Meteoritics & Planetary Science 41, Nr 10, 1571–1586 (2006)
Abstract available online at http://meteoritics.org

Effect of volatiles and target lithology on the generation and emplacement of impact crater fill and ejecta deposits on Mars

Gordon R. OSINSKI

Canadian Space Agency, 6767 Route de l'Aeroport, Saint-Hubert, Quebec, J3Y 8Y9, Canada
E-mail: osinski@lycos.com

(Received 15 October 2005; revision accepted 15 March 2006)

Abstract–Impact cratering is an important geological process on Mars and the nature of Martian impact craters may provide important information as to the volatile content of the Martian crust. Terrestrial impact structures currently provide the only ground-truth data as to the role of volatiles and an atmosphere on the impact-cratering process. Recent advancements, based on studies of several well-preserved terrestrial craters, have been made regarding the role and effect of volatiles on the impact-cratering process. Combined field and laboratory studies reveal that impact melting is much more common in volatile-rich targets than previously thought, so impact-melt rocks, melt-bearing breccias, and glasses should be common on Mars. Consideration of the terrestrial impact-cratering record suggests that it is the presence or absence of subsurface volatiles and not the presence of an atmosphere that largely controls ejecta emplacement on Mars. Furthermore, recent studies at the Haughton and Ries impact structures reveal that there are two discrete episodes of ejecta deposition during the formation of complex impact craters that provide a mechanism for generating multiple layers of ejecta. It is apparent that the relative abundance of volatiles in the near-surface region outside a transient cavity and in the target rocks within the transient cavity play a key role in controlling the amount of fluidization of Martian ejecta deposits. This study shows the value of using terrestrial analogues, in addition to observational data from robotic orbiters and landers, laboratory experiments, and numerical modeling to explore the Martian impact-cratering record.

INTRODUCTION

Hypervelocity impact craters are some of the most common geological landforms on Mars. The Martian impact-cratering record is more diverse than that of other terrestrial planets (e.g., Strom et al. 1992); therefore, observations of impact craters on Mars may provide insights into the composition, structure, and physical characteristics of the Martian crust and its volatile inventory. One of the most unusual aspects of Martian impact craters is the presence of lobate or fluidized ejecta deposits, often comprising two or more lobes or layers of ejecta (Strom et al. 1992), collectively termed "layered ejecta structures" (Barlow et al. 2000). These features have been attributed to either 1) interaction of ejecta with volatiles derived from the subsurface (e.g., Carr et al. 1977), or 2) interaction of ejecta with the atmosphere (e.g., Schultz and Gault 1979). The former theory is the most widely accepted and has been used as evidence for the presence of H_2O in the Martian subsurface (e.g., Carr et al. 1977; Gault and Greeley 1978; Wohletz and Sheriden 1983), although exactly how and in what state H_2O is incorporated into the ejecta is unclear (Squyres et al. 1992). More recently, it has been suggested that both processes may play a role in forming layered ejecta structures on Mars (Barlow 2005a).

Observational data from robotic orbiters and landers, laboratory experiments, and numerical modeling have provided important information about Martian impact structures (see Barlow 2005a for a review). Interpretations of Mars must, however, begin by using the Earth as a reference, particularly given the fact that Earth possesses both an atmosphere and volatile-rich (i.e., sedimentary) rocks. The aim of this paper is to provide an up-to-date assessment of the processes and products of impacts into volatile-rich targets on Earth and to synthesize this knowledge with observations of the Martian impact-cratering record. It is hoped that this will provide a better understanding of the relative effect of volatiles and the atmosphere on the types of impactites (impact-produced rocks) that may be found on Mars and their emplacement mechanism(s).

CLASSIFICATION OF IMPACTITES

The classification of impactites (“rocks affected by impact metamorphism”) (Stöffler and Grieve 1994) is still a topic of ongoing debate within the impact community; the most widely accepted and standardized scheme is that proposed by the IUGS Subcommission on the Systematics of Metamorphic Rocks (Fig. 1) (Stöffler and Grieve 1994, 1996). It is widely believed that the properties of target rocks control the type of impactite(s) produced during an impact event (e.g., Kieffer and Simonds 1980). For example, impact-melt rocks are not generally thought to form in impact craters developed in volatile-rich targets (Fig. 1).

CRATER-FILL IMPACTITES

Observations from Martian Impact Structures

It has generally been accepted that coherent impact-melt rocks are not generated in impact structures formed in volatile-rich sedimentary targets (Kieffer and Simonds 1980), which led Schultz and Mustard (2004) to suggest that large, coherent impact-melt sheets would not form on Mars. This is despite the fact that impacts in volatile-rich sedimentary rocks should produce as much or more melt than impacts in crystalline rocks (Kieffer and Simonds 1980). The apparent anomaly has been attributed to the release of enormous quantities of vapor (e.g., H_2O, CO_2, SO_2), resulting in the unusually wide dispersion of shock-melted sedimentary rocks (Kieffer and Simonds 1980). In impact structures formed in volatile-rich targets, the resultant impactites have, therefore, been referred to as lithic impact breccias that are supposedly melt-free or melt-poor (Fig. 1).

Without the required ground-truthing, it is hard to quantify the amount of impact melt preserved within crater-fill deposits on Mars or determine whether coherent impact-melt rocks are present. However, it is interesting to note that so-called “central remnant craters” have been explained as forming due to the localization of erosion around the edge of impact-melt sheets (Newsom 2001). This necessarily requires a resistant crater-fill unit, such as a coherent impact-melt layer. This is consistent with the preliminary results of numerical simulations of the formation of a generic crater 30 km in diameter on Mars, which suggest that the presence of ground ice does not appreciably effect the amount of impact melt generated compared to an impact event of the same energy in a “dry” target (Pierazzo et al. 2005).

Observations from Terrestrial Impact Structures

The Haughton impact structure, which is 23 km in diameter and ~39 Myr old, is a well-preserved and well-exposed complex crater in the Canadian High Arctic (see Osinski et al. 2005a for an overview). The target sequence at Haughton comprises a series of sedimentary rocks ~1880 m in thickness, predominantly carbonates with minor evaporites, sandstones, and shales, overlying crystalline basement. Distinctive pale gray crater-fill deposits form a discontinuous 54 km^2 layer in the central area of the structure (Figs. 2a, 2b, and 3) (Redeker and Stöffler 1988). Contrary to previous workers who interpreted these impactites as clastic matrix breccias or as fragmental breccias (Metzler et al. 1988; Redeker and Stöffler 1988), recent field, optical, and analytical scanning electron microscope (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 (Table 1) (Osinski et al. 2005b). The pale gray crater-fill deposits at Haughton can therefore be classified as impact-melt breccias or clast-rich impact-melt rocks according to the terminology of Stöffler and Grieve (1994, 1996) (Fig. 1). Thus, although the products of meteorite impact into volatile-rich target rocks (e.g., the pale gray impact-melt breccias at Haughton) (Figs. 2a and 2b) may appear very different from those developed in crystalline targets (e.g., coherent sheets of impact-melt rocks with classical igneous textures and features) (Fig. 2c), it is apparent that these different lithologies are genetically equivalent.

PROXIMAL EJECTA DEPOSITS

Observations from Martian Impact Structures

Of the 10,561 catalogued Martian impact craters >5 km in diameter that retain ejecta deposits, ~89% display lobate or fluidized ejecta deposits, often comprising two or more lobes or layers of ejecta (Fig. 4) (Barlow 2005a). Three main types of layered ejecta structures have been recognized, comprising single (SLE), double (DLE), or multiple (MLE) layers of ejecta (Figs. 4a–4c). The general characteristics and attributes of these different ejecta types are summarized in Table 2. The majority of layered ejecta blankets possess a ridge or rampart at their outer edge (Figs. 4a and 4d) (Carr et al. 1977; Garvin et al. 2000). DLE and MLE craters are typically characterized by the presence of radial striae that overprint different layers of ejecta. The DLE morphology is notably more common in the northern plains of Mars where periglacial features are also present (Mouginis-Mark 1981). There are different opinions as to the relationship of the different ejecta layers in DLE craters. For example, Carr et al. (1977) suggested that the innermost layer clearly overlies and transects the outermost layer of ejecta (cf. the crater shown in Fig. 4b), indicating successive deposition. In contrast, Mouginis-Mark (1981) proposed that the opposite is the case, with the inner layer being deposited first, followed by the areally more extensive outer unit.

