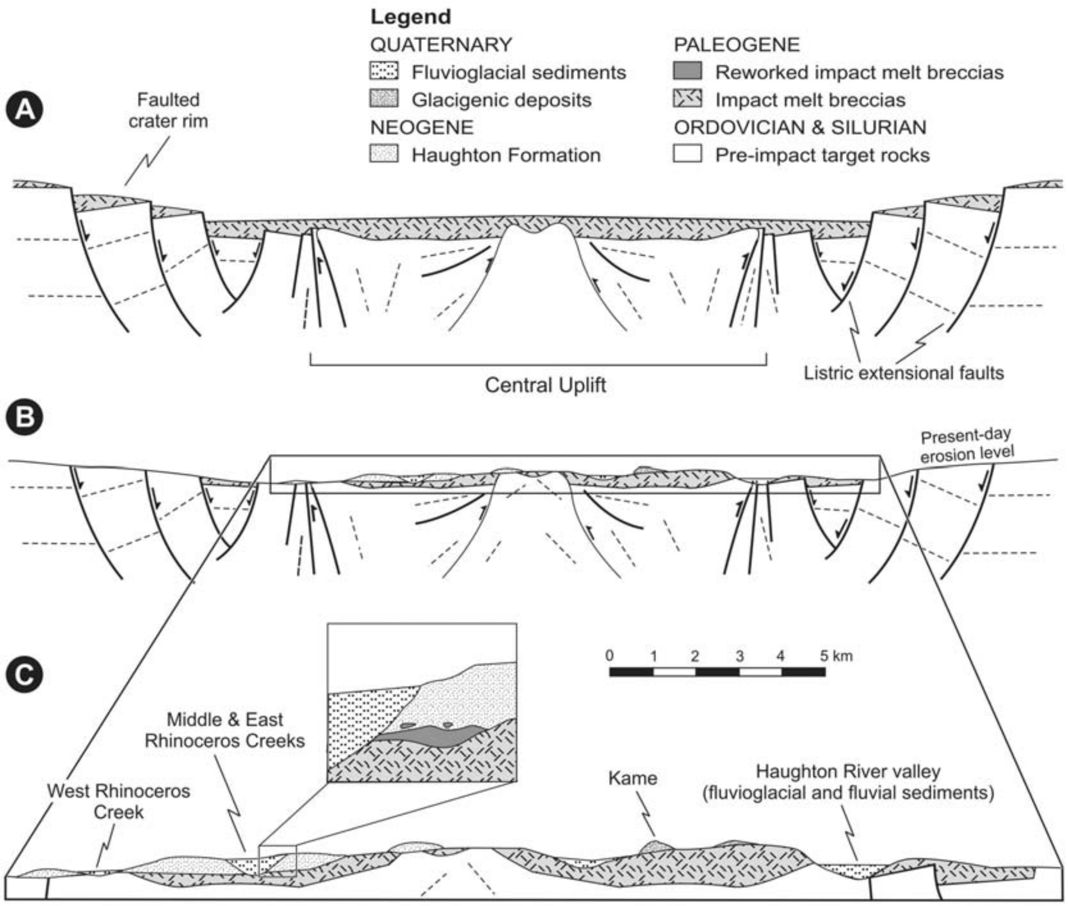

Fig. 3. A series of schematic diagrams showing the post-impact modification of the newly formed Haughton impact structure (a) through time and the present-day location of intra-crater sedimentary deposits (a–c). These diagrams are not meant to represent exact cross-sections through the crater; however, they do represent an idealized east–west section through the crater that is based on detailed mapping (see map insert and cross-sections in Osinski and Spray 2005). The vertical exaggeration is approximately 2× in (a) and (b), and 3× in (c).

B. An isolated exposure of Haughton Formation along the southern bank of Trinity Creek, separated from the main expanse (A) by a ridge of uplifted Allen Bay Formation strata.
C. A narrow outcrop of Haughton Formation strata between Middle and East Rhinoceros Creeks. Several drill holes and trenches reveal that this outcrop is very thin (<2 m in hole AH98-6) (J. Schutt, personal communication) and drapes reworked impact melt breccias (Fig. 4a).
D. Two isolated exposures of Haughton Formation in the center of the Haughton structure, separated from the main expanse by a ridge of impact melt breccias and uplifted Eleanor River Formation strata. A prominent mesa provides excellent outcrops at these localities (Fig. 5a). Hole AH98-7 reached a depth of 3.63 m without encountering impact melt breccias before having to be abandoned due to breakage of the lever arm on the auger head (Schutt et al. 2004).
E. An outcrop of Haughton Formation strata including a locality known as "Sand Bluff." This study expands considerably the outcrop initially mapped in this area by Hickey et al. (1988) and reports a new small outlier to the southeast.
F. Two small isolated outcrops of Haughton Formation in southern sector that occur at a higher elevation than the main Sand Bluff outcrops.

There are conflicting views as to the relationship of the Haughton Formation with other geological formations at Haughton. Frisch and Thorsteinsson (1978) note that parts of the main expanse of the Haughton Formation unconformably overlie Lower Paleozoic target rocks in the west. In contrast, Hickey et al. (1988) suggest that the formation entirely overlies impactites throughout its areal extent. Field mapping carried out as part of this study confirm the observations of Frisch and Thorsteinsson (1978). That is, Haughton Formation strata unconformably overlie impact melt breccias in the center of the structure and Lower Paleozoic target rocks in the south and west. For example, an outlier of Haughton Formation strata (point B in Fig. 2) onlaps onto uplifted blocks of the Allen Bay Formation. Much of the Sand Bluff locality also appears to overlie Lower Paleozoic sedimentary rocks (Fig. 2).

