The Role of Volatiles and Atmospheres on Martian Impact Craters

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Many questions remain about what Martian impact craters reveal about the planet's environment at the time of the impact and about the subsequent processes that have modified these craters. In particular, questions remain about the role of near-surface or "target" volatiles (volatiles within the upper few kilometers of the surface) and the planet's variable carbon dioxide (CO_2) atmosphere on ejecta formation and modification.

A recent meeting, "Workshop on the Role of Volatiles and Atmospheres on Martian Impact Craters," helped to better define these questions and review current understandings. The workshop was sponsored by the Lunar and Planetary Institute, Mars Crater Consortium, NASA, Johns Hopkins University's Applied Physics Laboratory, and the Mars Exploration Program Analysis Group.

The workshop's goal was to provide a forum for diverse communities to address the processes by which the impacting bodies interact with the volatile-rich Martian environment.

Approximately 70 researchers representing the Martian and terrestrial impact cratering, field geology, modeling, experimental, and nuclear explosion communities participated. The workshop included invited talks, tutorials, contributed oral and poster presentations, and extended discussion periods.

Learning from Crater Morphology

Martian impact craters display distinct morphologic and morphometric characteristics that could be the result of target and/or atmospheric volatiles during the formation and modification of the craters. James Garvin (NASA Goddard Space Flight Center) noted that the depth/diameter scaling for different morphology classifications for these craters (simple/complex/peak ring/multiring) displays more variability than is seen for lunar craters, and regional variations in morphometric characteristics may reflect changing distributions of subsurface volatiles, differences in target properties and stratigraphy, and/or differences in atmospheric conditions.

Ejecta blankets (layers of debris thrown out of a crater during impact) surrounding fresh Martian impact craters between ~3 and 50 km in diameter typically display a fluidized or layered appearance, with one, two, or multiple ejecta layers. These layered ejecta patterns have been interpreted to reflect emplacement either by a water-rich, ground-hugging flow similar to terrestrial landslides, or by the effects of ejecta interaction with the atmosphere, leading to emplacement by a gas-supported surge in a manner similar to volcanic base surges.

The smallest craters in a region that show a particular ejecta morphology have been used to constrain the minimum depth of target volatiles through well-established excavation depth-diameter relationships.

Using this technique with new Mars Express data, Dennis Reiss (Institute of Planetary Research, Berlin) reported evidence that subsurface volatile reservoirs have migrated to greater depths over time in most areas of the planet. Alternately, these observations could be explained by a temporal decline in atmospheric density leading to weaker basal surges (gas-supported surface flows). This illustrates some of the debate that occurred during the meeting. There was much discussion as to whether there are diagnostic features that can distinguish between the near-surface volatile versus atmospheric emplacement models. This is one example of how both models can explain the observation,

Laboratory experiments and some analytical and numerical studies have helped to determine how these layered ejecta morphologies could result from impacts into volatile-rich target material or interactions of the released debris with the Martian atmosphere. In addition, recent advances in the equations of state for rock/ice mixtures have allowed Elisabetta Pierazzo (Planetary Science Institute, Tucson, Ariz.) and colleagues to improve the numerical modeling of impacts into volatile-rich targets and show that considerable melt and vapor are produced by such impacts. These results lend support to models suggesting that water produced the Martian layered ejecta morphologies and interior central pits. Experiments have shown that impacts on bodies with atmospheres create vortices that interact with fine-grained ejecta to produce layered ejecta morphologies similar to those seen on Mars.

The runout distances (maximum flow distances) of Martian layered ejecta are comparable to those of terrestrial landslides, indicating that terrestrial debris flow studies can provide important insights into how Martian layered ejecta morphologies are formed. Tutorials by Mauri McSaveney (Institute of Geological and Nuclear Science, New Zealand) and Charles Campbell (University of Southern California, Los Angeles) about the mechanics of such landslides suggest that granular flow mechanics also may be important for ejecta. High-resolution imagery shows that ejecta is often diverted around pre-existing topography, suggesting ejecta flow velocities of less than 100 meters per second. Many of the observations of near-rim ejecta are consistent with ejecta emplacement by gas-rich basal surges.

