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The effect of target lithology on the products of impact melting

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Abstract–Impact cratering is an important geological process on the terrestrial planets and rocky and icy moons of the outer solar system. Impact events generate pressures and temperatures that can melt a substantial volume of the target; however, there remains considerable discussion as to the effect of target lithology on the generation of impact melts. Early studies showed that for impacts into crystalline targets, coherent impact melt rocks or "sheets" are formed with these rocks often displaying classic igneous structures (e.g., columnar jointing) and textures. For impact structures containing some amount of sedimentary rocks in the target sequence, a wide range of impact-generated lithologies have been described, although it has generally been suggested that impact melt is either lacking or is volumetrically minor. This is surprising given theoretical constraints, which show that as much melt should be produced during impacts into sedimentary targets. The question then arises: where has all the melt gone? The goal of this synthesis is to explore the effect of target lithology on the products of impact melting. A comparative study of the similarly sized Haughton, Mistastin, and Ries impact structures, suggests that the fundamental processes of impact melting are basically the same in sedimentary and crystalline targets, regardless of target properties. Furthermore, using advanced microbeam analytical techniques, it is apparent that, for the structures under consideration here, a large proportion of the melt is retained within the crater (as crater-fill impactites) for impacts into sedimentary-bearing target rocks. Thus, it is suggested that the basic products are genetically equivalent but they just appear different. That is, it is the textural, chemical and physical properties of the products that vary.

INTRODUCTION

The melting of significant volumes of target rock is one of the most characteristic features of relatively large hypervelocity impact events. The products of impact melting at terrestrial impact structures range from glassy fragments within impact breccias to large kilometer-thick coherent sheets of igneous-textured impact melt rocks. These products are found within a variety of settings within and around the source impact structure. Pioneering field and analytical studies carried out in the 1960s and 1970s at several Canadian impact structures (e.g., Brent, Manicouagan, Mistastin, and the twin Clearwater Lake structures) provided observational information as to the character and distribution of impact-melted material in terrestrial impact structures (Grieve 1975, 1978; Simonds et al. 1978; Palme et al. 1979). This information, in turn, provided valuable constraints on processes operating during hypervelocity impact events (Grieve et al. 1977). However, our understanding of the impact cratering process, and that of impact melting, is incomplete. This is due to several factors, including the erosional degradation of many terrestrial impact structures such that outcrops of impact melt-bearing lithologies preserving their entire original context are relatively rare (Grieve et al. 1977). Other complicating factors are introduced due to inconsistent nomenclature and unqualified use of terms, such as "suevite," for several types of impactites with somewhat different genesis (e.g., impactites with glass contents ranging up to ~90 vol% have been termed suevites at Popigai impact structure; Masaitis 1999). This complicates the use of current classification schemes developed for impact melt-bearing impactites (Stöffler and Grieve 2007). In recent years, the potential effect of target lithology on various aspects of the impact cratering process, in particular the generation and emplacement of impact melt rocks, has emerged as a major research topic, as evidenced by discussions at the recent Bridging the Gap II meeting in Montreal, Canada, September 2007.

Various impact melt-bearing lithologies are found within the interior of complex impact structures (i.e., the region encompassing the original transient cavity). Collectively, these may be termed "crater-fill impactites" (Stöffler and Grieve 2007). In terms of impact melting, it is important to note that several early studies in North America focused on impact structures developed in dense non-porous crystalline rocks of the Canadian Shield (Dence 1971; Grieve et al. 1977; Simonds et al. 1978). In Europe and northern Asia, however, there was more diversity in the target types but the bulk of the studies were largely on the description of impact lithologies from structures in mixed targets of sedimentary lithologies overlying crystalline basement (Stöffler 1977; Masaitis et al. 1980; Engelhardt and Graup 1984). Based on these various studies, there are apparently different responses of volatile-rich, porous sedimentary and coherent crystalline rocks during the impact process.

Within complex impact structures formed entirely in crystalline targets, coherent impact melt rocks or "sheets" are formed. These rocks can display classic igneous structures (e.g., columnar jointing) and textures. Impact craters formed in "mixed" targets (e.g., crystalline basement overlain by sedimentary rocks) display a wide range of impact-generated lithologies, the majority of which were typically classed as "suevites" (Stöffler et al. 1977; Masaitis 1999). (Note that we use the original definition of suevite (Stöffler et al. 1977), which is a polymict impact breccia with a clastic matrix/groundmass containing fragments and shards of impact glass and shocked mineral and lithic clasts.) Minor bodies of coherent impact melt rocks are also sometimes observed, often as lenses and irregular bodies within larger bodies of suevite (e.g., Popigai; Masaitis 1999). In impact structures formed in predominantly sedimentary targets, impact melt rocks were not generally recognized, with the resultant crater-fill deposits historically referred to as clastic, fragmental or sedimentary breccias (e.g., Redeker and Stöffler 1988; Masaitis et al. 1980; Masaitis 1999). These observations have led to the conclusion that no, or only minor, impact melt volumes are apparently present in impact structures formed in predominantly sedimentary targets (Kieffer and Simonds 1980; Grieve and Cintala 1992; Dressler and Reimold 2001). Kieffer and Simonds (1980) suggested that this "anomaly" may be due to "the formation and expansion of enormous quantities of sediment-derived vapour" (e.g., H_2O, CO_2, SO_2), which could result in the unusually wide dispersion of shock-melted sedimentary rocks.

However, more recent work, summarized in Osinski et al. (2008), suggests that impact melting is more common in sedimentary targets than has, hitherto, been believed. These authors note that evidence for the melting of carbonates during hypervelocity impact has now been recognized at 5 terrestrial impact structures (Chicxulub [Jones et al. 2000], Haughton [Osinski and Spray 2001], Meteor Crater [Osinski et al. 2003], Ries [Graup 1999], and Tenoumer [Pratesi et al. 2005]). Carbonate impact melts have been observed as groundmass-forming phases within impact melt-bearing crater-fill and proximal ejecta deposits; as globules and irregularly-shaped masses within impact glass clasts from proximal ejecta deposits; and as individual particles and spherules within the proximal and distal ejecta deposits. The melt origin for these carbonates is provided by textural and chemical evidence, which includes: (1) liquid immiscible textures; (2) quench textures; (3) carbonate spherules; (4) euhedral calcite crystals within impact glass clasts; (5) carbonates intergrown with CaO–MgO-rich silicates; (6) CaO–MgO–CO_2-rich glasses; and (7) unusual carbonate chemistry. A similar case can be made for the melting of other sedimentary lithologies, such as sandstones, shales and evaporites (see Osinski et al. 2008 for a summary). These observations are generally consistent with a recent numerical modeling study (Wünnemann et al. 2008), which also suggests that the volume of melt produced by impacts into dry porous sedimentary rocks should be greater than that produced by impacts in a crystalline target.

The purpose of the present paper is to critically discuss and examine the effect of target lithology on the generation of impact melts, with particular emphasis on the resultant products (impactites). This has important implications for our understanding of cratering processes in general. We focus on a comparative study of three well-studied, mid-sized, complex impact structures formed in different target rocks: Haughton, Ries, and Mistastin (Fig. 1). The systematic study of mid-size impact structures was one of the three main recommendations for focused research programs resulting from the first Bridging the Gap Conference in 2003 (Herrick and Pierazzo 2003) and provided the motivation for this study. We begin with an overview of theoretical constraints on the process of impact melting, followed by a summary of the impact melt products at the Haughton, Ries, and Mistastin structures. The various factors controlling the physical and chemical properties of impact melts in the context of current classification schemes are also examined. We then discuss the effect of target lithology on the products of impact melting and attempt to synthesize the results of recent numerical modelling with field and laboratory observations to examine whether the current widely held beliefs about the products of impact melting in various target lithologies are valid.

GENERATION OF IMPACT MELTS: THEORETICAL CONSIDERATIONS

It is widely understood that impact melting occurs upon decompression from high shock pressure and temperatures (Melosh 1989). A portion of this impact melt is ejected from

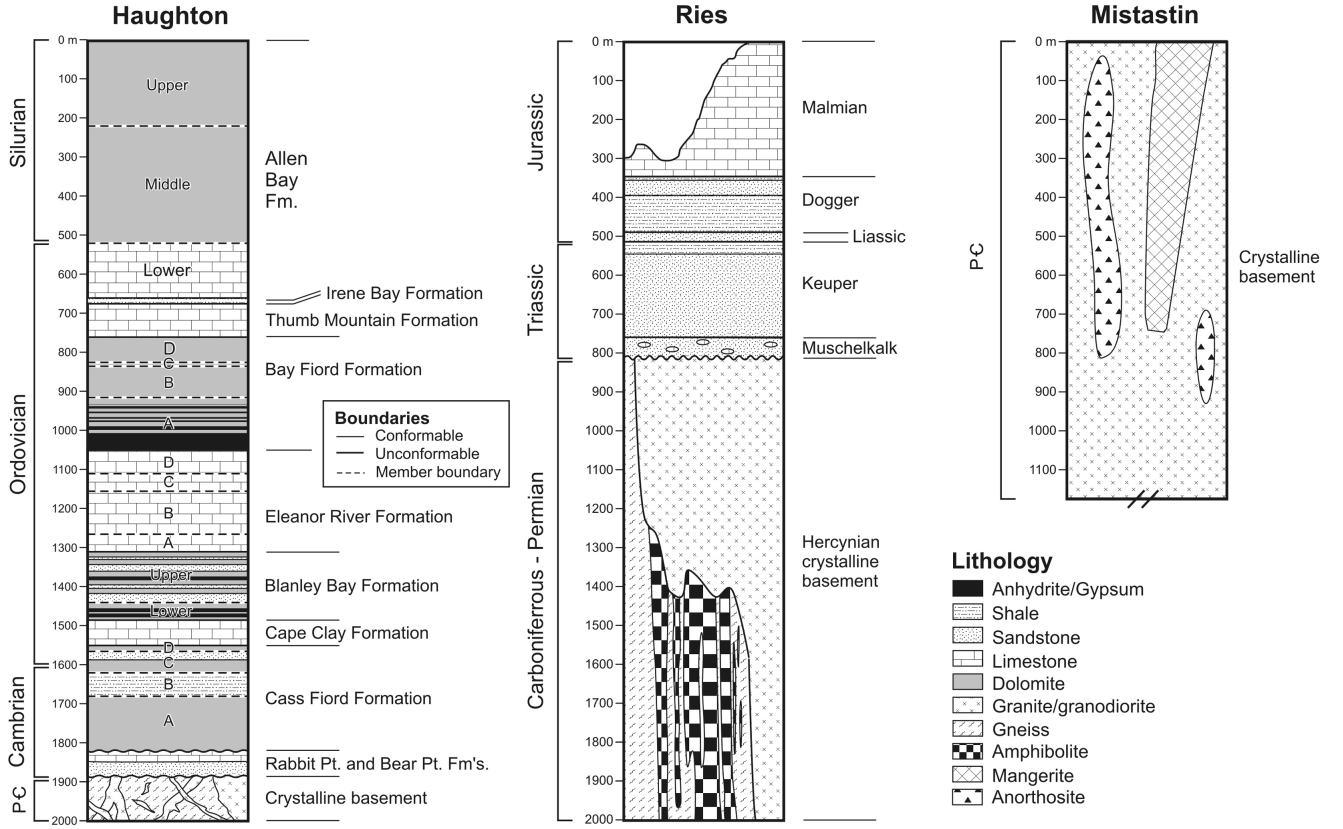

Fig. 1. Comparison of the target stratigraphy at the Haughton, Ries, and Mistastin impact structures. Compiled with data from Currie (1971), Schmidt-Kaler et al. (1978), and Thorsteinsson and Mayr (1987).

the transient cavity to be included in proximal or distal ejecta deposits. The remainder, which originates beneath the point of impact, is driven downward into the growing transient cavity, where it entrains less shocked lithic and mineral debris as clasts. As noted by Kieffer and Simonds (1993), the superheated impact melt can subsequently digest some of the entrained clasts, resulting in total impact melt rock volume somewhat exceeding the original impact melt volume.

