Mapping the Planets—Geology Stakes Its Claim

***Harry Y. McSween Jr.**, Dept. of Earth and Planetary Sciences, University of Tennessee, Knoxville, Tennessee 37996-1410, USA; mcsween@utk.edu*

ABSTRACT

Planetary geoscience had very little presence in GSA's first century, but it has a long history in GSA publications. Beginning with the Moon, the transformation of the planets and their satellites from astronomical objects into geological worlds has taken place largely by geologic mapping using telescope and spacecraft imagery and by the application of stratigraphic principles to these new data sets. Compositional data from orbital remote sensing, chronological information from crater densities, and the added dimension of petrology and geochemistry from surface rovers and laboratory analyses of samples, where available, have cemented geology's central place in planetary exploration. The present focus on characterizing planetary paleoenvironments and the search for life further buttresses geology's role in planetary exploration and serves as the next step in the expansion of our discipline beyond Earth.

PLANETARY GEOLOGY AND GSA

The inaugural GSA Presidential Address (Stevenson, 1899) ended this way: "The world must advance or retrograde; it cannot stand still." J.J. Stevenson was referring to the world of science, and more specifically to geology. As prescient as he was, the Society's first President might not have imagined that geology would advance to other worlds. At that time, the only body besides the Moon with features that were resolved through telescopes was Mars, and that planet famously was argued to have canals built by sentient beings. In fact, the better part of a century of GSA history would elapse before the Planetary Geology Division was established in 1981.

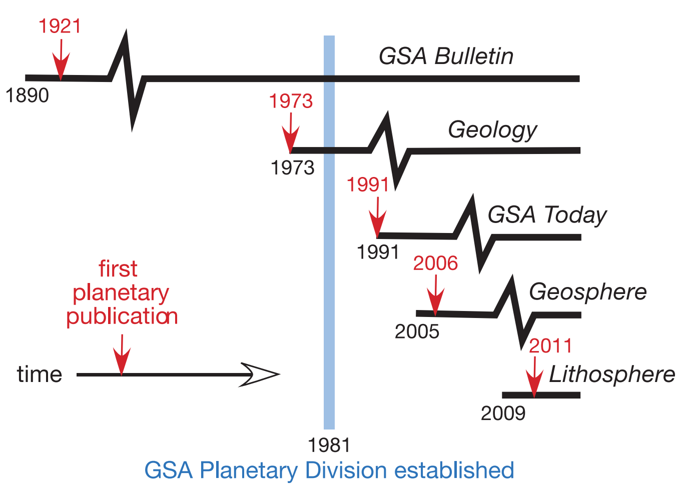

Figure 1. A timeline of GSA publications, comparing dates of establishment and publication of first planetary papers (red arrows), as well as establishment of GSA's Planetary Geology Division.

Planetary geoscience, though, has had a surprisingly long presence in GSA publications (Fig. 1). *GSA Bulletin* featured what I consider to be its first planetary paper in 1921. Other GSA publications have followed suit: The very first issue of *Geology* contained two planetary papers; *GSA Today* published its first planetary article during its first year, *Geosphere* during its second year, and *Lithosphere* during its third year.

BEGINNING WITH THE MOON

Planetary geology began, appropriately enough, with the geologic mapping of our nearest neighbor. Although cartography from telescopic observations of the Moon had been conducted for more than three centuries, the first lunar geologic map of the region surrounding Copernicus crater (Fig. 2), based on the stratigraphic principles so useful in terrestrial geology, appeared in a landmark study by Shoemaker in 1962. Later that same year, Shoemaker and Hackman (1962) divided the lunar timescale into periods delineated by cataclysmic impacts, with major formations defined as the ejecta blankets of these impact basins (Fig. 3). That was a new twist on time and rock units, but it was respectful of the principle of linking rocks and time and has worked well for heavily cratered planets. Lunar geologic units, as in terrestrial maps, were integrated into a stratigraphic column, and were dated first with relative ages determined from crater-density measurements. Shoemaker recognized the value that geologic maps would have in selecting landing sites for the Apollo program and in extrapolating data from these sites to the rest of the Moon. By 1966, 28 lunar quadrangle maps had been produced from telescopic imagery; subsequent lunar geologic maps and cross sections have been based on observations at higher spatial resolution from orbiting spacecraft. Similar to stratigraphic columns on Earth, which initially had only relative ages until radioactive isotope dating techniques were developed, lunar stratigraphy was relative until crater densities could be calibrated with radiometric ages from volcanic or shock-melted rocks returned by the Apollo astronauts.

