Meteoritics & Planetary Science 41, Nr 10, 1613–1624 (2006)
Abstract available online at http://meteoritics.org

Chesapeake Bay impact structure: Morphology, crater fill, and relevance for impact structures on Mars

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(Received 28 September 2005; revision accepted 26 July 2006)

Abstract–The late Eocene Chesapeake Bay impact structure (CBIS) on the Atlantic margin of Virginia is one of the largest and best-preserved "wet-target" craters on Earth. It provides an accessible analog for studying impact processes in layered and wet targets on volatile-rich planets. The CBIS formed in a layered target of water, weak clastic sediments, and hard crystalline rock. The buried structure consists of a deep, filled central crater, 38 km in width, surrounded by a shallower brim known as the annular trough. The annular trough formed partly by collapse of weak sediments, which expanded the structure to ~85 km in diameter. Such extensive collapse, in addition to excavation processes, can explain the "inverted sombrero" morphology observed at some craters in layered targets.

The distribution of crater-fill materials in the CBIS is related to the morphology. Suevitic breccia, including pre-resurge fallback deposits, is found in the central crater. Impact-modified sediments, formed by fluidization and collapse of water-saturated sand and silt-clay, occur in the annular trough. Allogenic sediment-clast breccia, interpreted as ocean-resurge deposits, overlies the other impactites and covers the entire crater beneath a blanket of postimpact sediments.

The formation of chaotic terrains on Mars is attributed to collapse due to the release of volatiles from thick layered deposits. Some flat-floored rimless depressions with chaotic infill in these terrains are impact craters that expanded by collapse farther than expected for similar-sized complex craters in solid targets. Studies of crater materials in the CBIS provide insights into processes of crater expansion on Mars and their links to volatiles.

INTRODUCTION, STRUCTURE, AND MORPHOLOGY

The late Eocene Chesapeake Bay impact structure (CBIS) on the Atlantic margin of Virginia (Fig. 1) may be Earth's best-preserved large impact crater formed in a shallow marine, siliciclastic, continental-shelf environment (Powars and Bruce 1999; Horton et al. 2005a, 2005c). It is the largest impact crater known in the United States and one of the best-preserved "wet-target" craters on Earth (Koeberl et al. 1996; Poag 1997, 1999; Poag et al. 1994, 1999, 2004; Powars and Bruce 1999). As an example of a large planetary impact structure, this complex crater has special features that make it an accessible analog for understanding impact processes in layered and/or wet targets on volatile-rich planets such as Mars (Ormö et al. 2004; Horton et al. 2005d; Kenkman and Schönian 2005). Geologic evidence indicates that Mars is rich in water and other volatiles, that its surface has been significantly modified by the action of liquid water, and that substantial amounts of water still reside beneath the surface as permafrost and ground ice (Carr and Schaber 1977; Squyres and Carr 1986; Squyres 1989; Clifford 1993).

The CBIS formed in a layered target of water ≤340 m in depth (Horton et al. 2005c), weak clastic sediments >400 m in thickness (Powars et al. 2003), and crystalline rock (details in Horton et al. 2005a). It is well-preserved beneath about 150 to 400 m of postimpact sediments (Horton et al. 2005c; Powars et al. 2005). The general shape of the ~85 km wide buried structure is commonly compared to an inverted sombrero (Powars and Bruce 1999). The inverted sombrero morphology of the CBIS is expressed as a filled central crater (~38 km wide, ~1.6 km deep) in the crystalline basement and overlying sediments surrounded by a shallower brim (Fig. 1). This circular brim is known as the annular trough (Powars and