For impacts into porous, volatile-rich targets, it has been noted for some time that large amounts of compression and shock heating occur (Kieffer 1971; Ahrens and Cole 1974). Theoretical calculations made by Kieffer and Simonds (1980) suggested that the volumes of target material shocked to pressures sufficient for melting are not significantly different in sedimentary or crystalline rocks and that both wet and dry sedimentary rocks should yield greater volumes of melt on impact than crystalline targets. At that time, however, the generally accepted observation was that impact melt rocks were not present in impact structures formed in sedimentary targets (Fig. 2). Faced with this apparent discrepancy between theory and observation, Kieffer and Simonds (1980) suggested that this anomaly may be due to the formation and expansion of enormous quantities of sediment-derived vapour (e.g., H_2O, CO_2, SO_2), resulting in the widespread dispersion of shock-melted sedimentary rocks away from the impact site.

Recent numerical modelling results provide insight into impact melt production in mixed sedimentary and crystalline target rocks. Collins et al. (2008) investigated the effect of sedimentary layer thickness on the formation of mid-sized complex craters on Earth by numerically simulating impacts into three targets with different thicknesses of sedimentary cover. In each case, the impactor diameter was 1.5 km, the impactor density was 2.68 g/cm^3, and the impact velocity was 15 km/s. In these simulations, the thermodynamic response of the target layers was modelled using the Tillotson equation of state for limestone (sediment layer; Allen 1967) and a tabular ANEOS-derived equation of state for granite (basement; Pierazzo et al. 1997). Porosity in the target rocks was not considered. Both of these material models oversimplify the complex response of natural rocks to shock compression and decompression, but include a reasonable representation of the Hugoniot curve for the nonporous material. The results presented by Collins et al. (2008) using these two equations of state suggest that the volumes of target material shocked to pressures sufficient for melting are not significantly different in sedimentary or crystalline rocks, which supports earlier theoretical calculations made by Kieffer and Simonds (1980). This is illustrated in Fig. 3, which shows little difference in peak shock pressure distribution between the three numerical models of craters formed in different mixed sedimentary-

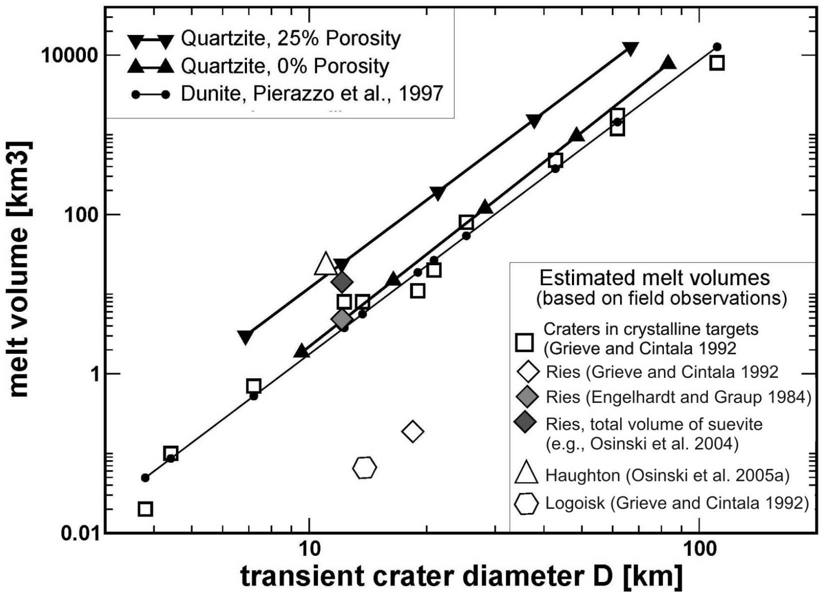

Fig. 2. Comparison between observed melt volumes at various terrestrial craters of different size (Grieve and Cintala 1992) and hydrocode-generated data for nonporous dunite (Pierazzo et al. 1997) and 0 and 25% porous quartzite (Wünnemann et al. 2008). See text for details concerning the new estimates for melt volume at the Haughton and Ries impact structures. Figure from Wünnemann et al. (2008) published with permission of Elsevier Ltd.

crystalline targets from Collins et al. (2008). The results of these models also suggest that the majority of the target material that experiences shock pressures sufficient to induce melting remains within the final crater. It should be noted that the similarity between the final distribution of shock pressure beneath and around the craters in Figure 3 demonstrates that the differences between existing material models (equation of state and strength model) for the limestone and granite layers in the target are not sufficient to substantially affect the cratering process. Improved equations of state for sedimentary rocks that properly represent important phase changes and the effects of wet and dry porosity are required to confirm these results. The effect of dry porosity—an important property of many sedimentary rocks—on impact melt production was investigated numerically by Wünnemann et al. (2008). They showed that dry porosity significantly reduces the critical pressure required for melting, enhancing melt production (Fig. 2). This effect is reduced but not totally diminished by faster shock wave decay in porous materials. Thus, all other factors being equal, impact melt production is greater when target porosity is higher (Wünnemann et al. 2008). The presence of water in the pore space may diminish the effect of dry porosity on the production of impact melt; however, the effect of pore water on melt production and dispersion has yet to be quantified. Currently, therefore, theoretical considerations and modelling studies suggest that as much, or even more, melt should be produced during hypervelocity impact into sedimentary, compared to crystalline, target rocks.

Given the theoretical and numerical modelling results that suggest a similar amount of melt should be produced in sedimentary target impacts, the question then arises as to where is the impact melt in structures developed in sedimentary rock-bearing targets? As outlined below, we suggest that the impact melt is actually present and that the apparent documented lack of impact melt products in some craters developed in sedimentary targets is due to past observational difficulties in recognizing impact melt products derived from such target lithologies.

CLASSIFICATION OF IMPACT MELT-BEARING IMPACTITES: THE CURRENT PARADIGM

Following the generation of impact melt within the transient cavity, cratering processes acting during the final excavation and modification stages result in, firstly, the transportation and, secondly, the emplacement of a variety of melt-bearing lithologies in a range of different physical settings in and around the impact structure. The classification of impact-generated rocks has been the subject of much discussion over the past several decades. As part of the IUGS Subcommission on the Systematics of Metamorphic Rocks, a study group formulated a series of recommendations for the classification of impactites: “The term ‘impactite’ is a collective term for all rocks affected by one or more hypervelocity impact(s) resulting from collision(s) of planetary bodies.” (Stöffler and Grieve 2007). This group suggested that impactites from a single impact should be classified into 3 major groups irrespective of their geological setting: 1) *shocked rocks*, which are non-brecciated, melt-free rocks displaying unequivocal effects of shock metamorphism; 2) *impact melt rocks*, which can be further

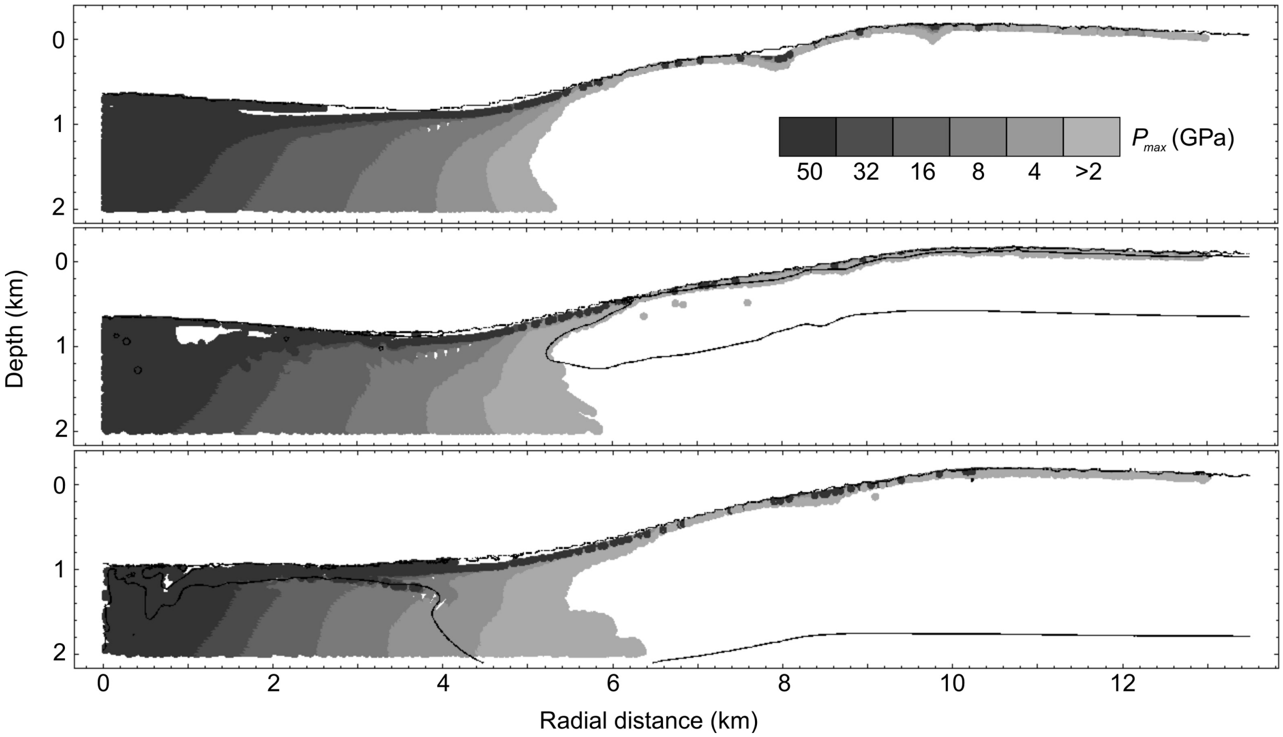

Fig. 3. A comparison of peak shock pressure (P_{max}) distribution predicted by numerical models of three craters formed in different mixed sedimentary-crystalline targets. Top: granite half-space; middle: 660 m limestone layer, above granite half-space; bottom 1.8 km limestone layer, above granite half-space. All three models assumed a 1.5 km diameter granite projectile, impacting vertically at 15 km/s. For more model details see Collins et al. (2008). The thickness of the limestone layer has little effect on the amount and final distribution of material that experienced high peak shock pressures. In each model, most material that experienced a maximum shock pressure greater than 50 GPa remained inside the final crater rim.

subclassified according to their clast content (i.e., clast-free, -poor, or -rich) and/or degree of crystallinity (i.e., glassy, hypocrystalline, or holocrystalline); 3) *impact breccias*, which can further classified according to the degree of mixing of various target lithologies and their content of melt particles (e.g., lithic breccias, suevites). In this study, we use the original definition of suevite, which is a polymict impact breccia with a clastic matrix/groundmass containing fragments and shards of impact glass and shocked mineral and lithic clasts (e.g., Stöffler et al. 1977).

