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Proceedings of the Workshop on the Role of Volatiles and Atmospheres on Martian Impact Craters

Impact craters on different solar system bodies typically display many similar features: approximately circular planform, raised rim, crater floor below surrounding terrain, bowl-shape for small craters, and wall terracing and central peaks for larger craters. However, it is the morphologic and morphometric variations among craters on different worlds that provide important insights into the different environmental conditions operating during crater formation. Lunar craters have become the "standard" by which impact craters elsewhere are compared. Fresh lunar craters are surrounded by a hummocky ejecta blanket within approximately 1 crater radius of the rim (the "continuous ejecta blanket"), which grades into radial chains of secondary craters (the "discontinuous ejecta blanket"). This ejecta pattern is easily modeled as ballistic emplacement of ejected material which has no interaction with subsurface volatiles or an atmosphere. The most common type of interior structure associated with lunar impact craters is the central peak or peak complex, a mountainous uplift resulting from rebound of the highly shocked floor material.

While radial ejecta patterns and central peaks are common features in lunar impact craters, they are not always seen in craters on other bodies. Mariner 9 imagery first revealed that Martian impact craters display morphologies which are distinct from their lunar counterparts. Subsequent orbital observations from the Viking, Mars Global Surveyor, Mars Odyssey, and Mars Express missions and ground-based investigations by the Mars Exploration Rovers have further detailed the non-lunar nature of Martian impact structures. Fresh Martian impact craters are typically surrounded by one of several layered ("fluidized") ejecta patterns, most terminating in a distal ridge or rampart. Interior structures include not only central peaks but also central pits which can occur directly on the crater floor or atop a central peak or rise. In addition, modification has affected the Martian impact craters to a greater extent than with lunar craters. The volatile-rich nature of Mars is the likely cause of these differences: unlike the Moon, Mars has a thin carbon-dioxide-rich atmosphere and evidence of extensive reservoirs of subsurface ice. Since Earth also is volatile-rich, Martian and terrestrial impact crater features are probably more analogous than the comparisons with lunar craters.

Great strides have been made in understanding the role of the Martian atmosphere and its subsurface ice reservoirs on impact crater formation and modification. These advances have resulted from geomorphic studies of impact craters on Mars and other solar system bodies, numerical modeling, laboratory experiments, and terrestrial field studies. To enhance and encourage interaction between these diverse research communities, the Workshop on the Role of Volatiles and Atmospheres on Martian Impact Craters was held July 11–14, 2005, at the Johns Hopkins University Applied Physics Laboratory (JHUAPL). Approximately 70 researchers attended the workshop, presented the current state of understanding for their particular research area, and participated in the extended discussion periods. The papers in this proceedings volume represent a cross-section of the topics discussed at the workshop.

Characteristics of Martian impact craters which are attributed to the atmosphere/subsurface volatiles are described in the first five papers. Barlow describes the distribution and characteristics of layered ejecta morphologies and central pit craters, and argues that subsurface volatiles have played the dominant role in forming these features. The smallest crater which displays a layered ejecta pattern is often used to estimate the depth to a subsurface ice layer. This technique, combined with crater age-dating information, was used by Reiss et al., who report evidence that the ground ice table has lowered over time. A small number of fresh Martian impact craters display secondary crater chains extending beyond the layered ejecta blanket. Hartmann and Barlow find a diameter-terrain dependence for secondary crater occurrence, which they propose is correlated with the thickness of a volatile-rich regolith. This relationship might explain why Martian meteorites are preferentially ejected from younger volcanic surfaces. Mouginis-Mark and Baloga present the morphometric characteristics of single-layer and multiple-layer ejecta patterns, providing important constraints on the ejecta emplacement process. Herrick and Hessen provide a new analysis of ejecta planforms of low-angle impact craters, finding a number of similarities between Martian low angle impacts and those produced in dry environments like the Moon but few correlations with impacts into a dense atmosphere like Venus. They conclude that Martian ejecta are emplaced in two stages: ballistic emplacement followed by modest surface flow.