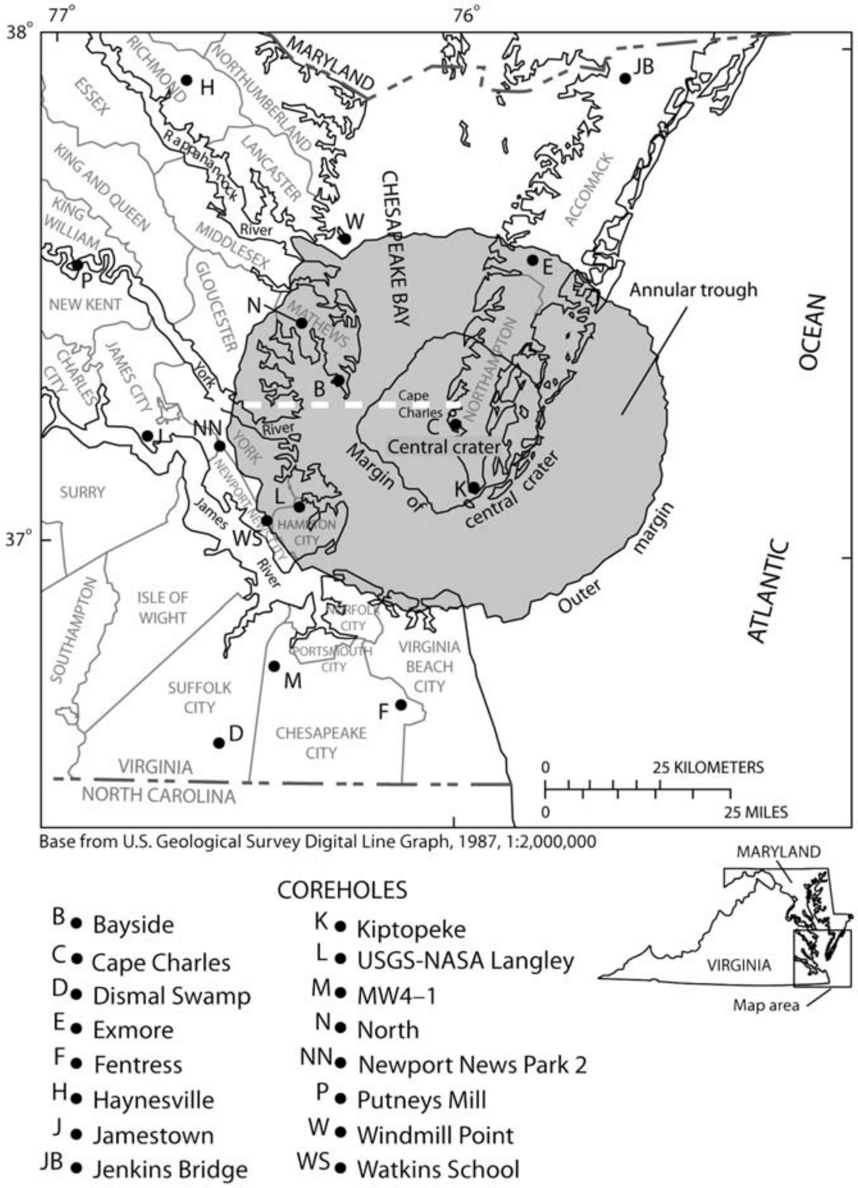

Fig. 1. A map showing the location of the Chesapeake Bay impact structure and coreholes in southeastern Virginia. The white dashed line indicates the approximate location of the interpretive cross-section in Fig. 2. Locations of the central crater and outer margin are from Powars and Bruce (1999). Modified from Horton et al. (2005c, Fig. A1).

Bruce 1999), although it is not a trough in the sense of a linear depression bounded by walls on two sides. The central crater has a relatively steep outer margin, and it contains an elliptical moat that encircles a broad central uplift (Fig. 2) (Horton et al. 2004, 2005b). The inverted sombrero morphology of the CBIS is attributed to differences in strength of rocks and sediments in the layered target affecting the crater modification (Collins and Wünnemann 2005; Horton et al. 2005c). Similar inverted sombrero morphologies, however, may be produced by shallow excavation, as interpreted for some other complex craters on Earth (Melosh 1989) and Mars (Ormö et al. 2004). Ormö and Lindström (2000) made a distinction between inverted sombrero type craters (or concentric craters) that obtained their morphology by slumping and those that obtained it from a shallow excavation flow. Both processes involve an upper weak target layer.

The annular trough is a prominent feature of the CBIS; it formed by the extensive collapse of thick, poorly consolidated sediments (Horton et al. 2005a). The collapse expanded the structure to a diameter far exceeding the transient cavity, likely better expressed by the nested central crater (Figs. 1 and 2). In a homogenous solid target, the transient crater of the CBIS (about 28 km, according to Collins and Wünnemann 2005) would have expanded due to collapse by about 60% (Melosh 1989). The central crater diameter of 38 km is slightly smaller than that expected from a 60% expansion

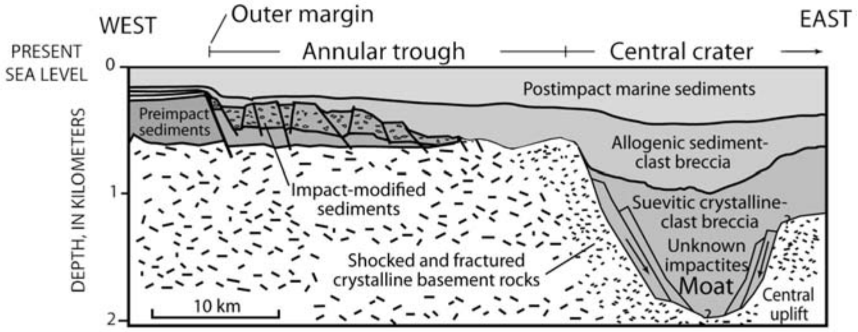

Fig. 2. An interpretive cross-section, western half of Chesapeake Bay impact structure along line shown in Fig. 1, 10× vertical exaggeration; modified from Horton et al. (2005c, Fig. A7).

beyond 28 km, but the much larger outer crater (85 km diameter) in collapsed sediments shows a total expansion of about 200%. High-resolution seismic reflection profiles indicate that large-scale collapse and block slumping of sediments in the annular trough occurred along numerous small-displacement faults, including normal faults and décollements at multiple levels, rather than a single through-going décollement (Catchings et al. 2005). This collapse and slumping in the annular trough of the CBIS may be a useful analog for craters that appear to have expanded by slumping in the chaotic terrains on Mars.

Seismic profiles across the annular trough of the CBIS indicate that extensional collapse structures (0.5–3.9 km in width) are concentrated in structural rings that partly coincide with impact-generated compressional structures in the basement (Powars et al. 2003). These concentric rings of normal faults and associated collapse structures may have been important for effective radial enlargement of the final crater beyond the nested central crater. They also coincide with the zones of greatest postimpact subsidence in the annular trough (Powars et al. 2003).

CRATER-FILL MATERIALS

Impact-generated crater-fill materials (impactites) in the CBIS include suevitic crystalline-clast breccia and megablocks in the central crater, impact-modified autochthonous to parautochthonous sediments in the annular trough, and allogenic sediment-clast breccia deposited over the entire crater and nearby areas.

The suevitic crystalline-clast breccia was discovered in drill core from the 2004 USGS Cape Charles test hole (Fig. 1, locality C) over the central uplift within the central crater, where it consists of metamorphic and igneous rock fragments and less abundant particles of impact-melt rock (Horton et al. 2004, 2005b). It contains megablocks of brecciated crystalline rock, is interpreted as a fallback deposit, and shows pervasive hydrothermal alteration (Horton et al. 2004, 2005b, 2006). A preliminary site report for the 2005 ICDP-USGS deep corehole confirms the presence of suevitic breccia at another locality in the central crater northeast of Cape Charles (Gohn et al. 2006). Suevitic breccias (i.e., breccias that contain fragments of impact-melt rock) are not found in all meteorite impact structures. Their occurrence appears to be partly a function of target composition, and the presence of crystalline silicate rocks in the target may be important (French 1998). Impacts into volatile rich targets can produce abundant suevite, and Kieffer (2005) suggests that suevitic breccias are found only in structures where the targets were wet or contained other sources of volatiles (see also Kieffer and Simonds 1980).