EXPLORING PLANETS AND SMALL BODIES

From that beginning, geoscientists have moved forward with the audacious goal of mapping the entire solar system. Interestingly, geologic mapping of the planets has moved in an opposite direction from mapping on Earth. Local maps of our own planet are pieced together to produce regional and eventually global maps. On the other hand, planetary explorers have had a

GSA Today, v. 25, no. 1, doi: 10.1130/GSAT-14PresAdrs.1

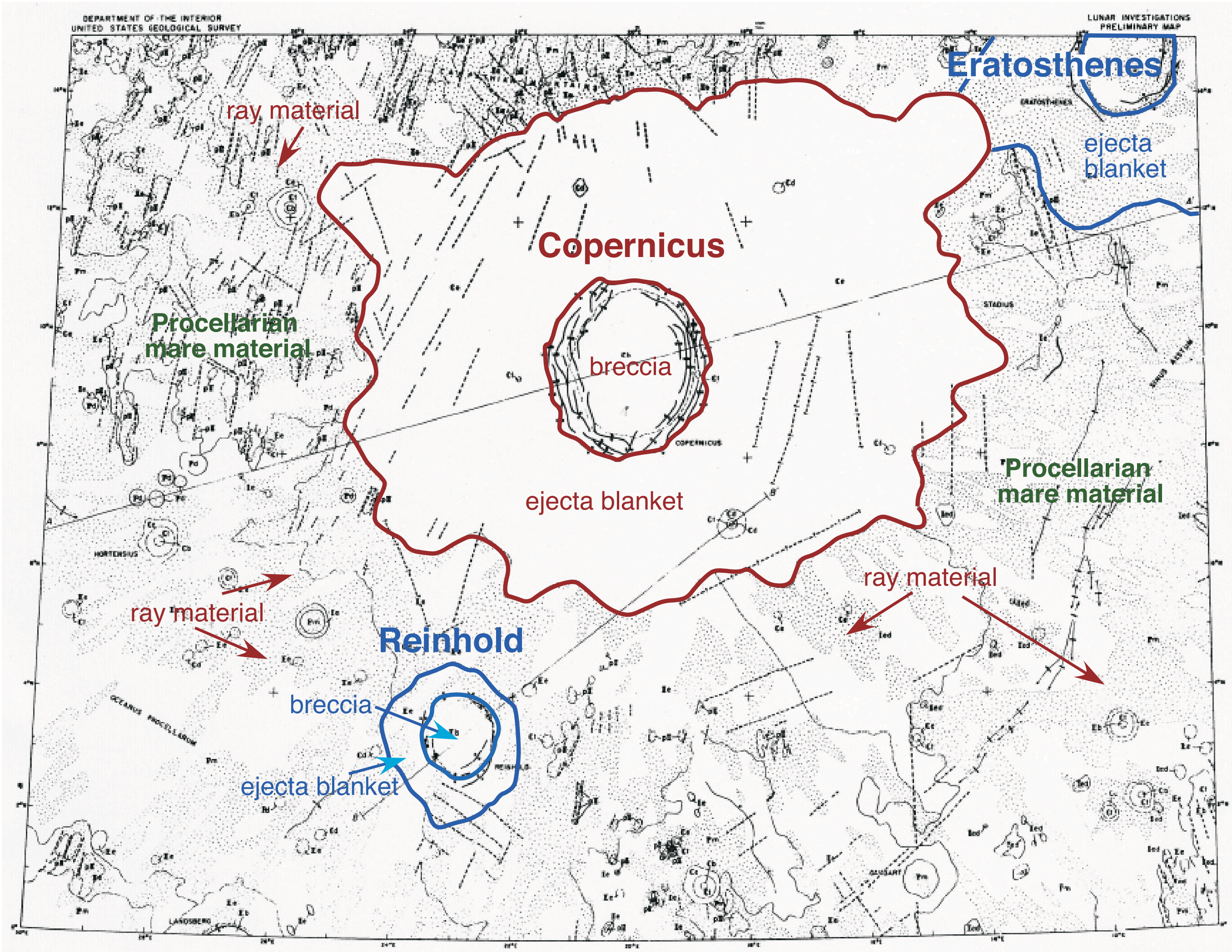

Figure 2. The earliest lunar geologic map based on stratigraphic principles (Shoemaker, 1962), shown without the legend or cross sections. This map of the Copernicus region was originally published in black and white; colorized unit contacts and labels have been added for legibility.

global perspective from the outset, and their maps progress downward to regional and local scales as spatial resolution improves.