IMPACT MELT-BEARING IMPACTITES AT THE HAUGHTON, RIES AND MISTASTIN IMPACT STRUCTURES

We focus here on a comparative study of the Haughton, Ries and Mistastin impact structures (see Table 1 for a list of the basic parameters for these impact sites). Most importantly, these structures are similar in size and are relatively well-studied and well-preserved. A variety of impact melt products are also present at these sites (Table 2). An important variable for these structures is that, in terms of target composition and the proportion of sedimentary versus crystalline rocks, Haughton and Mistastin can be viewed as two end-members, with Ries being "intermediate" (Fig. 1). Thus, a comparison of these three sites has the potential to yield valuable information as to the effect of target lithology on the products of impact melting. Interested readers are also referred to a companion paper in this special issue by Collins et al. that focuses on a comparative numerical modeling study of the Haughton, Ries, and El'gygytgyn impact structures; some of these results are used and discussed here.

Haughton Impact Structure, Canada

The 23 km diameter, ~39 Ma Haughton structure was formed in a ~1880 m thick sequence of Lower Paleozoic sedimentary rocks of the Arctic Platform, overlying Precambrian metamorphic basement rocks of the Canadian Shield (Thorsteinsson and Mayr 1987; Osinski et al. 2005b; Sherlock et al. 2005) (Fig. 1). A variety of impactites are present within and around the Haughton structure, with a consistent upward sequence of lithologies from target rocks to impact melt breccias (Osinski et al. 2005a) (Fig. 4). The products of impact melting are concentrated in the clast-rich impact melt rocks (Fig. 5), which form a discontinuous 53.8 km^2 layer in the central area of the structure (Table 2). Impact melt products are also present in isolated remnants of the proximal impact ejecta in the southwest of the crater rim region (Osinski et al. 2005a).

Table 1. Summary of the important statistics and parameters of the Haughton, Mistastin, and Ries impact structures.

	Haughton		Mistastin		Ries	
Parameter	Value	Notes and reference(s)	Value	Notes and reference(s)	Value	Notes and reference(s)
Age	39 ± 2 Ma	(Sherlock et al. 2005)	36.4 ± 2 Ma	(Mak et al. 1976)	14.3	(Laurenzi et al. 2003)
Thickness of sedimentary cover	1880 m	Predominantly carbonates, with minor evaporites and sandstones, overlying Precambrian metamorphic crystalline basement (Thorsteinsson and Mayr 1987; Osinski et al. 2005b)	0 m	Anorthosite, mangerite and granodiorite intrusive rocks (Currie 1971)	470–820 m	Predominantly sandstone, siltstone, marl and limestone overlying Hercynian crystalline basement (Schmidt-Kaler 1978)
Apparent crater diameter	23 km	Outermost ring of concentric normal faults at present-day erosion level (Osinski and Spray 2005)	28 km	(Grieve 1975)	22–23 km	(Pohl et al. 1977)
Rim (final crater) diameter	~16 km	Location of large displacement normal fault (Osinski and Spray 2005)	18 km	(Marion 2008)	24–26 km	(Pohl et al. 1977)

Table 2. Comparison of the various types of allochthonous crater-fill impactites at the Haughton, Mistastin, and Ries impact structures, and their characteristics.[a]

	Underlying main mass			Main mass		
	Haughton[b]	Mistastin[c]	Ries[d]	Haughton[b]	Mistastin[c]	Ries[d]
	Clastic breccias	Clastic breccias		Clast-rich impact melt rocks	Impact melt rock[e]	Crater suevite
Physical characteristics						
Max. current thickness (m)	4	~11	?	125	80	~300 m
Est. original thickness (m)	<10	?	?	>200	200	~300 m
Present volume (km^3)	~0.1	?	?	7		~15
Est. original volume (km^3)	~0.5	?	?	22.5	20	~15
Distribution of deposits	Isolated patches	Isolated patches	?	Continuous	Continuous	Continuous
Groundmass						
Average proportion	Up to ~30 vol%	up to 25 vol%	?	~50–60 vol%	Up to 95 vol%	~60 vol%
Texture	Clastic	Clastic	?	Melt	Melt	Altered
Mineralogy	Cc (<30 vol%), dol (<25 vol%), anhy (<10 vol%), other (<5 vol%)	Pl, Qtz, kfd, cpx, gl, op	?	Cc (~20–25 vol%), gl (25–30 vol%), anhy (0–90 vol%)	Pl (50–85 vol%), cpx (10–20 vol%), gl (<5–25 vol%), op (<10 vol%), other (<5 vol%)	Zeolite, clay, K-feldspar
Clasts						
Average proportion	Up to ~70 vol%	up to ~80%	?	~40–50 vol%	<10%	~30–35 vol%
Lithologies present	Lst, dol, sst, sl, evp, gr, gn	An, mn, gn, gd, gl	?	Lst, dol, sst, sl, evp, gr, gn, gl	An, mn, gd	Gn, gr, sst, sl,
Depth of origin in target sequence (km)	>0.3 to ~1.9	?	?	>0.7 to ~2	?	>0.35 to >2
Shock level (GPa)	Up to ~5 GPa	<1 to >60	?	<1 to >60	<1 to >60	<1 to >60

[a]Abbreviations: Est. = estimated; Cc = calcite; dol = dolomite; anhy = anhydrite; lst = limestone; sst = sandstone; sl = shale; evp = evaporite; an = anorthosite; mn = mangerite; granodiorite = gd; gr = granite; gn = gneiss; gl = silicate glass; cpx = pyroxene; kfs = K-feldspar; Qtz = quartz; op = opaques.
N/A = not applicable.
[b]Data from Osinski et al. (2005b).
[c]Data from Grieve (1975) and Marion (2008).
[d]Reliable data only available for melt-rich suevite. Data from Stöffler et al. (1977).
[e]Details given for the most abundant melt type, the fine- to medium-grained poikilitic melt rock typical of the Discovery Hill locality.

Impact melt products are present in two main forms in the clast-rich impact melt rocks: as clasts, either angular shards or spherules, and as a groundmass-forming constituent (Osinski et al. 2005a). SEM studies reveal that the groundmass of these impactites consists of three main components (Table 2; Fig. 5): (1) microcrystalline calcite; (2) silicate impact melt glass; and (3) anhydrite. Although these crater-fill impactites were once thought to be clastic (Redeker and Stöffler 1988), the

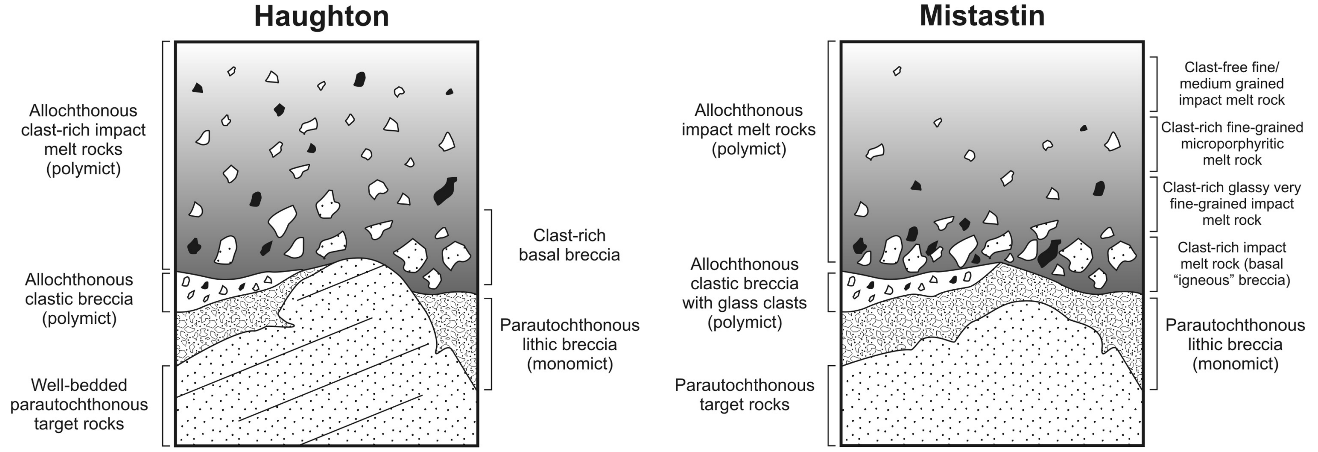

Fig. 4. Schematic cross sections showing the different types of impactites and their stratigraphic sequence in the crater interior of the Haughton and Mistastin impact structures. Compiled with data from Osinski et al. (2005) and Grieve (1975).