Impact-modified sediments in the annular trough include block-faulted Lower Cretaceous fluvial target sediments that have been locally fluidized in their upper part (Horton et al. 2005a); these are overlain by megablocks of collapsed, parautochthonous Lower and Upper Cretaceous sediments (Figs. 3 and 4) characterized by rotated and inclined beds, fluidized sands, fractured clays, soft-sediment folds, faults (mainly normal and steeply dipping to subhorizontal), and matrix zones of injected sediments (Fig. 5) that include exotic, disaggregated Upper Cretaceous and lower Tertiary target sediment particles (Gohn et al. 2005; Horton et al. 2005a). Deformation generally increases upward. This impact-modified section is interpreted to have formed in response to acoustic-wave vibrations and subsequent gravitational collapse (Gohn et al. 2005; Horton et al. 2005a).

The allogenic sediment-clast breccia (Fig. 6) is a heterogeneous, unstratified, and unsorted polymict diamicton that consists of mixed-age clasts in a muddy quartz-glauconite sand matrix (Powars and Bruce 1999; Edwards and Powars 2003; Horton et al. 2005a). It ranges in thickness from 8 to 400 m and overlies the other impactites and preimpact deposits. It is interpreted to consist of subaqueous deposits of ocean-resurge sediment-gravity flows (Horton et al. 2005a) that have been influenced by turbulence, current oscillations, and tsunamis (Powars and Bruce 1999; Powars 2000). The uppermost sediment-clast breccia fines upward into fine sand and silt that probably represent the fallout of suspended sediment from the water column in response to a

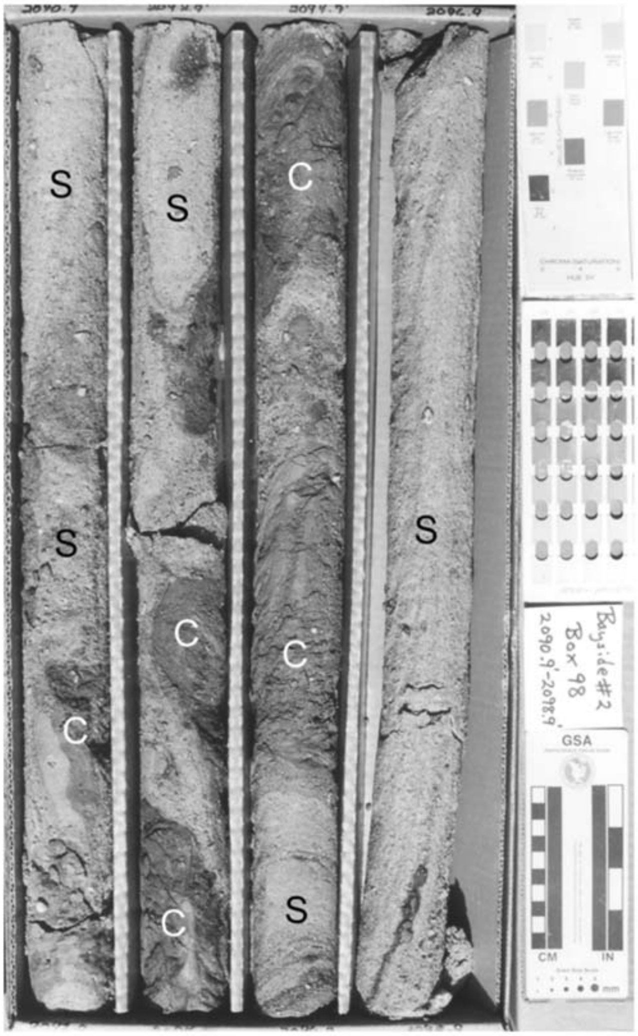

Fig. 3. A photograph of impact-modified sediment from the annular trough showing blocks of dark greenish gray clay (C) and very light gray muddy sand (S). Convolute lamination in sand ranges from gently inclined to subvertical. Lamination within relatively competent clay blocks is folded and locally truncated against sand at block margins. Some clay blocks show pull-apart structure. USGS Bayside core, box 98; depth values increase from upper left (637.3 m, logged 2090.9 ft) to lower right (639.7 m, logged 2098.9 ft). Nominal core diameter is 6.1 cm (2.4 in).

gradual decrease in the energy of resurge and tsunami current oscillations and turbulence. These uppermost late-stage resurge deposits grade upward into postimpact marine sediments. The burial of crater-fill deposits has protected them from subsequent erosion.

Field relations indicate that slumping of sediments in the outer part of the CBIS generally preceded deposition of the overlying resurge sediments. While allogenic sediment-clast breccia (Fig. 6) provides a record of the strong resurge, there is no evidence that resurge flow was needed to drive the crater expansion by slumping. The features observed in collapsed sediments (Figs. 3 and 4) beneath the resurge sediments indicate that fluidization of water-saturated sediments and soft-sediment deformation were closely associated with the slumping. Thus, the CBIS provides a terrestrial analog for studies of crater expansion by collapse of partly fluidized, volatile-rich, poorly consolidated, thick sediments.

MARTIAN COMPARISONS

Studies of crater materials in the Chesapeake Bay impact structure may provide insights into the processes of crater expansion by collapse in areas of volatile-rich sediments on Mars. Special features of the CBIS pertinent to Mars and examples of circular structures on Mars that have similarities to the CBIS are discussed below.

