Ancient Mars: Wet in Many Places

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New results from the Mars Express Orbiter mission reveal multiple deposits of minerals formed in the presence of liquid water. They reinforce the conclusion that ancient Mars was warmer and wetter than it is today, and increase the number of promising localities to search for evidence of past life.

We are in the midst of a veritable flood of new evidence for the past presence of liquid water on Mars. The latest deluge is emanating from the OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité) instrument aboard the European Space Agency's Mars Express Orbiter (Fig. 1) in the form of visible and near-infrared spectra of the martian surface. The results, published this week in *Science* (*1*–*6*), show evidence for multiple, localized ancient sedimentary deposits containing minerals that can only form in the presence of liquid water. They make it clear that ~3 billion years ago, water-rich environments such as those currently being explored by NASA's Mars Exploration Rovers (*7*, *8*) existed in many locations.

Mars scientists have been searching for water-formed minerals on Mars for some time. The story behind OMEGA's new discoveries illustrates not only the ability of Mars to hide its secrets, but also the hit-or-miss nature of planetary exploration with spacecraft. Near-infrared reflectance spectroscopy had been a mainstay of planetary science and Earth remote-sensing methods for many decades, but it has taken many attempts to get a high-resolution near-infrared spectrometer in orbit around Mars. The French ISM Imaging Spectrometer for Mars aboard the partially successful 1988 Soviet Phobos 2 mission was the first imaging spectrometer to acquire a data set from another planet. However, ISM's low spatial resolution and limited spatial coverage prevented it from detecting the spectral signatures of water-formed minerals. In 1985, NASA had firm plans to equip its Mars Observer Orbiter with VIMS (Visual and Near Infrared Mapping Spectrometer). However, because of budgetary difficulties project-wide, VIMS was dropped from the payload well before launch of the mission, which ended in failure just before Mars orbit insertion in 1993. Subsequently, the next-generation French OMEGA spectrometer was launched on the Russian-ESA Mars '96 mission, which failed in Earth orbit in 1996. Like many of the Mars Express instruments, the currently operating OMEGA is a rebuilt copy of the lost Mars '96 version.

Although OMEGA has firmly established near-infrared reflectance spectroscopy as a productive approach for identifying water-formed minerals on Mars, it is not the only technique that has been successfully applied from orbit. NASA's Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) and Mars Odyssey Thermal Emission Imaging System (THEMIS) are both currently searching for these mineral signatures using longer wavelength thermal emission spectroscopy, a laboratory and remote-sensing technique that is also routinely applied on Earth. Their most significant discovery to date has been the identification by TES of water-formed crystalline hematite at Meridiani Terra (*9*), which was the driving motivation for the selection of the MER Opportunity Rover landing site (*8*). With this one notable exception, the positive identification of other water-formed minerals on Mars with TES and THEMIS data sets has proven difficult, apparently because of the nature of the mineral deposits themselves. Thermal emission spectroscopy generally works best on smooth rocks containing coarse-grained minerals that produce strong thermal emission signatures (*10*). At its landing site at Meridiani Terra, the Opportunity Rover found the surface to be littered with smooth, millimeter-sized spherules of coarse crystalline hematite dubbed "blueberries," which formed from the chemical precipitation of hematite from iron-rich fluids within the sediments (*8*). The MER images clearly show that the hematite spherules are concentrated at the surface by the erosion of the fine-grained sedimentary units in which they formed (*8*), making them ideal targets for detection by TES from orbit. OMEGA has observed exposed sedimentary units associated with those explored at the Opportunity site and found spectral evidence for the hydrated sulfate mineral kieserite (*5*). This new observation is entirely consistent with the conclusion that fine-grained sediments at the MER Opportunity site contain abundant sulfate salts (*8*). Taken together, OMEGA's new results suggest the widespread exposure of water-formed minerals in fine-grained sedimentary deposits that produce thermal emission signatures that may be too weak to be detected from orbit by TES and THEMIS.

In addition to reinforcing recent conclusions regarding the presence of surface liquid water environments early in Mars's history, OMEGA is providing valuable new information about the global distribution of exposed water-formed minerals. Thus far, having mapped only 50% of the planet, and only 3% at highest resolution, OMEGA has identified hydrated sulfates and hydrated silicates almost exclusively in locations where relatively recent processes have exposed ancient materials of sedimentary origin. High-resolution MGS Mars Orbiter Camera images have revealed the presence of a much larger number of layered outcrops in a range of ancient geologic settings (*11*). The OMEGA results increase the likelihood that these outcrops contain sedimentary rocks. At martian mid-latitudes, the Mars Odyssey Gam-