It is clear that layered ejecta deposits were highly fluidized at the time of their emplacement (Mouginis-Mark 1987) and that they were emplaced as relatively thin ground-

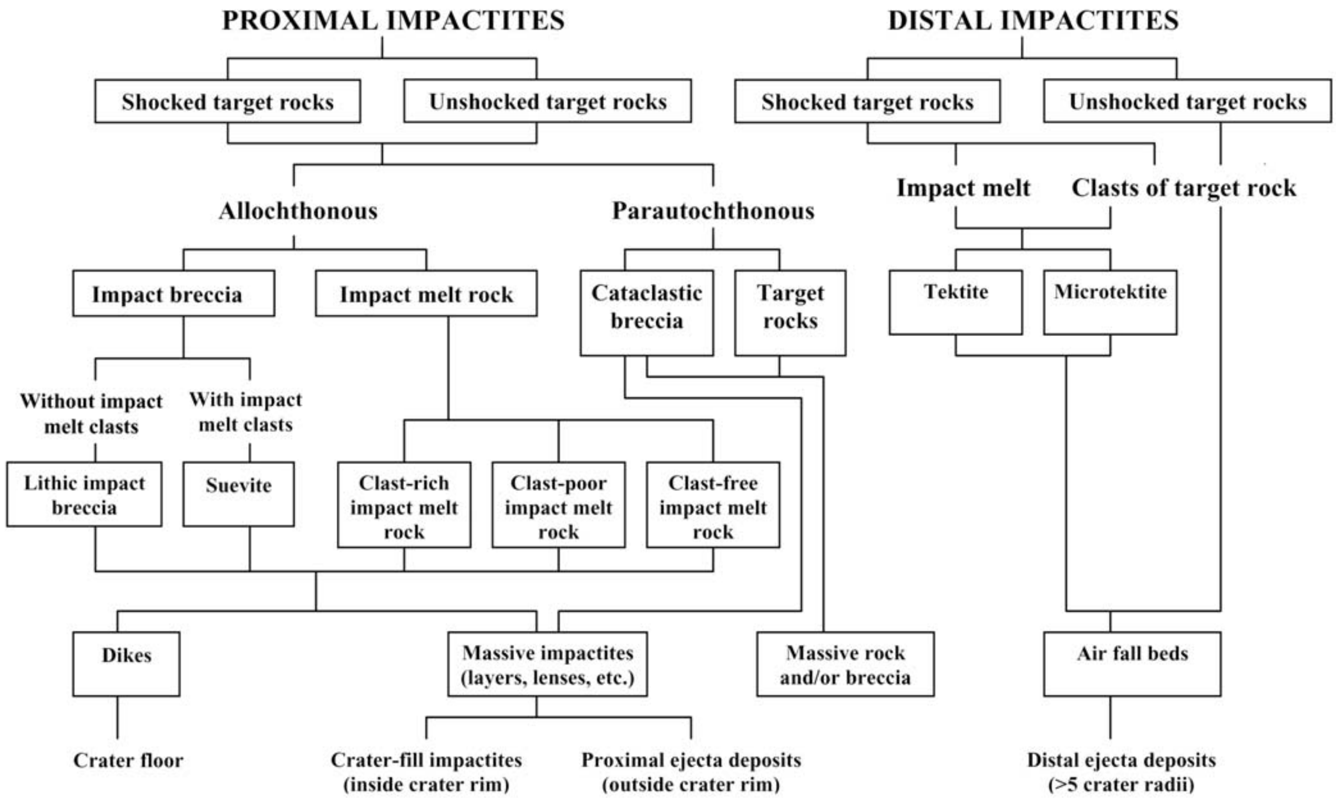

Fig. 1. The classification of impactites from a single impact event, modified from Stöffler and Grieve (1996). Note that lithic impact breccias have been referred to as clastic matrix breccias or fragmental breccias at many impact sites. Although this scheme was drawn up based mainly on the terrestrial impact-cratering record, most of these impactite types should also be expected on Mars.

hugging flows rather than simple ballistic ejecta (Carr et al. 1977). The flow(s) are also hypothesized to have been more analogous to debris flows than to low-density, gas-rich base surges (Carr 1977). Evidence for this includes flow lines around obstacles, large runout distances, and the absence of ejecta on top and on the lee side of obstacles themselves (Figs. 4a, 4c–4e) (Carr et al. 1977). These features rule out subaerial deposition. Therefore, it is clear that the features of fluidized ejecta deposits around Martian impact craters do not simply reflect ballistic emplacement as do the majority of lunar and Mercurian craters. The ejecta emplacement process also involves a component of radial flow. However, what is not clear is the emplacement mechanism(s) of these ejecta deposits. Originally attributed to modification by wind action (McCauley 1973; Arvidson 1976), two main models have been proposed to account for the fluidized nature of layered ejecta deposits on Mars: 1) vaporization of volatiles in the subsurface produces a volatile-rich vapor plume which causes the entrained ejecta to flow following initial ballistic deposition (e.g., Carr et al. 1977; Wohletz and Sheridan 1983); and 2) interaction of the ejecta curtain with the Martian atmosphere creates a vortex ring, which then entrains, transports, and deposits the ejecta in successive flows, with the fine-grained material forming the upper layers (e.g., Schultz and Gault 1979; Schultz 1992; Barnouin-Jha and Schultz 1998). In both these models, the fluidized, multiple layers of ejecta are formed via interaction of the primary ballistic ejecta curtain with some medium. Given that neither of these two models can explain all the observations, Barlow (2005a) suggested that a combination of the two processes was probably responsible.

The contribution of impact melt to proximal ejecta deposits has not received much attention to date. As with crater-fill impactites, the sedimentary, volatile-rich nature of the Martian crust has generally been assumed to preclude the formation of significant impact melt (Kieffer and Simonds 1980), thus resulting in melt-poor or melt-free proximal impactites (i.e., lithic impact breccias or suevites). Based on studies of terrestrial impact glasses derived from Argentine loess deposits (Schultz et al. 1998), Schultz and Mustard (2004) suggested that large, meter-size vesicular glass bombs should be formed on Mars and incorporated into proximal ejecta deposits. Such deposits could be termed suevites (Fig. 1). Schultz and Mustard (2004) reinterpreted the “dark [in visible wavelengths], blocky ejecta and rays around small (<0.5 km) craters” on Mars as impact melts and melt breccias. Drawing analogies with the Argentine impact glasses, these authors also suggested that darker streaks emerging from ejecta facies around larger Martian impact craters might also represent impact-melt glasses.

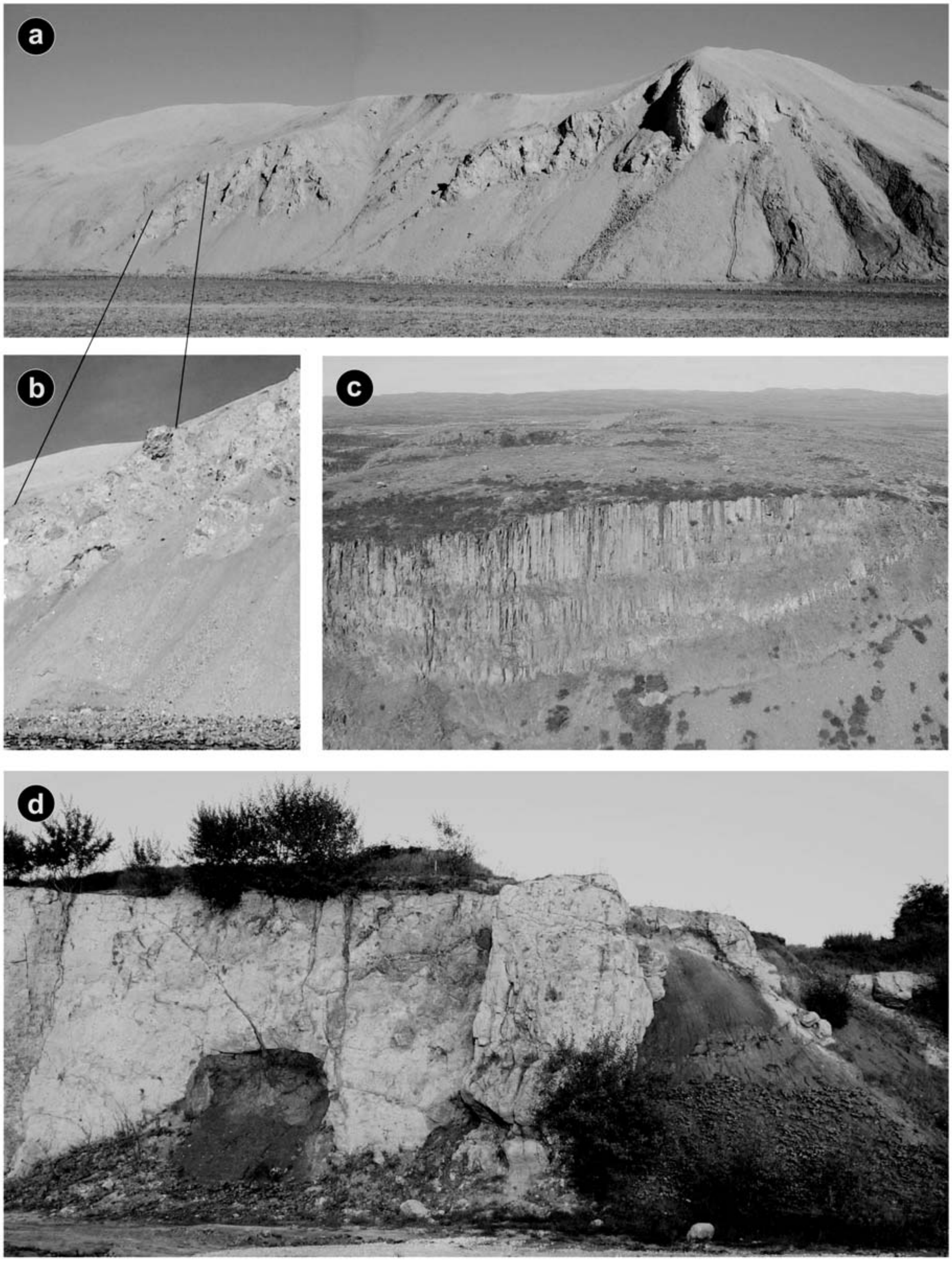

Fig. 2. a) A field photograph of a well-exposed cross-section through the base of the crater-fill impact-melt breccias at the Haughton impact structure, Nunavut. The vertical distance to the highest point is 35 m. b) A close-up view of the crater-fill impact-melt breccias. Note the large, meter-size clasts of sedimentary lithologies (Figs. 2a and 2b are modified after Osinski et al. 2005b). c) An 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. d) A field photograph of the east wall of the Aumühle quarry near the northern rim of the Ries impact structure. Note the sharp irregular contact between the suevite (light gray/green) and underlying Bunte breccia (dark brown/red). The height to the top of the outcrop is ~9.5 m.