A prominent feature of the Chesapeake Bay impact structure is the outer brim of slumped and collapsed sediments, which extends far beyond the original transient crater as well as the present filled basement crater. This outer collapsed zone is due to the relatively thick layer of poorly consolidated, water-saturated sediments in the upper part of the target (above the crystalline basement) that slumped inward after the initial crater excavation. The slumping expanded the crater headward and outward until it finally

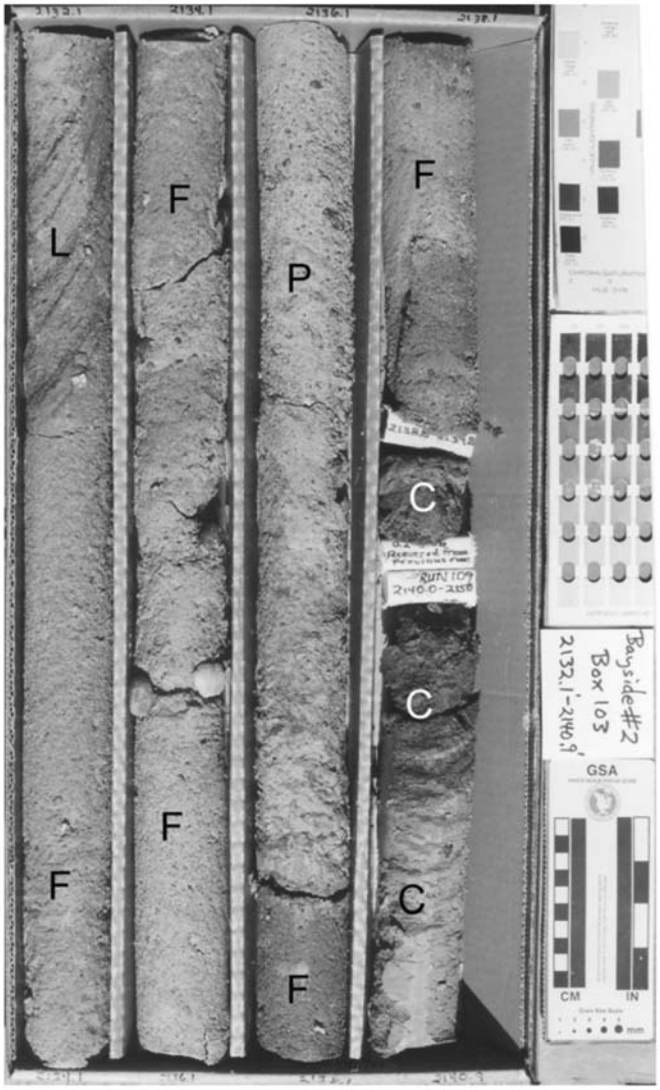

Fig. 4. A photograph of impact-modified sediment from the annular trough showing massive fluidized sand (F) containing disseminated quartz granules and pebbles, as well as variably rotated sediment blocks. These blocks include sand with steeply inclined laminations (L), poorly bedded gravelly sand (P) with moderately inclined beds, and clay (C) with gently inclined beds. USGS Bayside core, box 103; depth values increase from upper left (649.9 m, logged 2132.1 ft) to lower right (652.6 m, logged 2140.9 ft).

ended with a relatively steep scarp that lacks an elevated rim. The crater interior became filled with a chaotic deposit of large blocks surrounded by finer debris. Such extensive expansion of the crater by collapse is rarely observed in terrestrial craters, although similar features are observed in craters that formed in targets of water-saturated, soft sediments overlying hard rock. Other terrestrial examples include the southern sector of the Wetumpka impact structure in Alabama (King et al. 2005) and the Mjolnir impact structure in the Barents Sea (Tsikalas et al. 1998).

On Mars, circular structures with similarities to the CBIS are common in the old, layered highland terrain. Areas of this terrain that are broken into rotated blocks are closely associated with large fluvial features. The formation of such chaotic terrains (i.e., areas of large collapse structures) is commonly assumed to be linked to the release of volatiles from a sequence, several kilometers thick, of layered deposits that may include impact breccias, eolian and fluvial sediments, and volcanic flows (Rotto and Tanaka 1995). The main volatile most likely is frozen water in a thick permafrost zone, but liquid water and gas hydrates (clathrates) have been suggested to exist below this permafrost (see the review in Rodriguez et al. 2005).

Martian chaotic terrains may have formed by fluidization of stratified material due to catastrophic melting of ground ice and rapid dissociation of clathrate hydrate (Komatsu et al. 2000). Clathrate hydrate consists of hydrogen-bound water molecules in an open arrangement with cavities that contain gas molecules, and it has physical properties similar to ice (Buffett 2000). Chaotic terrain may have formed in direct