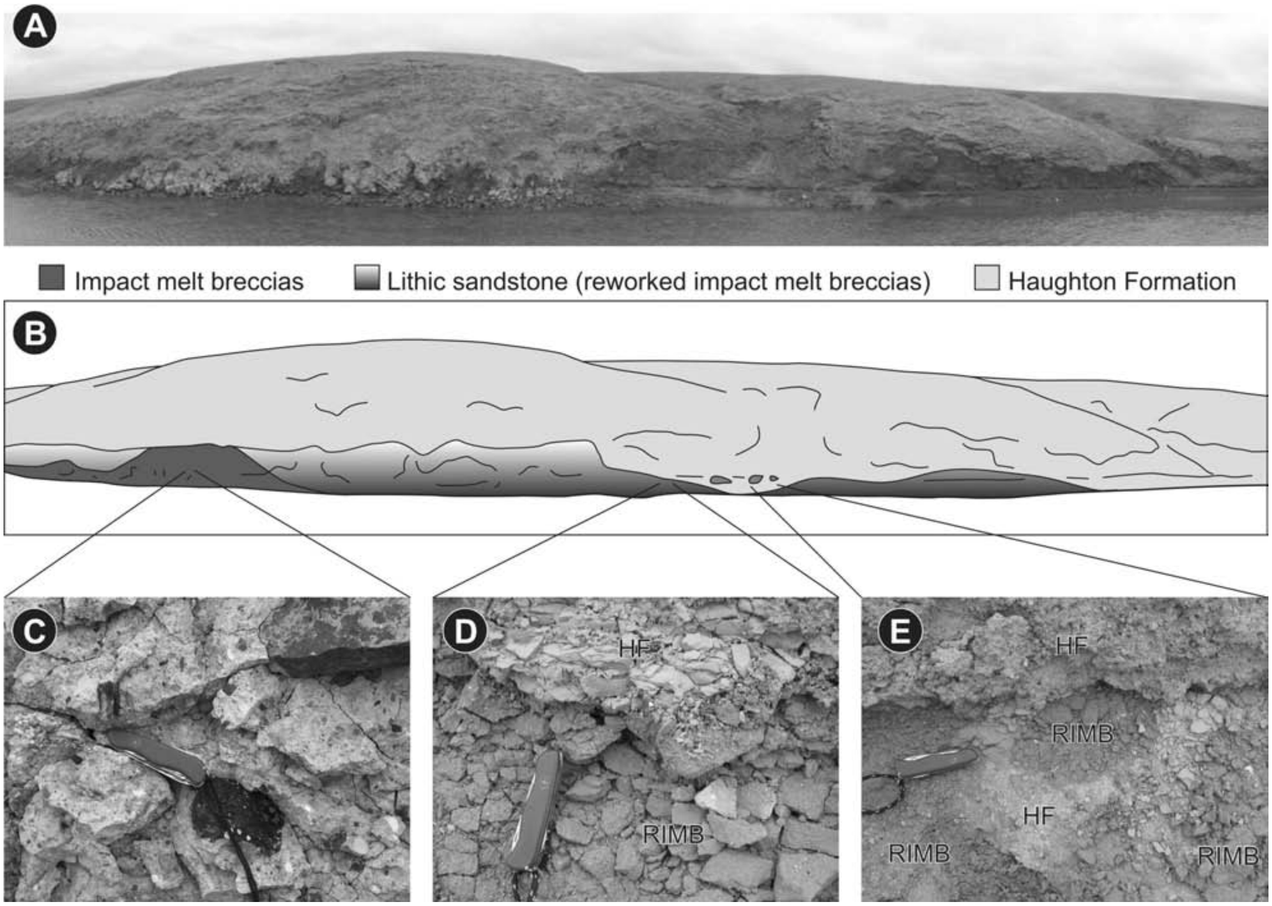

Fig. 4. a) A panoramic field photograph and b) a line drawing showing the transition from pristine impact melt breccias, through reworked impact melt breccias, and up in to lacustrine sediments of the Haughton Formation. The height to the top of the outcrop is ~6.5 m. c) An image of pristine impact melt breccias. Note the large clasts of carbonate and crystalline rocks from the pre-impact target sequence. d) The transition from reworked impact melt breccias (RIMB) (bottom) to Haughton Formation (HF) strata (top) is marked by an unconformity. Note the well-sorted nature and absence of clasts in the reworked impact melt breccias. e) Rip-up clasts of reworked impact melt breccias are sometimes present in the basal parts of the Haughton Formation. 10 cm long penknife for scale in (c–e). 423,132 m.E. 8,369,863 m.N.

The Haughton Formation ranges in color from pale gray to pale yellow-brown and consists of unconsolidated dolomitic silts and muds with subordinate fine-grained dolomitic sands (Frisch and Thorsteinsson 1978; Robertson and Sweeney 1983; Hickey et al. 1988). X-ray diffraction (XRD) analysis of silts and muds revealed that dolomite is the dominant component (cf. Hickey et al. 1988), with minor amounts of calcite and quartz (calcite > quartz). The Haughton Formation is generally well-bedded on a millimeter to centimeter scale, although beds of massive silt and sand comprise ~30% of the sections (Figs. 5b and 5c). From a distance, color banding on a scale of 1–2 m can be seen, although it is often not possible to discern at the outcrop scale (cf. Hickey et al. 1988). Well-developed varves are present at the Sand Bluff locality and in the extreme south of the main expanse of the Haughton Formation (Fig. 5d).

The basal contacts of the Haughton Formation have been studied at several localities and in two drill holes (AH98-5 and AH98-6) (Fig. 2). In all instances, the base of the Haughton Formation is an unconformity (e.g., Figs. 4a, 4b, 4d, and 4e), that differs in elevation between outcrops by up to ~10 m. Rip-up clasts of the underlying reworked impact melt breccias and scours with minor channel fills have been observed (Figs. 4a, 4b, and 4e).

The present study identified the existence of rare concretionary layers as previously documented by Frisch and Thorsteinsson (1978) and Hickey et al. (1988). However, several new observations and results are of note. Discontinuous beds (~1–15 cm thick and typically <50 m^2 in areal extent) and isolated nodules (~1–10 cm thick and <40 cm long) of light gray limestone have been found in situ in the lowermost parts of the Haughton Formation (Fig. 5e). Notably, the nodules frequently contain well-preserved fossil remains of fish, animals, and plants. The fossils occur in the very center of the nodules and are surrounded by several concentric rings of discolored carbonate.

