Meteoritics & Planetary Science 40, Nr 12, 1759–1776 (2005)
Abstract available online at http://meteoritics.org

Geological overview and cratering model for the Haughton impact structure, Devon Island, Canadian High Arctic

Gordon R. OSINSKI[1, 2*], Pascal LEE[3], John G. SPRAY[2], John PARNELL[4], Darlene S. S. LIM[5], Theodore E. BUNCH[6], Charles S. COCKELL[7], and Brian GLASS[5]

[1]Canadian Space Agency, 6767 Route de l'Aeroport, Saint-Hubert, QC J3Y 8Y9, Canada
[2]Planetary and Space Science Centre, Department of Geology, University of New Brunswick, 2 Bailey Drive, Fredericton, NB E3B 5A3, Canada
[3]Mars Institute, SETI Institute and NASA Ames Research Center, MS 245-3 Moffett Field, California 94035–1000, USA
[4]Geofluids Research Group, Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, AB24 3UE, UK
[5]NASA Ames Research Center, MS 245-3 Moffett Field, California 94035–1000, USA
[6]Department of Geology, Bilby Research Center, Northern Arizona University, Flagstaff, Arizona, USA
[7]Planetary and Space Sciences Research Institute, The Open University, Milton Keynes, MK7 6AA, UK
*Corresponding author. E-mail: gordon.osinski@space.gc.ca

(Received 08 February 2005; revision accepted 11 November 2005)

Abstract–The Haughton impact structure has been the focus of systematic, multi-disciplinary field and laboratory research activities over the past several years. Regional geological mapping has refined the sedimentary target stratigraphy and constrained the thickness of the sedimentary sequence at the time of impact to ~1880 m. New ^{40}Ar–^{39}Ar dates place the impact event at ~39 Ma, in the late Eocene. Haughton has an apparent crater diameter of ~23 km, with an estimated rim (final crater) diameter of ~16 km. The structure lacks a central topographic peak or peak ring, which is unusual for craters of this size. Geological mapping and sampling reveals that a series of different impactites are present at Haughton. The volumetrically dominant crater-fill impact melt breccias contain a calcite-anhydrite-silicate glass groundmass, all of which have been shown to represent impact-generated melt phases. These impactites are, therefore, stratigraphically and genetically equivalent to coherent impact melt rocks present in craters developed in crystalline targets. The crater-fill impactites provided a heat source that drove a post-impact hydrothermal system. During this time, Haughton would have represented a transient, warm, wet microbial oasis. A subsequent episode of erosion, during which time substantial amounts of impactites were removed, was followed by the deposition of intra-crater lacustrine sediments of the Haughton Formation during the Miocene. Present-day intra-crater lakes and ponds preserve a detailed paleoenvironmental record dating back to the last glaciation in the High Arctic. Modern modification of the landscape is dominated by seasonal regional glacial and niveal melting, and local periglacial processes. The impact processing of target materials improved the opportunities for colonization and has provided several present-day habitats suitable for microbial life that otherwise do not exist in the surrounding terrain.

INTRODUCTION

Haughton is a well-preserved complex impact structure situated near the western end of Devon Island in the Canadian Arctic Archipelago (75°22′N, 89°41′W) (Figs. 1, 2). This structure was created ~39 million years ago in a practically flat-lying, predominantly sedimentary target sequence. Since that time, Devon Island has remained tectonically stable and, despite being subjected to several ice ages, Haughton remains well preserved and is also one of the best exposed terrestrial impact structures. This is largely due to the predominantly cold and relatively dry environment that has prevailed in the Arctic since the Eocene. Accordingly, Haughton offers exceptional research opportunities to further our understanding of mid-size (e.g., ~15–30 km diameter) impact structures.

The following papers and fold-out map insert in this issue are the result of work carried out during the course of eight

© The Meteoritical Society, 2005. Printed in USA.

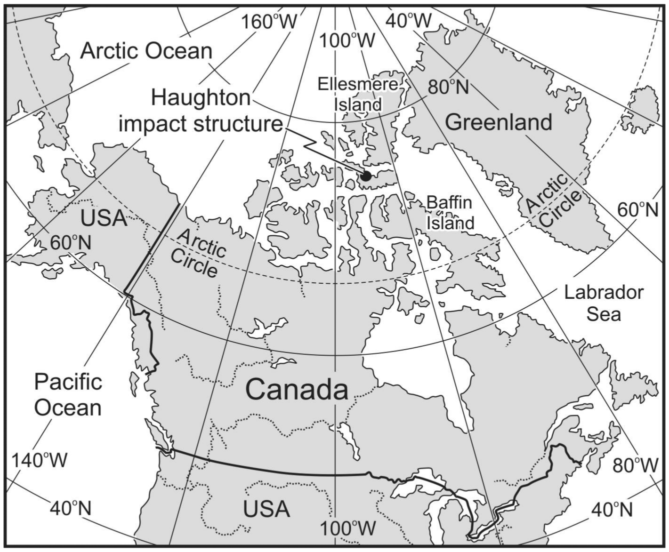

Fig. 1. Location of the Haughton impact structure in the Canadian High Arctic.

field seasons (1997–2004) under the auspices of the Haughton-Mars Project (HMP) (see Lee and Osinski [2005] for an overview of the HMP). This paper summarizes the current state of our knowledge of the geology of the Haughton impact structure based on articles in this issue, together with other recent results published elsewhere, in addition to previous studies carried out prior to the HMP. To borrow a few words from a recent paper by Bevan French (French 2004), these recent studies at Haughton demonstrate the value of "new and closer looks at the existing terrestrial impact cratering record….and looking at once-studied rocks again and seeing them in new ways."

PREVIOUS WORK

During Operation Franklin in the 1950s, this structure was mapped as a salt dome by Greiner (1963), who considered it to be associated with a group of similar features developed in the Sverdrup Basin ~400 km to the north. However, the isolation of the structure from these other salt tectonic features prompted Dence (1972) to include it in a list of "possible impact structures." These early workers named this feature the Haughton Dome after the Reverend Samuel Haughton who was a distinguished geologist, medical doctor, and reverend, and who published one of the first geological accounts of the Canadian High Arctic (Haughton 1860a, b). An impact origin for Haughton was subsequently confirmed by the discovery of shatter cones (Robertson and Mason 1975) and coesite-bearing gneiss clasts from impact breccias (Frisch and Thorsteinsson 1978). Frisch and Thorsteinsson (1978) conducted regional mapping and assigned a Miocene, or possibly Pliocene, age to the impact event based on paleontological studies of post-impact lacustrine sediments deposited in the crater. Extensive sampling and further mapping, particularly of impactites, was undertaken in 1977 (reported in Robertson and Grieve [1978] and Robertson and Plant [1981]) and in 1981 (reported in Robertson and Sweeney [1983]).

Field studies carried out in 1984, under the auspices of the multidisciplinary Haughton Impact Structure Studies (HISS) project, resulted in a substantial increase in our knowledge of Haughton (summarized in Grieve 1988). The first detailed surface structural studies (Bischoff and Oskierski 1988) were augmented by seismic reflection, gravity, and magnetic studies of the subsurface structure (Scott and Hajnal 1988; Pohl et al. 1988). Geochemical analysis of impactites was carried out for the first time (Redeker and Stöffler 1988; Metzler et al. 1988). Jessberger (1988) reported an ^{40}Ar–^{39}Ar age of 23.4 ± 1.0 Ma on biotites from highly shocked gneiss clasts from the impactites, consistent with a fission-track age on apatites from similar clasts of 22.4 ± 1.4 Ma (Omar et al. 1987).

Many subsequent studies were performed on samples collected during the HISS project (e.g., Deutsch and Schärer 1990; Schärer and Deutsch 1990; Stephan and Jessberger 1992; Martinez et al. 1993; Martinez et al. 1994). The most recent wave of field investigations began in 1997 with separate studies led by V. L. Sharpton and P. Lee, the latter in the context of the first field season of the HMP. These studies have led to a number of conference abstracts reporting new insights into the shock metamorphism of crystalline rocks (Bunch et al. 1998; Dressler and Sharpton 1998), the structure of Haughton (Sharpton et al. 1998; Sharpton 1999), and the geomorphology of Haughton and surrounding terrain and its potential relevance to Mars (Lee et al. 1998; Zent et al. 1998).

TARGET STRATIGRAPHY

The target rocks at Haughton comprise a thick series of predominantly Lower Paleozoic sedimentary rocks of the Arctic Platform, overlying Precambrian metamorphic basement of the Canadian Shield (Figs. 2–4). The exact thickness of sedimentary rocks present in the pre-impact target sequence at Haughton has been constrained to ~1880 m. This will be discussed, following a description of the various lithologies.

Canadian Shield

The Canadian Shield consists mainly of Archean metamorphic rocks exposed in the eastern coastal regions of Devon Island (Fig. 2). These rocks constitute part of the Alexandra Subprovince of the Churchill Structural Province (Stockwell 1982) and represent a group of terranes that were juxtaposed during a series of Early Proterozoic (Hudsonian) orogenies (Trettin 1991). Most of the main Devon Island ice cap, which covers the eastern quarter of the island, appears to overlie these rocks (Fig. 2; Thorsteinsson and Mayr 1987). The ~2.5 Ga basement rocks comprise a series of

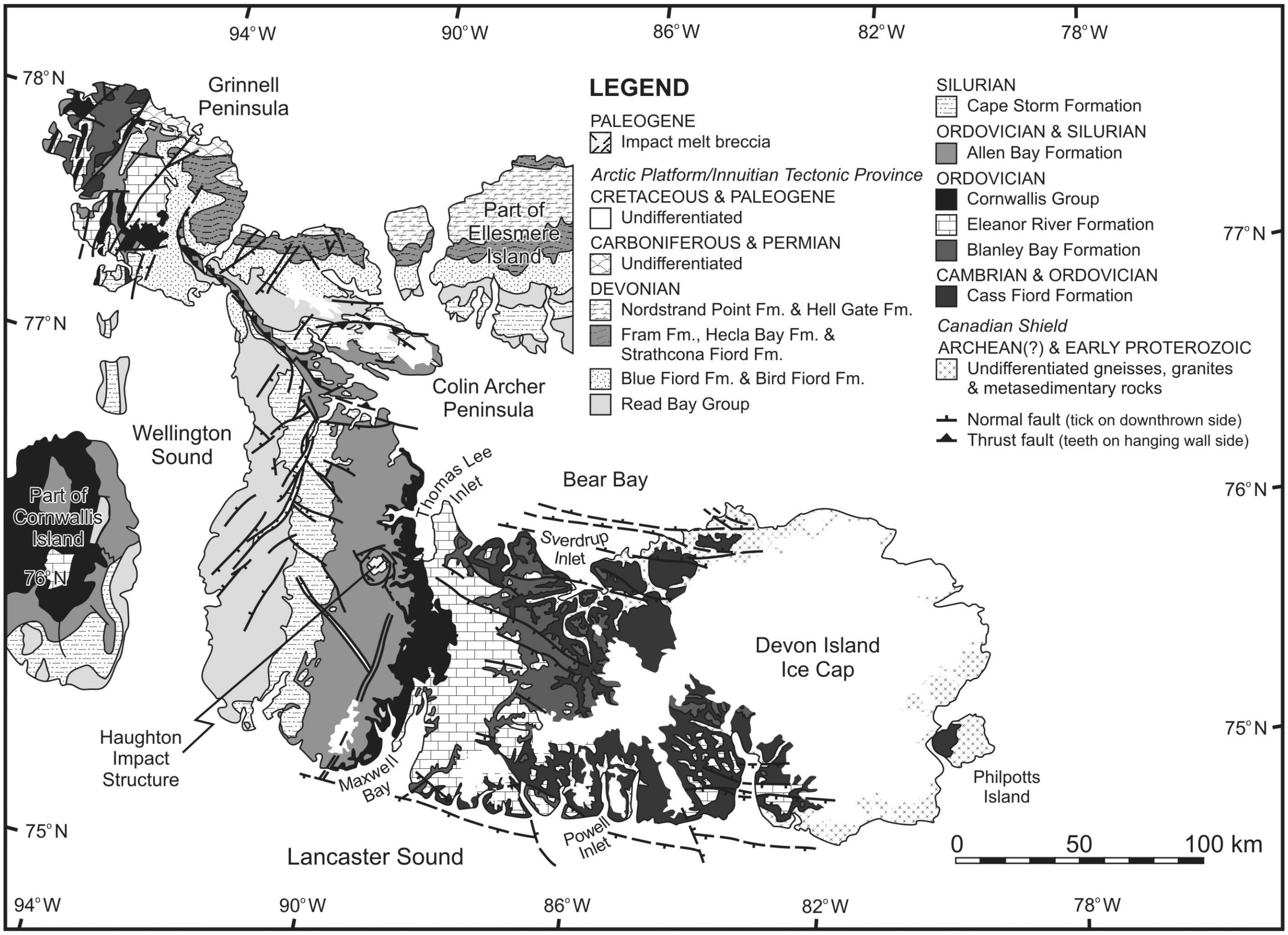

Fig. 2. Geological map of Devon Island, after Okulitch (1991). Abbreviation: Fm. = Formation.