Geologic mapping of the planets (see Carr, 2013, for a recent historical review) nowadays still depends on imagery but has been augmented by the application of remote-sensing tools. The identification of minerals from their visible, near-infrared, and thermal infrared spectra provides a means of mapping compositional units on the Moon, Mars, and Mercury. Spectroscopy can often identify only a few minerals with diagnostic absorption or emission features, and then only if they are sufficiently abundant, but adding any mineralogic information to maps allows much more rigorous interpretation. Even from orbital altitudes, the spatial resolution of spectral maps can be as small as a few tens of meters, although coarser resolutions are more common. For example, the CRISM spectrometer on the Mars Reconnaissance Orbiter has distinguished and mapped concentrations of olivine and phyllosilicates. Orbital tools for geochemical analysis are also available. Gamma-ray and neutron spectroscopy measures only a handful of elements at fairly coarse spatial resolution, but any chemical abundances are useful in distinguishing and interpreting geologic units. A prime example is a global map of compositional terranes on the Moon (Jolliff et al., 2000) based only on iron and thorium abundances obtained by the orbiting Lunar Prospector (Fig. 4). Gamma-ray spectra are especially sensitive to these two elements, and their concentrations vary greatly in different lunar lithologies.

Other planetary bodies present different challenges. The surfaces of Venus and Titan (a moon of Saturn) are obscured by thick clouds. However, they have been imaged using radar, allowing the mapping of geologic units based on their topography and radar reflectivity.

Mapping is not restricted only to large planets. Geologic maps have been compiled for all the satellites imaged by orbiting or flyby spacecraft. Moons of the giant planets show remarkably complex geologic units, comprised of jumbled blocks of icy crust (Europa), crosscutting tectonic features and superposed impact ejecta (Ganymede), erupting volcanoes with associated pyroclastic deposits of compositionally exotic materials (Io), and lakes of liquid methane (Titan). Even smaller bodies—asteroids and comet nuclei—have been mapped where spacecraft imagery is available. The most recent example is a geologic map of asteroid 4 Vesta (Williams et al., 2014), assembled from images and spectra obtained by the *Dawn* orbiter (Fig. 5).

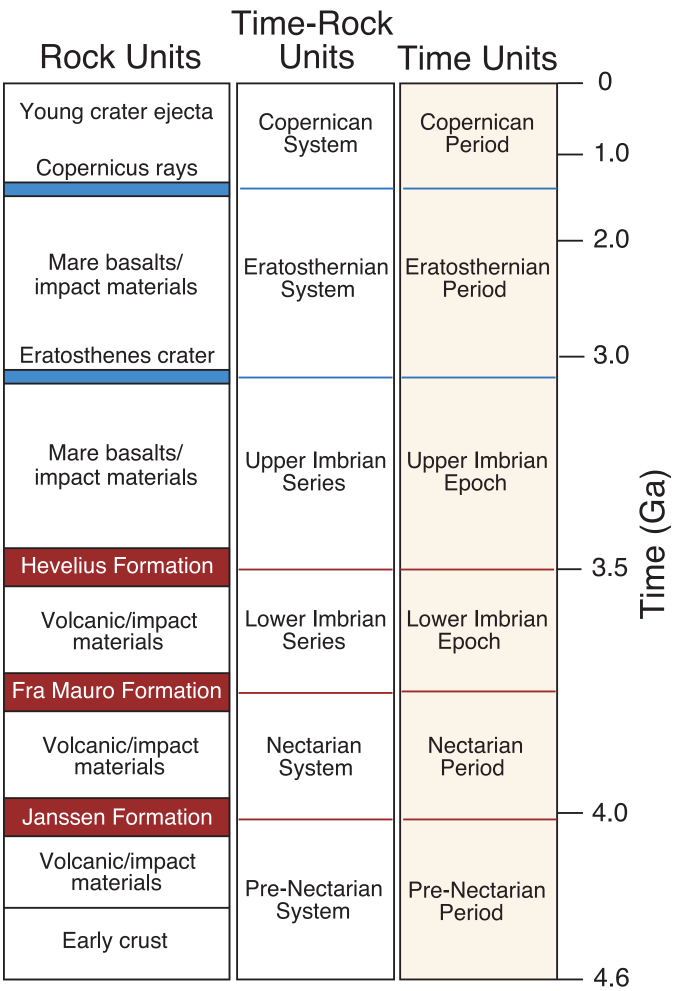

Figure 3. The lunar time-stratigraphic system, with major time units defined by widespread formations produced as ejecta blankets from large impact basins. Adapted from Wilhelms (1987).