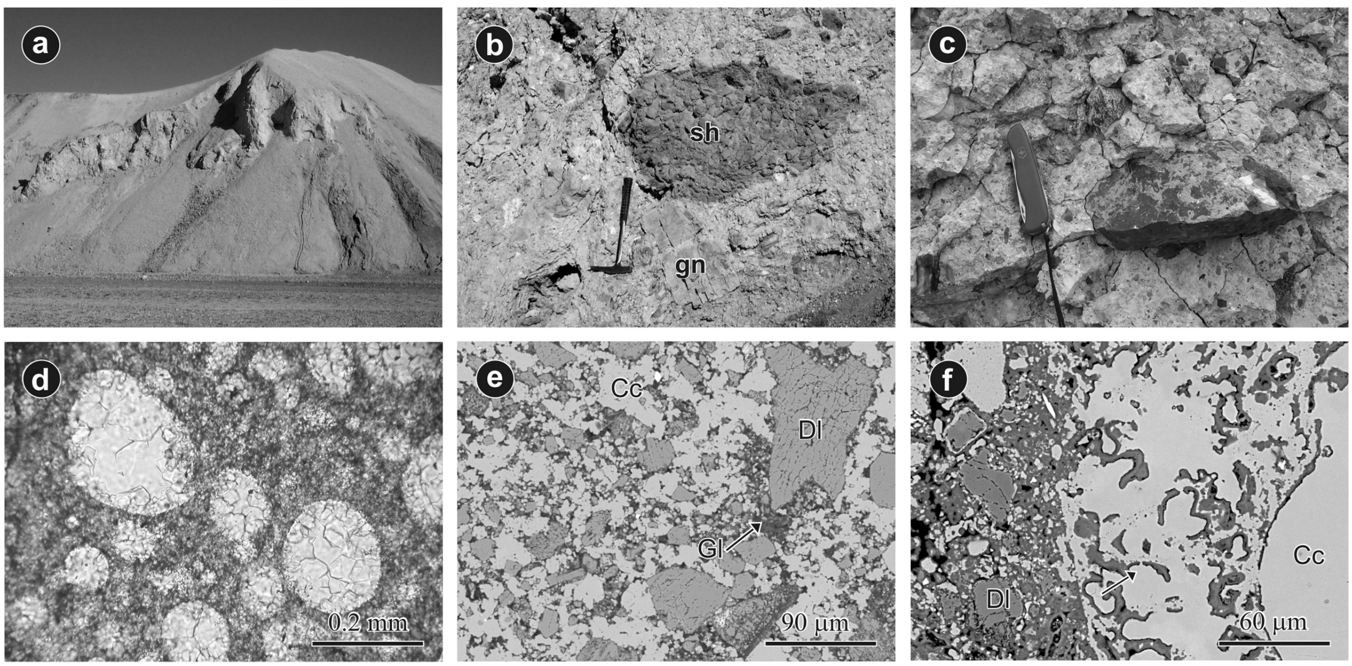

Fig. 5. Impactites of the Haughton impact structure. a) Field photograph of a well-exposed section of the crater-fill impact melt breccias. b) Close-up view of the lower levels of the crater-fill impact melt breccias, which are typically clast-rich with above average (i.e., meter length) clast sizes. The clasts are mainly carbonate but with large shale [sh]) and crystalline basement (e.g., gneiss [gn]) clasts also present. 40 cm long rock hammer for scale in (c) close-up view of impact melt breccias at a higher level than (b). The majority of clasts in this picture are carbonates. At this height in the outcrop, clasts rarely exceed ~20–30 cm in diameter. Also note the fine-grained microscopic nature of the pale grey groundmass. 12 cm long penknife for scale. d) Plane-polarized light photomicrograph of calcite melt spherules. Note that these features are not vesicle fillings as discussed by Osinski and Spray (2001) and Osinski et al. (2005b). e) Backscattered electron photomicrograph showing shocked dolomite clasts (pale grey) within a predominantly microcrystalline calcite melt groundmass (white). f) Intermingling of groundmass-forming calcite melt (white) and silicate glass (dark grey). Dolomite clasts (pale grey) are also present. Figure compiled with unpublished images and from Osinski and Spray (2001) and Osinski et al. (2005b).

more recent work utilizing the SEM has revealed that these groundmass phases are impact melt products (Osinski and Spray 2001, 2003; Osinski et al. 2005a) and should, therefore, be termed clast-rich impact melt rocks. These melt-bearing crater-fill impactites have a present volume of ~7 km^3 and an estimated original volume of >22.5 km^3 (Osinski et al. 2005a).

Ries Impact Structure, Germany

The target rocks for the ~24 km diameter, ~14.5 Ma Ries impact structure, southern Germany, comprise a flat-lying Triassic-Jurassic sequence of predominantly sandstone, siltstone, marl and limestones (~470 m thick in the north and

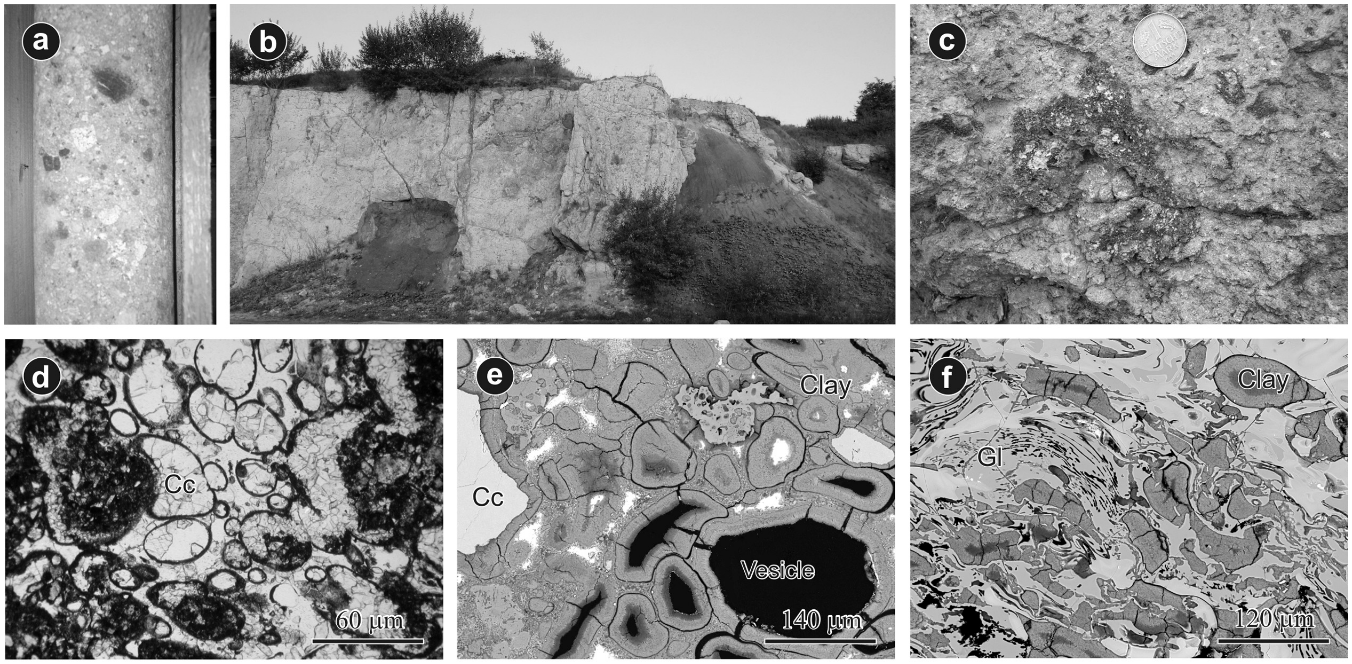

Fig. 6. Impactites of the Ries impact structure. a) Crater-fill suevite from the Nördlingen 1973 drill hole. b) Field photograph showing surficial suevite (light grey) overlying Bunte Breccia (dark grey) at the Aumühle quarry. c) Close-up view of the surficial suevite showing the fine-grained groundmass and macroscopic irregular silicate glass bodies. d) Plane-polarized light photomicrograph of groundmass/matrix of surficial suevite showing globules of calcite within a silicate glass–calcite groundmass. Sample 01–025 a from the Zipplingen locality. e) and f) Backscattered electron photomicrograph of groundmass/matrix of surficial suevite showing the intermingling of various impact melt phases (calcite, silicate glasses and what are now clay minerals), indicating that these phases were in the liquid state at the same time. Both images are from sample 00–052a from the Seelbronn locality. Deformation of globules and vesicles indicates that these phases were at least partially molten during transport and upon deposition. In (f) two different glass compositions are present, as evidenced by their different grey scale in BSE mode, indicating the importance of liquid immiscibility in inhibiting homogenization of these impact melts. Figure compiled with unpublished images and from Osinski et al. (2004).

~820 m thick in the south) that unconformably overlies Hercynian crystalline basement (Pohl et al. 1977; Schmidt-Kaler 1978; Engelhardt 1990; Laurenzi et al. 2003). A series of impactites is present at the Ries structure, including a thick series of crater-fill rocks (so-called "crater suevite") and various types of proximal ejecta deposits (Table 2) (Pohl et al. 1977). Unfortunately, the crater-fill impactites are only accessible via drill holes and only the 1206 m deep Nördlingen 1973 drill hole penetrated the entire suevite layer, with ~270 m of suevite core being recovered (Fig. 6a). All impact melt products in this unit have been completely hydrothermally altered. However, similar, but not identical, surficial suevites around the crater rim region (Figs. 6b–e) offer some insights into the original nature and origin of the altered crater suevites.

The origin and emplacement of the Ries surficial suevites is debatable. Previous workers, based on optical microscopy studies, suggested that the groundmass is essentially clastic—with melt present as glass fragments—with a generally an airborne mode of emplacement (Stöffler 1977; Engelhardt and Graup 1984; Engelhardt 1990; Engelhardt et al. 1995; Engelhardt 1997). More recent work, utilizing scanning electron microscopy, provides evidence for melt products in the groundmass, with the interpretation of flow during and after emplacement and consistent with an origin as melt-rich flows with entrained clasts that emanated from different regions of the growing crater (Osinski et al. 2004). However, it seems clear that the surficial suevites are predominantly comprised of impact melt products, or former impact melt products. A detailed assessment of the these impactites shows that ~70–80 vol% of the surficial suevite is calcite (with a primary impact melt origin), mesostasis or clay (altered silicate glass) and silicate glass (Osinski et al. 2004). This is comparable with an estimate by Engelhardt et al. (1995), who suggested that the groundmass comprises 30–40 vol% clays and 30–50 vol% silicate glasses.