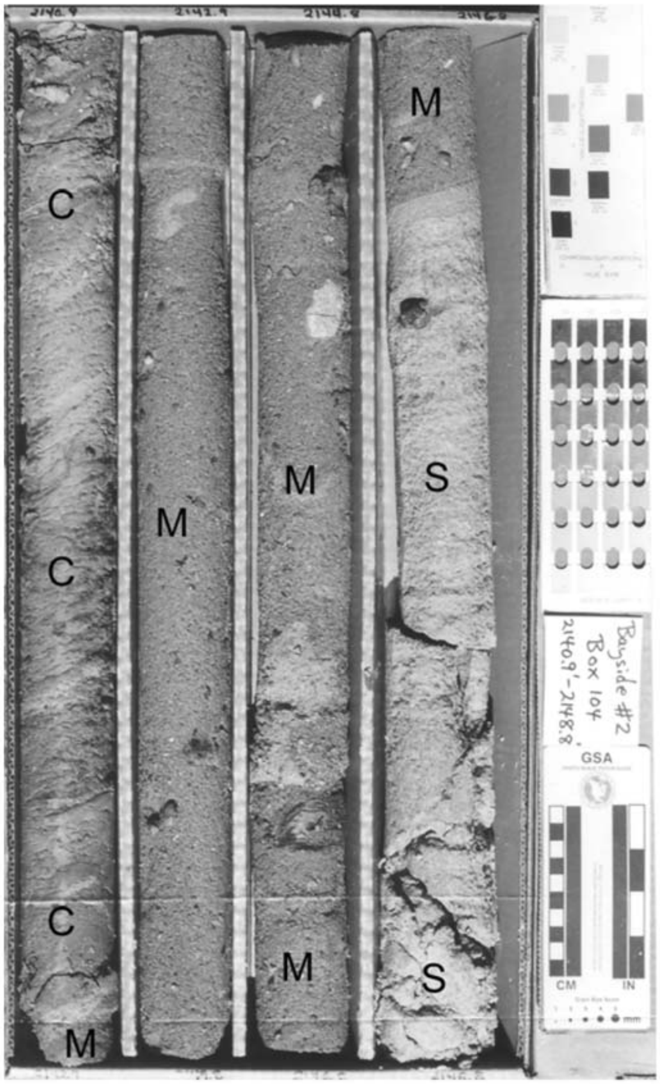

Fig. 5. A photograph of impact-modified sediment from the annular trough showing matrix zone (M) of dark greenish gray, muddy quartz-glauconite sand between megablocks of grayish red clay-silt (C), which grades up to greenish gray silty sand, and of very light gray silty sand (S). The megablocks are probably parautochthonous Cretaceous nonmarine sediments, whereas the glauconite suggests the presence of exotic particles derived from Tertiary preimpact marine deposits. Differences in bedding dip (~15° in megablock C and ~30° in megablock S) indicate block rotation. The matrix zone in this photograph is the deepest recognized in the Bayside core (~54 m above the weathered granite basement), and it is significantly deeper than similar zones documented in cores farther from the center of impact. The boundaries of the matrix zone are approximately parallel to bedding in blocks above and below, suggesting that it was emplaced as a sill-like injection of soft sediment along a bedding-parallel zone of weakness. An alternative interpretation is that the deep exotic matrix zone at Bayside represents the lowest part of resurge mixing and reworking of slump blocks. USGS Bayside core, box 104; depth values increase from upper left (652.6 m, logged 2140.9 ft) to lower right (655.0 m, logged 2148.8 ft).

connection with episodic, catastrophic outflows of trapped ground water (Carr 1979; Baker and Milton 1974), or by the collapse of saturated cavern systems that acted as reservoirs for the water (Rodriguez et al. 2005). This possibly long-lived or episodic collapse seems to have been initiated in the Late Noachian, peaked in the Hesperian, and lasted well into the Amazonian (Rodriguez et al. 2005). These geological conditions make areas such as the Oxio Palo and Coprates regions suitable to search for extensively collapsed impact craters.

For terrestrial craters, an impact origin can be confirmed by the occurrence of diagnostic shock effects in minerals or by the presence of a meteoritic component. Due to the absence of such information for Mars, the recognition of a Martian impact crater is based on analogy in morphology with known impact craters on Earth or other solid objects in the solar system where most other crater-forming processes can be excluded (e.g., the Moon). For comparison with the CBIS, we examined 513 Mars Orbiter Camera wide-angle (MOC WA) images over the Oxio Palo and Coprates regions

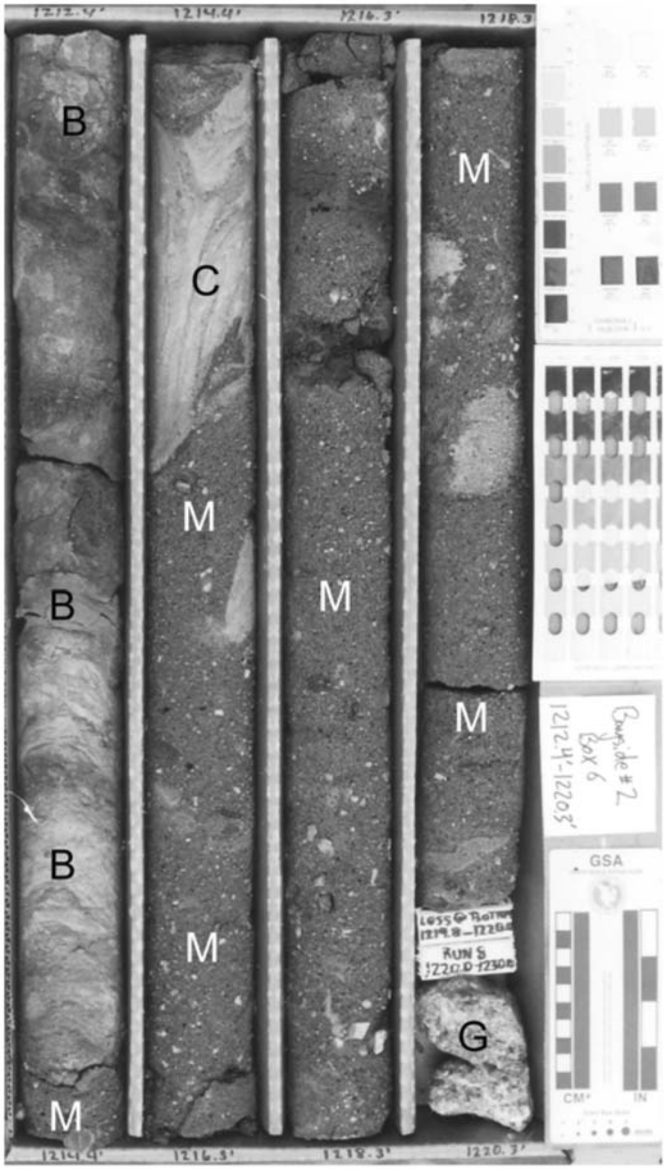

Fig. 6. A photograph of allogenic sediment-clast breccia known as the Exmore beds (informal name as discussed in Horton et al. 2005a and Gohn et al. 2005). This sedimentary breccia is a heterogeneous, unstratified, unsorted, polymict diamicton that contains clasts derived from most of the preimpact target units. Labeled features include: dark greenish gray muddy, phosphatic, quartz-glauconite sand matrix (M), boulder (B) of mottled grayish green sandy clay and clayey sand, clast of very light gray silty clay (C) containing convolute lamination and soft-sediment slump folds, and clast of pinkish gray granite (G). This heterogeneous mixture of sediment is attributed to ocean resurge modified by turbulence and tsunamis. USGS Bayside core, box 6; depth values increase from upper left (369.5 m, logged 1212.4 ft) to lower right (372.0 m, logged 1220.3 ft).

