Mars and Mine Dumps

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Abundant sulfates appear to exist on the surface of Mars and have commonly been attributed to a planet-wide volcanogenic 'acid fog'—where clouds of acid mist react directly with surface rocks or acidify surface waters —from which the sulfates precipitated [e.g., *Clark and Baird*, 1979]. In particular, Meridiani Planum, a plain located just south of the Martian equator, hosts many sulfate minerals.

Squyres et al. [2004, 2006] and *Squyres and Knoll* [2005] hypothesized that the sulfate minerals there, particularly acid sulfates such as jarosite, precipitated from high concentrations of sulfuric acid in flowing and standing water and groundwater. However, such explanations are problematic, because magnesia and alkali-bearing minerals in the basaltic regolith should have been able to neutralize sulfuric acid rapidly, making precipitation of acid sulfates such as jarosite impossible.

Alternatively, the sulfate-rich sediments at Meridiani can be explained in terms of impact surge deposition [e.g., *Knauth et al.*, 2005]. The only water involved in making jarosite, in this explanation, is moisture (i.e., frost or water vapor), none of it initially acidic.

One facet of this explanation, discussed here, is an implied analogy between ancient impact craters on Mars and open-pit sulfide mines on Earth (Figures 1 and 2). Coarse-grained breccias occurring near an impact crater are analogous to mine dumps, and finer-grained impact ejecta (impact surge and fallout deposits) are analogous to comminuted (ground-up) mine tailings. As on mine dumps and tailings, moist weathering of dispersed iron sulfides is all that is needed to produce abundant sulfates.

Such weathering on Earth is commonly accompanied by intense microbial activity. Might microbial activity have accompanied sulfide oxidation on early Mars? Regardless of the presence or absence of biotic environments, no life-hostile atmospheric, surface, or subsurface reservoirs of sulfuric acid are implied by this hypothesis.

Impacts and the Gossan Hypothesis of Roger Burns

Iron sulfides in mining waste typically oxidize rapidly, so that an open-pit sulfide mine and its wastes tend to be strongly colored by minerals such as hematite (ferric oxide or 'red rust'), goethite (ferric hydroxide or 'yellow rust'), and jarosite (a group of acid ferric iron sulfates, typically yellow or brown). These rust colors and minerals also occur on Mars; jarosite in particular reportedly occurs in abundance on Meridiani Planum. *Burns* [1987, 1988] proposed that jarosite and other ferric sulfates may well form analogously, by weathering of iron sulfide minerals contained in Martian igneous rocks. Because Martian basalts tend to be at least twice as rich in iron (Fe) as terrestrial equivalents, he argued that Martian igneous rocks should also be enriched in cumulate Fe and nickel (Ni) sulfides. These are dense, immiscible droplets that 'rain out' of the liquid magma body and accumulate at the bottom, much as molten metal sulfides accumulate beneath silicate slag in a smelter.

Weathering of sulfide deposits on Earth typically produces Mars-colored, sulfate-rich deposits called gossans (rusty areas long sought by metal prospectors as indicators of underlying ores). Burns proposed that the same process of gossan formation could have occurred on Mars, producing the same minerals, including jarosite. However, in his multiple discussions of gossans, Burns never considered impact cratering into sulfide deposits and the resultant excavation, comminution, turbulent mixing, and wide dispersal of sulfides (or gossan minerals) across Mars.

Sulfate Formation

Fine particles in mine tailings are easily eroded by wind and water, although sulfates formed by weathering of sulfides can cement them together into resistant masses. On Mars, sulfide-free impact fines should have been largely removed by wind erosion, whereas sulfide-rich deposits could have weathered into sulfate-cemented resistant deposits, such as those encountered at Meridiani Planum. Sulfides before weathering have high densities that could have allowed them to form wind-resistant lag concentrations on the surface.