predominantly granulite facies tonalitic and granitic gneisses, with a diverse series of intercalated metasedimentary rocks (Frisch 1983; Frisch and Trettin 1991). Charnokitic plutonic bodies of tonalitic to granitic composition of anatectic origin have intruded the gneisses syntectonically at ~1.9 Ga (Frisch 1983; Frisch and Trettin 1991). All the pre-Paleozoic rocks, including the overlying Proterozoic sedimentary rocks, are cut by massive, brown- or black-weathering dolerite dikes of Sinian age (~600–800 Ma; Frisch 1983).

Arctic Platform

The Arctic Platform comprises a thick sequence of Proterozoic to Paleogene sedimentary rocks that have not been folded or thrust-faulted on a regional scale (Thorsteinsson and Tozer 1970; Douglas 1970). Although Proterozoic to Cenozoic sedimentary rocks of the Arctic Platform are exposed on Devon Island, the preserved sedimentary succession is incomplete (Figs. 2 and 4). The sedimentary record is stratigraphically divisible into three major structurally conformable successions that are separated from one another by regional unconformities (Fig. 4; Thorsteinsson and Mayr 1987).

1. The Proterozoic is represented by the up to 177 m thick Strathcona Sound Formation, with outcrops limited to the shores of Powell Inlet and Cuming Inlet on the south coast of the island (Fig. 2). This formation is, therefore, absent from the target sequence at Haughton. The Strathcona Sound formation unconformably overlies the Archean crystalline basement and comprises a thin sequence of unmetamorphosed, thinly bedded, dusky red-weathering siltstones and sandstones (Thorsteinsson and Mayr 1987).
2. The Lower Paleozoic rocks of Devon Island encompass the greater part of the sedimentary succession, in terms of both age span and thickness of strata (Thorsteinsson and Mayr 1987). This structurally conformable sequence of Early Cambrian to Silurian-Devonian age rocks lie in a west-dipping homoclinal succession (regional dip ~2–5°) that exposes approximately north-south trending units of progressively younger strata to the west (Fig. 2). The oldest Paleozoic unit, the Rabbit Point Formation

(Kurtz et al. 1952), is bounded above and below by unconformities (Fig. 4). In the south of the island, the formation lies unconformably on sedimentary rocks of the Proterozoic Strathcona Sound Formation. However, throughout most of its area of distribution, the formation lies unconformably on Archean basement rocks. The Bear Point Formation is similarly bounded above and below by unconformities and is eroded out in places (Fig. 4; Thorsteinsson and Mayr 1987). The overlying Middle Cambrian to Ordovician-Silurian sedimentary sequence comprises predominantly thick units of limestone and dolomite with subordinate amounts of evaporites, shale, and sandstone that together form an overall westward thickening wedge (Figs. 2 and 4; Thorsteinsson and Mayr 1987). The Lower Paleozoic carbonates have been investigated for their hydrocarbon potential (Parnell et al. 2005a). Like other outcrops of Laurentian platform carbonates in Greenland, Newfoundland, and Ontario, the Canadian High Arctic exposures show numerous traces of bitumen, which represent migrated oil (Stuart-Smith and Wennekers 1977).

3. Carboniferous to Late Jurassic-age rocks are not present on Devon Island. The youngest rocks of the Arctic Platform are of Early Cretaceous age (Fig. 2). These soft and easily weathered rocks are preserved in a series of grabens in the northwest of Devon Island where they lie unconformably on various older Paleozoic formations (Fig. 2; Thorsteinsson and Mayr 1987). The Eureka Sound Formation of Late Cretaceous (Maastrichtian) age lies unconformably on the Lower Paleozoic sequence (Thorsteinsson and Mayr 1987). Fortier (1963) has described a ~210 m thick sequence of this formation in a graben near the head of Viks Fiord (Fig. 2), where it consists mainly of unconsolidated nonmarine quartzose sandstone, siltstone, and shale. Elsewhere in the Canadian High Arctic, Eureka Sound beds of Paleocene and Eocene age have been documented, but this is not the case on Devon Island (Thorsteinsson and Mayr 1987).

Thickness of the Pre-Impact Sedimentary Sequence

The present-day outcrop of the Haughton structure lies entirely within carbonate strata of the Upper Ordovician Allen Bay Formation (Fig. 4). Two peneplaned surfaces can be used to establish the chronological sequence of structural events on Devon Island (Thorsteinsson and Mayr 1987). The oldest is marked by the base of the Eureka Sound Formation and is Albian in age (99–112 Ma) or older, but younger than the Lower Paleozoic sedimentary succession (Thorsteinsson and Mayr 1987). The younger peneplane is represented by the present-day topography and is Paleogene in age. On Greenland, Axel Heiberg Island and Ellesmere Island, to the north of Devon Island (Fig. 1), the same regional peneplane is overlain by beds of the Beaufort Formation of middle to late Miocene age (Bustin 1982), providing an upper age limit for the peneplane. Two lines of evidence suggest that this plateau represents a peneplanation event that occurred after the down-faulting of the Eureka Sound Formation and is, therefore, early Eocene in age or younger (Frisch and Thorsteinsson 1978): 1) the Eureka Sound Formation is preserved exclusively in down-faulted grabens; 2) there is no evidence for fault scarps on the plateau surface across fault traces, as might be expected in the case of an erosional surface. Consequently, Frisch and Thorsteinsson (1978) concluded that the impact took place after the erosion of the Eureka Sound Formation and, therefore, after the development of the present day peneplane.

A contrasting view is held by Hickey et al. (1988) who propose that >200 m of Eureka Sound strata rested unconformably on the Paleozoic sequence at the time of impact. This view is based on the presence of a small amount of reworked pollen and spores of Maastrichtian, Paleocene, and possibly Eocene age, and reworked dinoflagellates of Sonatinas to Campanian age in the post-impact lacustrine sediments. However, Frisch and Thorsteinsson (1978) also noted the presence of these reworked components and suggested that the source was from down-faulted Eureka Sound strata present in the Viks Fiord graben ~30 km to the west of Haughton.

It is noted here that if Eureka Sound strata were present at the time of impact, "remnants" of this unit should also be preserved in down-faulted blocks of the crater rim. However, detailed mapping carried out as part of this study reveals that the youngest sedimentary rocks preserved around the Haughton structure belong to the Middle and Upper Members of the Allen Bay Formation. Thus, it is concluded that impact took place after erosion of the Eureka Sound Formation (cf. Frisch and Thorsteinsson 1978). Therefore, the sedimentary sequence at the time of impact was ~1880 m thick. This value represents the thickness to the top of the Allen Bay Formation and is based on a review of data in Thorsteinsson and Mayr (1987), augmented by field data collected by the authors. This is also consistent with the regional estimates of thermal maturity due to burial (Gentzis et al. 1996).

GEOLOGY OF THE HAUGHTON IMPACT STRUCTURE

A summary of the important statistics and parameters of the Haughton impact structure are presented in Table 1. Originally thought to be Miocene in age, recent high-precision ^{40}Ar–^{39}Ar laser probe dating of potassic glasses contained in highly shocked basement clasts yields an age of 39 ± 2 Ma for Haughton (Sherlock et al. 2005). As noted above, the target rocks at Haughton comprise an ~1880 m thick series of Lower Paleozoic sedimentary rocks of the Arctic Platform, overlying Precambrian metamorphic

Table 1. Summary of the important statistics and parameters of the Haughton impact structure.

Parameter	Value	Notes and references
Age	39 ± 2 Ma	^{40}Ar–^{39}Ar laser probe dating of potassic glasses in highly shocked crystalline basement clasts (Sherlock et al. 2005).
Target stratigraphy	1880 m	~1880 m of sedimentary rocks overlying crystalline basement (Thorsteinsson and Mayr 1987; Osinski 2004a).
Amount of erosion	>100<200 m	Average value of erosion (Osinski 2004a).
Apparent crater diameter	23 km	Outermost ring of concentric normal faults at present-day erosion level (Osinski and Spray 2005).
Rim (final crater) diameter	~16 km	Outer limit of a topographic depression; semi-continuous line of concentric normal faults that record large-scale (>100–400 m) displacements of slump blocks in toward the crater center (Osinski and Spray 2005; this study).
Gravity anomaly?	See notes	~24 km diameter negative bouger gravity anomaly; central minimum of ~3 mgal; weaker relative maxima at 6–7 km radius (Pohl et al. 1988).
Magnetic anomaly?	See notes	~3 km diameter, 300–500 nT central magnetic anomaly (Glass et al. 2005).
Diameter of "melt sheet"	~9 km	~9 km (present day); ~12 km (original).
Structural uplift	~1450 m	Observed amount of uplift undergone by the deepest marker horizon now exposed in the crater center (cf. Grieve et al. 1981).
Diameter of excavated and transient craters	~10–12 km	(Osinski and Spray 2005; this study). Diameter of the transient and excavation craters are assumed to be equal (Grieve et al. 1981).
Depth of excavation	~750 m	Based on clast content and melt phases in ballistic ejecta deposits (Osinski et al. 2005a; this study).
Depth of transient crater	>1880 m ~1500–2250 m	Based on clast content of crater-fill impactites (this study). Scaling from depth of excavation (this study).
Depth of melt zone	~450–1880 m	(Osinski et al. 2005a).

basement of the Canadian Shield (Fig. 1). Carbonates and evaporites comprise ~75–80% and ~8%, respectively, of the target sequence at Haughton.

Several estimates for the diameter of Haughton have been proposed. Frisch and Thorsteinsson (1978) suggested a value of 16 km based on the limit of the inner topographic depression. The outer limit of this topographic depression roughly corresponds with the "structural rim diameter" of 14–19 km as proposed by Bischoff and Oskierski (1988). Robertson and Sweeney (1983) mapped a so-called "outer ring" of disconnected peaks at a diameter of 20.5 km, which they took as the "apparent crater diameter." The most recent and currently accepted apparent crater diameter for Haughton is 24 km, which corresponds to the outermost concentric normal fault seen on a single seismic reflection profile through the northwest of the structure (Scott and Hajnal 1988). This metric also corresponds to the ~24 km in diameter negative Bouger gravity anomaly seen at Haughton (Pohl et al. 1988).