Laboratory experiments and numerical modeling of impacts into volatile-rich environments have seen major advances in recent years. Schulson's paper gives an overview of how ice fractures during application of different types of stresses—knowledge that is necessary to adequately model impacts into ice-rich targets. Stewart and Valiant test the accuracy of numerical model predictions by comparing those results with actual geometric measurements of fresh Martian impact craters. The results include the first constrained set of parameters for layered ejecta deposits and proposed modifications to the scaling laws. However, subsurface volatiles may not be the only influence on crater/ejecta morphology. Wrobel et al. discuss their numerical modeling of impact-induced vapor blasts in the Martian atmosphere giving rise to pedestal craters elevated above the surrounding terrain. A new paradigm for layered ejecta emplacement involves granular flow, as discussed by Wada and Barnouin-Jha. Their model suggests that the layered ejecta morphology could simply result from granular flow over hard-smooth or slightly erodible surfaces, reducing or eliminating the need for subsurface volatiles or the atmosphere in layered ejecta formation.

Formation models are best constrained by ground-truth and the only place where extensive field studies of impact craters have been conducted is Earth. Osinski and Kenkmann and Schönian compare ejecta and interior features of Martian impact craters to five terrestrial craters: Haughton in Canada (impact into ice-rich target), Ries in Germany and Chicxulub in Mexico (impacts into volatile-rich targets), and Meteor Crater in Arizona and Lonar in India (small impacts into sedimentary rocks and basaltic lava flows, respectively). Their reports are among the first to identify layered ejecta morphologies for the terrestrial impacts and both papers report key evidence of the role of target volatiles in the formation of the terrestrial ejecta blankets. Although liquid water cannot exist on the Martian surface today, there is evidence of lakes (and possibly oceans) existing on Mars in the past. Thus, terrestrial impacts into marine environments represent analogs for another category of volatile-rich impacts. Impacts into marine environments alter the late excavation and early modification stages of crater formation, resulting in unique morphologies such as the inverted-sombrero appearance of some marine craters. The latest field studies and modeling of the Lockne (Sweden), Chesapeake Bay (Maryland), and Wetumpka (Alabama) impact structures, and their implications for impacts into volatile-rich targets on Mars, are described in papers by Ormö et al., Horton et al., and King et al.

Martian impact craters display a wide range in preservation, a result of volcanic, tectonic, impact, eolian, fluvial, and glacial processes which have modified the planet's surface features. Fluvial and glacial processes have operated episodically throughout Mars' history in conjunction with climatic change induced by the large obliquity oscillations experienced by the planet. Kreslavsky and Head report that deposition of ice-rich mantles during high obliquity periods can explain the variations in crater depth, wall steepness, and ejecta roughness of impact craters in the northern lowlands of Mars. Meresse et al. suggest that the concentration of perched craters in the 40–70° latitude zone resulted from multiple episodes of erosion and sublimation of ice-rich materials. Crater modification by glacial processes is highlighted in the Garvin et al. paper, which discusses evidence of at least five phases of glacial advance and retreat in a crater located near 70°N. Modification and erosion of impact craters allows identification of structural features produced in association with crater formation, as noted in the study of a crater 75 km in diameter along the Martian hemispheric dichotomy by Head and Mustard. The faults and breccia dikes revealed in this crater are analogous to those seen in many terrestrial craters and provide important insights into crater formation processes on both Earth and Mars.

The workshop presentations and the papers in this proceedings volume demonstrate the enhanced insights which result when researchers from various fields bring their different perspectives to bear on a common conundrum. Scientific knowledge typically advances through incremental steps—major and sudden paradigm shifts are the exception rather than the rule. Although no major paradigm shifts resulted from the workshop, the resulting papers provide several additional steps toward our goal of understanding the respective roles of subsurface volatiles and atmospheres on impact crater formation and modification on Mars, Earth, and other volatile-rich worlds.

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