and selected circular structures for which an impact origin can be assumed. Circular collapse features are common in these areas, but may not necessarily be collapsed impact craters. Some are linked in pit chains that suggest a collapse along tectonic lineaments (Ferrill et al. 2004; Wyrick et al. 2004). The specific structures identified in this study are, however, randomly distributed and seem not to be structurally controlled. Hence, we assume them to be degraded impact craters. The locations of the selected structures are shown on a map of the Xanthe Terra and Margaritifer Terra regions (Fig. 7) and the images are shown in Fig. 8. Our intention was to select structural depressions lacking evidence of tectonic control that appeared to have expanded by extensive collapse. We did not specifically focus on structures with inverted sombrero morphology as we consider this to be just one special variety of collapsed craters. The inverted sombrero morphology can also have different causes linked to either crater excavation or modification as discussed below. For comparison, two examples of structures with a more distinct inverted sombrero morphology are illustrated in Fig. 9. These

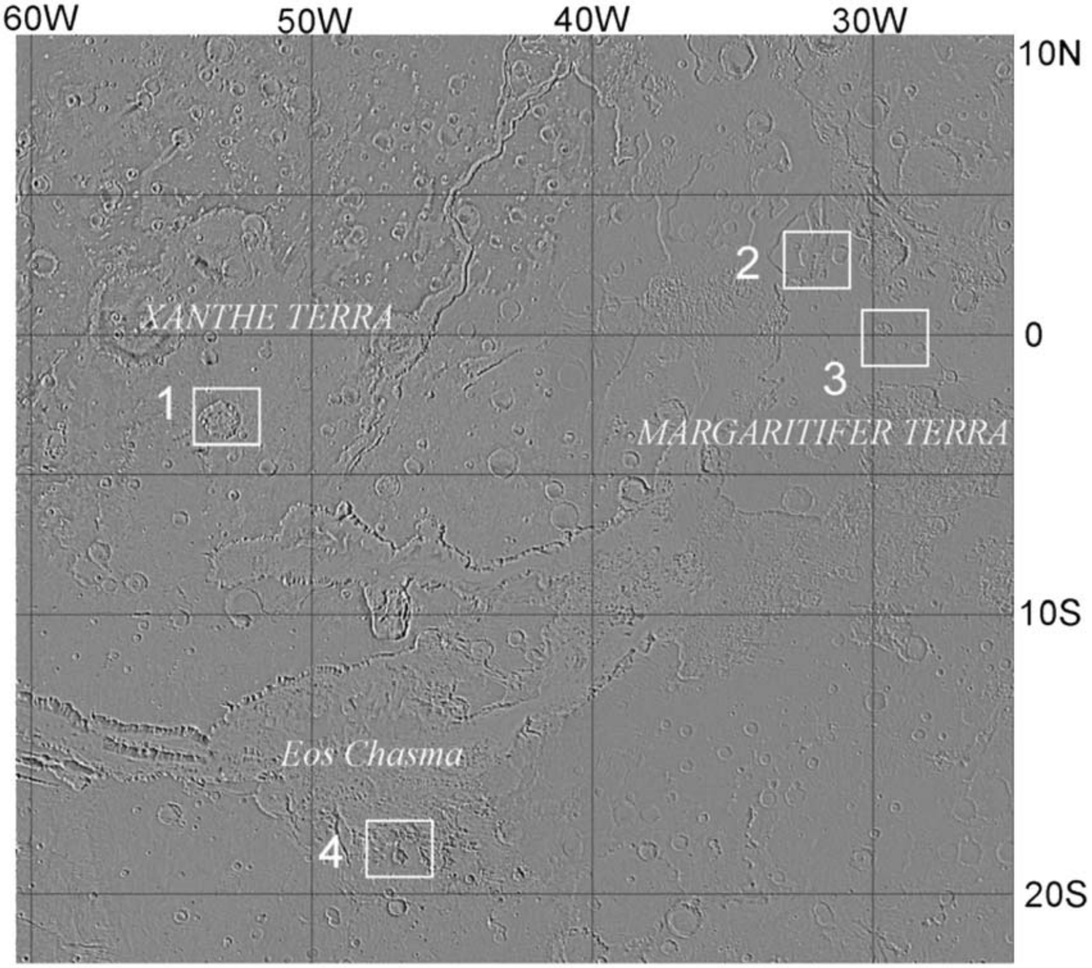

Fig. 7. An image map of the Xanthe Terra and Margaritifer Terra region on Mars. These regions are characterized by chaotic terrain, which probably formed by collapse of a thick volatile-rich permafrost layer, and associated outflow channels. Numbered rectangles 1–4 (each approximately 110 km in width) are the locations of Mars Orbiter Camera (MOC WA) images in Fig. 8. Adapted from Mars Digital Image Mosaic (MDIM 2.0) from the USGS Astrogeology Geology Research Program (http://pdsmaps.wr.usgs.gov; accessed September 2005).

images were produced by the Mars Odyssey Thermal Emission Imaging System (THEMIS) in visible wavelengths (Christensen et al. 2004).

Image 1 of Fig. 8 shows a subcircular depression of roughly the same size as the CBIS. Its perimeter is set by a steep scarp that lacks any sign of an elevated rim. The scarp is irregularly dissected by arcuate slump scars indicating a headward expansion of the feature. Much of the slumped material seems either to have disappeared from the interior of the depression, possibly by wind erosion and subterranean flow, or to have experienced a volume decrease, possibly by release of a volatile. The effect is a flat floor extending almost all the way to the scarp. This flat-floor morphology is shared with most other similar structures such as the circular features surrounding an outflow channel in image 2 of Fig. 8. However, in images 3 and 4 of Fig. 8, the floors of the circular depressions are significantly rougher, possibly due to preserved slumped material.

The craters shown in Fig. 9 are located in two other regions of Mars that have areas of layered deposits. The crater in Fig. 9a is situated in the infill of a much larger crater in the Western Arabia region. Its impact origin is indicated by preserved ejecta. The ejecta blanket forms a rampart suggesting an emplacement as fluidized ejecta from impact into a volatile-rich target (Barlow 2005). A wide slump terrace gives the crater an inverted sombrero appearance. The concentric structure in Fig. 9b is situated near the southern border of Amazonis Planitia areas affected by extensive outflows from the Tharsis region. An impact origin is suggested by knobby material resembling remnants of an ejecta layer that has been modified by selective erosion. The structure has a rimmed inner depression surrounded by a relatively shallow outer zone that clearly resembles the annular trough of the CBIS. However, there is little evidence of slumping. Thus, it is uncertain if the morphology was produced by processes that are truly analogous to the CBIS.