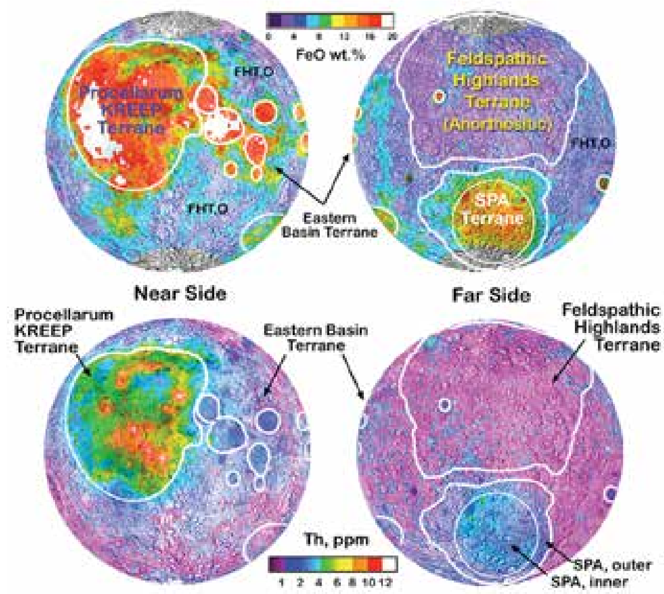

Figure 4. Global lunar maps of compositional terranes, based solely on orbital measurements of iron and thorium by Lunar Prospector. Modified from Jolliff et al. (2006).

SURFACE GEOLOGY AT HUMAN SCALE

Once a planetary body has been mapped from orbit, the next logical step is landing on its surface. The recent operation of mechanical rovers on Mars has allowed high-resolution geologic mapping at scales with which field geologists can readily identify. The traverse maps made by Mars rovers resemble those compiled from observations of the Apollo astronauts on the Moon, but rovers have extended their traverses much farther. Images and remote sensing data from *Spirit*, *Opportunity*, and *Curiosity* provide the basis for surface outcrop maps. An example is *Spirit*'s 7.7-km, 6-year traverse map though the Columbia Hills in Gusev crater (Crumpler et al., 2011), reproduced in part in Figure 6. Identifications of rock types analyzed by the rover have been extended farther afield using spectrometers that can “see” for tens of meters, making the traverse map more representative. Mars surface mapping has also been supplemented with detailed stratigraphic context from the mapped and analyzed walls of impact craters, such as the Burns Formation section in Endurance crater analyzed by *Opportunity* (Fig. 7) (Grotzinger et al., 2005). Spectroscopic analyses of chemistry and mineralogy, and spatial context and textural analyses from panoramic and microscopic imagers, of the bedded rocks encountered provide sufficient information to make detailed interpretations of geologic processes and histories. These rovers have become virtual field geologists, allowing their science teams to project human observational and mapping skills onto the surface of Mars. The rovers have become so anthropomorphic that *Sojourner*, the first primitive rover on the Mars Pathfinder mission, was named a GSA Honorary Fellow in 1997. And *Spirit*, *Opportunity*, and *Curiosity* have refined the melding of humans, machines, and instruments to the point where planetary geologic mapping can arguably be done as well or better (albeit more slowly) by rovers than by astronauts.

PLANETARY SAMPLES

The return of lunar samples to Earth and the identification of meteorites from the Moon, Mars, and asteroid Vesta have also provided valuable ground truth for spacecraft remote sensing and better geologic interpretations of these data. For example, lithologic interpretation of lunar compositional terranes from their thorium and iron abundances (shown previously in Fig. 4) required comparison with laboratory measurements of those elements in Apollo rocks (Jolliff et al., 2000). Interpretation of the unexpected discovery of hydrogen in Vesta's regolith (Fig. 8) using neutron absorption measurements by the *Dawn* spacecraft (Prettyman et al., 2012) was made possible because some meteorite breccias from Vesta contain water-bearing chondrite clasts. Comparisons of laboratory geochemical analyses of geologically young martian basaltic meteorites with rover and orbiter analyses of older volcanic rocks on the ground (Fig. 9) have provided new insights into the evolution of martian magmatism through time (McSween et al., 2009). Although the specific locations from which meteorites were extracted from their parent bodies is not known, the ability to perform petrologic and geochemical