Isolated slabby fragments of iron oxide-cemented dolomitic sandstone are common on the present-day erosional

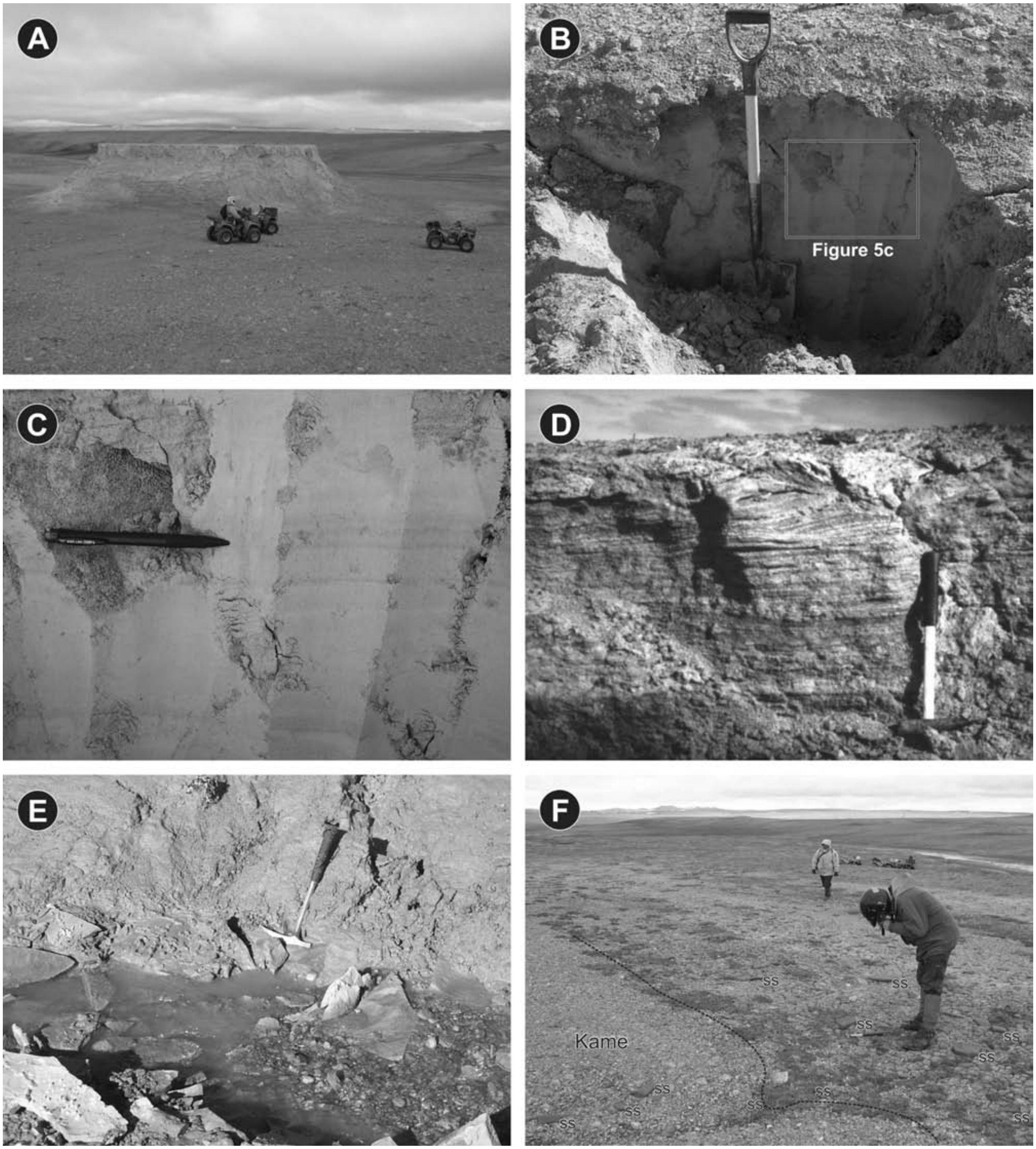

Fig. 5. A series of field photographs of the Haughton Formation. a) A prominent mesa in the center of the Haughton structure (area D on Fig. 2). All-terrain vehicles and field assistant (Pauline Akeeagok) in foreground for scale. 424,464 m.E. 8,367,702 m.N. b) A shallow trench dug in the Haughton Formation. Note the presence of glacigenic gravels and cobbles on the upper erosional surface. 419,914 m.E. 8,369,104 m.N. c) Although the sediments appear massive at the decimeter scale in Fig. 5c, close inspection reveals a series of millimeter-scale laminations. 14 cm long pencil for scale. 419,914 m.E. 8,369,104 m.N. d) Varved sediments from the Sand Bluff locality (area E on Fig. 2). 40 cm long rock hammer for scale. 422,431 m.E. 8,363,833 m.N. e) An outcrop of slabby limestone, overlain by muddy gelifluction deposits, along the edge of a creek. 40 cm long rock hammer for scale. 419,293 m.E. 8,368,520 m.N. f) An image showing slabby fragments of reddish dolomitic sandstone lying on the present-day erosional surface of the Haughton Formation, and incorporated into a kame. Cobbles of Allen Bay Formation carbonates are also scattered over the surface. John Parnell (University of Aberdeen) for scale in foreground. 420,938 m.E. 8,369,552 m.N.