Recent structural mapping reveals that concentric faults with strike lengths of several kilometers are present at radial distances of 12 km in the north, west, and south, and 11 km in the east of the structure (Osinski and Spray 2005). This gives an apparent crater diameter of 23 km for Haughton using the terminology of Grieve et al. (1981) and Turtle et al. (2005). However, this does not represent the rim (final crater) diameter (defined as the diameter of the topographic rim that rises above the outermost slump block not concealed by ejecta; Grieve et al. 1981; Turtle et al. 2005), which is the metric quoted by numerical modelers and that is required to derive the impact energy through scaling laws (e.g., McKinnon and Schenk 1985; Schmidt and Housen 1987).

Is it possible to estimate the rim (final crater) diameter of Haughton? As noted by Frisch and Thorsteinsson (1978), Haughton comprises an inner topographic depression 16 km across. The outer limit of this depression is marked by a semi-continuous line of concentric normal faults that record large-scale (>100–400 m) displacements of slump blocks in toward the crater center (Osinski and Spray 2005). Outside of this region, displacements along concentric normal faults are rarely >50 m so that it is highly likely that, in the newly formed Haughton crater, the outermost concentric faults would have been concealed by ejecta. Thus, the most robust estimate for the rim (final crater) diameter of Haughton is ~16 km.

Detailed mapping carried out as part of the HMP confirms the conclusions of Bischoff and Oskierski (1988) that Haughton is not a multi-ring basin, as originally proposed by Robertson and Sweeney (1983). There is no topographic central peak or peak ring at Haughton as the uplifted lithologies in the center of the crater were originally covered by crater-fill impact melt breccias (Osinski and Spray 2005). The central uplift comprises three main structural zones, moving outwards from the crater center (Fig. 5): a) a central, ~2 km in diameter core of sub-vertical, differentially uplifted megablocks, with a maximum observable stratigraphic uplift of ~1450 m; b) kilometer-size fault-bounded blocks displaying moderate dips (~10–40°), uplifted by up to ~1300 m (radial distance of ~2–5 km); c) a structural ring of intensely faulted (sub-) vertical and/or overturned strata at radial distance of ~5.0–6.5 km, with stratigraphic uplifts of >250 to <750 m. Recent airborne geomagnetic surveys confirm that the central megabreccia core of the central uplift at Haughton is associated with a 300–500 nT magnetic anomaly (Glass et al. 2002, 2005), coinciding

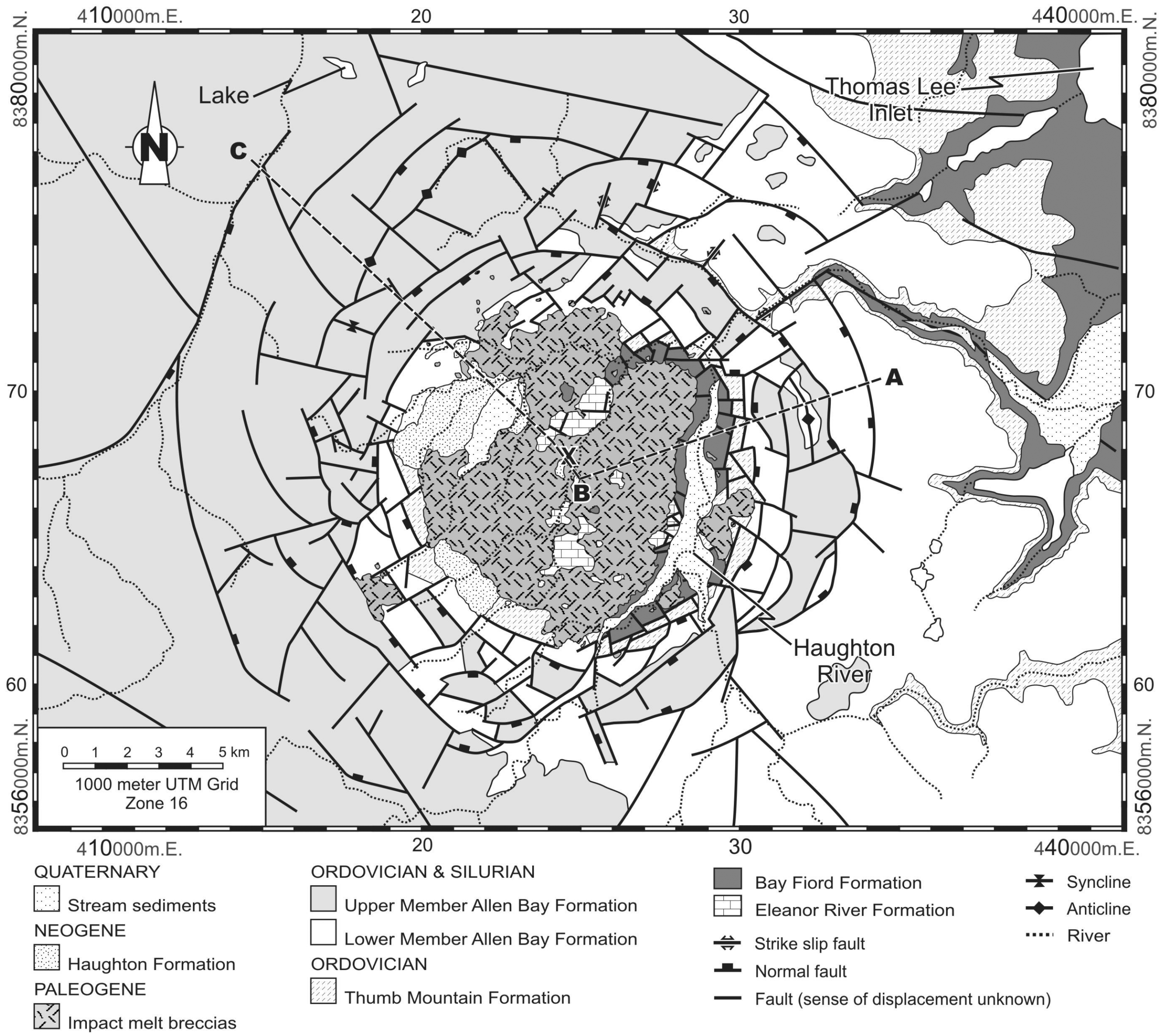

Fig. 3. Simplified geological map of the Haughton impact structure. “X” = location of Anomaly Hill. See the fold-out map insert in this issue for an enlarged and more detailed geological map of Haughton. The line of the cross sections from Fig. 5 are shown.

with a gravity minimum of ~3 mgal with very steep gradients (Pohl et al. 1988). A faulted terrace region extends out from the outer edge of the central uplift (radial distance of ~5.0–6.5 km) to 11–12 km from the crater center (Fig. 5). This region comprises a series of interconnected inward- and outward-dipping concentric and radial faults (Fig. 5; Osinski and Spray 2005).

Contrary to previous work, detailed mapping has revealed that a series of different impactite types are present at Haughton (Fig. 6; map insert; Table 2; Osinski et al. 2005a). In the crater interior, there is a consistent upward sequence from parautochthonous target rocks overlain by parautochthonous lithic (monomict) breccias, through allochthonous lithic (polymict) breccias, into pale grey allochthonous crater-fill deposits (Fig. 6a; Table 2; Osinski et al. 2005a). The pale grey crater-fill deposits currently form a discontinuous 54 km^2 layer in the central area of the structure. These are volumetrically by far the most dominant impactite at Haughton (Fig. 3; map insert; Table 2). The pale grey crater-fill deposits were initially described as “polymict impact breccia” and were interpreted as clastic matrix breccias or as fragmental breccias (Frisch and Thorsteinsson 1978; Metzler et al. 1988; Redeker and Stöffler 1988). However, detailed field, optical and analytical SEM studies reveal that the groundmass of these impactites comprises calcite, silicate impact melt glass, and anhydrite, which represent a series of impact-generated melts that were molten at the time of, and following, deposition (Osinski and Spray

Table 2. Summary of the various typesof impactites at Haughton and their characteristics.[a]

	Impactites of the crater interior			Impactites of the crater-rim region	
	Parautochthonous lithic breccias	Allochthonous lithic breccias	Allochthonous impact melt breccias	Yellow allochthonous impact melt breccias and megablocks	Grey allochthonous impact melt breccias
Physical characteristics:					
Present distribution (km^2)	<1	<1	53.8	<1.5	1.28
Estimated original distribution (km^2)		~2	115	>100	>50
Maximum current thickness (m)	10	4	125	<40 m	75 m
Estimated original thickness (m)	<20	<5 (discontinuous)	>200	>100	<120
Present volume (km^3)			7	0.2	0.1
Estimated original volume (km^3)			22.5	>10	>5
Clasts:	Up to ~80 vol%	Up to ~70 vol%	~40–50 vol% (av.)	~20–40 vol% (av.)	~30–40 vol% (av.)
Lithologies present					
- limestone	Up to 80 vol%	Up to ~50 vol%	Up to ~6 vol%	Up to ~20 vol%	Up to ~12 vol%
- dolomite	Up to 80 vol%	Up to ~70 vol%	~10–45 vol%	Up to ~25 vol%	~20–35 vol%
- sandstone and shale	None	Up to ~3 vol%	Up to ~1–2 vol%	None	<0.1 vol%
- evaporite	Up to 80 vol%	Up to ~50 vol%	Up to ~9 vol%	None	None
- metagranite and gneiss	None	Up to ~5 vol%	Up to ~2–8 vol%	None	None
- silicate glass	None	None	Up to ~10 vol%	None	None
Depth of origin in target sequence	>400 m <1000 m	>300 m up to ~1900 m	>700 m up to ~2000 m	0 m to ~750 m	>200 m <1300 m
Shock level	<1–2 GPa	Up to ~5 GPa	<1 to >60 GPa	<10 GPa	<40 GPa
Depth of origin of shock-melted clasts	n/a	n/a	>900 m <1880 m	n/a	n/a
Groundmass/matrix:	Up to ~20 vol%	Up to ~30 vol%	~50–60 vol% (av.)	~60–80 vol% (av.)	~60–70 vol% (av.)
Mineralogy					
- calcite	Up to ~20 vol%	Up to ~25 vol%	~20–25 vol% (av.)	Up to ~50 vol%	~50–60 vol% (av.)
- dolomite	Up to ~20 vol%	Up to ~25 vol%	<<0.1 vol%	None	None
- anhydrite	Up to ~15 vol%	Up to ~10 vol%	0–90 vol%	None	None
- silicate glass	None	None	~25–30 vol% (av.)	Up to ~60 vol%	~5–10 vol% (av.)
- other	Up to ~5 vol%	Up to ~5 vol%	Rare celestite	None	None
Clastic or impact-generated melt?	Clastic	Clastic	Impact-generated melt	Impact-generated melt	Impact-generated melt
Depth of origin of melt phases	n/a	n/a	>500 m <1800 m	0 to 750 m	>200 m <900 m

[a]Compiled with data from Osinski (2004a) and Osinski et al. (2005a). Abbreviations: av. = average; N/A = not applicable.