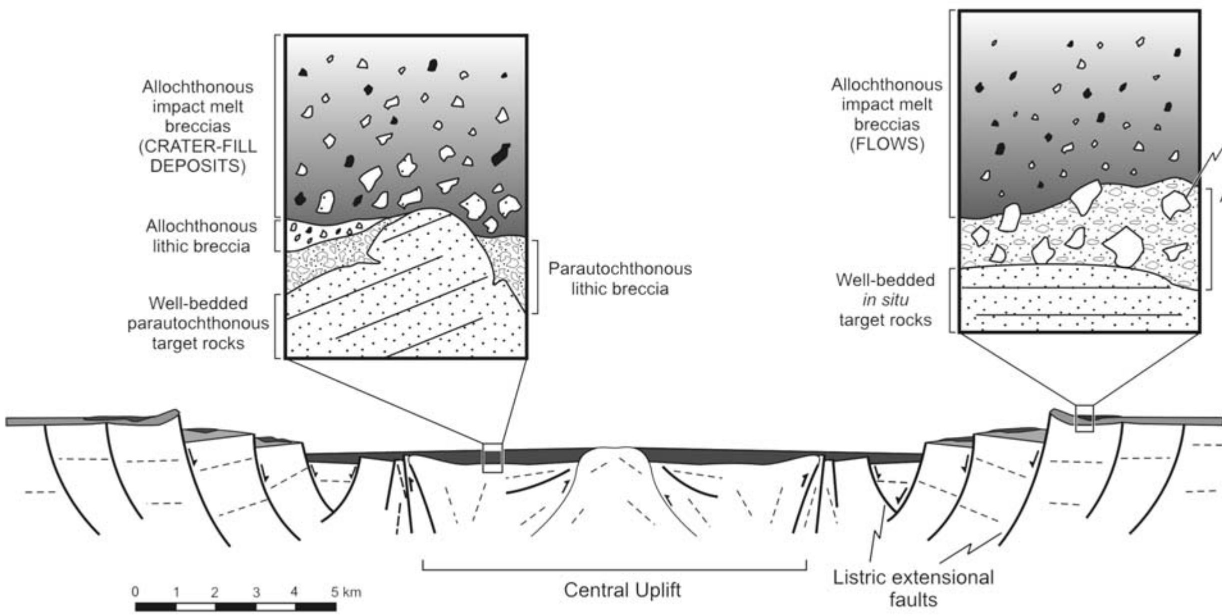

Fig. 3. A schematic cross-section of the Haughton impact structure, modified after Osinski et al. (2005a). The insets show the different types of impactites and their stratigraphic sequence in the crater interior and near-surface crater rim region.

Observations from Terrestrial Impact Structures

Due to postimpact erosional processes there are, unfortunately, no impact craters >1 km in diameter with pristine ejecta deposits on Earth. Nonetheless, several relatively young (<65 Myr), well-preserved impact structures developed in a range of different target rocks are known from the terrestrial impact-cratering record. Three of the best and most-studied complex impact craters are the similarly sized Ries impact structure, Germany and the Haughton impact structure, Canada, and the much larger Chicxulub impact structure, Mexico. Other younger complex impact structures, such as Zhamanshin, Kazakhstan, may also provide good analogies to Mars, but the lack of detailed field studies hampers such comparisons. In terms of ejecta deposits associated with small, simple impact craters (i.e., <2–4 km diameter on Earth), Meteor Crater, Arizona, and Lonar crater, India, may offer some important insights.

Ries Impact Structure

The Ries impact structure, Germany, which is ~24 km in diameter and ~14.5 Myr old, is one of the best-preserved terrestrial impact structures. The Ries target sequence comprises ~500–800 m of sedimentary rocks (carbonates, sandstones, shales) overlying crystalline basement (Schmidt-Kaler 1978). The structure possesses a thick sequence of crater-fill impactites ("crater suevite") and three main types of proximal ejecta (Table 3) (Pohl et al. 1977): 1) Bunte breccia, 2) surficial, or "fallout," suevites, and 3) coherent impact-melt rocks. The latter two lithologies are stratigraphically equivalent and overlie Bunte breccia, with a very sharp contact between the two formations (Fig. 2c). According to the terminology of Barlow et al. (2000), Ries can, therefore, be classified as a DLE structure.

The Bunte breccia is a poorly sorted, glass-free polymict breccia, derived predominantly from the uppermost sedimentary target lithologies (Table 3) (Hörz 1982; Hörz et al. 1983). Bunte breccia is volumetrically the most abundant type of proximal ejecta and consists of two main components (Hörz et al. 1983): 1) ~31 vol% primary ejecta excavated from the initial crater, which comprises predominantly sedimentary rocks with minor admixtures of crystalline rocks; and 2) ~69 vol% local material or "secondary ejecta," derived from where the primary ejecta was initially deposited and subsequently mobilized and incorporated by the secondary cratering action of the primary ejecta (Hörz et al. 1983). Thus, the Bunte breccia was emplaced via a combination of ballistic deposition and subsequent radial flow.

Surficial suevites were deposited on an uneven upper Bunte breccia surface that had several meters relief (Fig. 2c) (von Engelhardt et al. 1995). The groundmass of suevites was originally thought to be clastic in nature (e.g., von Engelhardt 1990; von Engelhardt et al. 1995); however, analytical data and microtextures indicate that calcite, silicate glass, francolite (carbonate-hydroxy-fluor-apatite), and clay minerals of the groundmass of the Ries suevites represent a series of impact-generated melts that were molten at the time of, and following, deposition (Osinski et al. 2004). In terms of the depth of origin of clasts and melt phases, suevites are derived from deeper in the target sequence than Bunte breccia (Table 3). In contrast to the Bunte breccia, the emplacement

Table 1. Summary of the various types of impactites at Haughton and their characteristics. From Osinski et al. (2005a).

	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	Gray allochthonous impact-melt breccias
Physical characteristics					
Present distribution (km^2)	<1	<1	53.8	<1.5	1.28
Estimated original distribution (km^2)	>30	~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)	~0.7	~0.1	7	0.2	0.1
Estimated original volume (km^3)	>2	~0.5	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 up 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

Abbreviations: av. = average; N/A = not applicable.

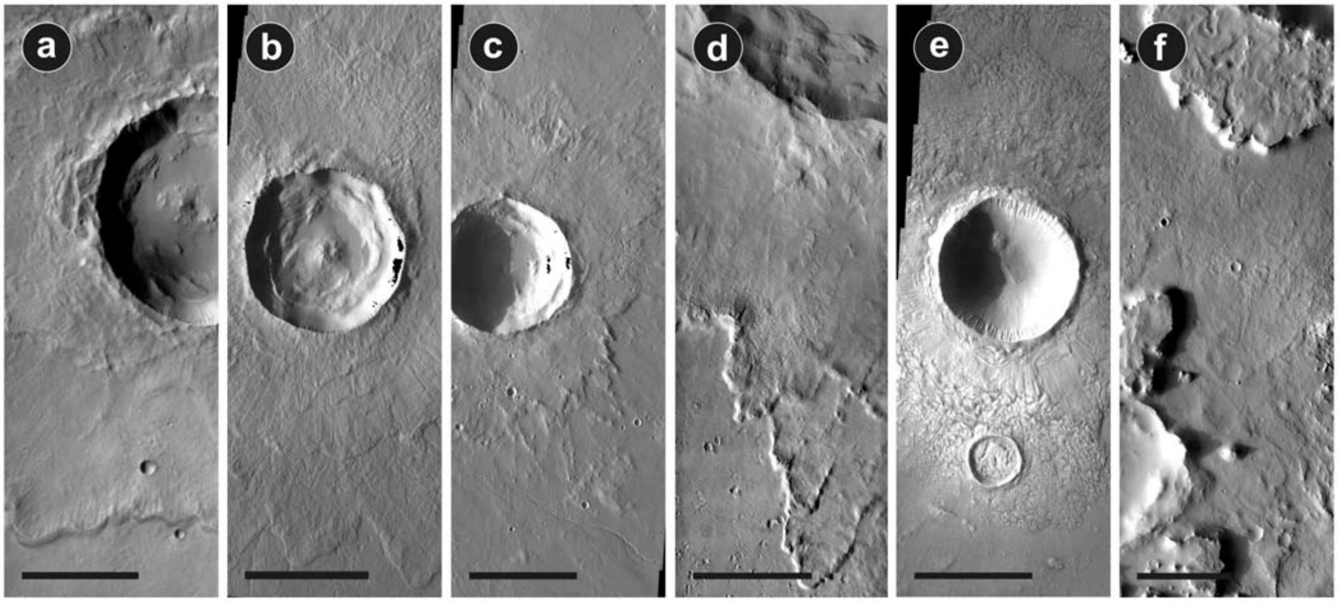

Fig. 4. A series of THEMIS visible images (Christensen et al. 2004) showing various aspects of Martian layered ejecta structures. All scale bars are 10 km. North is up in each image. a) A typical single-layer ejecta (SLE) structure with a pronounced rampart at the outer edge of the ejecta layer. A portion of THEMIS image V04333003. b) This central peak crater is surrounded by two distinct layers of ejecta, classifying it as a double-layer ejecta (DLE) structure. A portion of THEMIS image V05199007. c) A multiple-layer ejecta (MLE) structure. A portion of THEMIS image V05962014. d) A close-up of an SLE or DLE structure showing the well-developed rampart. A portion of THEMIS image V01990003. e) The layered ejecta around this crater has flow around and into the smaller crater to the south, yielding evidence for relatively thin ground-hugging debris flows. A portion of THEMIS image V13277010. f) The mesa-like features and the top and bottom of this image are, in fact, eroded remnants of the ejecta deposits around two so-called "perched" or "pedestal" craters. A portion of THEMIS image V06029018. Image credits: NASA/JPL/ASU.

mechanism(s) of the suevites is less well understood. It was generally accepted that these impactites were deposited subaerially from an ejecta plume (Pohl et al. 1977; von Engelhardt 1990). However, recently, it has been shown that surficial suevites were emplaced as surface flow(s), either comparable to pyroclastic flows (Newsom et al. 1990; Bringemeier 1994), or as a ground-hugging impact melt-rich flows that were emplaced outwards from the crater center during the final stages of crater formation (Osinski et al. 2004). This has also been suggested for the impact-melt rocks at the Ries, which also form part of the proximal ejecta deposits (Osinski 2004). Importantly, the Ries impact-melt rocks were derived entirely from the crystalline basement, whereas the volumetrically dominant suevites incorporated substantial amounts of volatiles from the sedimentary cover (i.e., the Ries suevites represent volatile-bearing melt-rich flows; Osinski et al. 2004). It is notable that the volatiles were incorporated into the suevites in the form of volatile (H_2O, CO_2)-rich melts, predominantly carbonate melt phases and hydrous impact glasses (Osinski et al. 2004).