Metal-sulfur bonds are weaker than metal-oxygen bonds because the sulfide ion is considerably larger than the oxide ion. This feature makes sulfides brittle and soft compared with rock-forming oxides and silicates. Sulfides also are more easily weathered and have much lower melting temperatures. Bond weakness implies that impact-affected sulfides should have been thoroughly shattered or even melted before they were dispersed into impact-generated rock debris. Fine sulfide particles presumably could not long resist oxidation on the extremely oxidizing surface of Mars; this may explain why none have yet been detected. Furthermore, most sulfates are readily able to take up and retain moisture, and thus they attract moisture from the atmosphere. This property implies a tendency for moisture-related oxidation of sulfides to sulfates to go to completion via positive feedback (autocatalysis).

Only ephemeral acid ferric sulfates, such as jarosite, typically form by sulfide weathering (commonly as colorful, powdery coatings). Jarosite and other acid sulfates are ephemeral because, as 'solid acids,' they dissolve incongruently when exposed to liquid water—they break down into rust (goethite or hematite) plus dissolved sulfuric acid (such as that in acid mine drainage). In contrast, stable neutral sulfates like those of calcium (Ca) and magnesium (Mg) could have crystallized from liquid water during the great surface evaporation and freezing events thought to have occurred on Mars almost four billion years ago [e.g., *Burt and Knauth*,

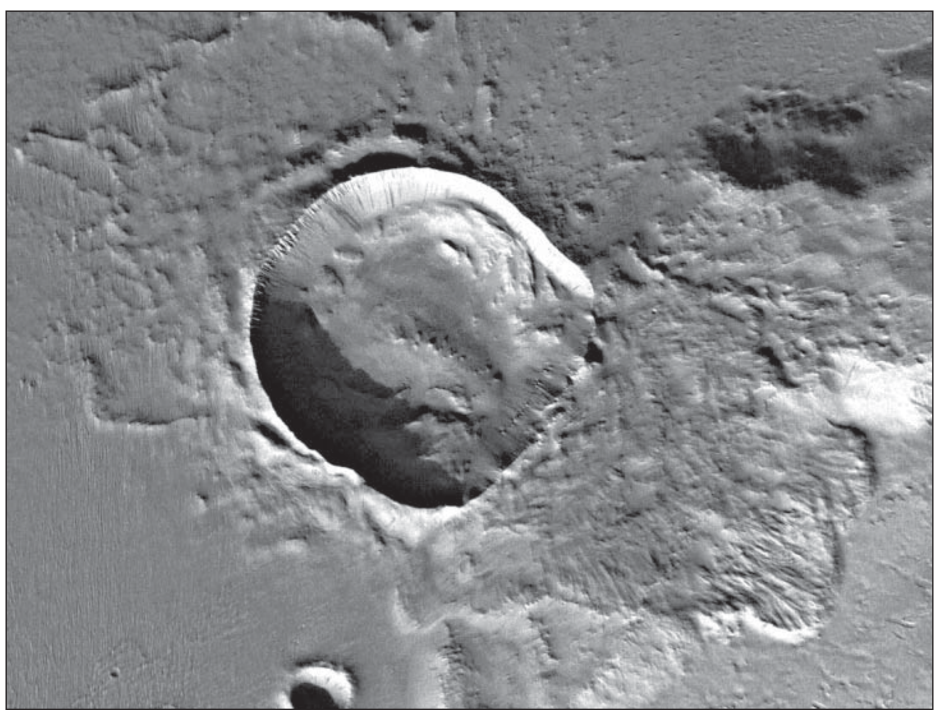

Fig. 1. A small (10-kilometer diameter) Martian impact crater in Medusae Fossae region, surrounded by erosion-resistant ejecta, resembles an excavated open-pit mine surrounded by dumps and tailings. Credit: ESA/DLR/FU Berlin (G. Neukum).

D. M. Burt, K. H. Wohletz, and L. P. Knauth

2003]. Later impacts intersecting subsurface brines and salts then could have dispersed the neutral salts planet-wide [*Burt and Knauth*, 2003] along with brine-soaked basalt and sulfides that would later weather into acid sulfates such as jarosite.