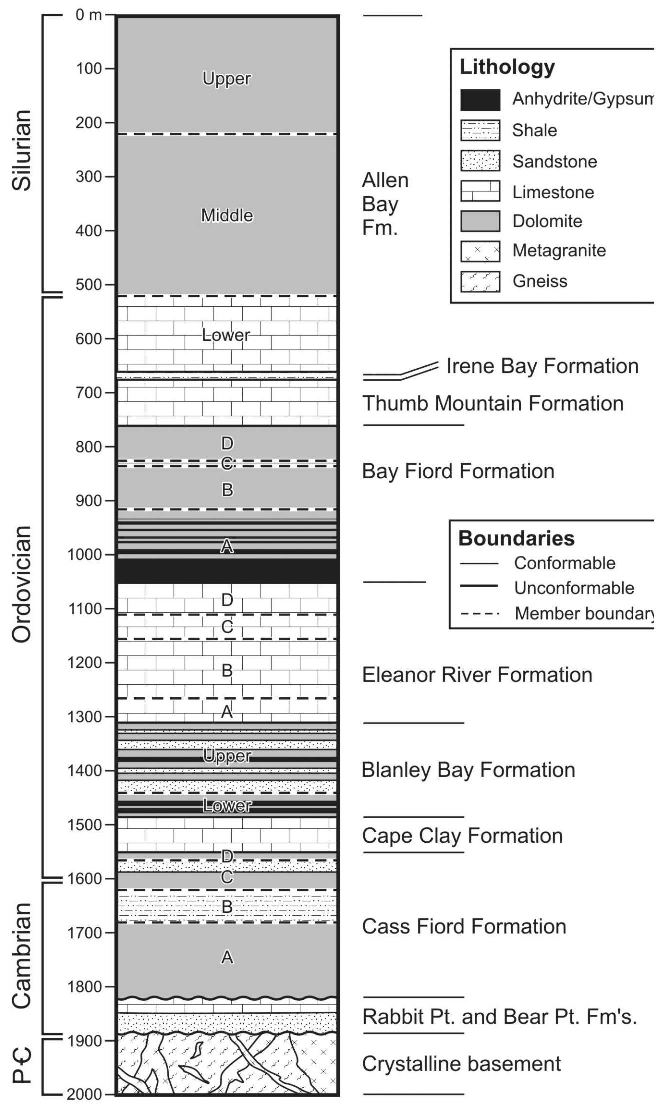

Fig. 4. Stratigraphic column showing the target sequence at the Haughton impact structure. Abbreviations: Fm. = Formation; Pt. = Point. Compiled with data from Thorsteinsson and Mayr (1987) and the authors' field observations.

2001, 2003; Osinski et al. 2005a). The pale grey crater-fill deposits at Haughton can, therefore, be classified as impact melt breccias according to the terminology of Stöffler and Grieve (1994, 1996).

Two principal impactites have been recognized in the near-surface crater rim region of Haughton (Figs. 3, 6b; map insert; Osinski et al. 2005a). Pale, yellow–brown allochthonous impact melt breccias and megablocks are overlain by pale grey allochthonous impact melt breccias. The former are interpreted as remnants of the continuous ejecta blanket (Osinski et al. 2005a). The pale grey impact melt breccias, although similar to the impact melt breccias of the crater interior, are more carbonate-rich and do not appear to have incorporated clasts from the crystalline basement. Appraisal of groundmass-forming impact melt phases and impact glass clasts from the various types of impactites indicates that the melt zone at Haughton incorporated strata from depths of ~450 to ~1880 m (Fig. 4; Table 2).

Impact-induced hydrothermal activity at Haughton 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 (Table 3; Osinski et al. 2001, 2005a). Heating associated with this hydrothermal activity, combined with residual heat from the shock wave, has resulted in the increased thermal maturity of organic matter in the central uplift at Haughton, relative to the same lithologies outside the crater (Parnell et al. 2005b).

Early workers at Haughton recognized the presence of a series of post-impact lacustrine sediments overlying crater-fill impactites (Frisch and Thorsteinsson 1978; Robertson and Sweeney 1983) that were later named the Haughton Formation by Hickey et al. (1988). This unit is composed of interbedded, dolomite-rich lacustrine silt, fine sand, and mud (Hickey et al. 1988), and contains a rich assemblage of pollen, plant macrofossils, and the only known record of early Neogene Arctic vertebrates (Whitlock and Dawson 1990). Recent work has confirmed the early hypothesis of Robertson and Sweeney (1983), who proposed that the Haughton Formation was deposited after an erosional period and that they do not represent an immediate post-impact crater lake deposit (Osinski and Lee 2005; Sherlock et al. 2005). Detailed organic geochemical characterization of a hydrocarbon-impregnated band found in a shallow drill core (AH98-3; map insert) reveals a complex source history for the Haughton Formation (Eglinton et al. 2005).

The lacustrine deposits of the Haughton Formation preserve a wealth of paleoclimatological data. Pollen, plant macrofossil and vertebrate fossils, captured high latitude faunal and floral developments during the early Neogene (Hickey et al. 1988; Whitlock and Dawson 1990). Recently, Lim (2004), as part of the HMP, investigated the aquatic ecology of the Haughton Formation paleolake for the first time. As documented by Lim (2004), three subsamples of a shallow drill core (AH98-3; map insert) yielded either fragments or whole remnants of fossil freshwater diatoms. None of the diatom remnants were fully intact and, as a result, precise species identifications could not be made. However, given the general morphological characteristics of some of the fossil diatoms recovered, they are possibly from the *Cymbella*, *Cocconeis*, and *Aulacosira* or *Thalassiosira* genera (Lim 2004). If so, the preliminary results of this study provide the first documentation of the possible presence of freshwater diatoms in the Canadian High Arctic during the Miocene (Lim 2004).

A series of glacial and fluvio-glacial sediments unconformably overlie all units within the crater and attest to the complex erosional and sedimentary infilling history of the

Table 3. Summary of the important characteristics and different styles of post-impact hydrothermal mineralization at Haughton.[a]

Setting	Style of alteration	Distribution[b]	Hydrothermal minerals (decreasing order of abundance)	Temperature range (°C)	Stage Early	Main	Late
Interior of central uplift	Cementation of breccias	<3 km	Quartz (SiO_2)	<60; 90–250	A	R	A
Outer margin of central uplift	Veins	~5.0–6.5 km	Calcite ($CaCO_3$)	~150 to ~60	X	A	A
Within impact melt breccias	Vugs and veins	up to ~7 km[c]	Calcite	210 to <60	R	A	A
			Selenite ($CaSO_4.2H_2O$)	<80	X	R	A
			Marcasite (FeS_2)	~200 to 80	X	A	X
			Fibroferrite ($Fe(SO_4)(OH).5H_2O$)	<80	X	X	R
			Quartz	>200; <80	R	X	R
			Celestite ($SrSO_4$)	~200 to 80	X	R	X
			Barite ($BaSO_4$)	~200 to 80	X	R	X
			Fluorite (CaF_2)	~200 to 80	X	R	X
Faulted crater periphery	Hydrothermal pipe structures; veins	>7 km	Calcite	>200 to <60	?	A	A
			Quartz		?	A	A
			Marcasite		?	A	R
			Pyrite (FeS_2)		?	A	R

[a]Compiled with data from Osinski et al. (2001), Osinski (2004a), and Osinski et al. (2005b). Abbreviations: A = abundant; R = rare; X = absent.
[b]Given as the radial distance from crater center.
[c]Mineralization within the crater-fill impact melt breccias is concentrated in the lower levels of the impact melt breccia layer.

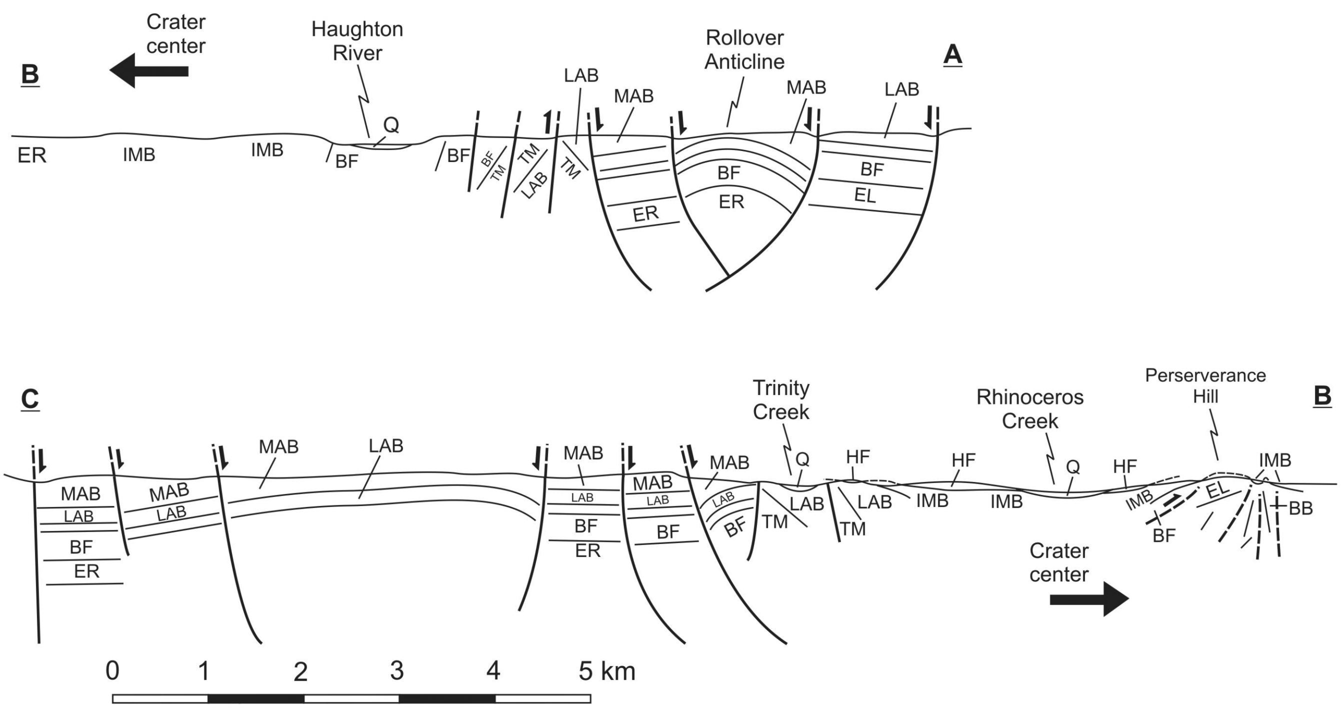

Fig. 5. Representative cross sections across the Haughton structure (modified after Osinski and Spray 2005). See Fig. 3 for location of sections. Q = quaternary deposits; HF = Haughton Formation; IMB = impact melt breccias; MAB = Middle Member Allen Bay Formation; LAB = Lower Member Allen Bay Formation; TM = Thumb Mountain Formation; BF = Bay Fiord Formation; ER = Eleanor River Formation; BB = Blanley Bay Formation.