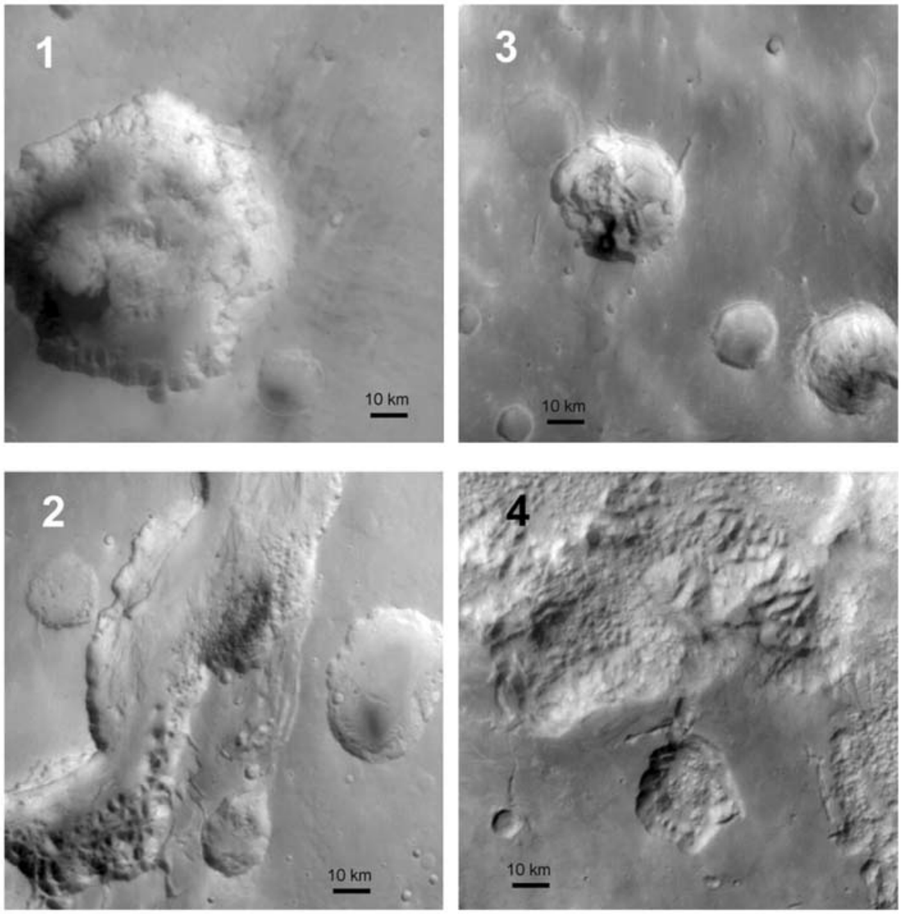

Fig. 8. Martian features interpreted to be impact craters that expanded due to collapse; the collapse may have been associated with block slumping and fluidization of sediments caused by rapid dissociation of volatiles in the upper crust (Komatsu et al. 2000). Images 1–4 correspond to numbered locations in Fig. 7. Mars Orbiter Camera wide-angle (MOC WA) images courtesy of Malin Space Science Systems. 1) MOC WA image R10-02030 (52.05°W, 2.91°S) shows a subcircular depression bounded by an outer scarp, which is dissected by arcuate slump scars that indicate headward expansion. The effect is a flat floor extending almost all the way to the scarp. 2) MOC WA image R10-00044 (31.15°W, 2.79°N) shows circular collapse features surrounding an outflow channel that has collapsed margins. The circular collapse features share a flat-floor morphology. 3) MOC WA image R11-02897 (28.54°W, 0.08°N) shows circular depressions in which the floors are significantly rougher; the largest of these depressions appears to contain rotated slump blocks. 4) MOC WA image R17-02406 (46.19°W, 18.23°S) also shows circular depressions in which the floors are significantly rougher.

DISCUSSION AND CONCLUSIONS

If found on Mars, resurge sediments would demonstrate a significant surface-water column at the time of impact. However, suevitic breccias or fluidized, collapsed sediments could form in volatile-rich targets on Mars with or without the presence of surface water.

Circular depressions having morphologies similar to that of the Chesapeake Bay impact structure, as well as apparent crater diameters significantly wider than the initial transient crater, may have formed by impacts on Mars where near-surface preimpact sediments are thick and contain volatiles or significant pore-fluid pressures. Flat-floored, rimless impact structures are associated with layered terrains in several places on Mars, and some of these structures have chaotic interiors. The formation of chaotic terrain in these areas indicate instabilities in the layered deposits. The formation of these chaotic terrains is inferred to be collapse due to the episodic outflow of volatiles released from a permafrost zone consisting of frozen water, possibly underlain by zones of liquid water and clathrates. Although the latest collapse significantly postdates the initial crater modification in many cases, the collapse features that caused extensive enlargement of some Martian craters resemble those of the CBIS, which expanded by collapse of partly fluidized, water-saturated sediments. Impact-modified sediments in the outer brim or annular trough of the CBIS provide insights into the processes involved in the expansion of craters on Mars and their links to volatiles.