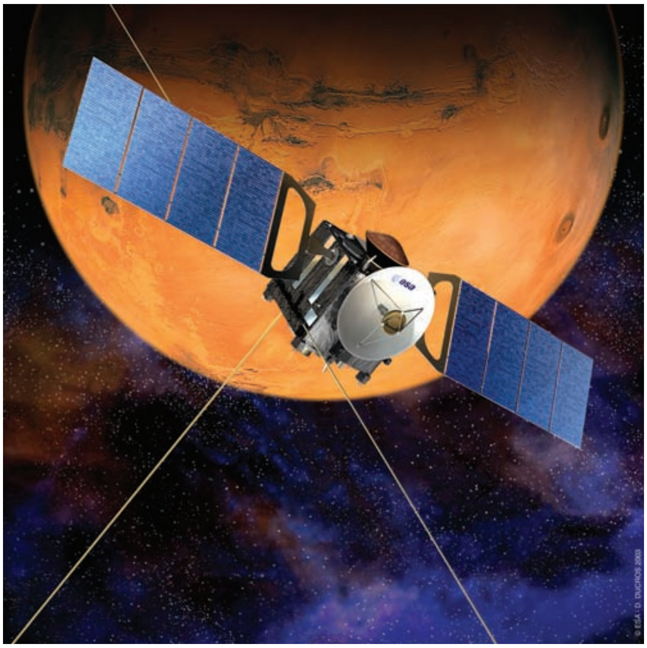

Fig. 1. The European Space Agency's Mars Express spacecraft orbits the planet Mars.

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ma Ray Spectrometer (GRS) has discovered extensive regions of enhanced near-surface hydrogen abundance that are estimated to contain up to 5 to 10% water by mass (*12*). OMEGA's positive detection of hydrated minerals in selected exposed outcrops increases the likelihood that some, if not most, of the mid-latitude hydrogen detected by the GRS is also in the form of hydrated minerals (*1*). The ensemble of water-bearing mineral species identified thus far on Mars, and the geological settings in which they are found, appear to require surface climatic conditions that were distinctly warmer and wetter than they are today. Determining whether these more clement environments were local or global, transient or long-lived, will require a more complete knowledge of the range of mineral species present, and their geological context.

OMEGA's discovery of multiple ancient water-rich Earth-like surface environments on Mars should redouble efforts to explore the martian surface widely for signs of past life. Later this year, NASA's Mars Reconnaissance Orbiter will be launched with a powerful suite of new remote-sensing instruments that include CRISM, the Compact Reconnaissance Imaging Spectrometer for Mars, which has more than 10 times the spatial resolution of OMEGA. If all goes as planned, CRISM will join OMEGA to further define the extent and nature of martian water-formed mineral deposits. The future for orbital remote sensing of Mars continues to look rosy. However, as we look ahead to NASA and ESA's plans for the next decade, there are signs that a large and obvious "rover gap" is developing, given that the two or three rovers currently planned will not be sufficient to explore the diversity of scientifically exciting surface sites identified from orbit. If the successful ongoing Mars missions are teaching us anything, it is that the surface of Mars is even more diverse than had previously been thought, especially at sub-kilometer spatial scales. While the fine-scale diversity of the martian surface increases the chances of finding evidence for previously habitable or inhabited environments, it also increases the number of places that need to be searched. As best we can now determine, Mars has exposed on its surface today a record of its early environment that is better preserved than, and at least as interesting as, that of Earth. If true, then achieving equivalent levels of insight into the early histories of both planets will ultimately require equivalent levels of exploration and investigation.

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RESEARCH ARTICLE

Mars Surface Diversity as Revealed by the OMEGA/Mars Express Observations

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The Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité (OMEGA) investigation, on board the European Space Agency Mars Express mission, is mapping the surface composition of Mars at a 0.3- to 5-kilometer resolution by means of visible–near-infrared hyperspectral reflectance imagery. The data acquired during the first 9 months of the mission already reveal a diverse and complex surface mineralogy, offering key insights into the evolution of Mars. OMEGA has identified and mapped mafic iron-bearing silicates of both the northern and southern crust, localized concentrations of hydrated phyllosilicates and sulfates but no carbonates, and ices and frosts with a water-ice composition of the north polar perennial cap, as for the south cap, covered by a thin carbon dioxide–ice veneer.

Many questions about the evolution of Mars, including the nature of surface-atmosphere interactions, the water and CO_2 cycles on short to long time scales, crustal formation and evolution, and the role of water in creating and sustaining habitable environments, require understanding its mineralogy and composition. Analyses of data from OMEGA (*1*), the hyperspectral visible and infrared imaging spectrometer on board the Mars Express European Space Agency (ESA) mission (*2*), reveal a diverse and complex surface mineralogy pertinent to these outstanding Mars problems. Here, we describe key surface materials in the form of mafic iron-bearing silicates, ices and frosts, and hydrated minerals and sediments, which have been identified by OMEGA.

During the first 9 months of operations, OMEGA has acquired the spectra of more than 20 million pixels along ~100 tracks. With an

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