The volume of the surficial suevites is insignificant compared to the crater suevite (Table 2). As noted above, all silicate glass phases within the crater suevites have been hydrothermally altered and been replaced by clays. If, however, the clays and zeolites are replacing primary impact melt phases—as in the surficial suevites (Engelhardt et al. 1995; Osinski et al. 2004)—then ~70–80 vol% of the crater suevite was originally impact melt. Thus, when making comparisons between the amounts of melt present within terrestrial impact structures, we suggest that a maximum estimate of 15 km^3, which represents the volume of the crater suevite, be used for the Ries impact structure. This calculation

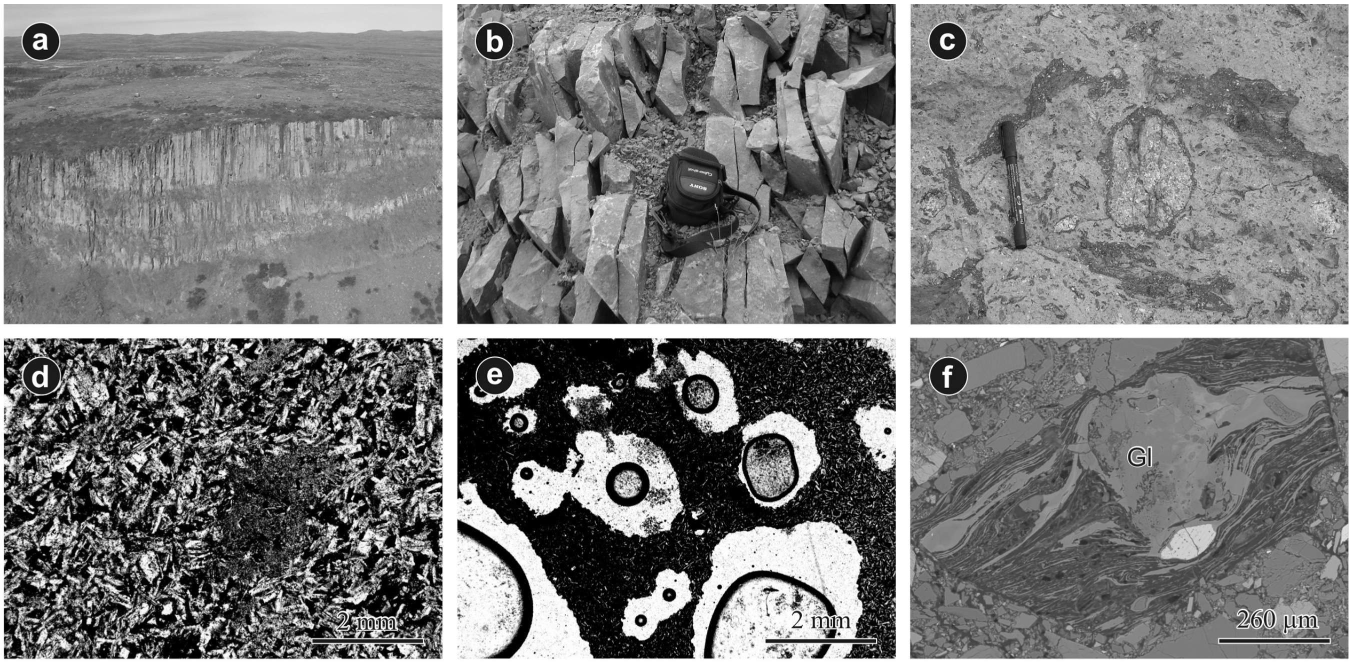

Fig. 7. Impactites of the Mistastin impact structure. a) Oblique aerial view of the ~80 m high cliffs of impact melt rock at the Discovery Hill locality, Mistastin impact structure, Labrador. Photograph courtesy of Derek Wilton. b) Close-up view of massive fine-grained (aphanitic) impact melt from the Discovery Hill locality. Camera case for scale. c) Close-up view of the suevite underlying the impact melt sheet at Mistastin, in this case, the photo is of a suevite dyke within monomict breccia. Note the fine-grained groundmass and macroscopic flow-textured silicate glass bodies (large black fragments). Steep Creek locality. Marker/pen for scale. d) Plane-polarized light photomicrograph showing the aphanitic groundmass of the impact melt rocks, comprising predominantly plagioclase, pyroxene and oxides. e) Plane-polarized light photomicrograph of a vesicular sample of impact melt rock. f) Backscattered electron photomicrograph of suevite showing an angular impact glass clast within a fragmental groundmass.

of melt plus clasts, is the same employed by Grieve and Cintala (1992) and enables the comparisons on Fig. 6 to be made.

It is notable that no coherent impact melt sheet has been documented at the Ries structure to date; however, given that impact melt rocks derived from the crystalline basement are preserved around the crater rim (Engelhardt et al. 1969; Osinski 2004) and that the drill hole may not be representative of the entire crater-fill impactites sequence (Stöffler 1977), it has been suggested that a small melt body(s) may be present within the interior of the Ries structure (Stöffler 1977; Dressler and Reimold 2001; Osinski 2004).

Mistastin Impact Structure, Canada

The ~28 km diameter, ~36 Ma Mistastin impact structure, Labrador, was formed entirely within crystalline rocks of the ~1.4 Ga Mistastin Lake Batholith, comprising mangerite, anorthosite, and minor granodiorite and granitic gneiss (Currie 1971; Grieve 1975; Mak et al. 1976; Marchand and Crocket 1977; Marion et al. 2007) (Fig. 1). At Mistastin, the erosional remnant of a coherent impact melt sheet is represented by ~60–80 m of impact melt rocks at the Discovery Hill locality, displaying classic columnar jointing, typical of volcanic and intrusive igneous rocks (Figs. 4, 7). This impact melt rock layer has been subdivided into 4 gradational subunits (Fig. 4). A variety of impactites are present below the coherent impact melt sheet (Figs. 4–7c; Table 2), some of which resemble suevite. They are, however, volumetrically insignificant, with impact melt products being present as glassy clasts within underlying clastic breccias and as small, centimeter-scale dykes in the pre-impact target rocks (Grieve 1975). The original impact melt sheet at Mistastin has been estimated at 200 m thick, yielding an original melt volume estimate of ~20 km^3 (Grieve 1975).

THE EFFECTS OF TARGET LITHOLOGY ON THE PRODUCTS OF IMPACT MELTING

Effect on Textures

Despite different methods of production, impact-melt bearing impactites have similarities to endogenous igneous rocks. Igneous rocks are typically classified on the basis of mineralogy, chemistry, and texture. The texture of a rock refers to variations in the size, shape and relationship of mineral grains and particles in a rock. In igneous rocks, texture is controlled by three main properties (McBirney 2006): 1) cooling rate; 2) melt composition and temperature, and 3) gas content of the melt. The same is also likely true for impact-

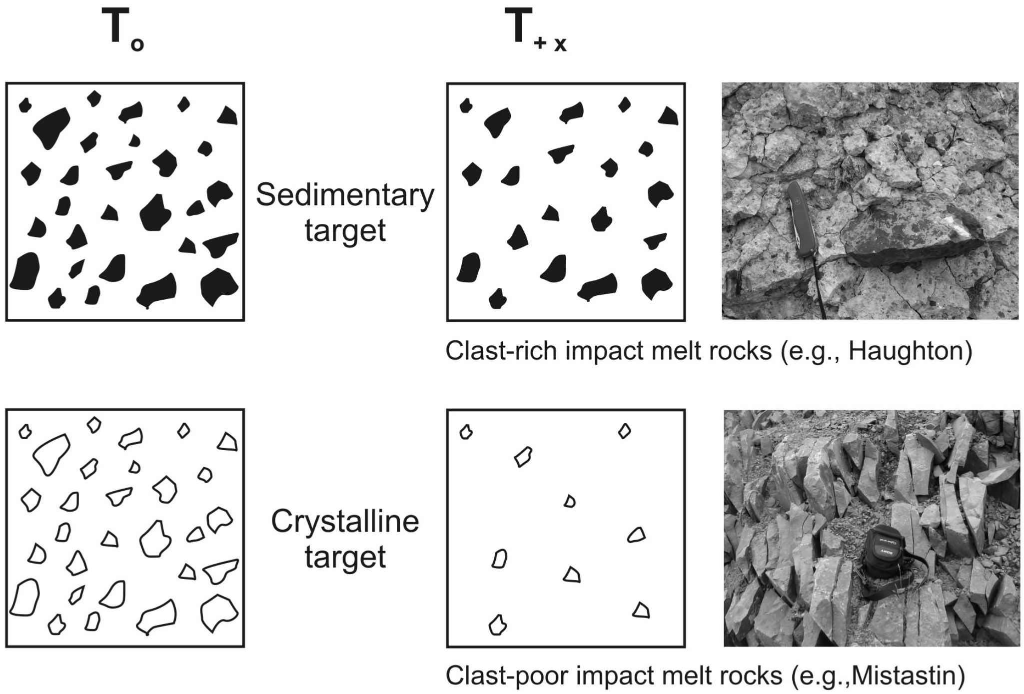

Fig. 8. Schematic diagram showing the clast content for a body of shock melt produced from an impact into a sedimentary (top) versus a crystalline target (bottom). Given the same initial conditions, the sediment-derived shock melt will quench faster and assimilate fewer clasts.

generated melts, with the added complication of the variable amounts of entrained clastic debris, which acts to cool the impact melt at a faster rate (Onorato et al. 1978), and also the subsequent attempt by the impact melt to assimilate this debris. Igneous rocks are typically classified according to texture as being phaneritic (coarse-grained), aphanitic (fine-grained), porphyritic, glassy, vesicular, or fragmental (McBirney 2006).

Cooling Rate

The rate of cooling of a body of impact melt determines the relative rate of crystal nucleation and growth and, therefore, exerts a major control on texture. To a first approximation, larger bodies of melt will cool more slowly. For example, the 3 km-thick impact melt layer at the 250 km diameter Sudbury structure is typically coarse-grained (Grieve and Therriault 2000); whereas, similar rocks at the 28 km diameter Mistastin structure, which were estimated to be originally ~200 m thick, are typically fine-grained to glassy (Grieve 1975). However, stratigraphic setting will also play a major control. For example, impact melt dykes emplaced in the crater floor will cool more slowly than melt contained within proximal ejecta deposits, so that the former may be fine-grained crystalline rocks; whereas, the latter are invariably glassy. Consideration of the Haughton, Mistastin, and Ries structures suggests that an additional major factor governing cooling rate is the composition of the target rocks. It is apparent that target lithology affects both the composition of the primary impact melt and the proportion of clasts that are assimilated by the melt in forming the final impact melt products.

Kieffer and Simonds (1980) noted that the enthalpies of H_2O-bearing and carbonate systems are such that a much smaller amount of entrained and admixed sedimentary rock than of anhydrous crystalline rock is required to quench a melt to subsolidus temperatures (Kieffer and Simonds 1980). Given the same original volume of impact melt and the same entrained clast content, this has the important consequence of resulting in faster cooling rates and a lower percentage of clasts from sedimentary rocks being assimilated by the melt, than clasts from crystalline rocks, before a melt is quenched (Fig. 8). This will result in higher final clast contents for impact melts derived from impacts into sedimentary, as opposed to crystalline targets (e.g., compare the clast content of crater-fill impactites at the Haughton and Mistastin structures; Table 2). This is consistent with the glassy state of the silicate melt phases within the crater-fill impactites at Haughton (Osinski et al. 2005a).

Further complications arise as carbonate melts do not quench to form glass, even under extremely rapid cooling (Barker 1989). This is due to the ionic nature of carbonate melts. They are composed of discrete anions and cations bound together by ionic forces, and consequently, they do not polymerize (Treiman 1989), which is a requirement for forming glasses. In other words, if a pure limestone (calcite) melts, it will quench to reform calcite, so that the product may bear striking similarities to the original source rock.