Haughton structure (Fig. 4, map insert; Osinski and Lee 2005). Roots (1963) emphasized that the present day plateau surface of Devon Island is being eroded by stream and marine processes, with frost and glacial action being responsible only for a modification of details. 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

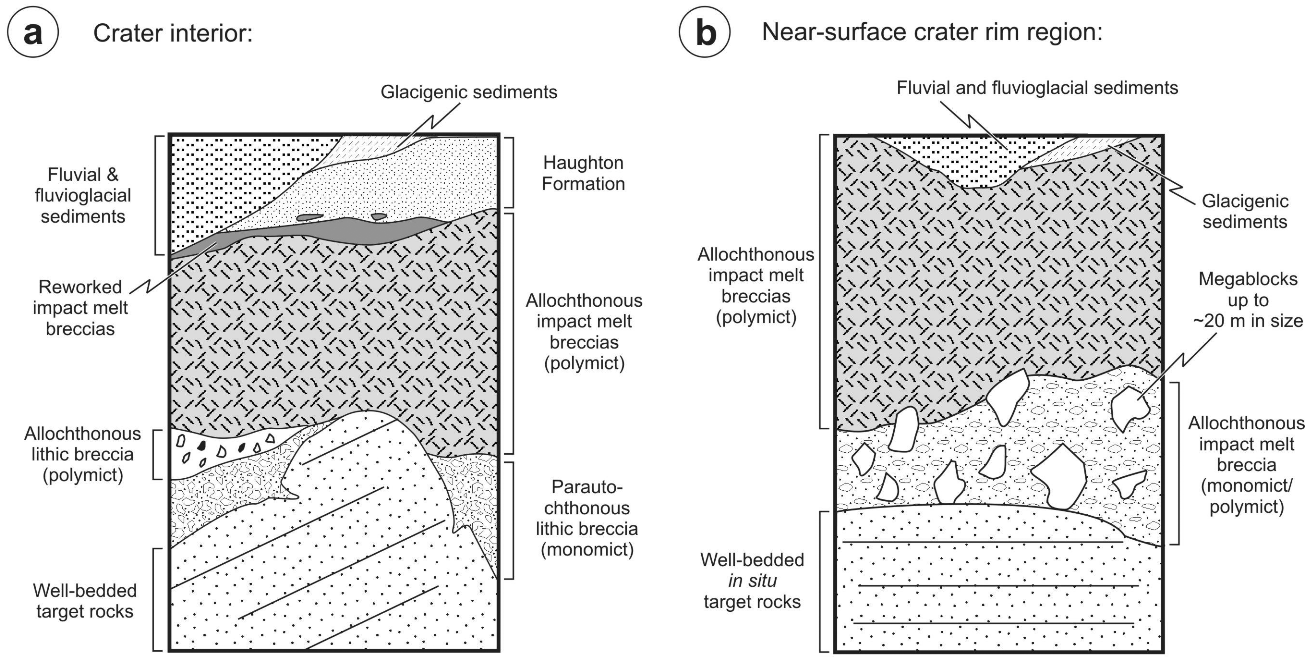

Fig. 6. Schematic cross sections showing the different types of impactites and post-impact sedimentary deposits and their stratigraphic sequence in the crater interior (a) and near-surface crater rim (b) regions of the Haughton impact structure.

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 Late Tertiary and Pleistocene glaciations also remain unknown (Hodgson 1989).

Modern modification of the landscape is dominated by seasonal regional glacial and niveal melting, and local periglacial processes, which include gelifluction, patterned ground formation, mass wasting, debris flow formation, and gullying on steeper slopes. Present-day lakes (depth >2 m) and ponds (depth <2 m) both occur within the limits of the Haughton structure and throughout the rest of Devon Island. Lim and Douglas (2003) conducted a detailed limnological survey of the lakes and ponds found in the Haughton region, as well as across Devon Island (Lim 2004). Overall, the general limnological trends for lakes in the Haughton region (Lim and Douglas 2003) were similar to those identified in the broader survey of Devon Island (Lim 2004). However, those lakes and ponds in close contact with the carbonate-rich impact melt breccias within the Haughton structure were distinguished from the larger data set due to their elevated Mg^{2+}, SO_4^{2-}, Ba^{2+}, Sr^{2+}, and SiO_2 concentrations (Lim and Douglas 2003).

CONCEPTUAL CRATERING MODEL FOR THE HAUGHTON IMPACT EVENT

The various parameters and important characteristics of the Haughton impact structure are presented in Table 1. Using this data and previous models of the cratering process, we attempt to provide a realistic model for the Haughton impact event (Fig. 7).

The first stage of an impact event begins when the projectile, be it an asteroid or a comet, contacts the surface of the target (Fig. 7a). The type of projectile that created Haughton is currently unknown. Modeling of the impact process suggests that the projectile penetrates no more than 1–2 times its diameter (Kieffer and Simonds 1980; O'Keefe and Ahrens 1982). The intense kinetic energy of the projectile is then transferred into the target in the form of shock waves that are created at the boundary between the compressed and uncompressed target material (Melosh 1989). When the reflected shock wave reaches the "free" upper surface of the projectile it is reflected back into the projectile as a rarefaction, or tensional wave (Ahrens and O'Keefe 1972), causing it to unload from high-shock pressures, resulting in the complete melting and/or vaporization of the projectile itself (Gault et al. 1968; Melosh 1989). The increase in internal energy accompanying compression and subsequent rarefaction also results in the melting and/or vaporization of a small volume of target material close to the point of impact (Ahrens and O'Keefe 1972; Grieve et al. 1977). While universally accepted for impacts into crystalline targets, this has not always been the case for impacts into volatile-rich sedimentary targets. However, at Haughton, it is clear that sedimentary strata at depths from ~450 to ~1880 m underwent melting (Osinski et al. 2005a), which suggests that the projectile released the bulk of its energy at a relatively shallow level in the target sequence.

The transition from the initial contact and compression stage into the excavation stage is a continuum. It is during this stage that the actual impact crater is opened up by complex interactions between the expanding shock wave and the original ground surface (Figs. 7b–d; Melosh 1989). During the excavation stage, the roughly hemispherical shock wave propagates out into the target sequence, which causes the target material to be set in motion, with an outward radial trajectory (Figs. 7b and 7c). At the same time, shock waves that initially traveled upwards intersect the ground surface and generate rarefaction waves that propagate back downwards into the target sequence (Melosh 1989). The combination of the outward-directed shock waves and the downward-directed rarefaction waves produces an "excavation flow" and generates the so-called "transient cavity" (Fig. 7b) (Dence 1968; Grieve and Cintala 1981; Melosh 1989). Based on detailed mapping at Haughton, it is apparent that during this initial compressive outward-directed growth of the transient cavity, several new structures were produced (Fig. 7c; Osinski and Spray 2005): 1) sub-vertical radial faults and fractures; 2) sub-horizontal bedding parallel detachment faults; 3) minor concentric faults and fractures.

The different trajectories of material in different regions of the excavation flow field result in the partitioning of the transient cavity into an upper "excavated zone" and a lower "displaced zone" (Fig. 7b) (Dence 1968; Stöffler et al. 1975; Grieve and Cintala 1981; Melosh 1989). The presence of clasts from the crystalline basement in the crater-fill impactites at Haughton is generally used to infer a depth of excavation of >1880 m (e.g., Redeker and Stöffler 1988; Sharpton and Dressler 1998). However, it is notable that all material from the excavated zone is ejected from the transient cavity to form proximal or distal ejecta deposits (Dence 1968; Stöffler et al. 1975; Grieve and Cintala 1981). The material incorporated into crater-fill deposits never leaves the transient cavity (Grieve et al. 1977). That is, crater-fill deposits originate from the displaced zone in Fig. 7b. Consequently, the true measure of the depth of excavation comes from ejecta deposits, which, for Haughton, gives a maximum depth of excavation of ~750 m, based on the clast content and melt phases in ejecta deposits documented by Osinski et al. (2005a) (Table 2). What then does this say of the depth of the transient cavity at Haughton? Experiments and theoretical considerations of the excavation flow suggest that the excavated material is derived only from the upper one-third to one-half the depth of the transient cavity (Stöffler et al. 1975). This would suggest a transient cavity depth of ~1500 to 2250 m for Haughton. This is consistent with the presence of clasts from the crystalline basement in the crater-fill deposits, which indicates that the displaced zone involved material down to >1880 m.

A portion of the melt and rock debris that originates beneath the point of impact remains in the transient cavity. This material is also deflected upward and outward parallel to the base of the cavity, but must travel further and possesses less energy, so that ejection is not possible (Figs. 7c and 7d; Grieve et al. 1977). Thus, at the end of the excavation stage, a mixture of melt and rock debris "forms a lining to the transient cavity and the basic stratigraphy of melt overlying mixed breccia with both clastic and melt components and/or basement is established" (Fig. 7d; Grieve et al. 1977). Importantly, it is this material, which does not leave the transient cavity, that forms the melt-rich crater-fill deposits in complex impact structures, both in craters developed in crystalline targets (Grieve et al. 1977) and, we suggest, in craters in sedimentary targets (Fig. 7d). In other words, it is apparent that the crater-fill deposits at Haughton are genetically equivalent to coherent impact melt rocks found at craters developed in crystalline targets.

An interesting outcome of the geometry of flow lines within the transient cavity is that melt that is directly beneath the point of impact is driven downwards and picks up proportionally more highly shocked inclusions than melt that is displaced outwards (Dence et al. 1977; Grieve et al. 1977). In craters developed in crystalline target rocks, this results in a melt-rich, inclusion-poor lens in the center of the structure, which also contains more highly shocked clasts with respect to the rest of the crater-fill unit (Grieve et al. 1977). This mechanism solves a long-standing enigma at Haughton: namely that the crater-fill deposits contain fewer clast of a smaller size, and that highly shocked sedimentary and crystalline clasts are concentrated in the center of the structure (Metzler et al. 1988). There are further observations of the crater-fill impact melt breccias at Haughton that can only be explained if they are genetically equivalent to coherent impact melt layers in crystalline targets. The greater abundance of crystalline clasts in the northeast sector of the Haughton structure (Frisch and Thorsteinsson 1978; Metzler et al. 1988) can only be explained if the crater-fill deposits originated by radial flow along the transient cavity walls (cf. Grieve 1988). That is, due to the gentle westerly dip of ~3–5° of the target stratigraphy, the sedimentary sequence would have been thinner in the eastern half of the transient cavity so that a higher proportion of crystalline rocks would have been incorporated. It is also apparent that the inclusion-rich basal melt layer seen in many craters is thickest toward the edge of the cavity. This is seen at Haughton where the basal megabreccia is best developed within ~1–3 km of the edge of the transient cavity (e.g., Rhinoceros Creek outcrop; Osinski and Spray 2003; Osinski et al. 2005a).

Despite the similarities noted above, there will be differences in the nature of crater-fill impact melt layers produced from impacts into sedimentary and crystalline targets. Firstly, it is important to note that impact melt bodies comprise shock melt produced upon decompression from a high-pressure impact, and melt derived from the assimilation of entrained clasts (Kieffer and Simonds 1980; Pope et al. 2004). In terms of initial shock melt, Kieffer and Simonds (1980) calculated that as much, or even more, melt should be