Haughton Impact Structure

A similar record of ejecta deposition is seen at the Haughton structure. Two principal proximal ejecta types have been recognized in the near-surface crater rim region of Haughton (Fig. 3; Table 1), signifying that this is a DLE structure (Barlow et al. 2000). Pale yellow-brown allochthonous impact-melt breccias and megablocks are overlain by pale gray impact-melt breccias (Osinski et al. 2005b). The former are interpreted as remnants of the continuous ejecta blanket, emplaced via a combination of ballistic deposition and subsequent radial flow. The pale gray impact-melt breccias are analogous to the surficial suevites at the Ries structure and are interpreted as melt-rich ground-hugging surface flows emplaced outwards from the crater center during the final stages of crater formation (Osinski et al. 2005b).

Chicxulub Impact Structure

The Chicxulub structure, Mexico, which is ~180 km in diameter and 65 Myr old, formed in a thick sequence (~3 km) of sedimentary rocks, predominantly carbonates and evaporites, overlying crystalline basement (Ward et al. 1995). As with the Haughton and the Ries structures, Chicxulub possesses two main types of proximal ejecta deposit (Sharpton et al. 1996; Kring 2005): 1) allochthonous polymict impact breccias up to ~300 m in thickness of low shock level that are interpreted as the continuous ejecta blanket, analogous to the Bunte breccia at the Ries structure; and 2) suevite deposits up to ~150 m in thickness that overlie the Bunte breccia–like deposits. The emplacement mechanism(s) of these impactites has not been addressed in any detail,

Table 2. Summary of the important attributes of Martian single-layered (SLE), double-layered (DLE), and multiple-layered (MLE) ejecta structures.

Property	SLE[a]	DLE[b]	MLE[c]
Abundance[d]	86%	9%	5%
Diameter range for source impact craters	~3–25 km within equatorial regions, but <1 km to >50 km at higher latitudes	~5–30 km	~15–60 km
Geographic distribution	Global	~25–60° N and S	Equatorial regions
Dependence on elevation?	No	No	No
Dependence on terrain type?	No	No	No
Dependence on terrain age?	No	No	No
Extent of ejecta[e]	1.5	1.5, inner layer 3.2, outer layer	2.2
Ramparts?	Yes	Yes; large on inner layer, small on outer	Yes

[a]Data from Barlow and Perez (2003) and Barlow (2005a).
[b]Data from Barlow and Bradley (2000); Barlow (2005a); Boyce and Mouginis-Mark (2005).
[c]Data from Barlow (2005a).
[d]Expressed as the proportion of those Martian impact structures displaying a layered ejecta morphology.
[e]Expressed using the average ejecta mobility (EM) ratio (=average extent of continuous ejecta layer/crater radius).

although Sharpton et al. (1996) suggested that the lowermost ejecta was emplaced in an analogous way to the Ries Bunte breccia deposits (see above).

The outer portion of the continuous ejecta blanket has been termed the Albion Formation and comprises a basal spheroid bed and an upper diamictite bed (e.g., Pope et al. 1999). Unfortunately, the lack of exposure and drill cores does not allow the exact relationship of the innermost proximal impactites and the Albion Formation to be constrained. The nature and emplacement mechanism(s) of the distal Albion Formation have been studied in detail in recent years. Both the basal spheroid bed and an upper diamictite bed preserve features such as cross-bedding and internal shear planes, indicative of lateral flow outwards from the crater center (e.g., Pope et al. 1999; Schönian et al. 2004). The following depositional model has been proposed by Schönian et al. (2004): following ballistic deposition at <<3 crater radii, ground-hugging flow occurred driven by the water content of the flow itself. At distances of >3.5 crater radii, the incorporation of local clays further fluidized the flow and allowed the flow to continue moving for greater distances than would have been possible if the substrate was resistant bedrock.

Meteor Crater

Possible evidence of fluidized ejecta deposits have been noted around the well-preserved Meteor Crater, 1.2 km in diameter and ~49 kyr old (Grant and Schultz 1993); however, the necessary detailed field studies have not been carried out to date. Meteor Crater formed in a thick series of sandstones and carbonates, without any involvement of crystalline rocks. Both Meteor Crater and Lonar crater (see below) possess one layer of ejecta and can, therefore, be classified as SLE structures, according to the terminology of Barlow et al. (2000).

Lonar Crater

The Lonar crater is a well-preserved simple impact crater ~1.8 km in diameter and ~52 kyr old. The target sequence comprises a thick sequence of basaltic lava flows of the ~65 Myr Deccan Traps (Fredriksson et al. 1973). Recent workers have documented a component of ground-hugging surface flow following ballistic deposition of the ejecta blanket (Stewart et al. 2005); however, the possible contribution of volatiles to the ejecta emplacement process at Lonar is not currently known.

DISTAL EJECTA DEPOSITS

Observations from Martian Impact Structures

By definition, distal ejecta is that deposited >5 crater radii away from the source crater. Schultz and Mustard (2004) explored the possibility of impact melts and glasses on Mars and concluded that it is probable that impact-generated glasses will comprise a substantial proportion of distal impact ejecta deposits, in the form of tektite-like strewnfields and glassy ejecta. These authors suggested that much of the dark mobile materials as seen in visible wavelengths on Mars may represent accumulations of impact melt materials.

Observations from Terrestrial Impact Structures

Distal ejecta deposits on Earth comprise two main types: strewnfields of glassy tektites and microtektites, and spherule beds comprising (formerly) glassy impact spherules and fragments of shocked target rocks. Collectively, these deposits are termed air-fall beds (Fig. 1). Geochemical data suggests that tektites are formed via melting of rocks in the uppermost parts of the target sequence (Koeberl 1994). Of the four tektite strewnfields, two (the Ivory Coast and Central

Table 3. Main attributes of impactites of the Ries impact structure, Germany (modified from Osinski 2005).

	Bunte breccia[a]	Surficial suevite[b]	Crater suevite[c]	Impact-melt rock[d]
Average thickness	~20 to >100 m	~30 m	~300 m	<10 m
Volume	~200 km^3	~0.084 km^3	~15 km^3	?
Radial range	~6 to 37 km	~6 to 22 km	<6 km radius	~9 to 12 km
Distribution of deposits	Continuous	Isolated patches	Continuous	Isolated
Nature of the groundmass	Clastic	Melt	?	Melt
Groundmass phases	N/A	Calcite, glass, clays, crystallites (plagioclase, garnet, pyroxene), francolite, zeolites	Zeolites, clays, K-feldspar	K-feldspar, glass, plagioclase
Total clast content (vol%)	100	30–40	~30–35	<15
Predominant clast type	Sedimentary	Crystalline	Crystalline	Crystalline
Maximum shock level of clasts (GPa)				
Crystalline	<40	~100	~100	
Sedimentary	<10	~100	<10	N/A

[a]Data from Hörz et al. (1983).
[b]Data from Pohl et al. (1977) and Osinski et al. (2004).
[c]Reliable data only available for melt-rich suevite. Data from Stöffler et al. (1977).
[d]Data from Osinski (2004).

European fields) have been linked to source craters (Koeberl 1994).

At least eight Phanerozoic spherule layers have been documented, with several more recognized in the Paleozoic to Cenozoic rock record (Simonson and Glass 2004). Primary glasses are typically replaced by secondary minerals such as clays and carbonates in the majority of the known spherule beds, hampering efforts to distinguish their target protolith. However, impact glasses from the distal ejecta of the Chicxulub structure in Haiti contain up to 30 wt% CaO and 1 wt% SO_2, indicating melting of carbonate-rich and evaporite-rich target rocks (Sigurdsson et al. 1991). As noted by Schultz and Mustard (2004), the recognition of tektite strewnfields and spherule beds demonstrate the substantial contribution of impact glasses to the terrestrial rock record. Unfortunately, on Earth much of this record has been erased by erosion, volcanic resurfacing, and plate tectonics.