As water on Mars disappeared, the acid sulfates near the surface of Mars persisted without converting into goethite or hematite, and give further evidence for a continuing lack of exposure to liquid water. In other words, despite what has been claimed, acid sulfates such as jarosite at Meridiani provide evidence against, not for, liquid water.

Other Interpretations

The common interpretation of the formation of Meridiani acid sulfates in terms of evaporation of relatively young sulfuric acid lakes and groundwaters [e.g., *Squyres et al.*, 2004; *Squyres and Knoll*, 2005; *Squyres et al.*, 2006] neglects two fundamental characteristics of Mars. First, Mars has long been an icy planet, and crystalline salts should accumulate at the base, not top, of the section if freezing is involved [*Burt and Knauth*, 2003]. Second, reaction with the base-rich basaltic regolith of Mars should rapidly neutralize any acid groundwaters or surface waters, as indicated by terrestrial experience involving acid mine drainage, and by a variety of Mars-related experiments involving basalts. Acid-base neutralization is not slow, and once the acids have been neutralized, they cannot precipitate or remain in equilibrium with acid sulfates.

The original acid brine evaporation/surface flow hypothesis for Meridiani [*Squyres et al.*, 2004] has many other problems [*Knauth et al.*, 2005], including an improbable mixture of highly soluble Mg-sulfates with nearly insoluble Ca-sulfates (improbable because relatively insoluble sulfates should precipitate long before highly soluble ones during evaporation); a scarcity of chlorides (despite high bromine values that imply fractional crystallization of large quantities of chloride salts; where are they?); a lack of shale beds (clays that invariably settle out of standing water); and stratigraphic incompatibility with a cooling, drying Mars (i.e., why should a record of a warm, wet Mars occur at the top, rather than the bottom, of the layered section at Meridiani?). Invoking wind transport of playa lake salts followed by later surficial water flow to explain the incompatible salt mixture and highly ambiguous bedding structures [*Squyres and Knoll*, 2005; *Squyres et al.*, 2006] does not eliminate most of these problems, and implies new ones.

These problems include the evident lack of a parent playa at Meridiani Planum, a failure of the Meridiani water to dissolve or recrystallize soluble salts, brine mixing problems related to density and permeability (brines segregate by density; salt-rich beds become impermeable as the salts recrystallize), and a lack of typical water-related features such as channel scours or bedding-confined mud cracks at Meridiani Planum. Furthermore, the flat and low-angle cross-beds at Meridiani do not resemble those typically formed by wind transport, and the uniformly sized and shaped spherules are unlike known terrestrial concretions.