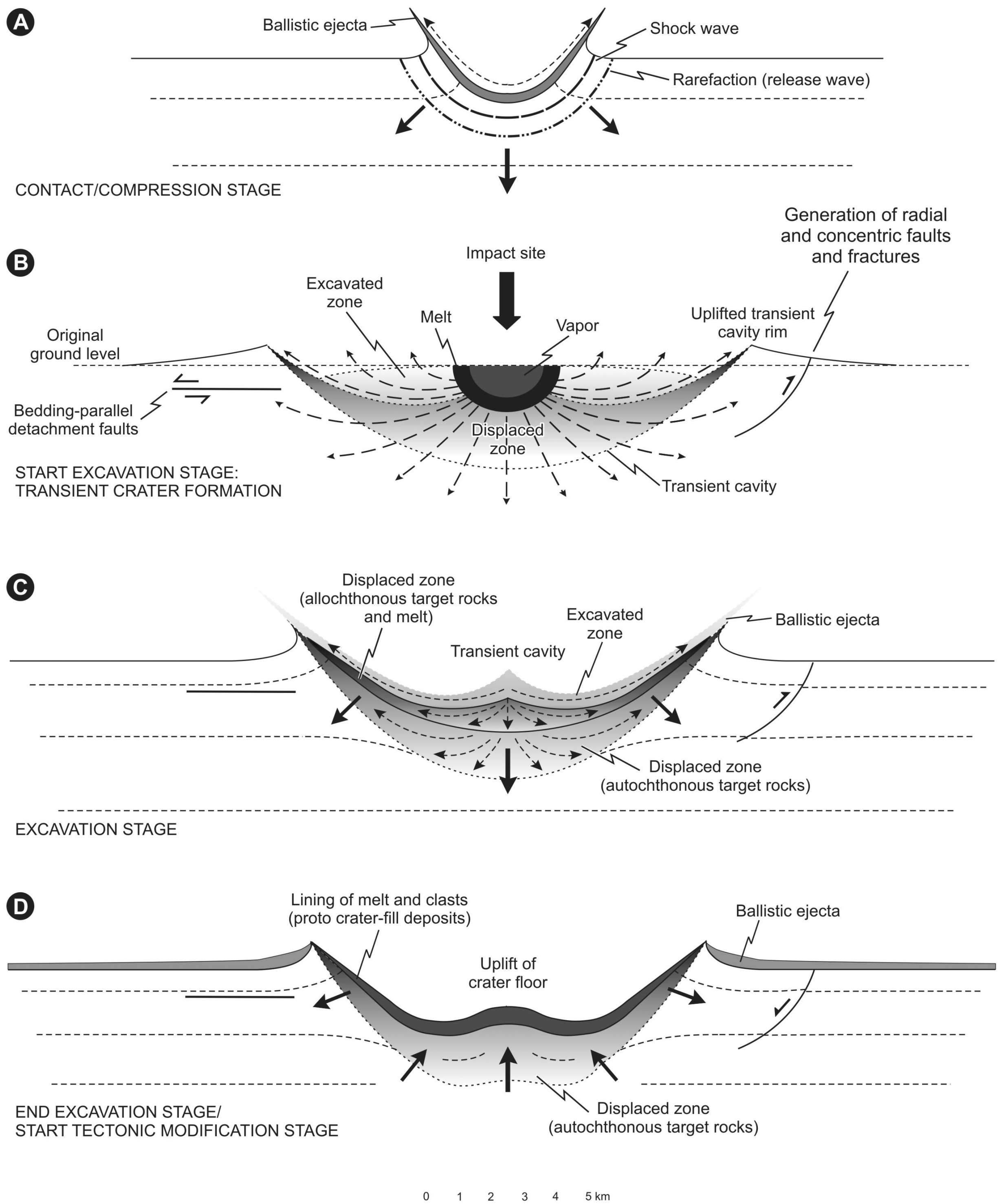

Fig. 7. Series of schematic cross sections depicting the formation and post-impact modification of the Haughton impact structure, based on an idealized east-west section through the crater. The first stage of the impact event began when the projectile, be it an asteroid or comet, contacted the surface of the target (a). During the subsequent excavation stage (b and c), a "transient cavity" was opened up by complex interactions between the expanding shock wave and the original ground surface (Melosh 1989). Material was excavated from the upper one-third to one-half the depth of the transient cavity. In the lower "displaced zone," target material was driven downward and outward and did not reach the surface (French 1998). At the end of the excavation stage, a mixture of melt and rock debris formed a lining to the transient crater (d). During the modification stage, uplift of the transient crater floor occurred leading to the development of a central uplift (d and e).

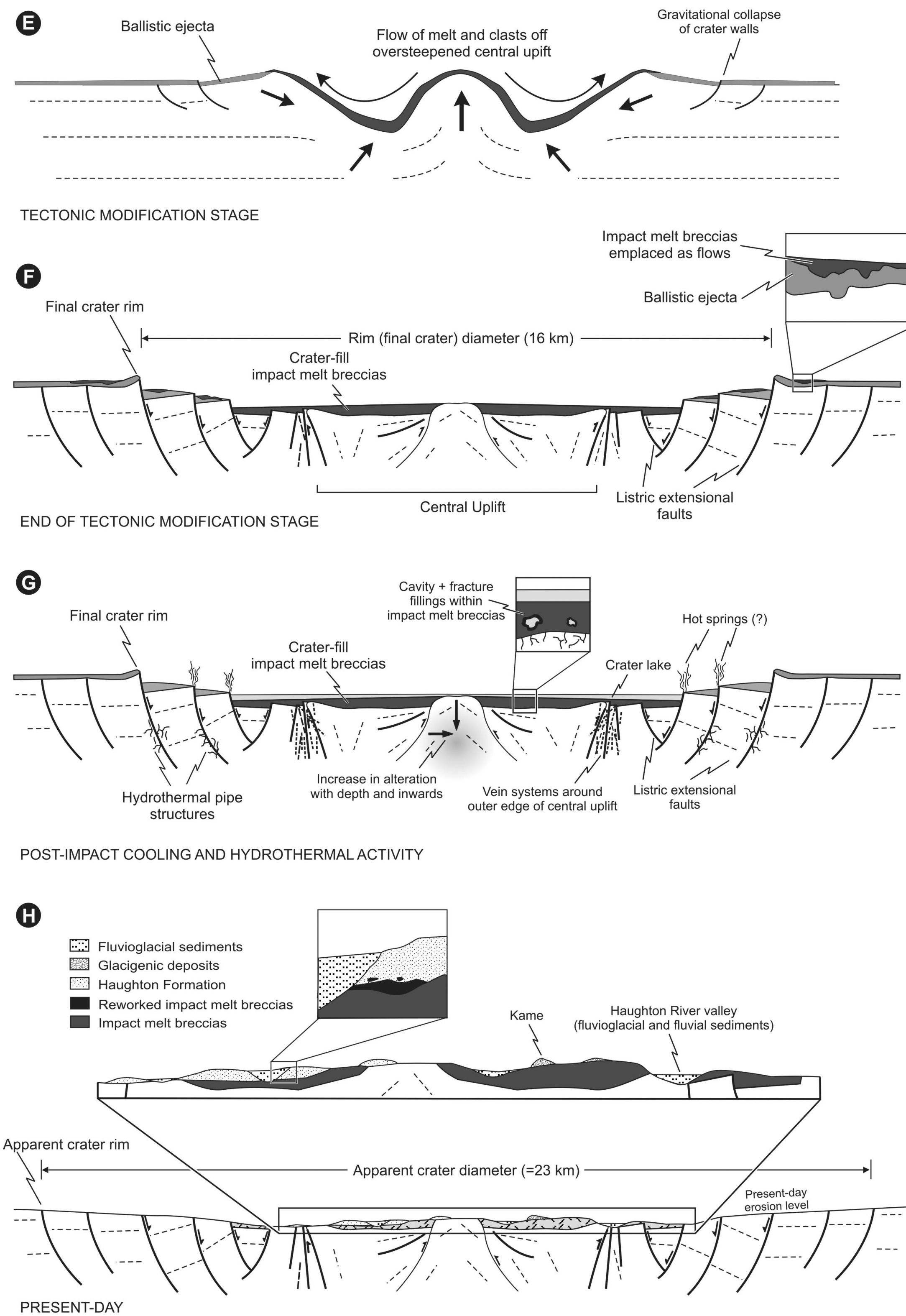

Fig. 7. *Continued*. Concomitantly, the initially steep walls of the transient crater collapsed under gravitational forces. During uplift, an outward-directed trajectory would have likely been imparted to the overlying impact melt and rock debris (e and f). The newly formed crater would have comprised an uplifted rim ~16 km in diameter, a terraced zone, and a buried central uplift (f). Immediately following the impact, the interaction of groundwaters with the hot, impact-generated crater-fill deposits, led to the development of a hydrothermal system (g). The present-day structure bears the signs of erosion and sedimentary infilling over the past 39 Ma (h). The crater rim has been eroded away, along with much of the ejecta deposits, exposing other concentric normal faults not visible in the newly formed Haughton crater (h). Modified after Grieve (1987), Melosh (1989), French (1998), Osinski and Lee (2005), Osinski and Spray (2005) and Osinski et al. (2005b).

produced during impacts into sedimentary targets, as opposed to crystalline targets. In contrast, the high enthalpies of H_2O-bearing and carbonate systems are so high that a much smaller proportion of admixed sedimentary rocks than of anhydrous crystalline rock is required to quench a melt to subsolidus temperatures (Kieffer and Simonds 1980). In terms of the rock record, all other conditions being equal, a lower percentage of sedimentary rocks will be assimilated than crystalline rocks, before a melt is quenched, resulting in higher final clast contents for melts derived from impacts into sedimentary as opposed to crystalline targets (cf. the clast content of crater-fill impact melt layers at the similarly-sized Haughton [up to ~40–50 vol%] [Osinski et al. 2005a] and Mistastin [up to ~20–30 vol%] [Grieve 1975] impact structures).

Toward the end of the excavation stage, uplift of the transient cavity floor occurs resulting in the formation of a central uplift (Fig. 7d) (i.e., the maximum depth of the transient cavity is attained before the maximum diameter is reached; Gault et al. 1968; Stöffler et al. 1975; Orphal 1977; Schultz et al. 1981; Kenkmann et al. 2000). Material originally displaced downwards and outwards in the floor of the transient cavity are transported inwards and upwards, creating a converging particle trajectory field in the center of the crater (Fig. 7d). At Haughton, kilometer-size fault-bounded blocks of the Eleanor River Formation and smaller (up to ~50–150 m across) blocks of the Blanley Bay Formation were uplifted >1050 to <1300 m and >1300 to <1450 m, respectively, above their pre-impact stratigraphic positions (Fig. 3; map insert). However, it is notable that no topographic central peak or peak ring formed at Haughton.

Shortly thereafter, the transient cavity reaches its maximum radial extent, which marks the end of the excavation stage and the onset of the modification stage (Fig. 7d). For complex impact structures such as Haughton, the transient cavity is unstable and undergoes modification by gravitational forces, producing a so-called complex impact crater (Figs. 7d and 7e). Two competing mechanisms are at work during crater modification: continued uplift of the transient crater floor and collapse of the initially steep transient crater walls. It is generally considered that the effects of the modification stage are governed by the size of the transient cavity and the properties of the target rock lithologies (Melosh 1989). However, mapping at Haughton suggests that structures such as radial faults and detachment faults generated during the excavation stage play an important role during the modification stage, including reducing the overall strength of the target sequence prior to crater collapse (Osinski and Spray 2005), as has been documented at other impact structures (Spray 1997, 1998; Spray et al. 2004).

The gravitational collapse of the transient crater walls at Haughton involved complex interaction of a series of interconnected inward- and outward-dipping concentric and radial faults (Osinski and Spray 2005). The faulted terrace region extends out from the outer edge of the central uplift (radial distance of ~5.0–6.5 km) to 11–12 km from the crater center. Converging movement/displacement during the collapse of the crater walls is accommodated by the formation of several types of structure, including sub-vertical radial faults and folds, positive flower structures, rollover anticlines in the hanging-walls of major listric faults, antithetic faults and crestal collapse grabens, and oblique strike-slip (i.e., centripetal) movement along concentric faults (see Osinski and Spray 2005).

Central uplifts can become over-heightened or unstable during the final stages of the impact cratering process (e.g., Collins et al. 2002; Wieland et al. 2003; Osinski and Spray 2005), resulting in a switch from a converging particle trajectory field involving compressional inward-directed movement to extensional, outward-directed movement (Osinski and Spray 2005). This has several important implications. Firstly, it may explain the lack of a central peak or peak ring at Haughton. That is, collapse of the central uplift could have resulted in the destruction of an early-formed central peak, but the collapse ended before a peak ring could be formed (cf. the numerical models of Collins et al. [2002]). In addition, complex interactions between the outward collapsing central uplift and inward collapsing crater walls created a zone of (sub-) vertical and/or overturned strata at Haughton at a radial distance from the center of ~5.0–6.5 km (Osinski and Spray 2005). The presence of similar structurally complex zones around the outer edge of central uplifts at other craters (e.g., Ries [Pohl et al. 1977] and Siljan [Kenkmann and von Dalwigk 2000]) and analogous features seen in numerical models (Collins et al. 2002) suggests that such interactions are an important part of the impact cratering process. Finally, movements associated with the collapse of an overheightened central uplift can impart an outward-directed vector to crater-fill impact melt breccias and coherent melt bodies, resulting in the transportation of some of this material, still within the original transient cavity, outward as flows and toward and beyond the final crater rim during the modification stage of crater formation (Fig. 7e; Osinski et al. 2005a). This resulted in the emplacement of pale grey impact melt breccias in the near-surface crater rim area of Haughton that are genetically equivalent to crater-fill deposits (Fig. 4). Such an origin has also recently been proposed for suevites and impact melt rocks in the near-surface crater rim region of the Ries structure (Osinski 2004b; Osinski et al. 2004).