DISCUSSION

Impact Melting on Mars

It has been generally assumed that the generation of impact melts on Mars will be limited due to the volatile-rich, sedimentary nature of the Martian crust (e.g., Kieffer and Simonds 1980). However, recent work at several terrestrial impact structures suggests that impact melting in sedimentary target rocks is much more common than previously thought (e.g., Graup 1999; Jones et al. 2000; Osinski and Spray 2001, 2003; Dressler et al. 2004; Osinski et al. 2004, 2005b; Tuchscherer et al. 2004). For example, it is clear from studies at the Haughton structure that sandstones, shales, carbonates, and sulfates can undergo melting during meteorite impact events (Osinski and Spray 2001, 2003; Osinski et al. 2005b). Early observations using the Mars Global Surveyor Mars Orbital Camera showed the presence of layered and massive outcrops on Mars that displayed the geomorphic attributes and stratigraphic relations of sedimentary rocks (Malin and Edgett 2000). Various types of sedimentary rocks, such as basaltic sandstones and sulfate-bearing lithologies, have now been documented at the Mars Exploration Rover landing sites (Squyres et al. 2004). Thus, it is suggested that impact-melt rocks and glasses are likely to be much more common on Mars than previously thought. This is supported by the results of numerical simulations and experiments, which suggest that substantial amounts of melt should be produced from impacts into ground-ice-rich targets on Mars (Pierazzo et al. 2005; Stewart and Ahrens 2005).

What are the implications regarding the types of impactites expected for Mars? Schultz and Mustard (2004) suggested that impact glasses are likely to be an important component of distal ejecta deposits, either in the form of tektites and/or glassy spherules. Based on recent studies of the terrestrial cratering record, it is suggested that crater-fill deposits and proximal ejecta deposits on Mars will also contain substantial amounts of impact-melted material, to the extent that impact-melt breccias, suevites, and coherent impact-melt rocks (Fig. 1) are likely to be present. This is consistent with the observations of so-called “perched” or “pedestal” impact craters on Mars, which are elevated above the surrounding terrain (Fig. 4f). Their preservation suggests a resistant proximal ejecta deposit, which is inconsistent with this material being unconsolidated lithic and fragmental breccias, but which is compatible with a melt-rich ejecta deposit (e.g., impact-melt breccias). Importantly, Barlow (2005b) showed that pedestal craters occur preferentially in ground-ice-rich regions of Mars. Stewart and Ahrens (2005) showed that more melt would be generated during impacts

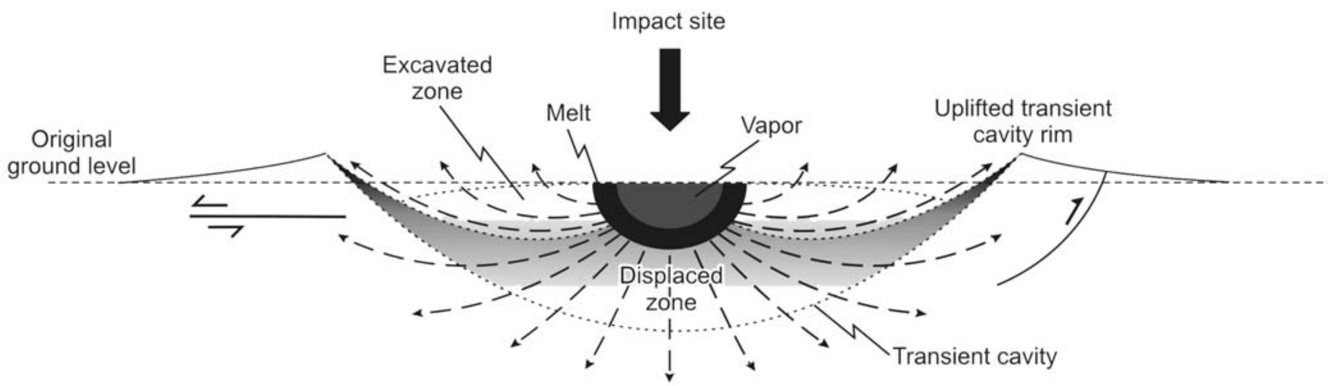

Fig. 5. A theoretical cross-section through a transient cavity showing the locations of impact-metamorphosed target lithologies. Excavation flow lines (dashed lines) open up the crater and result in excavation of material from the upper one-third to one-half the depth of the transient cavity. Modified after Grieve (1987) and Melosh (1989).

into ground-ice-rich targets, compared to "dry" targets resulting in particularly melt-rich ejecta deposits. At the Haughton and Ries structures, such deposits are very well cemented and resistant (e.g., Ries suevites have been used as a building stone for centuries) (Pohl et al. 1977). A similar case can be made for the existence of coherent melt-rich crater-fill deposits from observations of central remnant craters (Newsom 2001).

By analogy with the terrestrial impact-cratering record, it is important to note that the products of impact melting in volatile-rich targets on Mars are not likely to display classic igneous textures and features. Depending on the composition of the target, it is suggested that the melt products will be a combination of hydrous (i.e., H_2O-rich) and/or CaO-SO_2-rich glasses and/or crystalline phases such as carbonate and sulfate minerals. Thus, caution should be exercised when interpreting the presence of sulfates and carbonates as products of sedimentary or hydrothermal processes. Further complications arise as evidence from terrestrial craters indicates that silicate minerals can also crystallize from sediment-derived impact melts, although these phases typically display unusual compositions that vary considerably depending on the composition of the target stratigraphy. For example, the impact melting of sandstones and impure carbonates at Meteor Crater produced impact glasses containing high Ca pyroxenes (Hörz et al. 2002) and almost pure Mg-olivine (Osinski et al. 2003).

Emplacement of Layered, Fluidized Ejecta Deposits

The two main models proposed to account for the formation of fluidized, multiple layers of ejecta around Martian impact craters both invoke the interaction of the primary ballistic ejecta curtain with some medium, either a volatile-rich vapor plume (e.g., Carr et al. 1977; Wohletz and Sheridan 1983; Mouginis-Mark 1987), or the thin Martian atmosphere (e.g., Schultz and Gault 1979; Schultz 1992; Barnouin-Jha and Schultz 1998), although a combination of these two processes has also been suggested (Barlow 2005a). It is important to note that both these models predict that the different layers of ejecta in DLE and MLE Martian impact structures will be derived from the ballistic ejecta curtain, which originates from the excavated zone of the transient cavity (Fig. 5). Therefore, the layers will be lithologically similar, but not necessarily of the same grain size.

Observations of terrestrial impact structures with multiple layers of ejecta are not consistent with the models proposed for Martian layered ejecta structures. At the Chicxulub, Haughton, and Ries structures, the two layers of proximal ejecta are very different in terms of depth of origin of clasts within the transient cavity, in their melt content, and in their style and mechanism of emplacement (e.g., Tables 1 and 3). Furthermore, ejecta deposits around terrestrial impact structures typically preserve evidence for ground-hugging surface flow (Newsom et al. 1986; Bringemeier 1994; Osinski et al. 2004, 2005b; Stewart et al. 2005), also postulated for Mars, so that similar emplacement mechanisms should be expected. Synthesizing this recent work on ejecta deposits surrounding terrestrial impact structures with observations from Mars, a new possible mechanism for the formation of fluidized, layered ejecta deposits on Mars is proposed.

In order to understand the origin of ejecta deposits, it is necessary to understand the concept of the "transient cavity" (Fig. 5) (Dence 1968; Grieve and Cintala 1981). All impact craters, regardless of their final size and on the planetary body on which they form, are understood to entail the generation of a transient cavity (Dence 1968; Grieve and Cintala 1981; Melosh 1989). The transient cavity is partitioned into an upper "excavated zone" and a lower "displaced zone" (Fig. 5). Material in the upper zone is ejected ballistically beyond the transient cavity rim (i.e., this material represents the primary ballistic ejecta), while material in the displaced zone, comprising a mixture of melt and clastic debris, 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 (Stöffler et al. 1975; Grieve et al. 1977). Importantly, it is this material, which does not leave the transient cavity, that forms the crater-fill deposits in complex impact structures (Fig. 5) (Grieve et al. 1977; Osinski et al. 2005b). The ballistic ejecta will contain material from a range of different shock levels, including impact-generated melt, and both clasts and melt in the ejecta will be derived from shallower stratigraphic levels than that which remains in the transient cavity (Fig. 5).

Using the terminology of Barlow et al. (2000) for Martian impact craters, the Ries and Haughton structures are DLE structures. Due to poor exposure, it is unclear as to whether Chicxulub is a DLE or MLE structure. However, it is clear that the lowermost and most areally extensive layers of ejecta at Chicxulub, Haughton, and Ries represent material emplaced via a combination of ballistic deposition and subsequent ground-hugging flow (Hörz 1982; Hörz et al. 1983; Schönian et al. 2004; Osinski et al. 2005b). In other words, primary ballistic ejecta is excavated from the transient crater and incorporates local material or "secondary ejecta" upon deposition; this combined mass then flows for considerable distances outwards from the crater center as a series of debris flows. A similar mechanism has also been suggested for the ejecta deposits surrounding the SLE structures Meteor Crater and Lonar crater (Grant and Schultz 1993; Stewart et al. 2005).

Based on the observations outlined above, it is suggested that SLE deposits and the lowermost ejecta layers in DLE and MLE structures are emplaced in the following manner:

1. A mixture of melted and variably shocked target material originating from the excavated zone of the transient cavity is ejected upwards and outwards on ballistic trajectories (Figs. 6a and 6b).
2. Ballistic sedimentation of the primary ejecta results in the incorporation of local, surficial target materials ("secondary ejecta") derived from the uppermost (tens of meters) part of the target sequence (Fig. 6b).
3. Primary and secondary ejecta mix together and are transported outwards as ground-hugging debris flows.