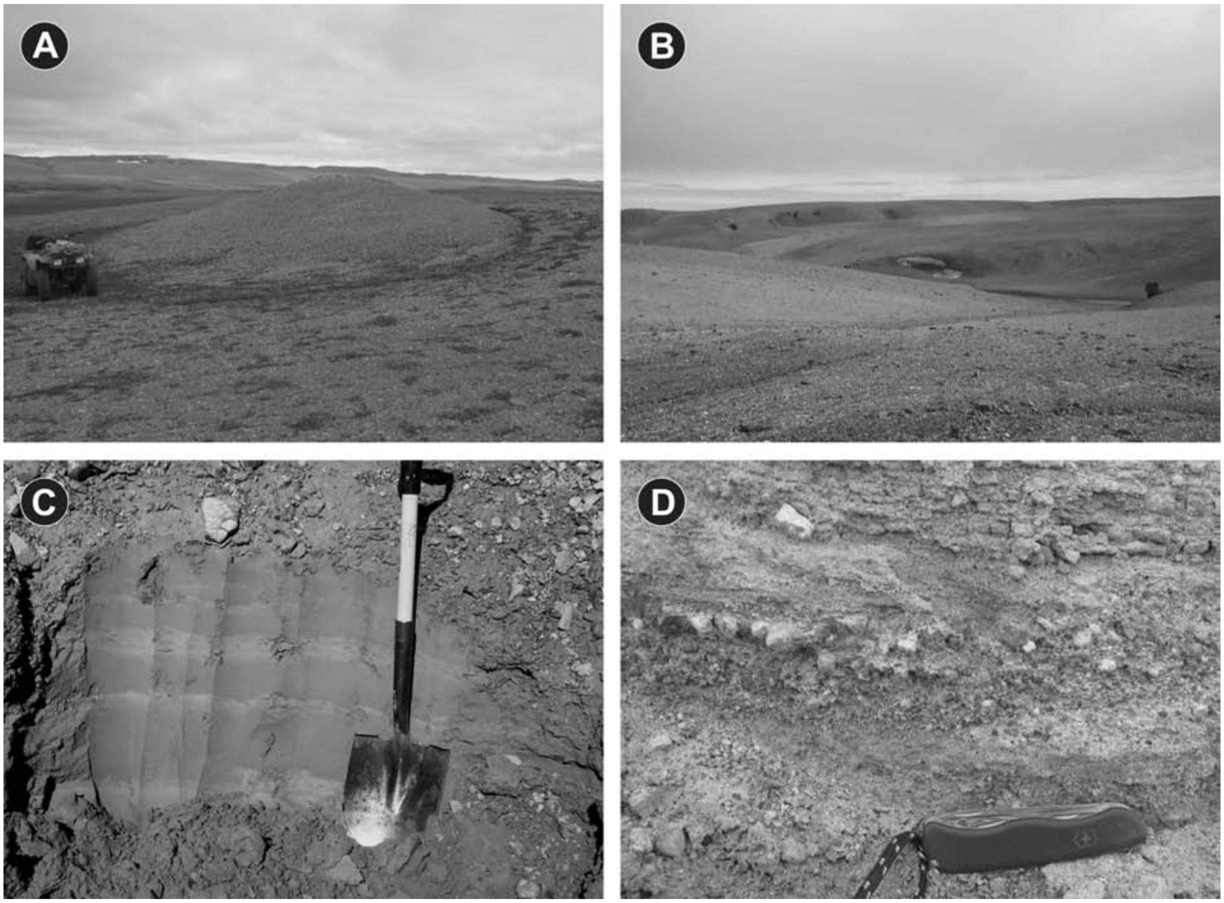

Fig. 6. Field photographs of various glacigenic and fluvioglacial sediments. a) An isolated kame of melt-out till unconformably overlying Haughton Formation strata. All-terrain vehicle to the left of the image for scale. 421,227 m.E. 8,369,607 m.N. b) The surface of the hills of impact melt breccia in the foreground are covered by pebble- and cobble-sized carbonate rocks (all the dark rocks in the foreground), derived from the pre-impact target sequence in the surrounding area. 418,024 m.E. 8,363,731 m.N. c) Shallow trench dug in to fluvioglacial sediments. Note the well-developed bedding and alternation of clays (pale) and sands (dark). 421,759 m.E. 8,372,918 m.N. d) Fluvioglacial sediments derived exclusively from underlying impact melt breccias. This unit consists of alternating layers of gravels/pebbles and sands with a high proportion of shocked clasts from the crystalline basement. 10 cm long penknife for scale. 424,795 m.E. 8,367,305 m.N.

surface of the Haughton Formation (e.g., Fig. 5e). XRD analysis reveals that this lithology is predominantly composed of dolomite with minor quartz and calcite. Hickey et al. (1988) suggest that this lithology forms a distinct layer in the uppermost part of the Haughton Formation. However, possible in situ samples of this lithology have only been observed at one locality. At all other localities, fragments of this reddish sandstone are always found associated with cobbles of carbonates derived from the surrounding hills (Fig. 5e). The cobbles are clearly drift of likely glacial origin. Another possible origin for the fragments of iron oxide-cemented dolomitic sandstone capping the Haughton Formation is that they were transported (either as part of a formerly single coherent block or as already fragmentary material) and deposited on the upper surface of the Haughton Formation by post-Miocene glacial action.

Several localities do not show the well-developed layering that is typical of the Haughton Formation. In particular, the narrow outcrop of Haughton Formation strata between Middle and East Rhinoceros Creeks and the outcrops in the very center of the crater (points C and D in Fig. 2, respectively). These sediments are also richer in pebbles and quartz than is typical. At the prominent mesa in the center of the structure, large pebbles up to ~10 cm across are suspended in fine-grained sands and muds. It cannot be ruled out that these latter sediments are glacial sediments emplaced sometime following deposition of the Haughton Formation.

Glacial and Fluvioglacial Deposits

Several primary glacigenic and fluvioglacial deposits occur inside the crater (Figs. 1 and 2). The two types of deposits are distinguished on the basis of the relative influence of fluvial and glacial processes in their formation. Glacial and fluvioglacial sediments unconformably overlie all lithologies within the Haughton structure (impact melt breccias, Haughton Formation, Lower Paleozoic target rocks). Mass-movement deposits such as talus and gelifluction deposits, which are associated with the present-day periglacial environment, are not covered here.