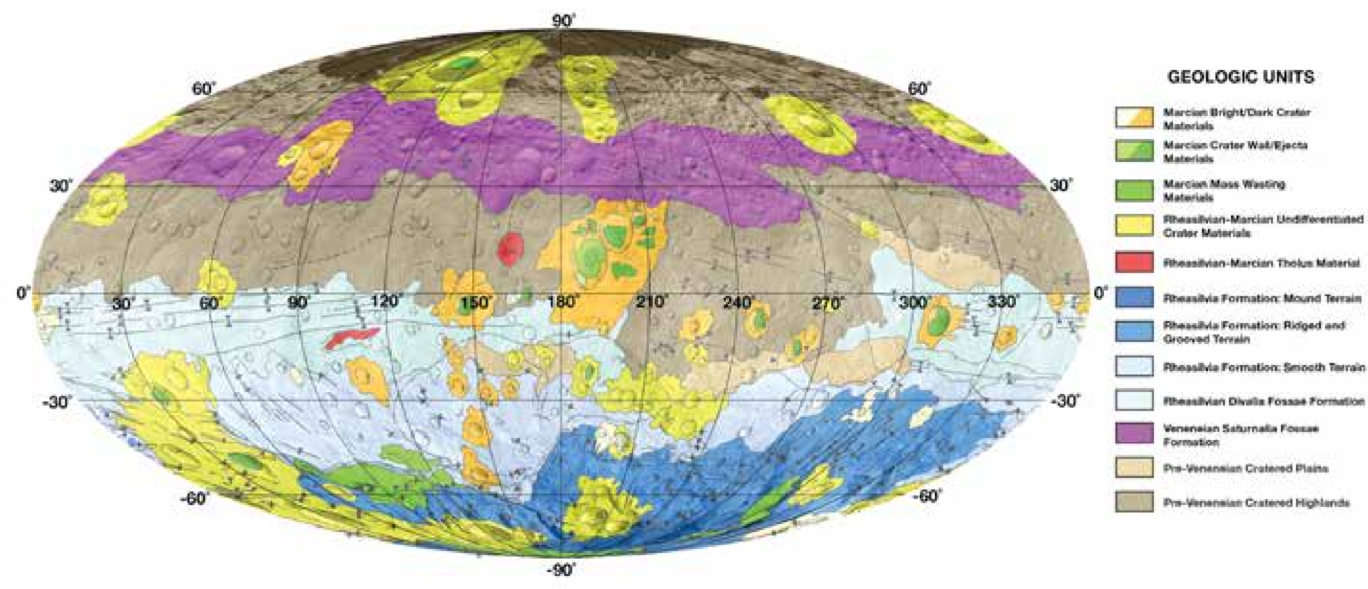

Figure 5. Geologic map of Vesta, the second-most massive asteroid, based on data from the *Dawn* orbiter. Modified from Williams et al. (2014).

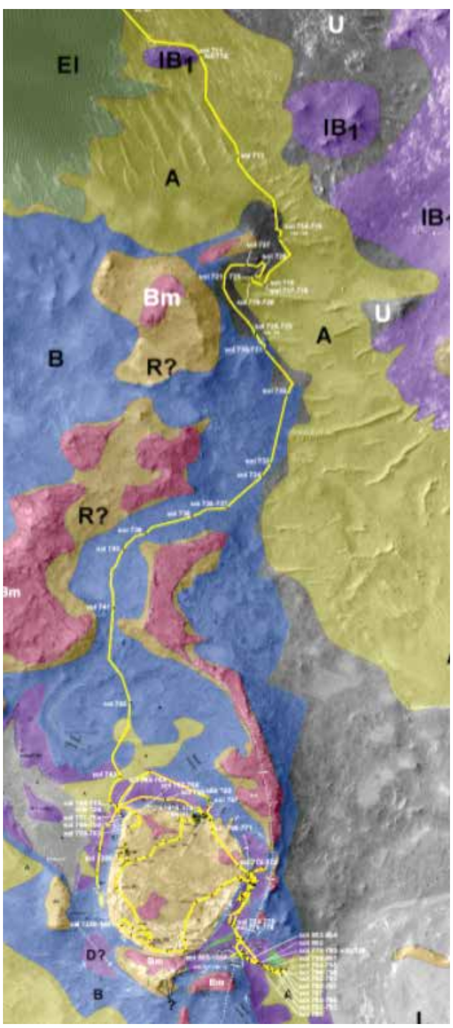

Figure 6. A portion of a geologic traverse map through the Columbia Hills in Gusev crater. The yellow line marks the route of the *Spirit* rover. For a larger version with a key of geologic units, see Crumpler et al. (2011).

analyses on rocks in the laboratory, not to mention the geochronology provided by analyses of radiogenic isotopes, strengthens the characterizations of mapped geologic units and the interpretations of geologic history.