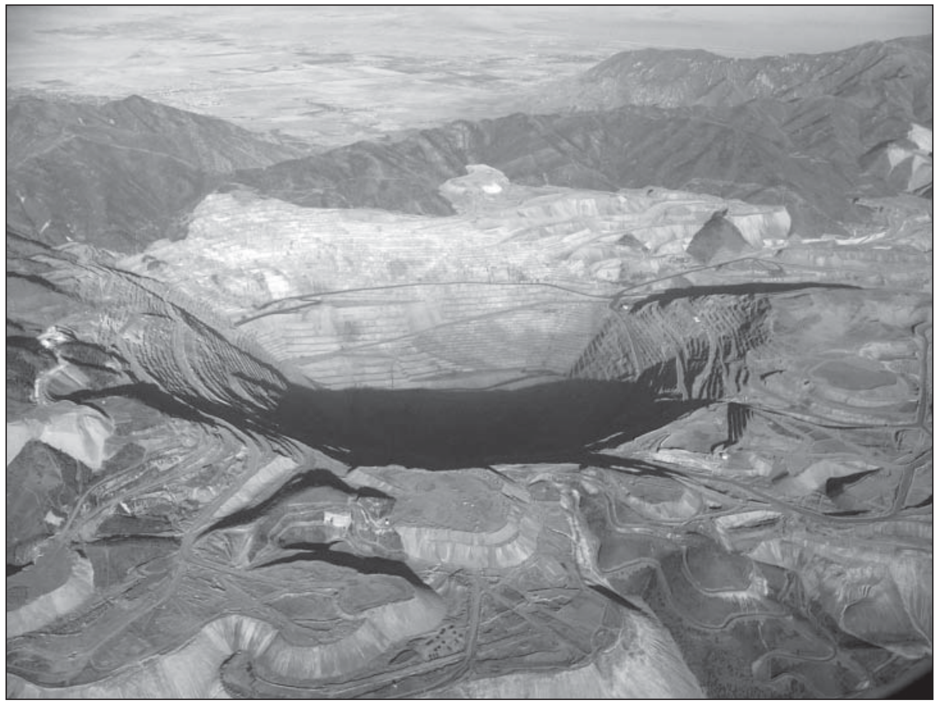

Fig. 2. The Bingham Canyon open-pit copper mine in Utah, with dumps in the foreground, resembles a Martian impact crater and its ejecta.

The impact surge hypothesis, including later diagenesis and weathering [*Knauth et al.*, 2005], encounters none of these problems, and accounts for all other reported features as well, including abundant cross-beds (mostly at shallow angles), crystals dissolved out during diagenesis, non-bedding-controlled dessication cracks, and Ni-enriched hematitic spherules dispersed in specific layers of rock.

Impact Surges

In contrast to the early Moon, early Mars had an atmosphere plus subsurface volatiles, so that impact cratering should have been distinctive. In particular, interactions of ejecta with the atmosphere, with impact-released vapor, and with the substrate are inferred to produce a dilute, ground-hugging, turbulent ejecta flow field (impact surge) that moves rapidly across the ground, radially away from the impact site. If impact melt interacts with target volatiles, multiple surge-producing events are theoretically possible [*Wohletz and Sheridan*, 1983].

Impact surges on Mars are inferred to be a multiphase transport system consisting probably of a heterogeneous mixture of atmosphere, steam, gaseous sulfur species, broken brine-soaked regolith, eroded soils, brines, salts, solid ice fragments, finely comminuted sulfides, and impact melts and droplets, plus various condensates and spherical accretionary lapilli. Notable of such multiphase transport systems are their highly variable bulk densities and moisture contents, their ability to erode the substrate, and their tendency to leave a wide range of deposits that can greatly resemble subaqueous and aeolian sediments.

The uniqueness of Mars has long been recognized with regard to young, small 'rampart craters' [e.g., *Wohletz and Sheridan*, 1983]. Nevertheless, any fine sediment deposited at a distance presumably was removed by the wind, making the observed ramparts erosional remnants only. On Earth, ground-hugging, high-velocity base surges (pyroclastic surges) produced by recent explosive volcanism (e.g., in 1980 at Mount St. Helens, Wash.) and by nuclear explosions are well documented, and are known to have produced sedimentary features similar to all of those seen at Meridiani Planum and at Mars' Gusev Crater in an area called 'Home Plate.'

Given the abundance of impact craters all across Mars and a lack of relatively young volcanism close to Meridiani Planum, the Meridiani Planum sediments presumably are related to impact rather than volcanic surge deposition. Numerous thick sequences of layered sediments have been observed from Mars orbit. Logically, many of these deposits could have resulted from impacts, inasmuch as the rate of early impact deposition should have greatly exceeded the rate of erosion. Contributions from wind and volcanism are also likely, however.

Implications for Early Mars

By the impact surge hypothesis, the surface of early Mars dried up and froze down while impacting continued. Impacts into partly frozen, salty, locally sulfide-rich basalt, followed by moist weathering, could have produced all of the features seen at Meridiani and Gusev and probably in many layered deposits elsewhere on Mars.