Primary glacigenic deposits are dominated by melt-out till, showing little evidence of significant fluvial transport or modification. This study provides the first report and map of these deposits inside the Haughton impact structure. Occurrences include relatively large exposures in the central part of the crater and near Lake Cornell and Trinity Creek, and minor exposures scattered in the interior and periphery of the structure (Fig. 2). It is notable that the present-day erosion surface of the Haughton Formation is marked by a ~1–5 cm thick veneer of till and isolated kames (Figs. 5b and 6a). In addition, many hills of impact melt breccias are draped by thin, patchy glacial deposits consisting of rounded carbonate cobbles up to ~80 cm in diameter (e.g., Fig. 6b). This material could represent true melt-out till, in which case the fine-grained fraction has been eroded away, or it could represent ice-rafted debris.

Fluvioglacial deposits, which include deposits emplaced and/or modified by flowing water, are common within the Haughton structure. These deposits include the large gravel bar dividing the main outcrop of the Haughton Formation along Middle Rhinoceros Creek (Fig. 2) and the wide fluvioglacial terraces of the Haughton River valley farther to the East (Fig. 1). This study refines outlines of these units previously mapped as "Quaternary" formations by Thorsteinsson and Mayr (1987b) and Hickey et al. (1988) and reports previously unmapped occurrences such as those along Trinity Creek (Fig. 2). Fluvioglacial deposits derived from impact melt breccias have been observed at a three localities in the center of the Haughton structure (e.g., Fig. 6d). These deposits are coarse-grained, poorly sorted, and unconsolidated, which clearly distinguishes them from the reworked impact melt breccias that underlie the Haughton Formation (cf. Fig. 6d with Figs. 4d and 4e).

The main sedimentological attributes of the glacigenic and fluvioglacial deposits are outlined below. These observations indicate that these deposits are distinctly different from Haughton Formation strata.

1. Primary glacigenic and fluvioglacial sediments are unconsolidated and lack concretionary layers/nodules.
2. XRD analysis reveals that these lithologies are dominated by dolomite with minor quartz and calcite (quartz > calcite; cf. Haughton Formation strata where calcite > quartz).
3. Glacigenic and fluvioglacial sediments are typically more coarse-grained and poorly sorted than the Haughton Formation strata (but see below), with a predominance of fine-grained sands and minor but ubiquitous layers of clast-supported gravel and isolated large (up to ~50 cm in diameter), angular to sub-rounded clasts of dolomite and limestone (Fig. 6). Gravel sheets are characteristic of episodic sediment movement and deposition during floods and subsequent waning flows (Benn and Evans 1998).
4. Glacial and fluvioglacial sediments are always unvegetated or very sparsely vegetated in contrast to outcrops of the Haughton Formation that support a variety of plant species and are the most fertile areas of Haughton structure and surrounding terrain (Cockell et al. 2001).
5. Fluvial sediments consisting of rounded gravels and cobbles are the youngest lithologies of the region and continue to be transported and deposited at the present day by the larger streams and rivers (e.g., the Haughton River) (Fig. 1).

DISCUSSION AND CONCLUSIONS

Deposition of the Haughton Formation and Its Timing Relative to the Impact Event

Hickey et al. (1988) suggest that the onset of lacustrine sedimentation occurred soon after the formation of the Haughton impact crater, because (a) the basal contact shows no sign of any protracted period of weathering between the formation of the impact structure and the onset of sedimentation, and (b) a reverse graded bed of fresh, angular debris, ~4 m thick, exists above the basal contact indicating the presence of unstable slopes of fresh rubble in the immediate area. These authors also cited the agreement, within the limits of error, between the fission-track date for Haughton of 22.4 ± 1.4 Ma (Omar et al. 1987) and the fossil remains of late Oligocene to middle Miocene (~20 ± 5 Ma) (Robertson et al. 1986), as further evidence that the Haughton Formation was deposited soon after impact. However, the results of our field studies, together with recent ^{40}Ar-^{39}Ar dating of Haughton impactites (Sherlock et al. 2005), suggest that this can be ruled out as follows.

Sediment Source

If the Haughton Formation was deposited immediately post-impact, then the major source of sediment would have been the impact melt breccias that filled the interior of the crater to depths of >200 m and ejecta deposits that blanketed the surrounding terrain for several kilometers beyond the crater rim, with only minor input from bedrock of the crater rim region. This is clearly not the situation, as the impact melt breccias comprise a groundmass of calcite + silicate glass ± anhydrite with variably shocked lithic and mineral clasts (Osinski et al. 2005c), whereas the Haughton Formation is dominated by dolomite. Furthermore, no shocked mineral or lithic clasts have been found in the Haughton Formation, even in the basal sections. This suggests that the main source of the this sedimentary unit is the dolomite-rich Middle Member of the Allen Bay Formation, which forms the uppermost exposed unit in the target sequence and that constitutes the eroded crater rim in the western half of the structure (Fig. 1). These results are also consistent with organic geochemical studies, which demonstrate that the hydrocarbon component of the Haughton Formation is derived from dolomites of the Allen Bay Formation and not from the impact melt breccias (Parnell et al. 2005).

Basal Contact of the Haughton Formation

The base of the Haughton Formation is marked by a crater-wide angular unconformity. In the interior of the crater, a layer of reworked impact melt breccia has been observed between the Haughton Formation and the "fresh" impact melt breccias in all instances where this sequence is exposed (e.g., Fig. 4). In the west of the crater, the Haughton Formation directly overlies pre-impact target rocks of the Allen Bay Formation (cf. Frisch and Thorsteinsson 1978). Recent work has shown that the crater-fill impactites at Haughton are impact melt breccias or clast-rich impact melt rocks that would have "settled out" during the final stages of crater formation to form a crater-filling layer with a (sub-) horizontal upper surface (Osinski and Spray 2001, 2003; Osinski et al. 2005c). At present, thick deposits of impact melt breccias are present in the east of the crater up to ~100 m higher in elevation that the Haughton Formation outcrops in the west. Thus, an episode of erosion, during which time significant quantities of the impact melt breccias were removed, occurred before the deposition of the Haughton Formation. This is evidenced by the presence of reworked impact melt breccias that unconformably overlie the fresh impact melt breccias. Substantial erosion of the impact melt breccias is also consistent with the considerable relief of the basal contact of the Haughton Formation (e.g., ~5–10 m; Hickey et al. 1988). Furthermore, the unconformable contact between the Haughton Formation and the reworked impact melt breccias indicates that a further episode of erosion occurred before deposition of the former. Thus, there was a significant temporal hiatus between the formation of the crater (i.e., emplacement of impact melt breccias) and the deposition of the Haughton Formation.