The formation of the Haughton impact crater would have taken only a few minutes from the initial contact of the projectile, to the gravitational collapse of the crater walls and formation of the central uplift. As French (1998) notes, the modification stage has no clearly marked end. Processes that are intimately related to complex crater formation, such as the uplift of the crater floor and collapse of the walls, merge into normal geological processes such as mass movement, erosion, and so on. In addition, geographically localized processes, such as impact-induced hydrothermal activity (see Osinski et al. 2001, 2005b) and intra-crater sedimentation (Hickey et al. 1988; Whitlock and Dawson 1990; Osinski and Lee 2005), occurred at Haughton immediately after its formation (Figs. 7f–h), with the latter continuing until the present day (Lim and Douglas 2003; Lim 2004; Osinski and Lee 2005).

CONCLUDING REMARKS

It is now widely recognized that impact cratering is a ubiquitous geological process that has played an important role in the evolution of the terrestrial planets as well as the rocky and/or icy bodies of the outer solar system (e.g., French 2004). The number of recognized terrestrial impact structures continues to rise each year (see Earth Impact Database 2005), with estimates on the order of several hundred more still awaiting discovery (e.g., Grieve 1991). However, the majority of these structures will likely be buried and/or deeply eroded. As noted by French (2004), "simply finding new meteorite impact structures is no longer enough." In terms of furthering our understanding of the impact cratering process, it is probable that the existing database of terrestrial impact structures offers the best candidates for study. In particular, complex impact structures in the size range ~15–30 km, have been identified as high-priority targets by the impact community. There are approximately 50 terrestrial impact structures of this size (Earth Impact Database 2005); however, very few are sufficiently well preserved or exposed and even fewer have been studied in any great detail.

The results summarized in this paper represent the outcome of the 1997–2004 field seasons of the Haughton–Mars Project. These studies have revealed many new insights into the impact cratering process, including the tectonics of crater formation, the response of sedimentary rocks to hypervelocity impact, the fate of organics, and the post-impact processes of hydrothermal activity, sedimentary infilling, and biological succession. In particular, it is apparent from recent studies at Haughton and other craters that impact melting in sedimentary targets is much more common than previously thought. This agrees with theoretical studies, which suggest that impacts into sedimentary targets should produce as much, or even greater volumes of melt, than do impacts into crystalline targets (Kieffer and Simonds 1980). There is also no unequivocal evidence for the decomposition of carbonates or evaporites at Haughton, in contrast to previous views (Martinez et al. 1994). On this basis, we suggest that a closer look at impactites in other terrestrial impact structures developed in sedimentary targets is warranted.

Recent studies at Haughton have also yielded valuable information about some of the "beneficial effects" of impact events, such as impact-associated hydrothermal activity (Osinski et al. 2001, 2005b), improved opportunities for (re-) colonization by microbial organisms (Cockell et al. 2002, 2003, 2005; Parnell et al. 2004), and the significance of intra-crater sedimentary deposits as records of post-impact environmental and biological recovery (Cockell and Lee 2002; Lim 2004; Eglinton et al. 2005; Osinski and Lee 2005). These studies suggest that impact craters may, therefore, have provided favorable habitats for the origin and evolution of early life on Earth, and possibly other planets such as Mars.

Acknowledgments–The studies summarized herein would not have been possible without the support of the Polar Continental Shelf Project (Natural Resources Canada), the Nunavut Research Institute, and the communities of Grise Fiord and Resolute Bay. We thank, in particular, Pauline and Rhoda Akeeagok, Joe Amarualik, Alain Berinstain, AC Hitch, "Kimmiq," Colleen Lenahan, Samson Ootoovak, John Schutt, and Nesha Trenholm; along with everyone involved in the Haughton-Mars Project for assistance during the HMP 1997–2004 field seasons. Funding for these activities came from the Natural Sciences and Engineering Research Council of Canada (NSERC), the US National Aeronautics and Space Administration (NASA), the Canadian Space Agency (CSA), the SETI Institute, and the Mars Institute. Philippe Claeys and an anonymous reviewer are thanked for their constructive and helpful comments. This is PASSC publication #42.

Editorial Handling—Dr. Elisabetta Pierazzo

REFERENCES

Ahrens T. J. and O'Keefe J. D. 1972. Shock compression and vaporization of Lunar rocks and minerals. *Moon* 4:214–249.
Bischoff L. and Oskierski W. 1988. The surface structure of the Haughton impact crater, Devon Island, Canada. *Meteoritics* 23: 209–220.
Bunch T. E., Grieve R. A. F., Lee P., McKay C. P., Rice J. W., Schutt J. W., and Zent A. 1998. Haughton-Mars 97–II: Preliminary observations on highly shocked crystalline basement rocks on the Haughton impact crater (abstract #1307). 29th Lunar and Planetary Science Conference. CD-ROM.
Bustin R. M. 1982. Beaufort Formation, eastern Axel Heiberg Island, Canadian Arctic Archipelago. *Canadian Petroleum Geology Bulletin* 30:140–149.
Cockell C. S. and Lee. P. 2002. The biology of impact craters: A review. *Biological Reviews* 77:279–310.
Cockell C. S., Lee P., Osinski G. R., Horneck G., and Broady P. 2002. Impact-induced formation of microbial endolithic habitats. *Meteoritics & Planetary Science* 37:1287–1298.
Cockell C. S., Osinski G. R., and Lee P. 2003. The impact crater as a habitat: Effects of impact alteration of target materials. *Astrobiology* 3:181–191.
Cockell C. S., Lee P., Broady P., Lim D. S. S., Osinski G. R., Parnell J., Koeberl C., Pesonen L., and Salminen J. 2005. Effects of asteroid and comet impacts on habitats for lithophytic organisms—A synthesis. *Meteoritics & Planetary Science* 40. This issue.
Collins G. S., Melosh H. J., Morgan J. V., Warner M. R. 2002. Hydrocode simulations of Chicxulub crater collapse and peak-ring formation. *Icarus* 157:24–33.
Dence M. R. 1968. Shock zoning at Canadian craters: Petrography

and structural implications. In *Shock metamorphism of natural materials,* edited by French B. M. and Short N. M. Baltimore: Mono Book Corp. pp. 169–184.

Dence M. R. 1972. The nature and significance of terrestrial impact structures. Proceedings, 15th International Geological Congress. pp. 77–89.

Dence M. R., Grieve R. A. F., and Robertson P. B. 1977. Terrestrial impact structures: Principal characteristics and energy considerations. In *Impact and explosion cratering,* edited by Roddy D. J., Pepin R. O., and Merrill R. B. New York: Pergamon Press. pp. 247–275.

Deutsch A. and Schärer U. 1990. Isotope systematics and shock-wave metamorphism. I: U–Pb in zircon, titanite, and monazite, experimentally shocked up to 59 GPa. *Geochimica et Cosmochimica Acta* 54:3427–3434.

Douglas R. J. W. 1970. Introduction. In *Geology and economic minerals of Canada.* Geological Survey of Canada Economic Geology Report 1, edited by Douglas R. J. W. Ottawa: Geological Survey of Canada. pp. 2–8.

Dressler B. O. and Sharpton V. L. 1998. Coexisting pseudotachylite and rock glasses at the Haughton impact crater, Canada (abstract). 29th Lunar and Planetary Science Conference. pp. 1384.

Earth Impact Database. 2005. <http://www.unb.ca/passc/ImpactDatabase/> Accessed: 10 September 2005.

Eglinton L. B., Lim D. S. S., Slater G., Osinski G. R., Whelan J. K., and Douglas M. Forthcoming. Geochemical characterization of a Miocene core sample from the Haughton impact structure, Devon Island, Nunavut, Canadian High Arctic. *Organic Geochemistry.*

French B. M. 1998. *Traces of catastrophe: A handbook of Shock-metamorphic effects in terrestrial meteorite impact structures,* LPI Contribution # 954. Houston: Lunar and Planetary Institute. 120 p.

French B. M. 2004. The importance of being cratered: The new role of meteorite impact as a normal geological process. *Meteoritics & Planetary Science* 39:169–197.

Frisch T. 1983. Reconnaissance geology of the Precambrian shield of Ellesmere, Devon and Coburg Islands, Arctic Archipelago: A preliminary account. Geological Survey of Canada Paper 82–10. Ottawa: Geological Survey of Canada. 11 p.

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

Frisch T. and Trettin H. P. 1991. Precambrian successions in the northernmost part of the Canadian Shield. In *Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland,* Geological Survey of Canada, Geology of Canada 3, edited by Trettin H. P. Ottawa: Geological Survey of Canada. pp. 103–108.

Gault D. E., Quaide W. L., and Oberbeck V. R. 1968. Impact cratering mechanics and structures. In *Shock metamorphism of natural materials,* edited by French B. M. and Short N. M. Baltimore: Mono Book Corp. pp. 87–99.

Gentzis T., de Freitas T., Goodarzi F., Melchin M., and Lenz A. 1996. Thermal maturity of Lower Paleozoic sedimentary successions in Arctic Canada. *AAPG Bulletin* 80:1065–1084.

Glass B. J., Lee P., and Osinski G. R. 2002. Airborne geomagnetic investigations at the Haughton impact structure, Devon Island, Nunavut, Canada: New results (abstract #2008). 33rd Lunar and Planetary Science Conference. CD-ROM.

Glass B. J., Domville S. and Lee P. 2005. Further geophysical studies of the Haughton impact structure (abstract #2398). 36th Lunar and Planetary Science Conference. CD-ROM.

Greiner H. R. 1963. Haughton Dome and area southwest of Thomas Lee Inlet. In *Geology of the north–central part of the Arctic Archipelago, Northwest Territories (Operation Franklin),* Geological Survey of Canada Memoir 320, 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., and Thorsteinsson R. Ottawa: Geological Survey of Canada. pp. 208–216.

Grieve R. A. F. 1975. Petrology and chemistry of impact melt at Mistastin Lake crater, Labrador. *Geological Society of America Bulletin* 86:1617–1629.

Grieve R. A. F. 1987. Terrestrial impact structures. *Annual Reviews of Earth and Planetary Science* 15:245–270.

Grieve R. A. F. 1988. The Haughton impact structure: Summary and synthesis of the results of the HISS project. *Meteoritics* 23:249–254.

Grieve R. A. F. 1991. Terrestrial impact: The record in the rocks. *Meteoritics* 26:175–194.

Grieve R. A. F. and Cintala M. J. 1981. A method for estimating the initial impact conditions of terrestrial cratering events, exemplified by its application to Brent crater, Ontario. Proceedings, 12th Lunar and Planetary Science Conference. pp. 607–1621.

Grieve R. A. F., Dence M. R., and Robertson P. B. 1977. Cratering processes: As interpreted from the occurrence of impact melts. In *Impact and explosion cratering,* edited by Roddy D. J., Pepin R. O., and Merrill R. B. New York: Pergamon Press. pp. 791–814.

Grieve R. A. F., Robertson P. B., and Dence M. R. 1981. Constraints on the formation of ring impact structures, based on terrestrial data. In *Proceedings of the Conference on Multi-Ring Basins: Formation and evolution,* edited by Schultz P. H. and Merrill R. B. New York: Pergamon Press. pp. 37–57.

Haughton S. H. 1860a. On the fossils brought home from the Arctic regions in 1859, by Captain Sir F. L. M'Clintock. *Journal of the Royal Dublin Society* 3:53–58.