In summary, impact melt generated from impacts into sedimentary, or mixed sedimentary-crystalline targets, will typically cool more rapidly and will assimilate fewer clasts than melt from crystalline targets. This will result in fine-grained or glassy, clast-rich impact melt products in craters developed in sedimentary targets compared to the generally more crystalline melt rocks of similar-sized craters in crystalline targets (Fig. 8).

Melt Composition and Temperature

The temperature and composition of a melt control its density and viscosity, which affects the ability of ions to migrate through a melt and form crystals (McBirney 2006). In impact melts, there is the additional factor of entrained lithic and mineral clasts, which will increase both density and viscosity depending on their relative proportions to melt. An added complication arises for large craters where there is the potential for clast temperature prior to impact to be highly variable depending on pre-impact depth. The composition of an impact melt body essentially depends on the composition of the target rock and is, thus, potentially different for every impact site. A dramatic example of the effect of target lithology on the properties of an impact melt is the low liquidus temperature of carbonate melts (typically ~500–600 °C (Barker 1989)), which is several hundred degrees lower than for typical silicate melts (e.g., ~1100 °C for a basaltic melt (McBirney 2006)).

Further complexities arise for impacts into carbonate-bearing terrains due to the potential for carbonate melts to decompose following decompression. However, the importance of decomposition still remains to be determined. A review of the relative importance and role of melting versus decomposition in carbonates is outside the scope of this paper but is presented in Osinski et al. (2008). The important points of note are that decomposition appears to be a post-impact contact metamorphic process, governed by the post-impact temperature of the melt-clast mixture (i.e., rapid quenching and/or low post-shock temperatures will inhibit carbonate decomposition). This applies only to calcite; it is unclear whether dolomite will decompose during impact events.

Impact melt derived from crystalline rocks is superheated, with initial average temperatures on the order of ~1500–2500 °C (Grieve et al. 1977). The presence of SiO_2—rich glasses or lechatelierite derived from sandstones at a number of terrestrial impact structures (e.g., Gosses Bluff (Milton et al. 1996); Haughton (Redeker and Stöffler 1988) Ries [Osinski 2003]); indicates that similar initial temperatures are also reached during impacts into sedimentary rocks.

Thus, the effects of target lithology on melt composition and temperature are varied. These properties will affect the relative ability of melts to form crystals, to flow, and to assimilate their entrained clasts.

Gas Content

The gas or volatile content of impact-generated melts will reflect the volatile content of the target rocks, which may, therefore, be highly variable and different for each impact site. Volatiles may be derived from crystal-bound phases (e.g., H_2O in clays, CO_2 in carbonates) or interstitial pore or fracture-bound waters. Thus, crystalline rocks may also be volatile-rich, if considerable fracture waters are present. The effect of gas content on melts is twofold. High gas contents reduce viscosity, which results in larger crystals even at low temperatures. Gas content also affects the explosivity of igneous melts (McBirney 2006); it is not clear at present as to the effect(s) of gas content on impact melts.

Effect on Chemistry and Mineralogy

It has long been suggested that impact melts typically display a large degree of compositional homogeneity (Grieve et al. 1977; Dressler and Reimold 2001). Indeed, this has been widely cited as a defining characteristic to distinguish impact-generated melt rocks and glasses from endogenic igneous magmas. Studies of impact melt bodies at Mistastin and other craters formed in crystalline rocks clearly show that impact melt rocks at these sites do indeed show a large degree of compositional homogeneity (Grieve 1975; Simonds et al. 1978). Complications arise when a structure is large enough for differentiation of the melt sheet to occur, as at the ~250 km diameter Sudbury structure (Warren et al. 1996; Zieg and Marsh 2005); the Vredefort Granophyre is, however, homogeneous on a regional scale although on a purely lateral level (Reimold and Gibson 2006). Cratering models show that impact melt is generated at various depths within the initial transient cavity. Subsequent high speed, turbulent transport of these different 'packages' of melt then occurs, and it is at this stage that mixing and homogenization takes place. Importantly, the target sequences for impacts into sedimentary and mixed sedimentary-crystalline targets, such as the Ries and Haughton structures, are typically considerably more heterogeneous than crystalline igneous and metamorphic sequences (Fig. 1). Initial impact melts in different regions of the transient cavity will, therefore, display widely varying compositions (e.g., melt derived from carbonates as opposed to sandstone, etc.). Thus, for the same volume of melt, a larger degree of mixing and homogenization will be required in order to generate a compositionally homogenous melt body. Studies of the impact melt products at structures in heterogeneous sedimentary targets show that this typically does not occur (Hörz et al. 2002; Osinski 2003; Osinski et al. 2005a). It is suggested that a major factor inhibiting the homogenization is the immiscibility of impact melts of widely different composition, as indicated by Figs. 5d–f and 6d–f.

In some igneous systems, liquid immiscibility is an important mechanism of magmatic differentiation. This describes the process whereby an initially homogeneous melt reaches a temperature at which it can no longer exist stably and so it unmixes into two liquids of different composition and density (Roedder 1978). For impact melts, the composition and temperature will, therefore, influence the ability of melts from different target rocks to mix and homogenize. For impacts into crystalline targets, this will not be very important given the relatively limited compositional heterogeneity of the target rocks; common igneous and metamorphic silicate rocks have a relatively limited compositional variability due to mineralogical compositions determined by thermodynamics and phase equilibria (Taylor and McLennan 1985). For impacts involving sedimentary rocks, however, it is possible that impact-generated melts from target rocks at different stratigraphic levels will have widely variable compositions (e.g., limestone versus sandstone) and may not completely mix or homogenize. Examples of this on a small-scale are widespread in impactites from the Haughton and Ries structures (e.g., Figs. 5f, 6d, 6f). This is not liquid immiscibility sensu stricto and the terminology "carbonate-silicate liquid immiscibility" should be avoided, unless there is unequivocal evidence for the unmixing of an originally homogeneous impact melt (Osinski et al. 2008).

Thus, homogenous coherent bodies of melt will only form where crystalline rocks are the dominant target lithology. In sedimentary, or mixed sedimentary–crystalline targets, the difference in composition and temperature of melts derived from different lithologies will result in unmixed and heterogeneous impact melt-bearing products (e.g., Figs. 5 and 6), even though the fundamental formational processes may be essentially identical. Rare exceptions may occur—although none are currently known—where homogeneous bodies of melt may be formed from impacts into homogenous sedimentary targets (e.g., pure limestone).

Effect on Observed Impact Melt Volumes

It has long been noted that the volume of impact melt rocks recognized in predominantly sedimentary and in mixed targets is on the order of two magnitudes less than for crystalline targets, in comparably sized impact structures (Kieffer and Simonds 1980; Grieve and Cintala 1992). It has also been noted, however, that the crater-fill deposits at the Haughton, Ries, and other similarly-sized impact structures developed in sedimentary-bearing targets, are stratigraphically equivalent to the coherent impact melt layers developed at craters in crystalline targets, such as Mistastin (Grieve 1988). Irrespective of the target composition, there is also a common general stratigraphic succession (Fig. 4). Furthermore, the estimated total volume of crater-fill impactites is approximately the same in all cases (e.g., Table 2).

There is no question that the crater-fill deposits at Mistastin are impact melt rocks (Grieve 1975; Fig. 7a). Thus, the simplest explanation is that the crater-fill impactites at the Haughton, Ries, and other sedimentary rock-bearing targets are genetically equivalent. This is supported by work at the Haughton structure, which demonstrates that the crater-fill deposits are melt-rich and can be classified as clast-rich impact melt rocks (Osinski et al. 2005). Such an origin is difficult to say unequivocally for the Ries structure due to the pervasive hydrothermal alteration of the crater-fill impactite (suevite) deposits (Newsom et al. 1986; Osinski 2005). As noted earlier, however, it is likely that the groundmass of these impactites also originally comprised a variety of impact melt phases (Engelhardt et al. 1995; Osinski et al. 2004). Thus, interpretations from field studies are in general agreement with numerical models (Wünnemann et al. 2008) in showing that similar volumes of impact melt are generated and preserved at similar-sized craters developed in sedimentary and crystalline targets (Fig. 2). We suggest that impactites at other craters with apparently low volumes of melt, such as Logoisk (Fig. 2) be re-evaluated. Discussions surrounding the paucity of melt at the Bosumtwi impact structure also highlight the need for more studies as to the fate of metamorphosed sedimentary rocks during the impact cratering process (e.g., the low amount of melt in drill cores at Bosumtwi has been explained as either the result of an oblique impact [Deutsch et al. 2007] or volatiles [Artemieva 2007]).

EMPLACEMENT OF CRATER-FILL IMPACTITES

Grieve et al. (1977) presented a cratering model for the genesis and emplacement of impact melt rocks. This widely accepted model was developed based on the properties of crater-fill impactites at craters formed within crystalline target rocks, such as Mistastin. In summary, compression and subsequent pressure release by rarefraction causes an increase in internal energy and the melting and vaporization of a small volume of the target close to the point of impact. The passage of the shock wave also imparts a particle velocity to the shocked material, such that the melt moves downwards and outwards along the base of the growing transient cavity. The leading edge of the melt at any particular time overruns increasingly less shocked target material and incorporates inclusions showing various degrees of shock deformation. A portion of mixed and melted/vaporized material is ejected from the growing cavity to form ejecta deposits. The remainder forms a lining to the transient cavity and, on transient cavity modification, forms the melt-rich crater-fill deposits in complex craters developed in crystalline targets and indicates that these crater-fill impactites were never airborne (Grieve et al. 1977). This is consistent with numerical models of vertical impacts, which show that the majority of the melt volume remains within and never leaves the transient cavity (Figs. 3 and 4) (Collins et al. 2008); although it should be noted that numerical models do not yet account for the effect of pore water and impact angle.