The craters in Fig. 8 have an advantage over those presented in Fig. 9 in comparisons with the CBIS due to their clear connection with extensive collapse. However, it is difficult to make a direct comparison with the CBIS, because

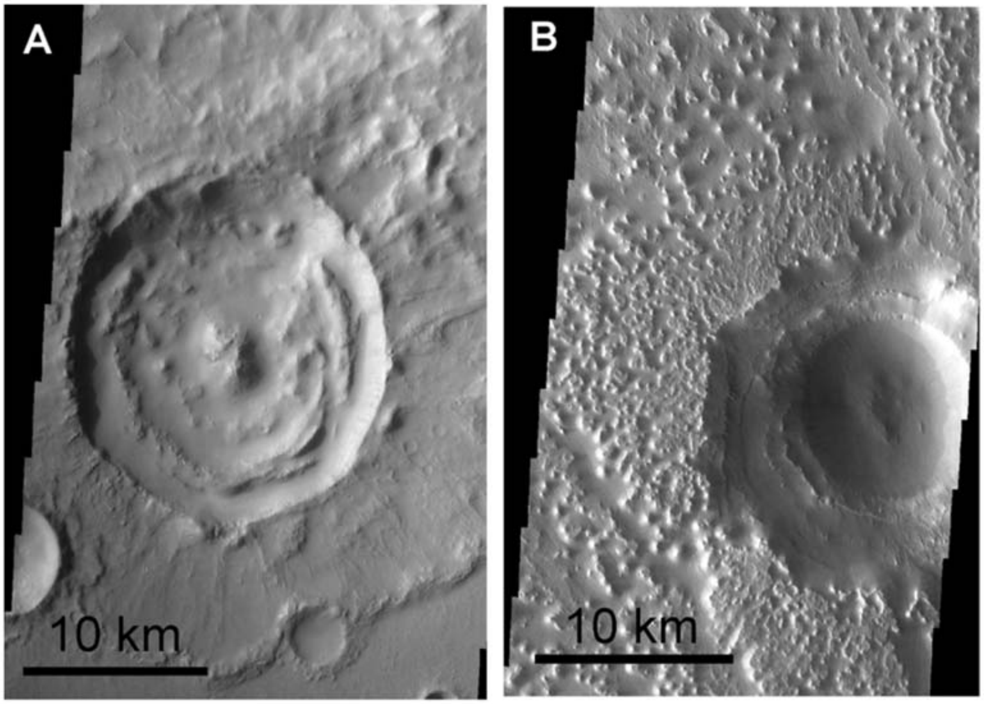

Fig. 9. Examples of Martian crater structures with an inverted sombrero morphology. a) A crater located in the western Arabia region (17.5°N, 6.0°E). The wide terrace could indicate collapse of a weak upper layer. Rampart ejecta support the existence of volatiles in the target. b) A crater located south of the Amazonis Planitia (4.9°N, 203.6°E). Concentric structure with a deeper nested crater surrounded by a shallow outer crater. The lack of obvious slumped deposits suggests that the morphology could be a response to differences in excavation flow in a layered (weak over strong) target, rather than late-stage collapse of a layered target (see Ormö et al. 2004). THEMIS (Christensen et al. 2004) images from THEMIS public data releases (Mars Space Flight Facility, Arizona State University, http://themis-data.asu.edu; accessed February 2006).

the timing of the collapse relative to the crater formation cannot be determined. In many cases, much of the collapse may have occurred long after the impact. Nonetheless, in analogy with the CBIS, these collapse features seem to represent craters that have grown extensively beyond the original transient crater, and they were most likely influenced by volatiles within rather than on the target rocks. Morphological similarities such as inverted-sombrero shape cannot be used alone as analog to the CBIS.

Other concentric craters in layered targets on Mars, such as those illustrated by Ormö et al. (2004), may or may not involve collapse and should be considered separately. Ormö et al. (2004) based their interpretations on both field data and numerical simulations of terrestrial craters formed in targets consisting of a weak layer (i.e., seawater and sediments) covering a crystalline basement. They suggested that a shallow excavation flow removed the parts of the weaker layer surrounding an inner deeper crater in the basement. The resulting concentric crater would lack a raised rim, and the outer parts corresponding to the brim of the inverted sombrero would be a surface blasted clean rather than covered by slumped material as in the CBIS. This circumstance may be illustrated by the crater in Fig. 9b.

It is likely that there has been an initial concentricity of the transient crater at the CBIS due to shallow excavation flow removing parts of the weak sediments. However, due to the extensive slumping during the modification stage, any earlier inverted sombrero shape, if present, would have been destroyed. The present CBIS morphology is a secondary result of crater modification due to collapse. Depending on the thickness and character of the weak sediments collapsing towards the excavated cavity, the resulting crater may take the shape of an inverted sombrero, be simply flat-floored, and/or have a chaotic interior. In all of these cases, the absence of a raised rim would be significant. It is difficult to determine if some concentric craters on Mars formed by extensive collapse of a soft upper layer as in the CBIS or by earlier excavation processes. The existence of chaotic infill seemingly derived from crater walls that have slump scars would be a stronger indication for collapse than merely an inverted sombrero morphology. This type of morphology would, in combination with signs of slumping, give information on the thickness of the collapsed layer. Future analog studies that compare the CBIS and different types of concentric craters in volatile-rich and layered targets on Mars may provide insights into the processes of crater excavation and modification. Studies of the deposits in the outer slumped zone of the CBIS may give information on the processes involved in the apparent expansion of many craters on Mars and their links to putative volatiles.

Acknowledgments–United States Geological Survey (USGS) investigations of the Chesapeake Bay impact structure are conducted in cooperation with the Hampton Roads Planning District Commission, the Virginia Department of Environmental Quality, and the National Aeronautics and Space Administration (NASA) Langley Research Center. The Hampton Roads Planning District Commission and the USGS provided funds for drilling the USGS-NASA Langley, North, Bayside, and Watkins School coreholes. The Virginia Department of Environmental Quality also provided funds for drilling the north corehole and provided extensive operational support at the other sites. The USGS provided funds for drilling the Cape Charles test hole. The work by J. Ormö was supported by the Spanish Ministry for Science and Education (References AYA2003-01203 and CGL2004-03215/BTE), and the Spanish Ramon y Cajal program. The authors acknowledge the use of Mars Orbiter Camera images processed by Malin Space Science Systems that are available at http://www.msss.com/moc_gallery (last accessed by the authors September 2005) and THEMIS public data releases (Mars Space Flight Facility, Arizona State University, last accessed by the authors February 2006, available at http://themis-data.asu.edu). We are grateful for constructive reviews by Nancy McKeown, Michael Ryan, Stephen Schindler, Thomas Kenkmann, and an anonymous reviewer. We especially thank Dr. Kenkmann for suggesting the THEMIS images.

Editorial Handling—Dr. Nadine Barlow

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