Haughton S. H. 1860b. Geological account of the Arctic Archipelago, drawn up from the specimens collected by Captain F. L. M'Clintock, R. N. from 1849 to 1859. *Journal of the Geological Society of Dublin* 8:196–213.

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.

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

Kenkmann T. and von Dalwigk I. 2000. Radial transpression ridges: A new structural feature of complex impact craters. *Meteoritics & Planetary Science* 35:1189–1201.

Kenkmann T., Ivanov B. A., and Stöffler D. 2000. Identification of ancient impact structures: Low-angle faults and related geological features of crater basements. In *Impacts and the early Earth.* Lecture notes in earth sciences, vol. 91, edited by Gilmour I. and Koeberl C. Berlin: Springer-Verlag. pp. 279–307.

Kieffer S. W. and Simonds C. H. 1980. The role of volatiles and lithology in the impact cratering process. *Reviews of Geophysics and Space Physics* 18:143–181.

Kurtz V. E., McNair A. H., and Wales D. B. 1952. Stratigraphy of the Dundas Harbour area, Devon Island. *American Journal of Science* 250:636–655.

Lee P. and Osinski G. R. 2005. The Haughton–Mars Project: Overview of science investigations at the Haughton impact structure and surrounding terrains, Devon Island, Canadian High Arctic, 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. J., Schutt J. W. 1998. Haughton–Mars 97–I:

Overview of observations at the Haughton impact crater, a unique Mars analog site in the Canadian High Arctic (abstract #1973). 29th Lunar and Planetary Science Conference. CD-ROM.
Lim D. S. S. 2004. Limnology and diatom paleoecology of lakes and ponds on Banks Island, N. W. T. and Devon Island, Nunavut, Canadian Arctic. Ph.D. thesis, University of Toronto, Toronto, Canada.
Lim D. S. S. and Douglas M. S. V. 2003. Limnological characteristics of 22 lakes and ponds in the Haughton Crater region of Devon Island, Nunavut, Canadian High Arctic. *Arctic, Antarctic, and Alpine Research* 35:509–519.
Martinez I., Agrinier P., Schärer U., and Javoy M. 1994. A SEM–ATEM and stable isotope study of carbonates from the Haughton impact crater, Canada. *Earth and Planetary Science Letters* 121: 559–574.
Martinez I., Schärer U., and Guyot F. 1993. Impact-induced phase transformations at 50–60 GPa in continental crust; an EPMA and ATEM study. *Earth and Planetary Science Letters* 119:207–223.
McKinnon W. B. and Schenk P. M. 1985. Ejecta blanket scaling on the Moon and Mercury and inferences for projectile populations. Proceedings, 16th Lunar and Planetary Science Conference. pp. 544–545.
Melosh H. J. 1989. *Impact cratering: A geologic process*. New York: Oxford University Press. 245 p.
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, Devon Island, Canada. *Meteoritics* 23: 197–207.
O'Keefe J. D. and Ahrens T. J. 1982. Cometary and meteorite swarm impact on planetary surfaces. *Journal of Geophysical Research* 103:28,607–28,625.
Okulitch A. V. 1991. Geology of the Canadian Archipelago and north Greenland; Figure 2. In *Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland.* Geology of Canada vol. 3, edited by Trettin H. P. Ottawa: Geological Survey of Canada. pp. 435–458.
Omar G., Johnson K. R., Hickey L. J., Robertson P. B., Dawson M. R., and Barnosky C. W. 1987. Fission-track dating of Haughton astrobleme and included biota, Devon Island, Canada. *Science* 237:1603–1605.
Orphal D. L. 1977. Calculations of explosion cratering – II: Cratering mechanics and phenomenology. In *Impact and explosion cratering,* edited by Roddy D. J., Pepin R. O., and Merrill R. B. New York: Pergamon Press. pp. 907–917.
Osinski G. R. 2004a. Hypervelocity impact into sedimentary targets: Processes and products. Ph.D. thesis, University of New Brunswick, Fredericton, Canada.
Osinski G. R. 2004b. Impact melt flows on Earth? Evidence from the Ries impact structure, Germany. *Earth and Planetary Science Letters* 226:529–543.
Osinski G. R. and Lee P. 2005. Intra-crater sedimentary deposits at the Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40. This issue.
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* 215:357–370.
Osinski G. R. and Spray J. G. 2005. Tectonics of the Haughton impact event, 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 of a transient, warm, wet oasis. *Meteoritics & Planetary Science* 36:731–745.
Osinski G. R., Grieve R. A. F., and Spray J. G. 2004. The nature of the groundmass of surficial suevites from the Ries impact structure, Germany, and constraints on its origin. *Meteoritics & Planetary Science* 39:1655–1683.
Osinski G. R., Spray J. G., and Lee P. 2005a. Impactites of the Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40. This issue.
Osinski G. R., Lee P., Parnell J., Spray J. G., and Baron M. 2005b. A case study of impact-induced hydrothermal activity: The Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40. This issue.
Parnell J., Lee P., Cockell C. S., and Osinski G. R. 2004. Microbial colonization in impact-generated hydrothermal sulphate deposits, Haughton impact structure, and implications for sulphates on Mars. *International Journal of Astrobiology* 3:247–256.
Parnell J., Osinski G. R., Lee P., Green P. F., and Baron M. J. 2005a. Thermal alteration of organic matter in an impact crater and the duration of post-impact heating. *Geology* 33:373–376.
Parnell J., Bowden S., Lee P., Osinski G. R., and Cockell C. S. 2005b. 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.
Pohl J., Stöffler D., Gall H., and Ernstson K. 1977. The Ries impact crater. In *Impact and explosion cratering,* edited by Roddy D. J., Pepin R. O., and Merrill R. B. New York: Pergamon Press. pp. 343–404.
Pohl J., Eckstaller A., and Robertson P. B. 1988. Gravity and magnetic investigations in the Haughton impact structure, Devon Island, Canada. *Meteoritics* 23:235–238.
Pope K. O., Kieffer S. W., and Ames D. E. 2004. Empirical and theoretical comparisons of the Chicxulub and Sudbury impact structures. *Meteoritics & Planetary Science* 39:97–116.
Redeker H. J. and Stöffler D. 1988. The allochthonous polymict breccia layer of the Haughton impact crater, Devon Island, Canada. *Meteoritics* 23:185–196.
Robertson P. B. and Grieve R. A. F. 1978. The Haughton impact structure. *Meteoritics* 13:615–618.
Robertson P. B. and Mason G. D. 1975. Shatter cones from Haughton Dome, Devon Island, Canada. *Nature* 255:393–394.
Robertson P. B. and Plant A. G. 1981. Shock metamorphism in sillimanite from the Haughton impact structure, Devon Island, Canada. *Contributions to Mineralogy and Petrology* 78:12–20.
Robertson P. B. and Sweeney J. F. 1983. Haughton impact structure: Structural and morphological aspects. *Canadian Journal of Earth Sciences* 20:1134–1151.
Roots E. F. 1963. Physiography. In Geology of the north-central part of the Arctic Archipelago, Northwest Territories (Operation Franklin), Geological Survey of Canada Memoir 320, 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. Ottawa: Geological Survey of Canada. pp. 164–179.
Schärer U. and Deutsch A. 1990. Isotope systematics and shock-wave metamorphism; II, U–Pb and Rb–Sr in naturally shocked rocks, the Haughton impact structure, Canada. *Geochimica et Cosmochimica Acta* 54:3435–3447.
Schmidt R. M. and Housen K. R. 1987. Some recent advances in the scaling of impact and explosion cratering. *International Journal of Impact Engineering* 5:543–560.

Schultz P. H., Orphal D. L., Miller B., Borden W. F., and Larson S. A. 1981. Multi-ring basin formation: Possible clues from impact cratering calculations. In *Proceedings of the Conference on Multi-Ring Basins: Formation and Evolution,* edited by Schultz P. H. and Merrill R. B. New York: Pergamon Press. pp. 181–196.

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

Sharpton V. L. 1999. The nature of central peak rings: Evidence from the Haughton crater (abstract). *Meteoritics & Planetary Science* 34:A107.

Sharpton V. L., Dressler B. O., and Sharpton T. J. 1998. Mapping the Haughton impact crater, Devon Island, NWT; implications for the shape and size of the excavation cavity (abstract #1867). 29th Lunar and Planetary Science Conference. CD-ROM.

Sherlock S., Kelley S., 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.

Spray J. G. 1997. Superfaults. *Geology* 25:579–582.

Spray J. G. 1998. Localized shock- and friction-induced melting in response to hypervelocity impact. In *Meteorites: Flux with time and impact effects*, edited by Grady M. M., Hutchison R., McCall G. J. H., and Rothery D. A. Special publication #140. London: Geological Society of London. pp. 171–180.

Spray J. G., Butler H. R., and Thompson L. M. 2004. Tectonic influences on the morphometry of the Sudbury impact structure: Implications for terrestrial cratering and modeling. *Meteoritics & Planetary Science* 39:287–301.

Stephan T. and Jessberger E. K. 1992. Isotope systematics and shock-wave metamorphism; III, K–Ar in experimentally and naturally shocked rocks; the Haughton impact structure, Canada. *Geochimica et Cosmochimica Acta* 56:1591–1605.

Stockwell C. H. 1982. Proposals for time classification and correlation of Precambrian rocks and events in Canada and adjacent areas of the Canadian Shield; Part 1: A time classification of Precambrian rocks and events. Geological Survey of Canada Paper 80–19. Ottawa: Geological Survey of Canada. 135 p.

Stöffler D. and Grieve R. A. F. 1994. Classification and nomenclature of impact metamorphic rocks: A proposal to the IUGS Subcommission on the Systematics of Metamorphic Rocks (abstract). 24th Lunar and Planetary Science Conference. pp. 1347–1348.

Stöffler D. and Grieve R. A. F. 1996. IUGS classification and nomenclature of impact metamorphic rocks: Towards a final proposal (abstract). International Symposium on the Role of Impact Processes in the Geological and Biological Evolution of Planet Earth, Postojona, Slovenia, September 27–October 2, 1996.

Stöffler D., Gault D. E., Wedekind J., and Polkowski G. 1975. Experimental hypervelocity impact into quartz sand: Distribution and shock metamorphism of ejecta. *Journal of Geophysical Research* 80:4062–4077.

Stuart-Smith J. H. and Wennekers J. H. N. 1977. Geology and hydrocarbon discoveries of Canadian Arctic islands. *AAPG Bulletin* 61:1–27.

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.

Thorsteinsson R. and Tozer E. T. 1970. Geology of the Arctic Archipelago. In *Geology and economic minerals of Canada,* Geological Survey of Canada Economic Geology Report 1, edited by Douglas R. J. W. Ottawa: Geological Survey of Canada. pp. 547–590.

Trettin H. P. 1991. Tectonic framework. In *Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland.* Geology of Canada vol. 3, edited by Trettin H. P. Ottawa: Geological Survey of Canada. pp. 57–66.

Turtle E. P., Pierazzo E., Collins G. S., Osinski G. R., Melosh H. J., Morgan J. V., Reimold W. U., and Spray J. G. 2005. Impact structures: What does crater diameter mean? In *Large meteorite impacts III,* , edited by Kenkmann T., Hörz F., and Deutsch A. GSA Special Paper #384. Boulder, Colorado: Geological Society of America. pp. 1–24.

Whitlock C. and Dawson M. R., 1990. Pollen and vertebrates of the Early Neogene Haughton Formation, Devon Island, Arctic Canada. *Arctic* 43:324–330.

Wieland F., Gibson R. L., Reimold W. U., and Lana C. 2003. Structural evolution of the central uplift of the Vredefort impact structure, South Africa (abstract). *Meteoritics & Planetary Science* 38:A21.

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