As discussed and described in Grieve (1988) and Osinski et al. (2005a), the cratering model presented by Grieve et al. (1977), and summarized above, also accounts for the properties of the crater-fill deposits at the Haughton impact

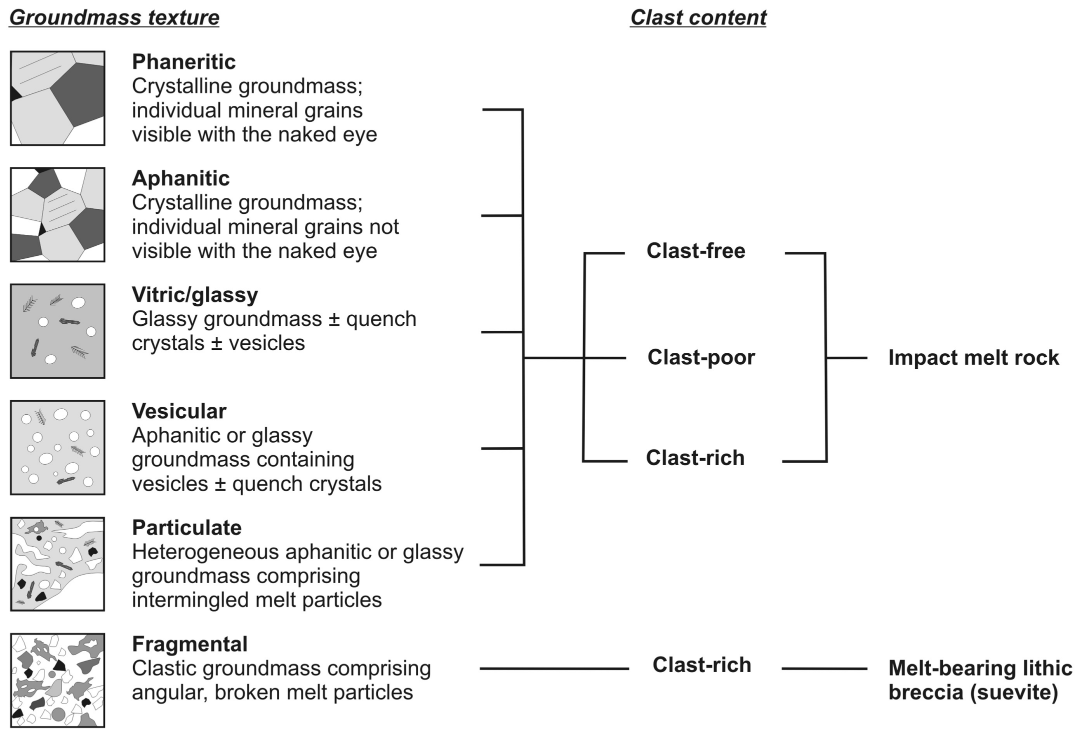

Fig. 9. Proposed clarifications to the classification scheme for impact melt-bearing impactites, based on textural characteristics of the groundmass/matrix, with respect to melt phases, and clast content. See text for details. Note that clast-rich impact melt rocks have also been termed impact melt breccias; this term is avoided following the recommendation of Stöffler and Grieve (2007). In this scheme, we apply the original definition of suevite, which is a polymict impact breccia with a clastic matrix/groundmass containing fragments of impact glass and shocked mineral and lithic clasts (Stöffler et al. 1977). Where there is evidence that the groundmass remained molten during and following deposition, but comprises a series of intermingled melts of different composition (e.g., see Figs. 5f, 6d–f), we propose the prefix "particulate." Thus, "particulate, clast-rich impact melt rock" describes some of the melt-rich crater-fill and ejecta impactites at impact craters developed in heterogeneous mixed sedimentary-crystalline targets, such as the Haughton and Ries impact structures (Figs. 5f, 6d–f). Fragmental melt-bearing lithic breccias (i.e., impactites conforming to the original definition of suevite) are present at some structures, for example, at Mistastin (Figs. 7c and 7f).

structure. In particular, the following lines of evidence can only be explained if the crater-fill deposits at Haughton formed by radial outflow within the transient cavity and not by an airborne mechanism (Grieve 1988; Osinski et al. 2005b):(1) the heterogeneous distribution of crystalline basement clasts and evaporite clasts in the crater-fill; and (2) the presence of less shocked, including unshocked, mineral grains compared to the recorded shock levels in clasts of their source rocks; and (3) the presence of 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. Thus, as with the crater-fill deposits at Mistastin, there is no evidence that the equivalent deposits at Haughton were airborne (i.e., ejected upwards within an expanding vapour or ejecta plume). It is suggested that the term "fallback deposit," which has often been used to describe, for example, the crater-fill suevite deposits at the Ries structure is misleading and should not be used. We also suggest that the same is the case for many other impact structures (e.g., those described by Masaitis 1999 and references therein). This view is supported by recent independent work at the Chesapeake Bay impact structure where Horton et al. (2008) propose that the crater-fill suevite and entrained megablocks "formed from impact-melt particles and crystalline-rock debris that never left the central crater, rather than as a fallback deposit" (Horton et al. 2008, p. 73). This view is supported by recent independent work at the Chesapeake Bay impact structure where Horton et al. (2008) propose that the crater-fill suevite and entrained megablocks "formed from impact-melt particles and crystalline-rock debris that never left the central crater, rather than as a fallback deposit" (Horton et al. 2008, p. 73).This is not to say that "fallback" deposits do not form; however, we suggest that such deposits are minor and represent airfall deposits due to the gradual settling out of material from the vapour plume. For example, an ~18 m thick normally graded unit of "suevite" overlies the main suevite mass at the Ries structure (Pernicka et al. 1987) and a similar ~30 cm thick unit occurs at Bosumtwi (Koeberl et al. 2007).

CONCLUSIONS

Given the above discussion, we suggest that the fundamental processes of impact melting are basically the same in sedimentary and crystalline targets, regardless of target properties. This is consistent with theoretical calculations and numerical models, which indicate that as much, or even more, melt should be produced during hypervelocity impact into sedimentary target rocks (Kieffer and Simonds 1980; Wünnemann et al. 2008). In contrast to previous suggestions, recent field and analytical studies show that, as for crystalline targets, a large proportion of the melt is retained within the crater (as crater-fill impactites) for impacts into sedimentary-bearing target rocks. This is consistent with numerical modelling studies (Fig. 3; Collins et al. 2008). Furthermore, consideration of the impact products at the structures under consideration here suggests the basic products are also the same (i.e., genetically equivalent) but they just *appear* different (i.e., it is the textures, chemistry and mineralogy of the products that vary). As discussed above, we suggest that these apparent differences between impact melt products derived from different target rocks are due to the different chemical and physical properties of the initial melt, which, for example, inhibits the ability of melts derived from sedimentary rocks to mix, homogenize and assimilate clastic debris.

Central to this is the recognition of impact melt products in craters such as Haughton and the Ries and the more discriminate use of the term "suevite." As shown above and summarized in Osinski et al. (2008), part of the misunderstanding surrounds the previous lack of recognition of impact melt phases in the groundmass of "breccias" and "suevites" at craters developed in sedimentary and mixed sedimentary-crystalline targets. Impact melts derived from carbonates, sandstones, and evaporites have now been recognized at a number of terrestrial impact sites (see Osinski et al. 2008 for a review and for a summary of the criterion that may be used to recognize such melts).

Figure 9 represents our attempt to provide a modified classification scheme for impact melt-bearing impactites, based on the current IUGS scheme (Stöffler and Grieve 2007). We suggest that there is, in effect, a continuum from clast-poor coherent impact melt rocks to clast-rich impact melt rocks, where various melt phases are intermixed with clasts. By utilizing well-accepted terms from igneous petrology, we suggest that this descriptive classification will prove useful in the field and laboratory setting. Importantly, this does not involve any reclassification of impact melt rocks in crystalline targets. We also note that this classification does not involve any genetic implications in terms of emplacement processes.

The important distinction surrounds the terms "particulate" and "fragmental." Where the groundmass is composed of a heterogeneous mixture of melt phases and there is evidence for these phases being fluid during and after transport, we propose the term *particulate* to distinguish these lithologies from coherent crystalline silicate melt rocks. The crater-fill impactites at Haughton would, therefore, be termed particulate clast-rich impact melt rocks. They are melt-rich but the melt is heterogeneous, dispersed and intermingled with clasts (Fig. 5), in contrast to the aphanitic impact melt rocks at Mistastin (Fig. 7).

Impactites with a purely *fragmental* groundmass or matrix (i.e., comprising angular lithic, mineral and glass fragments), conform to the original definition of suevite (i.e., a polymict impact breccia with a clastic matrix/groundmass containing fragments of impact glass and shocked mineral and lithic clasts) (Stöffler et al. 1977; Dressler and Reimold 2001). As an example, the impact breccias underlying the coherent melt sheet at Mistastin conform exactly to this definition. These were previously termed melt-bearing mixed breccias by Grieve (1975). Similar melt-bearing lithic breccias underlie the impact melt sheet at the Manicouagan impact structure (Simonds et al. 1978), form the proximal ejecta deposits at Meteor Crater (Osinski et al. 2006), and are present at other structures, such as Wanapitei (Grieve and Ber 1994).

It is critical, however, that this original definition of suevite be strictly applied. Indeed, Grieve et al. (1977) noted that "the unqualified use of the term suevite at other impact structures (other than the Ries) has resulted in what are considered to be unwarranted arguments and conclusions regarding the physical conditions accompanying the formation and distribution of melt-bearing breccias within the cavity." For example, impactites containing >70% melt, in the form of glass, have been termed suevites in the past (Masaitis 1999). Further complications arise given that the surficial suevites at the Ries impact structure may not conform to the original definition of suevite. Osinski et al. (2004) proposed that calcite, silicate glass, and clay minerals in the groundmass of the Ries surficial suevites represent a series of impact-generated melts and that the bulk of these phases were molten on deposition. A series of silicate phases then crystallized from the groundmass upon cooling. In other words, the groundmass of the Ries surficial suevites does not appear to be clastic; rather, according to the work of Osinski et al. (2004), these impactites could be termed *particulate* clast-rich impact melt rocks, and not "suevite."

Finally, we note that the long-accepted cratering model for the emplacement of impact melts in crystalline targets presented by Grieve et al. (1977) also accounts for the properties of the crater-fill deposits at the Haughton and Ries impact structures. Importantly, apart from thin upper graded units, there is no evidence that the crater-fill deposits at the structures studied here (Haughton, Mistastin, Ries) or at the Chesapeake Bay structure (Horton et al. 2008) were airborne, so that the term "fallback deposit" should not be used to describe them.

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REFERENCES

Artemieva N. 2007. Possible reasons of shock melt deficiency in the Bosumtwi drill cores. *Meteoritics & Planetary Science* 42:883–894.

Barker D. S. 1989. Field relations of carbonatites. In *Carbonatites: Genesis and evolution*, edited by Bell K. London: Unwin Hyman. pp. 38–69.

Currie K. L. 1971. *Geology of the resurgent cryptoexplosion crater at Mistastin Lake, Labrador.* Bulletin of the Geological Survey of Canada 207. Ottawa: Geological Survey of Canada. pp. 62.

Dence M. R. 1971. Impact melts. *Journal of Geophysical Research* 76:5552–5565.

Deutsch A., Luetke S., and Heinrich V. 2007. The ICDP Lake Bosumtwi impact crater scientific drilling project (Ghana): Core LB-08A litho-log, related ejecta, and shock recovery experiments. *Meteoritics & Planetary Science* 42:635–654.

Dressler B. O. and Reimold W. U. 2001. Terrestrial impact melt rocks and glasses. *Earth Science Reviews* 56:205–284.

Engelhardt W. V. 1990. Distribution, petrography and shock metamorphism of the ejecta of the Ries crater in Germany—A review. *Tectonophysics* 171:259–273.