Similarities on Other Planets

Impact craters on other planets and moons provide important information on how environment affects the formation of Martian crater features. The gravitational acceleration on Mars is similar to that on Mercury, and thus Mercury can provide insight on gravity's role in crater formation in a volatile-poor and atmosphere-free environment. Venus is a natural setting for studying the role of an atmosphere on crater formation, while the outer solar system's icy moons provide examples of crater features formed on ice-rich targets.

However, only impact craters on Earth have been subjected to the intense field study that can provide important insights into the role of target volatiles and atmospheres on crater formation.

As discussed by Milo Nordyke (Lawrence Livermore National Laboratory, Livermore, Calif.), craters produced by nuclear explosions show the effect of the target on the resulting crater, with craters in water-saturated targets showing slope failure and significant infilling. Such craters display larger diameters and shallower depths than explosion craters produced in dry targets.

Thomas Kenkmann (Humboldt University, Berlin) described evidence that the ejecta blanket surrounding Germany's Ries Crater was emplaced by a ground-hugging flow, and it shows striations on the ejecta similar to those seen on Martian double-layer ejecta blankets. Chicxulub's ejecta was derived from a turbulent water-rich debris cloud and Kevin Pope (GEO ECO ARC Research) noted that it shows similarities to Martian multiple-layer ejecta blankets. Even small impact craters in sedimentary (e.g., Meteor Crater, Arizona) and basaltic (e.g., Lonar Crater, India) targets show evidence for ejecta emplacement by ground-hugging flow.

Terrestrial marine impacts, such as the Chesapeake Bay Crater along the U.S. mid-Atlantic coast, display an "inverted sombrero" or nested crater morphology due to impact into a layered target (weak sediments overlying stronger crystalline basement), and they provide possible terrestrial analogs for Martian nested craters.

The Effects of Water

Impact craters are affected by volatile-rich targets and atmospheres not only during crater formation but also through subsequent modification. Hydrothermal alteration and migration of easily mobile elements are common in terrestrial craters, and recent numerical modeling by Oleg Abramov (University of Arizona) suggests that such hydrothermal systems can remain active for about 100,000 years in large craters. The ductile behavior of ice results in rapid deformation of features in ice-rich targets. Relaxed craters and features that are reminiscent of terrestrial permafrost features inside middle- and high- latitude craters also suggest the influence of ice-rich materials on Martian crater forms.

Small impact craters visited by the Mars Exploration Rovers (MER) show no evidence of aqueous alteration since their formation, leading Matthew Golombek (Jet Propulsion Laboratory) and John Grant (Smithsonian Institution) to suggest a change from a warm, wet climate in earliest Martian history to a cold, dry, desiccating one by about 3.5 billion years ago. The effects of an early period when liquid water may have been more abundant are seen in the topographic profiles of modified Martian impact craters, which Robert Craddock (Smithsonian Institution) argued most closely match those produced by fluvial erosive processes such as rainfall on Earth.

Many Martian craters display layered floor

deposits, suggesting that these were the sites of ancient lakes. Craters with channel-breached rims experienced significant degradation early in Martian history, but this degradation rate was slow by terrestrial standards and mature drainage basins did not develop. Erin Kraal's (University of California Santa Cruz) study of alluvial fans inside some Martian impact craters show that they display topographic and morphologic characteristics more similar to fluvially-produced alluvial fans on Earth than those resulting from the movement of rock and soil due to gravity alone (mass wasting).

The fact that liquid water has contributed to crater modification when current conditions on Mars preclude its occurrence indicates that Mars has undergone major climatic change. Scientists initially thought that Mars may have had a thicker atmosphere and warmer, wetter conditions during its first billion years, but that atmosphere thinned and the cold, dry conditions seen today have prevailed for the past 3.5 billion years.

However, Bruce Jakosky (University of Colorado, Boulder) described a new paradigm that suggests Mars alternates between wetter and drier conditions, produced by variations in obliquity (the angle between the planet's rotational axis and normal to the orbital plane), eccentricity (the shape of the planet's orbit), and orbital inclination (the tilt of the planet's orbit compared to the Earth's orbital plane) that are caused by gravitational perturbations from other planets. Liquid water may have been present for long, transient periods in Mars' past, according to these models. The lack of observable carbonates on the surface might be explained by the highly acidic environment discovered by the MER and Mars Express missions.

A major argument against liquid water being stable on the surface during Mars' earliest history is that most astrophysical models suggest the Sun was 30% fainter in early solar system history. This fainter Sun would result in temperatures too low for water to remain in its liquid form for long on the Martian surface.