This emplacement scenario accounts for the observation that secondary craters extend out from underneath layered ejecta blankets but are nowhere seen on top (Fig. 4d) (cf. Hartmann and Barlow 2006). Thus, secondary craters form during the initial ballistic ejecta phase and are subsequently overlain and infilled during the subsequent ground-hugging flow stage. While the model proposed here is similar to those proposed by previous workers (e.g., Carr et al. 1977; Wohletz and Sheridan 1983; Barlow 2005a), this scenario does not invoke the interaction of a volatile-rich vapor plume with the ejecta curtain. Instead, it is suggested that the fluidized nature of these ejecta deposits on Mars is due to two main factors:

1. *Volatile content and cohesiveness of surficial sediments present at the time of impact.* Based on observations at the Ries impact structure, the volatile content and cohesiveness (e.g., resistant bedrock versus unconsolidated material) of the uppermost target (tens of meters to ~100–200 m) outside the transient cavity will govern the efficiency and maximum extent of ground-hugging flow following ballistic deposition and the final volume of ejecta. For example, there is a clear correlation between runout distance and volume of the Bunte breccia at the Ries structure and the characteristics of surficial sediments present at the time of impact. In the north and east of the structure, the Bunte breccia contains low amounts of secondary material (Hörz et al. 1983) due to the fact that the primary ballistic ejecta was deposited onto resistant Malm limestones, which were difficult to erode and incorporate. In the south, where the underlying substrate at the time of impact was unconsolidated clays and sands, Bunte breccia is far more voluminous and flowed for greater distances (Hörz et al. 1983). Thus, the Bunte breccia was "fluidized" to varying degrees by the incorporation of surficial volatile-rich sediments after ballistic deposition, allowing subsequent ground-hugging flow to occur.
2. *Volatile content of target material in the excavated zone of the transient cavity.* Current models for the cratering process predict that primary ballistic ejecta will contain a small component of "highly shocked impact melt" (Melosh 1989). Importantly, the ballistic ejecta at Haughton contains melt derived from sedimentary lithologies (Osinski et al. 2005b). It is known that sedimentary rocks undergo melting at lower pressures and temperatures than crystalline rocks (e.g., Kieffer et al. 1976). Furthermore, recent work by Stewart and Ahrens (2005) reveals that H_2O ice will undergo complete melting at 2.5 ± 0.1 GPa at 263 K and 4.1 ± 0.3 GPa at 100 K, so that the proportion of melt versus shocked target rocks in primary ballistic ejecta will be higher in regions of Mars with substantial ground ice and/or sedimentary rocks. Increased melt contents of primary ballistic ejecta would result in increased runout distances of SLE deposits and the lowermost layers in DLE and MLE craters.

It is suggested that the latter factor is most important in determining the properties of fluidized layered ejecta structures as it could explain two important observations: 1) the large variation in diameter and runout distance of SLE structures, which appears to correspond to the distribution of subsurface ice (Clifford 1993); and 2) the lower average ejecta mobility (EM) of SLE deposits with respect to the outermost layer of DLE structures (Table 2). DLE structures are more common in ground-ice-rich regions of Mars and so the primary ballistic ejecta will contain more melt. Thus, in accord with previous workers (e.g., Carr et al. 1977; Mouginis-Mark 1981; Barlow and Perez, 2003), it is suggested that the relative amount of fluidization of these ejecta deposits reflects differences in the distribution of ground ice; however, the mechanism of emplacement proposed here is different than previous workers.

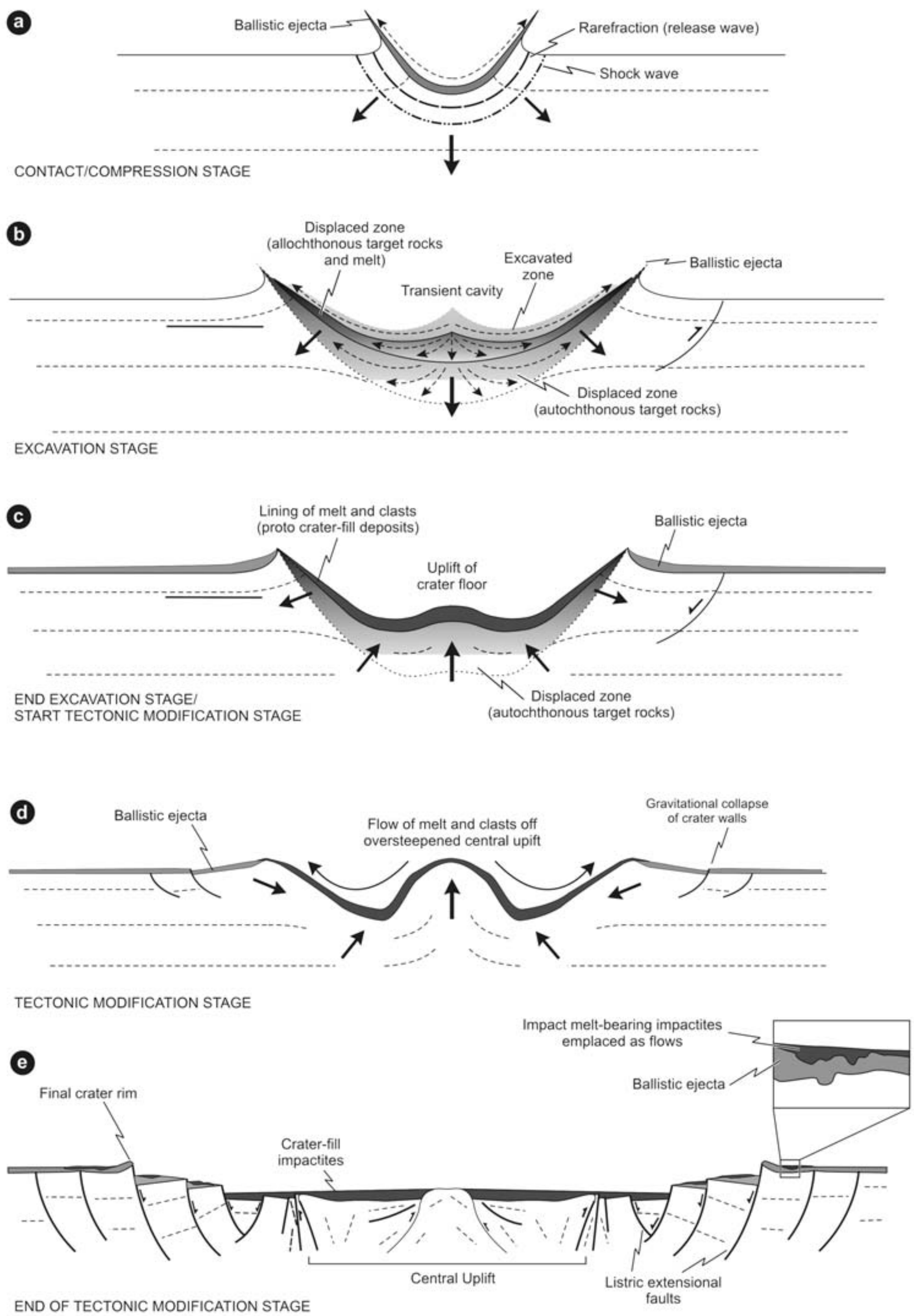

Fig. 6. A series of schematic cross-sections depicting the formation of a generic complex impact structure, based on a model for the formation of the Haughton impact structure (Osinski et al. 2005a). Following the impact of a projectile with a planetary body (a), the intense kinetic energy of the projectile is transferred into the target in the form of a shock wave that propagates both into the target sequence and back into the projectile itself (Melosh 1989). During the subsequent excavation stage (b), a "transient cavity" is opened up by complex interactions between the expanding shock wave and the original ground surface (Melosh 1989). An "excavation flow" results in excavation of material from the upper one-third to one-half the depth of the transient cavity, while in the lower "displaced zone," target material is driven downward and outward and does 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 (c). It is this material that forms allochthonous crater-fill impactites. During the modification stage, the transient cavity is modified by gravitational forces resulting in uplift of the transient crater floor and collapse of crater walls (d). This collapse can impart an outward trajectory to a portion of the impact melt and rock debris lining the transient cavity, resulting in the transport of melt and clasts from the upper reaches of the transient cavity outwards as flows resulting in a second episode of ejecta deposition (d and e). Modified after Grieve (1987), Melosh (1989), French (1998), Osinski and Spray (2005), and Osinski et al. (2005a, 2005b).

In terms of DLE deposits at the Haughton and Ries structures, there are several important aspects of the uppermost ejecta unit to note: 1) it is derived from deeper levels within the target sequence, actually within the displaced zone of the transient cavity and is genetically related to crater-fill impactites (Fig. 5); 2) it is emplaced during the final stages of the impact process (modification stage) after a substantial hiatus (Fig. 6d), hence the sharp contact between the Bunte breccia and suevites at the Ries structure (Fig. 2c); and 3) it is emplaced as a ground-hugging flow(s) outwards from the crater center during the modification stage of crater formation (Figs. 6d and 6e). Based on these observations, a similar mechanism is proposed to account for the formation of DLE and MLE deposits around Martian impact structures:

1. The lowermost, areally extensive layer of DLE and possibly MLE structures is emplaced in the same manner as SLE deposits (see above; Figs. 6a and 6b). Deposition of this first layer of ejecta takes place by the end of the excavation stage (Fig. 6c). A hiatus follows, during which time the original transient cavity undergoes modification by gravitational forces to varying extents that depend on its size.
2. For complex craters, movements associated with the formation of a central uplift and collapse of the crater walls can impart an outward-directed vector to material that remained in the transient cavity during the excavation stage (i.e., within the displaced zone) (Figs. 6c and 6d). This material is transported outwards towards and beyond the final crater rim as ground-hugging flows (Fig. 6d).
3. For small, simple craters, gravitational modification is minor so that any flows will either not make it past the crater rim, or may be patchy and thin and unlikely to be resolvable in orbital data.