Engelhardt W. V. 1997. Suevite breccia of the Ries impact crater, Germany: Petrography, chemistry and shock metamorphism of crystalline rock clasts. *Meteoritics & Planetary Science* 32:545–554.

Engelhardt W. V. and Graup G. 1984. Suevite of the Ries crater, Germany: Source rocks and implications for cratering mechanics. *Geologische Rundschau* 73:447–481.

Engelhardt W. V., Stöffler D., and Schnieder W. 1969. Petrologische Untersuchungen im Ries. *Geologica Bavarica* 61:229–295.

Engelhardt W. V., Arndt J., Fecker B., and Pankau H. G. 1995. Suevite breccia from the Ries crater, Germany: Origin, cooling history and devitrification of impact glasses. *Meteoritics* 30:279–293.

Graup G. 1999. Carbonate-silicate liquid immiscibility upon impact melting: Ries Crater, Germany. *Meteoritics & Planetary Science* 34:425–438.

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. 1978. The melt rocks at Brent crater, Ontario, Canada. Proceedings, 9th Lunar and Planetary Science Conference. pp. 2579–2608.

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. and Cintala M. J. 1992. An analysis of differential impact melt-crater scaling and implications for the terrestrial impact record. *Meteoritics* 27:526–538.

Grieve R. A. F. and Ber T. J. 1994. Shocked lithologies at the Wanapitei impact structure, Ontario, Canada. *Meteoritics* 29: 621–631.

Grieve R. A. F. and Therriault A. 2000. Vredefort, Sudbury, Chicxulub; three of a kind? *Annual Review of Earth and Planetary Sciences* 28:305–338.

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.

Herrick R. R. and Pierazzo E. 2003. *Results of the Workshop on Impact Cratering: Bridging the Gap Between Modeling and Observations.* LPI Contribution 1162. Houston: Lunar and Planetary Institute. 156 p.

Horton J. W. Jr., Gohn G. S., Powers D. S. and Edwards L. E. 2008. Origin and emplacement of impactites in the Chesapeake Bay impact structure, Virginia, USA. In *The sedimentary record of meteorite impacts*, edited by K. R. Evans, Horton J. W., King D. K. Jr., and Morrow J. R. GSA Special Paper 437. Boulder: Geological Society of America. pp. 73–97.

Hörz F., Mittlefehldt D. W., See T. H., and Galindo C. 2002. Petrographic studies of the impact melts from Meteor Crater, Arizona, USA. *Meteoritics & Planetary Science* 37:501–531.

Jones A. P., Claeys Ph., and Heuschkel S. 2000 Impact melting of carbonates from the Chicxulub Crater. In *Impacts and the early Earth*, ,edited by Gilmour I. and Koeberl C. Lecture Notes in Earth Sciences, vol. 91. Berlin: Springer-Verlag. pp. 343–361.

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.

Koeberl C., Brandstätter F., Glass B. P., Hecht L., Mader D., and Reimold W. U. 2007. Uppermost impact fallback layer in the Bosumtwi crater (Ghana): Mineralogy, geochemistry, and comparison with Ivory Coast tektites. *Meteoritics & Planetary Science* 42:709–729.

Laurenzi M. A., Bigazzi G., Balestrieri M. L., and Boužka V. 2003. $^{40}Ar/^{39}Ar$ laser probe dating of the Central European tektite-producing impact event. *Meteoritics & Planetary Science* 38:887–894.

Mak E. K., York D., Grieve R. A. F., and Dence M. R. 1976. The age of the Mistastin Lake crater, Labrador, Canada. *Earth and Planetary Science Letters* 31:345–357.

Marchand M. and Crocket J. H. 1977. Sr isotopes and trace element geochemistry of the impact melt and target rocks at the Mistastin Lake Crater, Labrador. *Geochimica et Cosmochimica Acta* 41: 1487–1495.

Marion C. L. 2008. Petrology of impact melts at the Mistastin impact structure, Labrador. Memorial University, St. Johns.

Marion C. L., Sylvester P. J., Tubrett M., and Shaffer K. 2007. Microbeam-based analytical approach to define melt composition and identify target rocks in impact melt sheets: An analogue study from the Mistastin Lake impact crater, Labrador. *Geological Association of Canada—Mineralogical Association of Canada Annual Meeting, Program with Abstracts* 32:53.

Masaitis V. L. 1999. Impact structures of northeastern Eurasia: The territories of Russia and adjacent countries. *Meteoritics & Planetary Science* 34:691–711.

Masaitis V. L., Danilin A. N., Maschak M. S., Raykhlin A. I., Selivanovskaya T. V., and Shadenkov Y. M. 1980. *The geology of astroblemes*. Leningrad: Nedra. 231 p. In Russian.

Mcbirney A. R. 2006. *Igneous petrology.* Boston: Jones & Bartlett Publishers. 550 p.

Melosh H. J. 1989. *Impact cratering: A geologic process*. New York: Oxford University Press. 245 p.

Milton D. J., Glikson A. Y., and Brett R. 1996. Gosses Bluff—A latest Jurassic impact structure, central Australia. Part 1: geological structure, stratigraphy, and origin. *Journal of Australian Geology and Geophysics* 16:453–486.

Newsom H. E., Graup G., Sewards T., and Keil K. 1986. Fluidization and hydrothermal alteration of the suevite deposit in the Ries Crater, West Germany, and implications for Mars. *Journal of*

Geophysical Research, B, Solid Earth and Planets 91:239–251.

Onorato P. I. K., Uhlmann D. R., and Simonds C. H. 1978. The thermal history of the Manicouagan impact melt sheet, Quebec. *Journal of Geophysical Research* 83:2789–2798.

Osinski G. R. 2003. Impact glasses in fallout suevites from the Ries impact structure, Germany: An analytical SEM study. *Meteoritics & Planetary Science* 38:1641–1668.

Osinski G. R. 2004. Impact melt rocks from the Ries impact structure, Germany: An origin as impact melt flows? *Earth and Planetary Science Letters* 226:529–543.

Osinski G. R. 2005. Hydrothermal activity associated with the Ries impact event, Germany. *Geofluids* 5:202–220.

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 shock melting of sulfates from the Haughton impact structure, Canada (abstract #5076). *Meteoritics & Planetary Science* 38:A45.

Osinski G. R., Bunch T. E., and Wittke J. 2003. Evidence for shock melting of carbonates from Meteor Crater, Arizona (abstract #5070). 66th Meteoritical Society Meeting. CD-ROM.

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* 40:1813–1834.

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* 39:1655–1684.

Osinski G. R., Spray J. G., and Lee P. 2005a. Impactites of the Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40:1789–1812.

Osinski G. R., Bunch T. E., and Wittke J. 2006. Proximal ejecta at Meteor Crater, Arizona: Discovery of impact melt-bearing breccias (abstract #1005). 37th Lunar and Planetary Science Conference. CD-ROM.

Osinski G. R., Grieve R. A. F., and Spray J. G. 2008. Impact melting in sedimentary target rocks: An assessment. In *The sedimentary record of meteorite impacts*, edited by Evans K. R., Horton W., King D. K. Jr., Morrow J. R., and Warme J. E. GSA Special Publication 437. Boulder: Geological Society of America. pp. 1–18.

Osinski G. R., Lee P., Spray J. G., Parnell J., Lim D. S. S., Bunch T. E., Cockell C. S., and Glass B. J. 2005b. Geological overview and cratering model for the Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40: 1759–1776.

Palme H., Gobel E., and Grieve R. A. F. 1979. The distribution of volatile and siderophile elements in the impact melt of East Clearwater (Quebec). Proceedings, 10th Lunar and Planetary Science Conference. pp. 2465–2492.

Pernicka E., Horn P., and Pohl J. 1987. Chemical record of the projectile in the graded fall-back sedimentary unit from the Ries Crater, Germany. *Earth and Planetary Science Letters* 86:113.

Pierazzo E., Vickery A. M., and Melosh H. J. 1997. A reevaluation of impact melt production. *Icarus* 127:408–423.

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.

Pratesi G., Morelli M., Rossi A. P. and Ori G. G. 2005. Chemical compositions of impact melt breccias and target rocks from the Tenoumer impact crater, Mauritania. *Meteoritics & Planetary Science* 40:1653–1672.

Redeker H. J. and Stöffler D. 1988. The allochthonous polymict breccia layer of the Haughton impact crater, Devon Island, Canada. *Meteoritics* 23:185–196.

Reimold W. U. and Gibson R. L. 2006. The melt rocks of the Vredefort impact structure—Vredefort Granophyre and pseudotachylitic breccias: Implications for impact cratering and the evolution of the Witwatersrand Basin. *Chemie der Erde* 66: 1–35.

Schmidt-Kaler H. 1978. Geological setting and history. In *Principle exposures of the Ries meteorite crater in southern Germany*, edited by Chao E. C. T., Hüttner R., and Schmidt-Kaler H. Verlag Bayerisches Geologisches Landesamt, München, Germany. pp. 8–11.

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 Haughton impact event. *Meteoritics & Planetary Science* 40:1777–1787.

Simonds C. H., Floran R. J., McGee P. E., Phinney W. C., and Warner J. L. 1978. Petrogenesis of melt rocks, Manicouagan impact structure, Quebec. *Journal of Geophysical Research* 83:2773–2778.

Stöffler D. 1977. Research drilling Nördlingen 1973: Polymict breccias, crater basement, and cratering model of the Ries impact structure. *Geologica Bavarica* 75:443.

Stöffler D. and Grieve R. A. F. 2007. Impactites. In *Metamorphic rocks*, edited by Fettes D. and Desmons J. Cambridge: Cambridge University Press. pp. 82–92.

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.

Taylor S. R. and Mclennan S. M. 1985. *The continental crust: It's composition and evolution*. Cambridge, Massachusetts: Blackwell. 312 p.

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.

Treiman A. H. 1989. Carbonatite magma: Properties and process. In *Carbonatites: Genesis and evolution*, edited by Bell K. London: Unwin Hyman. pp. 89–104.

Warren P. H., Claeys P., and Cedillo P. E. 1996. Mega-impact melt petrology (Chicxulub, Sudbury, and the Moon); effects of scale and other factors on potential for fractional crystallization and development of cumulates. In *The Cretaceous-Tertiary event and other catastrophes in Earth history*, edited by Ryder G., Fastovsky D., and Gartner S. GSA Special Paper 307. Boulder: Geological Society of America. pp. 105–124.

Wünnemann K., Collins G. S., and Osinski G. R. 2008. Numerical modelling of impact melt production on porous rocks. *Earth and Planetary Science Letters* 269:529–538.

Zieg M. J. and Marsh B. D. 2005. The Sudbury Igneous Complex: Viscous emulsion differentiation of a superheated impact melt sheet. *Geological Society of America Bulletin* 117:1427–1450.