Hydrothermal Alteration?

Interaction of hot impact-generated melt breccias with groundwaters at Haughton created a hydrothermal system, which led to the deposition of carbonates, sulfides, sulfates, and quartz within cavities and fractures in the impact melt breccias and the surrounding pre-impact target rocks (Osinski et al. 2001, 2005a). At the similarly sized Ries impact structure, Germany (~24 km diameter), a series of hydrothermal minerals, including clays and zeolites, have been found throughout the ~400 m thick sequence of intra-crater paleolacustrine sedimentary rocks (e.g., Stöffler et al. 1977). With this in mind, we carried out an intensive search of the Haughton Formation for hydrothermal alteration products, but to no avail. Given that hydrothermal activity probably continued for several tens of thousands of years following the impact event (Osinski et al. 2001), this would suggest that deposition of the Haughton Formation occurred after the hydrothermal system had cooled to ambient temperatures. In contrast, the onset of sedimentation at the Ries was rapid (Riding 1979), and occurred while the impact-induced hydrothermal system was still active (e.g., Newsom et al. 1986).

Radiometric and Biostratigraphic Age Constraints

A wide range of fossil remains, including a well-preserved vertebrate fauna, plant fossils, and ostracodes, present with the Haughton Formation, has been used to estimate its age. Unfortunately, because of the geographic isolation of Haughton and the lack of a well-developed framework for biostratigraphic correlation, the Haughton Formation cannot be more accurately dated than Late Oligocene (<29 Ma) to Middle Miocene (~14 Ma) (Hickey et al. 1988), although the predominance of Neogene taxa favors an early Miocene age (i.e., 20 ± 5 Ma; Robertson et al. 1986; Hickey et al. 1988). This age estimate agreed, within the limits of error, with radiometric dates obtained for the Haughton impact event (22.4 ± 1.4 Ma [Omar et al. 1987]; 23.4 ± 1.0 Ma [Jessburger 1988]). However, recent ^{40}Ar-^{39}Ar and isotopic age determinations of glasses, using improved techniques and instrumentation, reveal that Haughton was formed ~39 Ma (Sherlock et al. 2005). This new age data indicates that the Haughton impact event significantly pre-dates the earliest possible depositional age of the Haughton Formation, which is late Oligocene. Thus, there was a substantial (up to ~8–10 Ma) time gap between the impact event and deposition of the Haughton Formation.

Synthesis

Field relationships reveal that a considerable amount of impact melt breccia material was removed before the deposition of the Haughton Formation. This is consistent with the following: (1) the presence of reworked impact melt breccias, which unconformably overlie impact melt breccias and that are unconformably overlain by Haughton Formation strata, (2) the dolomite-rich Middle Member of the Allen Bay Formation as the dominant source of the Haughton Formation sediments, and (3) the absence of hydrothermal alteration products within the Haughton Formation. Together with the new age date for Haughton of ~39 Ma, this indicates that the lacustrine sediments of the Haughton Formation were deposited up to several Ma following the impact event. This concurs with the view of Robertson and Sweeney (1983) who suggested that the Haughton Formation was deposited following an erosional period and that "they therefore do not represent an immediate, post-crater lake deposit." This is not to say that a crater lake did not form immediately post-impact. Rather, it appears that any evidence of this early lake was removed along with much of the crater-fill impactites before the deposition of the Haughton Formation in a Miocene-age crater lake.

Importance of Glacial Processes in Modifying the Post-Impact Landscape

The present-day erosion surface surrounding Haughton comprises a dissected plateau bordered by spectacular sea cliffs along the shores of Thomas Lee Inlet (Fig. 1). Since the formation of the Haughton structure in the Late Eocene, climatic conditions in the High Arctic have been largely dominated by a polar desert regime, albeit with periods of significant warming and episodes of glaciation resulting in substantial but often localized erosion. Roots (1963) emphasized that the present day plateau surface is being eroded by stream and marine processes, with frost and glacial action being responsible only for a modification of details. Indeed, there is abundant evidence for subglacial and ice-marginal streams in the terrain surrounding the Haughton structure (e.g., Lee et al. 1999; Lee 2000). Thus, it appears that the ice caps, present in some areas of Devon Island, do not appreciably modify the underlying surface and that they effectively preserve it from frost and stream action (Roots 1963). This view is supported by the relative absence of constructional landforms and glacial deposits on the plateau surface of Devon Island (Roots 1963; Hodgson 1989). However, it should be noted that there is still considerable controversy over the extent of the last glaciation on Devon Island (Paterson 1977). The ages and styles of possible Neogene and Pleistocene glaciations also remain unknown (Hodgson 1989).

It is notable that constructional glacigenic/fluvioglacial landforms (e.g., kames) and deposits are relatively common within the Haughton impact structure, in contrast to the surrounding terrain. Thus, it appears that the topographical depression formed by the impact event once again provided a protected basin into which sediments were deposited at the end of the last glaciation. The preservation of the unconsolidated Haughton Formation and a large volume of impact melt breccias indicate that, as with the surrounding plateau, the ice caps did not appreciably modify the underlying surface (Roots 1963), although minor reworking of the Haughton Formation undoubtedly occurred.

Comparisons with Other Impact Craters

During an impact event, the original water table in the target sequence would be disrupted and partly eliminated by the extreme energy dissipation (Osinski et al. 2001). However, in the weeks and months following the event, groundwaters would rise from depth as well as being drawn in laterally from the water table in the relatively undisturbed rocks surrounding the crater. With the additional input of water through precipitation, a crater lake or lakes would have formed in the majority of terrestrial impact craters that occurred on land. Some exceptions may occur with small craters and in extreme arid environments where the water table did not intersect the bottom of the crater. For example, water ponding is not presently experienced at Barringer Crater, Arizona, and Wolfe Creek Crater, Australia, although it was in the past (Cockell and Lee 2002).