This model does not require a target with stratigraphic layers with different concentrations of volatiles (e.g., Costard and Kargel 1995); rather, the formation of multiple layers of ejecta and deposition as flows is a result of the mechanics of complex crater formation (Fig. 6). In terms of the terrestrial impact-cratering record, there is no evidence to date for the interaction of the atmosphere during the formation of SLE and DLE structures. In contrast to the primary ballistic ejecta, the second layer(s) of ejecta emplaced during the modification stage does not incorporate substantial local material during transport as emplacement takes the form of low-velocity ground-hugging flows (Osinski et al. 2004). Instead, the fluidized nature of these later ground-hugging flows is due to impact-generated melt and vapor derived from the target rocks (Osinski et al. 2004, 2005b). Volatile-rich melts, which include water derived from the melting of ground ice, possess low viscosities and low solidus temperatures so that runout distances and volume of melt will be larger than if the melts originated from anhydrous crystalline rocks (Figs. 5, 6b, and 6c).

In the model proposed above, SLE deposits should theoretically form only in simple impact craters (<7 km on Mars) (Garvin et al. 2000), with DLE deposits only being possible around complex impact structures. Clearly this is not the case (Table 2); however, the presence of SLE deposits around complex craters can be accounted for in several ways:

1. *Highly volatile-rich target rocks.* Multiple layers of ejecta could have been deposited, but if the underlying layers are still mobile due to high volatile contents, "mixing" of the different layers could occur. This is compatible with the size-dependence of SLE structures with respect to latitude: SLE deposits are typically found around craters ~5–20 km in diameter within the equatorial region of Mars, where there is thought to be less ground ice, compared to higher latitudes where SLE deposits are found around craters up to ~65 km in diameter (Barlow 2005a).
2. *Sublimation of volatiles from different ejecta layers and postimpact periglacial processes.* This could have obscured the contacts between different ejecta units and resulted in "homogenization" of the different layers.
3. *Volatile-poor deeper lithologies.* This would result in a low melt content and, therefore, lower volume of the ground-hugging flows resulting in patchy second ejecta layers that may not be observable from orbit (i.e., some Martian craters classed as SLE structures may actually have thin, patchy second layers of ejecta). This is the case at the Ries structure where the upper suevite layer (Fig. 2d) is patchy and likely would not be resolvable from orbit. These observations are consistent with the predominance of DLE structures in the northern plains (Mouginis-Mark 1981), where ground ice is thought to be present, and the scarcity of such structures elsewhere on Mars.

DLE deposits may also be present around a small number of simple craters <1 km in diameter on Mars (N. Barlow, personal communication), although this has yet to be documented in detail. If confirmed, this will require further explanation; however, it is notable that many of the examples recognized so far are pedestal craters. The mechanism(s) of ejecta emplacement may, therefore, reflect the unique conditions responsible for the formation of such craters, which remains to be determined.

With respect to MLE structures, as with previous workers, it is suggested that the origin of multiple flows during the modification stage of crater formation is a consequence of heterogeneities in the target sequence of larger impact craters (e.g., presence of ground water at depth) and/or instabilities in flow fronts (e.g., Wohletz and Sheridan 1983; Barlow and Bradley 1990). Indeed, it is clear from recent studies of impactites in the Yaxcopoil-1 drill hole at the ~180 km diameter Chicxulub impact structure, Mexico, that several layers of proximal ejecta can be produced in large impact events (e.g., Dressler et al. 2004; Tuchscherer et al. 2004). The lack of MLE structures on planetary bodies with little or no atmosphere, such as Ganymede (Neal and Barlow 2004), may suggest that ejecta interaction with the atmosphere (e.g., Schultz 1992) contributes to the formation of some MLE structures, although this is not thought to be the case with Chicxulub (Dressler et al. 2004; Tuchscherer et al. 2004).

SUMMARY

Consideration of the terrestrial impact-cratering record reveals that impact melting in volatile-rich targets is much more common than previously thought. Thus, impact-melt-bearing rocks and impact glasses should be common on Mars, not just in distal ejecta deposits as suggested by Schultz and Mustard (2004), but also within proximal ejecta and crater-fill impactites. However, the products of impact melting in the volatile-rich crust of Mars are not likely to display classic igneous textures and features. Instead, unusual (e.g., H_2O-CaO-SO_2-rich) glasses, crystalline phases such as carbonate and sulfate minerals, and silicate minerals with unusual compositions (e.g., Ca-rich pyroxenes) may be present. This will be dependent on the composition of the target rocks.

A new model has been proposed that may account for the origin of layered, fluidized ejecta structures on Mars. This model invokes the presence of subsurface and near-surface volatiles to account for the fluidized nature of these ejecta deposits, in agreement with previous workers (e.g., Carr et al. 1977; Wohletz and Sheridan 1983; Mouginis-Mark 1987; Barlow and Bradley 1990; Barlow and Perez 2003). Atmospheric interaction with the ejecta curtain appears to have no, or very little, effect on ejecta deposition around SLE and DLE structures. However, in contrast to previous workers who invoked the interaction of the ejecta curtain with a volatile-rich vapor plume, it is suggested that the formation of multiple fluidized flows is a result of the mechanics of complex crater formation in which two main episodes of ejecta deposition occur: 1) ballistic ejection and deposition of primary ejecta followed by incorporation of secondary ejecta and ground-hugging flow during the excavation stage, and 2) emplacement of ground-hugging flows outwards from the transient cavity during the modification stage. It is suggested that the different degrees of fluidization in different ejecta layers at the same crater and between different craters is controlled by two main properties: 1) volatile content and cohesiveness of surficial (uppermost tens of meters to perhaps 200 m) target present at the time of impact; and 2) volatile content of the target rocks within different regions of the transient cavity, which controls the amount of melt (including H_2O "melt" from ground ice) generated.

Further comparative studies using terrestrial analogues for Martian impact structures are planned. It is hoped that this work will stimulate discussion and a transfer of ideas between the Martian and terrestrial impact-cratering communities.

Acknowledgments–The author thanks the many individuals and institutions that have facilitated and funded fieldwork at various terrestrial impact structures, which forms the basis for this study. The author is supported by Canadian Space Agency (CSA) Space Science Research Project 05P-07. Nadine Barlow and Shawn Wright are thanked for their thorough and constructive reviews.

Editorial Handling—Dr. Nadine Barlow

REFERENCES

Arvidson R. E., Coradini M., Carusi A., Coradini A., Fulchignoni M., Federico C., Funiciello R., and Salomone M. 1976. Latitudinal variation of wind erosion of crater ejecta deposits on Mars. *Icarus* 27:503–516.

Barlow N. G. 2005a. A review of Martian impact crater ejecta structures and their implications for target properties. In *Large meteorite impacts III,* edited by Kenkmann T., Hörz F., and Deutsch A. Boulder, Colorado: Geological Society of America. pp. 433–442.

Barlow N. G. 2005b. A new model for pedestal crater formation (abstract #3041). Workshop on the Role of Volatiles and Atmospheres on Martian Impact Craters. pp. 17–18.

Barlow N. G. and Bradley T. L. 1990. Martian impact craters: Correlations of ejecta and interior morphologies with diameter, latitude, and terrain. *Icarus* 87:156–179.

Barlow N. G. and Perez C. B. 2003. Martian impact crater ejecta morphologies as indicators of the distribution of subsurface volatiles. *Journal of Geophysical Research,* doi:10.1029/2002JE002036.

Barlow N. G., Boyce J. M., Costard F. M., Craddock R. A., Garvin J. B., Sakimoto S. E. H., Kuzmin K. O., Roddy D. J., and Soderblom L. A. 2000. Standardizing the nomenclature of Martian impact crater ejecta morphologies. *Journal of Geophysical Research* 105:26,733–26,738.

Barnouin-Jha O. S. and Schultz P. H. 1998. Lobateness of impact ejecta deposits from atmospheric interactions. *Journal of Geophysical Research* 103:25,739–25,756.

Boyce J. M. and Mouginis-Mark P. J. 2005. Martian craters viewed by the THEMIS instrument: Double-layer ejecta craters (abstract #3009). Workshop on the Role of Volatiles and Atmospheres on Martian Impact Craters. pp. 27–28.

Bringemeier D. 1994. Petrofabric examination of the main suevite of the Otting Quarry, Nördlinger Ries, Germany. *Meteoritics* 29:417–422.

Carr M. H. 1977. Distribution and emplacement of ejecta around Martian impact craters. In *Impact and explosion cratering,* edited by Roddy D. J., Pepin R. O., and Merrill R. B. New York: Pergamon Press. pp. 593–602.

Carr M. H., Crumpler L. S., Cutts J. A., Greeley R., Guest J. E., and Masursky H. 1977. Martian impact craters and emplacement of ejecta by surface flow. *Journal of Geophysical Research* 82:4055–4065.

Christensen P. R., Jakosky B. M., Kieffer H. H., Malin M. C., McSween H. Y., Jr., Nealson K., Mehall G. L., Silverman S. H., Ferry S., Caplinger M., and Ravine M. 2004. The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey mission. *Space Science Reviews* 110:85–110.

Clifford S. M. 1993. A model for the hydrologic and climatic behavior of water on Mars. *Journal of Geophysical Research* 98:10,973–11,016.

Costard F. M. and Kargel J. S. 1995. Outwash plains and thermokarst on Mars. *Icarus* 114:93–112.

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, Maryland: Mono Book Corp. pp. 169–184.

Dressler B. O., Sharpton V. L., Schwandt C. S., and Ames D. E. 2004. Impactites of the Yaxcopoil-1 drilling site, Chicxulub impact structure: Petrography, geochemistry, and depositional environment. *Meteoritics & Planetary Science* 39:857–878.