WHAT PLANETARY GEOSCIENCE HAS WROUGHT

The geologic exploration of planetary bodies, along with the analysis of extraterrestrial samples, has demonstrated that the tried-and-true tools and methods of geology can be exported to other worlds. Like Earth, our planetary neighbors are geologic experiments conducted at a grand scale, but carried out with different starting compositions and under different physical conditions. From the study of other bodies, we can test the generality of the geologic processes we have worked so hard to understand on our own planet. And in some cases, we gain fundamentally new insights. A few examples are

- The early terrestrial planets, including Earth, had magma oceans, formed by heat from the decay of short-lived radionuclides and collisions with other bodies. Global-scale melting had profound implications for the differentiation into cores, mantles, and crusts, and for the geochemical partitioning of elements required by modern industries that fuel the world's economies.
- Plate tectonics dominates terrestrial geology, but Earth's moving plates are unique among solar system bodies. One-plate planets lose their internal heat in novel ways, and stagnant-lid tectonics allows a bewildering array of geologic structures.
- Magmatism on Earth occurs mostly at plate boundaries, so melting mechanisms on other planets are different. Basalts, albeit with distinctive compositions, are ubiquitous on all rocky bodies, but the pathways and extents of magma evolution differ, making granitic rocks virtually unrepresented outside our own planet.
- Impact cratering is the most significant geomorphic process on other planets and must have been on the early Earth as well.

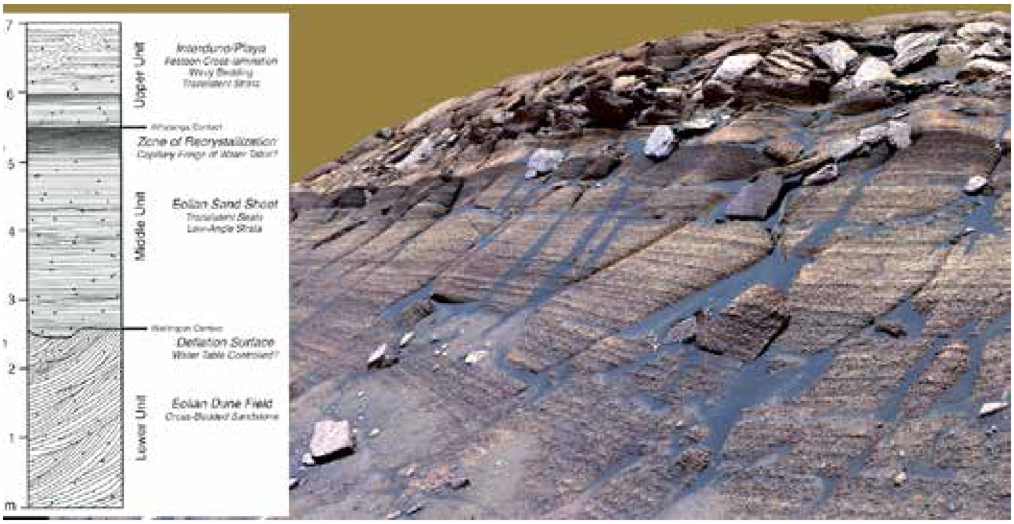

Figure 7. False-color image of the walls of Endurance crater, Mars, imaged by the *Opportunity* rover. Interpreted stratigraphic column modified from Grotzinger et al. (2005).

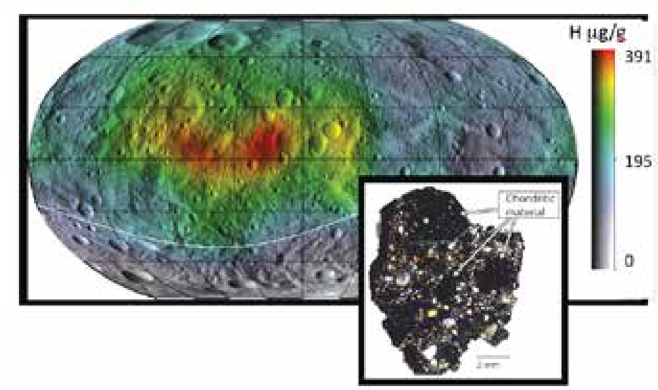

Figure 8. Global map of hydrogen on asteroid Vesta, based on neutron absorption measurements by the *Dawn* spacecraft. Also shown is a photomicrograph of a Vestan meteorite breccia containing dark, hydrous chondrite clasts. Map adapted from Prettyman et al. (2012).