Sulfur-rich Mars sediments then are potentially analogous to weathered sulfur-rich mine waste but with the mining and milling having been performed by impacts. Preservation of such easily eroded, easily dissolved, easily recrystallized fine sediments from their formation billions of years ago until the present implies that any early 'warm, wet' period was well over by the time they were laid down near the top of the stratigraphic section, and that near-surface liquid water, other than intergranular films, had little or no role in their deposition or later diagenesis.

Nevertheless, by analogy with terrestrial arid-region mine dumps, these heterogeneous deposits might have provided excellent, energy-rich habitats for any microbial life present on early Mars. For future Mars missions, impact-verifying features might include remnant sulfides in freshly-exposed rocks; local enrichments in platinum-group elements and copper; additional landing sites exposing low-angle thin cross-beds, acid sulfate minerals, and spherules in bedded terrains; grain sizes increasing towards parent impact craters; and the detection of textures and minerals typical of impacts (e.g., various amorphous and high-pressure phases).

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NEWS

Coordination of U.S. River Science

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The U.S. Geological Survey is well-poised to lead a national river science initiative but will need to expand its monitoring efforts and determine how to coordinate interdisciplinary research across USGS and other government agencies, according to a recent report from a committee of the U.S. National Academies.

Committee Chair Don Siegel, a hydrogeologist in the Department of Earth Sciences at Syracuse University, N.Y., said that the USGS has unique strengths—including a reputation for providing high-quality, unbiased data and expertise in many areas of river science—that would allow the agency to look at whole river systems at multiple scales and across state boundaries.

USGS conducts research in the areas of mapping, water resources, geological science, and biology, all of which are relevant to river science. Through integration of this research, including among the agency's modeling programs, USGS would be well-qualified to lead a river science initiative, Siegel said. However, he noted that the agency needs to find a method to let researchers collaborate more efficiently among themselves and with other federal, state, and local agencies, an effort that could require changes to USGS' internal structure.

The committee recommended that the USGS expand its monitoring programs so as to integrate the various aspects of river systems, including the floodplain, channel, and groundwater, as well as ecological and biological aspects. However, in recent years the USGS has had to shut down many of its stream gauges as funding has been discontinued.

Committee member William Woessner, a hydrogeologist in the Department of Geology at the University of Montana, Missoula, called the loss of stream gauges "worrisome." These long-term records are needed more than ever, he said, especially to address issues such as climate change. Instead of losing more stream gauges, they need to be modernized to make them more accessible and to collect data beyond surface flow, including sediment transport, and interactions between ground and surface water, he said.

Increasing the types of data collected on river systems would allow the USGS to better characterize the physical properties that govern how water is routed to streams, Siegel said. The agency then would be able to develop deterministic models of these processes that could be used in efforts such as flood forecasting. Siegel noted that hydrologists have used statistical methods for flood forecasting for more than 100 years, but these methods do not take into account how watersheds, climate, and land use change. Although moving to process-based approaches is more complicated, he said, these approaches can incorporate changing conditions and can extend beyond physical processes to biological and ecological systems.

Peter Wilcock, professor and associate chair of the Department of Geography and Environmental Engineering at Johns Hopkins University in Baltimore, Md., noted that monitoring additional variables would allow researchers to frame river management questions more appropriately and allow decision makers to make better informed decisions. "Rivers and their ecosystems have value to society," Wilcock said. "Society spends money managing those rivers. The better information we have, the more efficiently and effectively that money could be spent."

One area of river science that USGS could contribute more is in stream restoration efforts. Committee member John Pitlick, a geomorphologist in the Geography Department at the University of Colorado, Boulder, said that "the USGS has a lot of expertise that could help in guiding the high quality science" needed in these efforts, but they lack the mandate and resources.

Whether the USGS will be able to implement any of the report's recommendations remains a question. Seigel noted that to do so, "there would have to be an additional allocation of resources or, within the organization, a reallocation."

The report, "River Science at the U.S. Geological Survey," is available at http://www.nap.edu

—Sarah Zielinski, Staff Writer