Fredriksson K., Dube A., Milton D. J., and Balasundaram M. S. 1973. Lonar Lake, India: An impact crater in basalt. *Science* 180:862–864.

French B. M. 1998. *Traces of catastrophe: A handbook of shock-metamorphic effects in terrestrial meteorite impact structures.* Houston: Lunar and Planetary Institute. 120 p.

Garvin J. B., Sakimoto S. E. H., Frawley J. J., and Schnetzler C. 2000. North polar region craterforms on Mars: Geometric characteristics from the Mars Orbiter Laser Altimeter. *Icarus* 144:329–352.

Gault D. E. and Greeley R. 1978. Exploratory experiments of impact craters formed in viscous-liquid targets: Analogs for Martian rampart craters? *Icarus* 34:486–495.

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

Grant J. A. and Schultz P. H. 1992. Erosion of ejecta at Meteor Crater, Arizona. *Journal of Geophysical Research* 98:15,033–15,047.

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

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.

Hartmann W. K. and Barlow N. G. 2006. Nature of the Martian uplands: Effect on Martian meteorite age distribution and secondary cratering. *Meteoritics & Planetary Science* 41. This issue.

Hörz F. 1982. Ejecta of the Ries crater, Germany. In *Geological implications of impacts of large asteroids and comets on the Earth,* edited by Silver L. T. and Schultz P. H. Boulder, Colorado: Geological Society of America. pp. 39–55.

Hörz F., Ostertag R., and Rainey D. A. 1983. Bunte breccia of the Ries: Continuous deposits of large impact craters. *Reviews of Geophysics and Space Physics* 21:1667–1725.

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.

Hüttner R. and Schmidt-Kaler H. 1999. Erläuterungen zur geologischen Karte des Rieses 1:50,000. *Geologica Bavarica* 104:7–76.

Jones A. P., Claeys P., 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. 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.

Kieffer S. W., Phakey D. P., and Christie J. M. 1976. Shock processes in porous quartzite: Transmission electron microscope observations and theory. *Contributions to Mineralogy and Petrology* 59:41–93.

Koeberl C. 1994. Tektite origin by hypervelocity asteroidal or cometary impact: Target rocks, source craters, and mechanisms. In *Large meteorite impacts and planetary evolution,* edited by Dressler B. O., Grieve R. A. F. and Sharpton V. L. Boulder, Colorado: Geological Society of America. pp. 133–152.

Kring D. A. 2005. Hypervelocity collisions into continental crust composed of sediments and an underlying crystalline basement: Comparing the Ries (~24 km) and Chicxulub (~180 km) impact craters. *Chemie der Erde* 65:1–46.

Malin M. C. and Edgett K. S. 2000. Sedimentary rocks of early Mars. *Science* 290:1927–1937.

McCauley J. F. 1973. Mariner 9 evidence for wind erosion in the equatorial and mid-latitude regions of Mars. *Journal of Geophysical Research* 78:4123–4136.

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.

Mouginis-Mark P. 1981. Ejecta emplacement and modes of formation of Martian fluidized ejecta craters. *Icarus* 45:60–76.

Mouginis-Mark P. 1987. Water or ice in the Martian regolith? Clues from rampart craters seen at very high resolution. *Icarus* 71:268–286.

Neal J. E. and Barlow N. G. 2004. Layered ejecta craters on Ganymede: Comparisons with Martian analogs (abstract #1121). 35th Lunar and Planetary Science Conference. CD-ROM.

Newsom H. E. 2001. Central remnant craters on Mars—Localization of hydrothermal alteration at the edge of crater floors? (abstract #1402). 32nd Lunar and Planetary Science Conference. CD-ROM.

Newsom H. E., Graup G., Iseri D. A., Geissman J. W., and Keil K. 1990. The formation of the Ries impact structure, West Germany: Evidence of atmospheric interactions during a large cratering event. In *Global catastrophes in Earth history: An interdisciplinary conference on impacts, volcanism, and mass mortality,* edited by Sharpton V. L. and Ward P. D. Boulder, Colorado: Geological Society of America. pp. 195–205.

Osinski G. R. 2004. Impact melt flows on Earth? Evidence from the Ries impact structure, Germany. *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 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 complex crater formation as revealed by the Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40:1813–1834.

Osinski G. R., Bunch T. E., and Wittke J. 2003. Evidence for shock melting of carbonates from Meteor Crater, Arizona. *Meteoritics & Planetary Science* 38:A42.

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

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

Pierazzo E., Artemieva N. A., and Ivanov B. A. 2005. Starting conditions for hydrothermal systems underneath Martian craters: Hydrocode modeling. In *Large meteorite impacts III,* edited by Kenkmann T., Hörz F., and Deutsch A. Boulder, Colorado: Geological Society of America. pp. 443–457.

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.

Pope K. O., Ocampo A. C., Fischer A. G., Alvarez W., Fouke B. W., Webster C. L., Vega F. J., Smit J., Fritsche A. E., and Claeys P. 1999. Chicxulub impact ejecta from Albion Island, Belize. *Earth and Planetary Science Letters* 170:351–364.

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

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

Schönian F., Stöffler D., and Kenkmann T. 2004. The fluidized Chicxulub ejecta blanket, Mexico: Implications for Mars (abstract #1848). 35th Lunar and Planetary Science Conference. CD-ROM.

Schultz P. H. 1992. Atmospheric effects on ejecta emplacement. *Journal of Geophysical Research* 97:11,623–11,662.

Schultz P. H. and Gault D. E. 1979. Atmospheric effects on Martian ejecta emplacement. *Journal of Geophysical Research* 84:7669–7687.

Schultz P. H. and Mustard J. F. 2004. Impact melts and glasses on Mars. *Journal of Geophysical Research,* doi:10.1029/2002JE002025, 2004.

Schultz P. H., Zarate M., Hames W. E., Camilión C., and King J. 1998. A 3.3 Ma impact in Argentina and possible consequences. *Science* 282:261–263.

Sharpton V. L., Marin L. E., Carney J. L., Lee S., Ryder G., Schuraytz B. C., Sikora P., and Spudis P. D. 1996. A model of the Chicxulub impact basin based on evaluation of geophysical data, well logs, and drill core samples. In *The Cretaceous-Tertiary event and other catastrophes in Earth history,* edited by Ryder G., Fastovsky D., and Gartner S. Boulder, Colorado: Geological Society of America. pp. 55–74.

Sigurdsson H., d'Hondt S., Arthur M. A., Bralower T. J., Zachos J. C., von Fassen M., and Channell J. E. T. 1991. Glass from the Cretaceous/Tertiary boundary on Haiti. *Nature* 349:482–487.

Simonson B. M. and Glass B. P. 2004. Spherule layers—Records of ancient impacts. *Annual Review of Earth and Planetary Science* 32:329–361.

Squyres S. W., Clifford S. M., Kuzmin, R. O., Zimbelman J. R., and Costard F. M. 1992. Ice in the Martian regolith. In *Mars,* edited by Kieffer H. H., Jakosky B. M., Snyder C. W., and Matthews M. S. Tucson, Arizona: The University of Arizona Press. pp. 523–554.

Squyres S. W., Arvidson R. E., Bel J. F. III, Bruckner J., Cabrol N. A., Calvin W., Carr M. H., Christensen P. R., Clark B. C., Crumpler L., Des Marais D. J., d'Uston C., Economou T., Farmer J., Farrand W., Folkner W., Golombek M., Gorevan S., Grant J. A., Greeley R., Grotzinger J., Haskin L., Herkenhoff K. E., Hviid S., Johnson J., Klingelhofer G., Knoll A., Landis G., Lemmon M., Li R., Madsen M. B., Malin M. C., McLennan S. M., McSween H. Y., Jr., Ming D. W., Moersch J., Morris R. V., Parker T., Rice J. W., Jr., Richter L., Rieder R., Sims M., Smith M., Smith P., Soderblom L. A., Sullivan R., Wanke H., Wdowiak T., Wolff M., and Yen A. 2004. The Spirit Rover's Athena Science Investigation at Gusev crater, Mars. *Science* 305:794–799.

Stewart S. T., Louzada K. L., Maloof A. C., Newsom H. E., Weiss B. P., and Wright S. P. 2005. Field observations of ground-hugging ejecta flow at Lonar crater, India (abstract #3045). Workshop on the Role of Volatiles and Atmospheres on Martian Impact Craters. CD-ROM.

Stewart S. T. and Ahrens T. J. 2005. Shock properties of H_2O ice. *Journal of Geophysical Research,* doi:10.1029/2004JE002305, 2005.

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. pp. 89–90.

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.

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.

Strom R. G., Croft S. K., and Barlow N. G. 1992. The Martian impact-cratering record. In *Mars,* edited by Kieffer H. H., Jakosky B. M., Snyder C. W., and Matthews M. S. Tucson, Arizona: The University of Arizona Press. pp. 383–423.

Tuchscherer M. G., Reimold W. U., Koeberl C., Gibson R. L., and de Bruin D. 2004. First petrographic results on impactites from the Yaxcopoil-1 borehole, Chicxulub structure, Mexico. *Meteoritics & Planetary Science* 39:899–931.

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

von Engelhardt W., 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.

Wohletz K. H. and Sheridan M. F. 1983. Martian rampart crater ejecta: Experiments and analysis of melt-water interaction. *Icarus* 56:15–37.

Ward P. D., Keller G., Stinnesbeck W., and Adatte T. 1995. Yucatan subsurface stratigraphy: Implications and constraints for the Chicxulub impact. *Geology* 23:873–876.