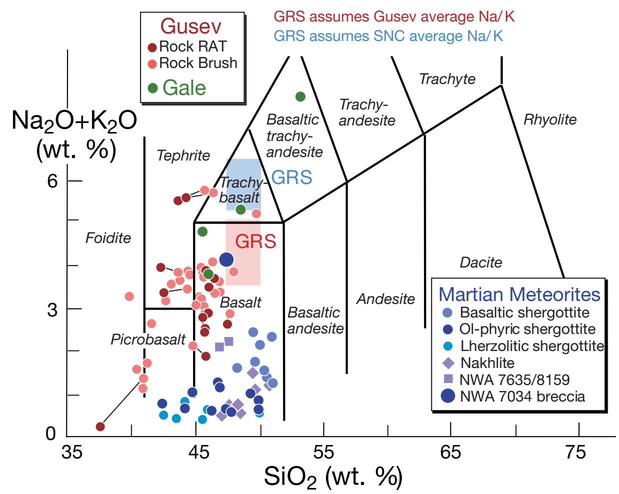

Figure 9. Geochemical classification diagram for volcanic rocks on Mars, showing the compositions of martian meteorites, Gusev and Gale crater rocks analyzed by the *Spirit* and *Curiosity* rovers, respectively, and orbital analyses by the Mars Odyssey gamma-ray spectrometer (colored rectangles labeled GRS). GRS does not measure sodium, so its abundance was estimated from Na/K ratios in Gusev rocks or martian (SNC) meteorites. Gusev rocks were either brushed or ground (RAT) by the Rock Abrasion Tool before analysis. Adapted from McSween et al. (2009), with additional data.

Large impacts have had disastrous consequences on life, and unraveling this history has prompted the realization that modern humans still live in the fast lane.

- Among the terrestrial planets, only the lithospheres of Earth and Mars have interacted with a hydrosphere. Other planetary surfaces are covered by impact-comminuted regolith.
- Active or past sedimentary processes, once thought to be unique to Earth, are now known on Mars, which hosts both clastic rocks and evaporates, and on Titan, where fluids other than water produce and distribute sediments.

As an aside, it is worth mentioning that all of geology benefits from the interest that the public displays for planetary exploration, where the application of geologic principles is played out on a large stage. It helps recruit the next generation of earth scientists and provides new data sets for our own planet. Terrestrial processes at a planetary scale can sometimes be better visualized or monitored from orbit.

WHAT THE FUTURE MAY HOLD

The reconnaissance phase of solar system exploration is well along, but geologic understanding of most planets has only scratched the surface. Science by spacecraft is complex and expensive, and large, multidisciplinary (often international) teams of scientists and engineers have to work together seamlessly. Mission operations can last for decades, requiring several generations of investigators. This can be a new experience for geoscientists used to working in isolation and on projects of limited duration.

Understandably, an important goal for planetary exploration is the search for extraterrestrial life. Efforts so far have focused on recognizing paleoenvironments that might have been conducive to organisms. The methods used by terrestrial paleontologists to study the distribution and evolution of organisms have not yet found application on other worlds. But life's signals, especially of primitive life forms far removed from us in time, may be more readily recognized by geochemistry or biomarkers than in physical forms. Robotic explorers increasingly carry instruments capable of identifying the organic or isotopic tracers of life, while at the same time examining rocks for microscopic indications of fossilized material.

And what of the newly recognized additions to the solar system's retinue of planets, now being found in the frigid regions beyond Pluto, and the bonanza of extrasolar planets (~1800 at last count) that have been discovered orbiting other stars? At present, any information about these bodies is extremely limited, but as more data accrue, geological reasoning will be needed for meaningful interpretation.

This is an opportunistic time for geoscientists—astronomy has basically abdicated much of the solar system to geology. Planets and smaller bodies are no longer astronomical points of light, but are increasingly recognized as worlds shaped by more or less familiar geologic processes. This shift of a substantial quantity of scientific real estate has literally redefined the reach of our discipline. Geology has staked its claim on the planets and must play the central role in exploring this frontier.