At other impact sites, substantial sequences of lacustrine sediments have been preserved. For example, at the Ries impact structure, Germany, which is ~24 km diameter, ~400 m of intra-crater paleolacustrine sedimentary rocks are present (Riding 1979). In the Ries case, it appears that the onset of sedimentation was rapid and prolonged with no or very little subsequent erosion of the intra-crater sedimentary record. At Haughton, however, a very different picture has emerged. The lacustrine sediments of the Haughton Formation are preserved sporadically in the west of the structure and were not laid down in the original crater lake (of which all record has been removed), but some time later (several million years later). Subsequent glaciations have also left their mark with glacial and fluvioglacial deposits unconformably overlying all units within the crater. These examples show that impact structures may serve as unique repositories of a well-preserved record of a complex sequence of climatic episodes and geological events in a given area.

Despite the different post-impact sedimentary histories of the Haughton and Ries impact structures, both contain a well-preserved fossil record. Indeed, impact crater lakes and lacustrine sediments in general can provide favorable environments for the preservation of fossils (slow decay rates; fine grain size of sediment; limited disturbance).

Finally, the wealth and complexity of geological and climatological information preserved as intra-crater deposits at Haughton suggests that craters on Mars with intra-crater sedimentary records might present us with similar opportunities, but also possibly significant challenges.

Acknowledgments–This research was conducted in part under the auspices of the Haughton-Mars Project with support provided to P.L. (P. I.) in part by NASA, the SETI Institute, and the Mars Institute. Additional support for this research was provided by the Canadian Space Agency through a post-doctoral research grant to G.R.O. (P. I.) at the Mars Institute. We are also grateful to the Polar Continental Shelf Project (Natural Resources Canada), the Nunavut Research Institute, and the Communities of Grise Fiord and Resolute Bay for their support. Special thanks are due to Pauline and Rhoda Akeeagok, Alain Berinstain, Geoffrey Briggs, Charles Cockell, Brian Glass, Anthony Gross, Colleen Lenahan, Chris McKay, Samson Ootoovak, John Parnell, John Schutt, Nesha Trenholm, and to the many participants of the Haughton-Mars Project during the HMP 1997–2004 field seasons. V. L. Sharpton is thanked for his helpful and constructive review.

Editorial Handling—Dr. Elisabetta Pierazzo

REFERENCES

Arp G. 1995. Lacustrine bioherms, spring mounds, and marginal carbonates of the Ries impact crater (Miocene, southern Germany). *Facies* 33:35–90.

Benn D. I. and Evans D. J. A. 1998. *Glaciers and glaciation*. London: Arnold Publishers. 734 p.

Cabrol N. A. and Grin E. A. 1995. A morphological view on potential niches for exobiology on Mars. *Planetary and Space Science* 43: 179–188.

Cabrol N. A. and Grin E. A. 1999. Distribution, classification, and ages of martian impact crater lakes. *Icarus* 142:160–172.

Cabrol N. A., Grin E. A., Newsom H. E., Landheim R., and McKay C. P. 1999. Hydrogeologic evolution of Gale Crater and its relevance to the exobiological exploration of Mars. *Icarus* 139: 235–245.

Cabrol N. A., Wynn-Williams D. D., Crawford D. A., and Grin E. A. 2001. Recent aqueous environments in Martian impact craters: An astrobiological perspective. *Icarus* 154:98–112.

Cockell C. S. and Lee. P. 2002. The biology of impact craters: A review. *Biological Reviews* 77:279–310.

Farmer J. D. 2000. Hydrothermal systems: Doorways to early biosphere evolution. *GSA Today* 10:7:1–9.

Frisch T. and Thorsteinsson R. 1978. Haughton astrobleme: A mid-Cenozoic impact crater, Devon Island, Canadian Arctic Archipelago. *Arctic* 31:108–124.

Grin E. A. and Cabrol N. A. 1997. Limnologic analysis of Gusev Crater paleolake, Mars. *Icarus* 130:461–474.

Gronlund T., Lortie G., Guilbault J. P., Bouchard M. A., and Saanisto M. 1990. Diatoms and arcellaceans from Lac du Cratere du Nouveau-Quebec, Ungava, Quebec, Canada. *Canadian Journal of Botany* 68:1187–1200.

Hall J. B., Swaine M. D., and Talbot M. R. 1978. An early Holocene leaf flora from Lake Bosumtwi, Ghana. *Paleogeography, Paleoclimatology, Paleoecology* 24:247–262.

Hickey L. J., Johnson K. R., and Dawson M. R. 1988. The stratigraphy, sedimentology, and fossils of the Haughton Formation: A post impact crater fill. *Meteoritics* 23:221–231.

Hodgson D. A. 1989. Quaternary geology of the Queen Elizabeth Islands. In *Quaternary Geology of Canada and Greenland. geological survey of Canada, geology of Canada 1*, edited by Fulton R. J. Ottawa: Geological Survey of Canada. pp. 441–477.

Jessburger E. K. 1988. ^{40}Ar-^{39}Ar dating of the Haughton impact structure. *Meteoritics* 23:233–234.

Kring D. A. 2000. Impact events and their effect on the origin, evolution, and distribution of life. *GSA Today* 10:8:1–7.

Lee P. 1997. A unique Mars/early Mars analog on Earth: The Haughton impact structure, Devon Island, Canadian Arctic (abstract). *1st Conference on early Mars: Geologic and hydrologic evolution, physical and chemical environments, and the implications for life*. LPI Contribution #916. Houston: Lunar and Planetary Institute. 50 p.

Lee P. 2000. Selective fluvial erosion on Mars: Glacial selective linear erosion on Devon Island, Nunavut, Arctic Canada, as a possible analog (abstract #2080). 31st Lunar and Planetary Science Conference. CD-ROM.