This problem may be alleviated by recent stellar models that suggest a slightly more massive early Sun, or through greenhouse warming caused by methane produced by impact-atmosphere interactions. In addition, simulations by Anthony Colaprete (NASA Ames Research Center, Moffett Field, Calif.) indicate that impactors as small as 8 km in diameter could have created meta-stable microclimates with increased levels of precipitation that lasted for hundreds of years on early Mars.

Giant impacts likely helped erode the early denser Martian atmosphere. New two-dimensional numerical modeling by Keiko Hamano (University of Tokyo) suggests more atmospheric loss by a single large impact than previously reported, although James Cho's (Harvard University, Cambridge, Mass.) simulations indicate that complete atmospheric blow-off by a single giant impactor is unlikely.

This workshop highlighted the current understanding of how the Martian atmosphere and target volatiles have affected impact craters. Much of the current emphasis is on impacts into volatile-rich targets or impact-atmosphere interactions. However, a complete understanding of the processes involved in formation of the layered ejecta morphologies likely involves the more complicated scenario of contributions from both target volatiles and the atmosphere.

With progress on both of these models, the Martian impact crater community can begin to address the relative effects of these major processes. Comparative planetology studies, closer interactions with terrestrial geologists, and new data from current and upcoming Mars missions will help constrain these effects. Temporal climate change, including microclimates, is a major complication to unraveling the impact crater story on Mars, and this needs more study.

Bringing together researchers from the various communities to share ideas was valuable, and it allowed a better definition of the research directions that could help produce advances in understanding how volatiles/atmospheres affect crater formation and modification on Mars and elsewhere.

The Workshop on the Role of Volatiles and Atmospheres on Martian Impact Craters was held 11–14 July 2005 at the Johns Hopkins University Applied Physics Laboratory (JHUAPL), in Laurel, Md.

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ABOUT AGU

Meet the Editor: *Global Biogeochemical Cycles*

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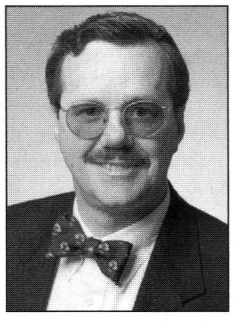
Meinrat Andreae was named the editor of the AGU's journal *Global Biogeochemical Cycles* last year.

Andreae, director of the biogeochemistry department at the Max Plank Institute for Chemistry (MPIC), located in Mainz, Germany, said that he plans to maintain the journal as a resource that highlights the broad spectrum of interdisciplinary themes that showcase the interactions between the biosphere and the geosphere. "Our special niche is in the field of larger-scale, more integrative studies that have global scope," he explained.

As a child, Andreae enjoyed reading about chemistry and playing with chemistry sets. In college, he had planned to major in chemistry, but found its study too remote from direct



applications to the Earth. Andreae instead switched his focus to geochemistry, and he earned a Vordiplom (B.S.) in Earth sciences from the University of Karlsruhe, Germany, in 1970.

In 1974, Andreae went on to earn his Diploma (M.S.) in Earth sciences from Germany's University of Göttingen. His thesis focused on the isotope and element geochemistry of rocks in southern Norway. Through this work, he became interested in biogeochemistry. "These were old, metamorphosed rocks, once exposed to extremely high temperatures and pressures deep in the Earth's crust," he recalled. "But there were signs that they formed by biological processes."

Building on these interests, Andreae earned his Ph.D. in 1978 from the Scripps Institution of Oceanography in San Diego, Calif., where he studied ocean and terrestrial biosphere interactions. After graduating, he served as a professor of oceanography at Florida State University, and, in 1987, became a professor at the MPIC. In 1988, Andreae received the World Meteorological Organi- zation's Gerbier-Mumm award for his discovery of a feedback loop between marine phytoplankton activity and global climate.

In addition to studying the role of marine biota as a source of climatically important trace gases, Andreae is interested in the sources and characteristics of atmospheric aerosols and their effects on precipitation and climate, and the effect of vegetation fires on ecology and atmospheric pollution. Through his research, Andreae has traveled to the Amazon basin, the jungles of central Africa, and, most recently, Siberia and China, where he is investigating the effect of atmospheric pollutants on climate systems.

—MOHI KUMAR, Staff Writer