REFERENCES CITED

Carr, M.H., 2013, Geologic exploration of the planets: The first 50 years: Eos (Transactions, American Geophysical Union), v. 94, p. 29–30, doi: 10.1002/2013EO030001.

Crumpler, L.S., Arvidson, R.E., Squyres, S.W., McCoy, T.J., Yingst, A., Ruff, S., Farrand, W., McSween, H.Y., Powell, M., Ming, D.W., Morris, R.V., Bell, J.F., III, Grant, J., Greeley, R., DesMarais, D., Schmidt, M., Cabrol, N.A., Haldemann, A., Lewis, K.W., Wang, A.E., Schröder, C., Blaney, D., Cohen, B., Yen, A., Farmer, J., Gellert, R., Guinness, E.A., Herkenhoff, K.E., Johnson, J.R., Klingelhöfer, G., McEwen, A., Rice, J.W., Jr., Rice, M., deSouza, P., and Hurowitz, J., 2011, Field reconnaissance geologic mapping of the Columbia Hills, Mars, based on Mars Exploration Rover *Spirit* and MRO HiRISE observations: Journal of Geophysical Research, v. 116, E00F24, doi: 10.1029/2010JE003749.

Grotzinger, J.P., Arvidson, R.E., Bell, J.F., III, Calvin, W., Clark, B.C., Fike, D.A., Golombek, M., Greeley, R., Haldemann, A., Herkenhoff, K.E., Jolliff, B.L., Knoll, A.H., Malin, M., McLennan, S.M., Parker, T., Soderblom, L., Sohl-Dickinson, J.N., Squyres, S.W., Tosca, N.J., and Watters, W.A., 2005, Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns Formation, *Meridiani Planum*, Mars: Earth and Planetary Science Letters, v. 240, p. 11–72, doi: 10.1016/j.epsl.2005.09.039.

Jolliff, B.L., Gillis, J.J., Haskin, L.A., Korotev, R.L., and Weiczorek, M.A., 2000, Major lunar crustal terranes: Surface expressions and crust-mantle origins: Journal of Geophysical Research, v. 105, E2, p. 4197–4216, doi: 10.1029/1999JE001103.

Jolliff, B.L., Wieczorek, M.A., Shearer, C.K., and Neal, C.R., 2006, New Views of the Moon: Mineralogical Society of America Reviews in Mineralogy and Geochemistry, v. 60, plate 3.10.

McSween, H.Y., Taylor, G.J., and Wyatt, M.B., 2009, Elemental composition of the martian crust: Science, v. 324, p. 736–739, doi: 10.1126/science.1165871.

Prettyman, T.H., Mittlefehldt, D.W., Yamashita, N., Lawrence, D.J., Beck, A.W., Feldman, W.C., McCoy, T.J., McSween, H.Y., Toplis, M.J., Titus, T.N., Tricarico, P., Reddy, R.C., Hendricks, J.S., Forni, O., Le Corre, L., Li, J.-Y., Mizzon, H., Reddy, V., Raymond, C.A., and Russell, C.T., 2012, Elemental mapping by *Dawn* reveals exogenic H in Vesta's regolith: Science, v. 338, p. 242–246, doi: 10.1126/science.1225354.

Shoemaker, E.M., 1962, Interpretation of lunar craters, *in* Kopal, Z., ed., Physics and Astronomy of the Moon: New York, Academic Press, p. 283–359.

Shoemaker, E.M., and Hackman, R.J., 1962, Stratigraphic basis for a lunar time scale, *in* Kopal, Z., and Miklhalov, S.K., eds., The Moon: London, Academic Press, p. 289–300.

Stevenson, J.J., 1899, Presidential address: Our Society: GSA Bulletin, v. 10, p. 83–98; reproduced *in* GSA Today, v. 23, no. 8, p. 4–11, http://www.geosociety.org/gsatoday/archive/23/8/article/i1052-5173-23-8-4.htm (last accessed 23 Sept. 2014).

Wilhelms, D.E., 1987, The Geologic History of the Moon: Washington, D.C., U.S. Geological Survey Professional Paper 1348, 302 p.

Williams, D.A., Jauman, R., McSween, H.Y., Marchi, S., Schmedemann, N., Raymond, C.A., and Russell, C.T., 2014, The chronostratigraphy of protoplanet Vesta: Icarus, doi: 10.1016/j.icarus.2014.06.027.