Lee P. and Osinski G. R. 2005. The Haughton-Mars Project: Overview of science investigations at the Haughton impact structure and surrounding terrains, and relevance to planetary studies. *Meteoritics & Planetary Science* 40. This issue.

Lee P., Bunch T. E., Cabrol N., Cockell C. S., Grieve R. A. F., McKay C. P., Rice J. W. Jr., Schutt J. W., and Zent A. P. 1998. Haughton-Mars 97 I: Overview of observations at the Haughton impact crater, a unique Mars analog site in the Canadian High Arctic (abstract). 29th Lunar and Planetary Science Conference. pp. 1973–1974.

Lee P., Rice J. W., Jr., Bunch T. E., Grieve R. A. F., McKay C. P., Schutt J. W., and Zent A. P. 1999. Possible analogs for small valleys on Mars at the Haughton impact crater site, Devon Island, Canadian High Arctic (abstract #2033). 30th Lunar and Planetary Science Conference. CD-ROM.

Lozej G. P. and Beals F. W. 1975. The unmetamorphosed sedimentary fill of the Brent meteorite crater, Southern-eastern Ontario. *Canadian Journal of Earth Sciences* 12:606–628.

Metzler A., Ostertag R., Redeker H. J., and Stöffler D. 1988. Composition of the crystalline basement and shock metamorphism of crystalline and sedimentary target rocks at the Haughton impact crater. *Meteoritics* 23:197–207.

Newsom H. E., Brittelle G. E., Hibbitts C. A., Crossey L. J., and Kudo A. M. 1996. Impact crater lakes on Mars. *Journal of Geophysical Research* 101:14,951–14,956.

Omar G., Johnson K. R., Hickey L. J., Robertson P. B., Dawson M. R., and Barnowsky C. W. 1987. Fission-track dating of Haughton astrobleme and included biota, Devon Island, Canada. *Science* 237:1603–1605.

Osinski G. R. and Spray J. G. 2001. Impact-generated carbonate melts: Evidence from the Haughton structure, Canada. *Earth and Planetary Science Letters* 194:17–29.

Osinski G. R. and Spray J. G. 2003. Evidence for the shock melting of sulfates from the Haughton impact structure, Arctic Canada. *Earth and Planetary Science Letters* 215:357–270.

Osinski G. R. and Spray J. G. 2005. Tectonics of complex crater formation as revealed by the Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40. This issue.

Osinski G. R., Spray J. G., and Lee P. 2001. Impact-induced hydrothermal activity within the Haughton impact structure, Arctic Canada: Generation or a transient, warm, wet oasis. *Meteoritics & Planetary Science* 36:731–745.

Osinski G. R., Lee P., Parnell J., Spray J. G., and Baron M. 2005a. A case study of impact-induced hydrothermal activity: The Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40. This issue.

Osinski G. R., Lee P., Spray J. G., Parnell J., Lim D. S. S., Bunch T. E., Cockell C. S., and Glass B. 2005a. Geological overview and cratering model of the Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40. This issue.

Osinski G. R., Spray J. G., and Lee P. 2005c. Impactites of the Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40. This issue.

Parnell J., Lee P., Osinski G. R., and Cockell C. S. 2005. Application of organic geochemistry to detect signatures of organic matter in the Haughton impact structure. *Meteoritics & Planetary Science* 40. This issue.

Paterson W. S. B. 1977. Extent of the late-Wisconsin glaciation in northwest Greenland and northern Ellesmere Island: A review of the glaciological and geological evidence. *Quaternary Research* 8:180–190.

Riding R. 1979. Origin and diagenesis of lacustrine algal bioherms at the margin of the Ries Crater, upper Miocene, southern Germany. *Sedimentology* 26:645–680.

Robertson P. B. and Sweeney J. F. 1983. Haughton impact structure: Structural and morphological aspects. *Canadian Journal of Earth Sciences* 20:1134–1151.

Robertson P. B., Ostertag R., Bischoff L., Oskierski W., Hickey L. J., and Dawson M. R. 1986. First results of a multidisciplinary analysis of the Haughton impact crater, Devon Island, Canada (abstract). 16th Lunar and Planetary Science Conference. p. 702.

Roots E. F. 1963. Physiography. In *Geology of the north-central part of the Arctic archipelago, Northwest Territories (Operation Franklin)*, edited by Fortier Y. O., Blackadar R. G., Glenister B. F., Greiner H. R., McLaren D. J., McMillan N. J., Norris A. W., Roots E. F., Souther J. G., Thorsteinsson R., and Tozer E. T. Geological Survey of Canada Memoir #320. Ottawa: Geological Survey of Canada. pp. 164–179.

Scott D. and Hajnal Z. 1988. Seismic signature of the Haughton structure. *Meteoritics* 23:239–247.

Sherlock S. C., Kelley S. P., Parnell J., Green P., Lee P., Osinski G. R., and Cockell C. S. 2005. Re-evaluating the age of the Haughton impact event. *Meteoritics & Planetary Science* 40. This issue.

Shock E. L. 1996. Hydrothermal systems as environments for the emergence of life. In *Evolution of hydrothermal ecosystems on Earth (and Mars?)*, edited by Bock G. R. and Goode J. A. Chichester: John Wiley & Sons. pp. 40–82.

Stöffler D., Ewald U., Ostertag R., and Reimold W. U. 1977. Research drilling Nördlingen 1973 (Ries): Composition and texture of polymict impact breccias. *Geologica Bavarica* 75: 163–189.

Thorsteinsson R. and Mayr U. 1987. *The sedimentary rocks of Devon Island, Canadian Arctic archipelago*. Geological Survey of Canada Memoir #411. Ottawa: Geological Survey of Canada. 182 p.

Zent A. P., Bunch T. E., Grieve R. A. F., Lee P., McKay C. P., Rice J. W. Jr., and Schutt J. W. 1998. The role of brecciation in controlling morphology at Haughton crater: Climatic implications for Mars (abstract). 29th Lunar and Planetary Science Conference. pp. 1301–1302.