

Investigating Martian History with the CRISM Imaging Spectrometer

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The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) is the powerful, technically innovative mineral-mapping camera on the Mars Reconnaissance Orbiter. The main objectives of the instrument are to map Mars' crustal composition and atmospheric processes, and to find and characterize past liquid water environments that might have provided a habitat for life. CRISM was designed, built, and tested at APL and is currently being operated from the CRISM Science Operations Center at the Laboratory. In Martian orbit, CRISM is mapping the global distribution of Mars' ices and minerals; measuring dust, ice, and trace gases in the atmosphere; and imaging several thousand key locations at high spatial and spectral resolution. First results are already changing our understanding of Martian history.

MARS, THE MOST EARTH-LIKE PLANET

Ever since astronomers have peered at Mars through telescopes, the red planet has fascinated scientists and the public for its potential similarity to Earth. From the beginning of spacecraft exploration of the planet with Mariner 4 in 1965, we have learned that Mars is a transitional body, with characteristics between the highly evolved, active Earth and the geologically quiet Moon.¹ Mars' surface consists of two main provinces: old, densely cratered highlands that dominate the southern hemisphere and younger, flat, low-lying plains that cover much of the northern hemisphere. Mars has the largest volcanoes in the solar system. Five of the biggest, with peaks 27 km above the northern plains, are clustered on and around a North America-sized

plateau known as Tharsis. Mars has tectonic features, fault zones and ridges formed by the movement of its outer rigid layer, the lithosphere. The most conspicuous tectonic features are long troughs surrounding Tharsis, including the mammoth Valles Marineris canyon system whose length, breadth, and depth approximate the Mediterranean if emptied of water. Like Earth, Mars rotates in about 24 h and is tilted on its axis, giving the planet seasons. Each polar region has an ice cap consisting of alternating layers of cleaner and dustier water ice sitting atop stacked layers of sediments. The climate is extraordinarily cold and arid, with surface temperatures rarely exceeding 0°C and dipping to -130°C during the polar night. The average atmospheric pressure is only about

600 Pa (0.6% of Earth's atmospheric pressure at sea level). In most locations water cannot exist stably as liquid and occurs instead only as ice or vapor.

Despite the thin, cold atmosphere, Mars resembles Earth in a way that is unique among other planets in our solar system: many parts of its surface are carved by what appear to be liquid water channels (Fig. 1). The channels differ in their age and characteristics. Some date to the planet's earliest history about 4 billion years ago, whereas a few have formed within the last few years.² The past occurrence of liquid water and its possible persistence to the present, even under harsh surface conditions, provided an environment that may have met the conditions necessary for life.

MRO AND CRISM

The effects of water on Mars' surface are the cross-cutting theme of NASA's Mars Exploration Program. When did water occur, and where does it still occur? How and for how long was the past climate different so as to permit flowing water? How did water affect Mars' geology, and did it and does it provide a biological habitat? In the modern environment, how does water cycle between polar ice and the atmosphere? To investigate these questions, a small flotilla of NASA and European Space Agency (ESA) spacecraft have investigated Mars from the surface while in orbit over the last decade (Fig. 2).

The Mars Reconnaissance Orbiter (MRO)³ is the seventh successful orbital mission to Mars. Its primary objectives are to

- Characterize present-day seasonal variations in water content of the surface and atmosphere
- Search for evidence of past and present liquid water environments
- Map the composition, geology, and layering of surface deposits

MRO has operated since November 2006 from a 255 × 320 km altitude, near-polar Sun-synchronous orbit that crosses the equator at 3 p.m. local solar time. Its complement of instruments includes a high-resolution imager that can resolve surface features as small as a meter, a weather camera and an IR atmospheric sounder to monitor clouds and trace gases, a radar to probe below the surface for ice and water, and a mineral-mapping, visible-IR imaging spectrometer, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM).⁴

In Martian orbit, CRISM is undertaking three major science investigations:

1. Mapping the mineralogy of key areas with resolution as good as 15 m/pixel over the 362- to 3920-nm wavelength range
2. Acquiring global imaging at a reduced spatial resolution of 200 m/pixel using 72 selected wavelengths to provide contextual maps of key minerals

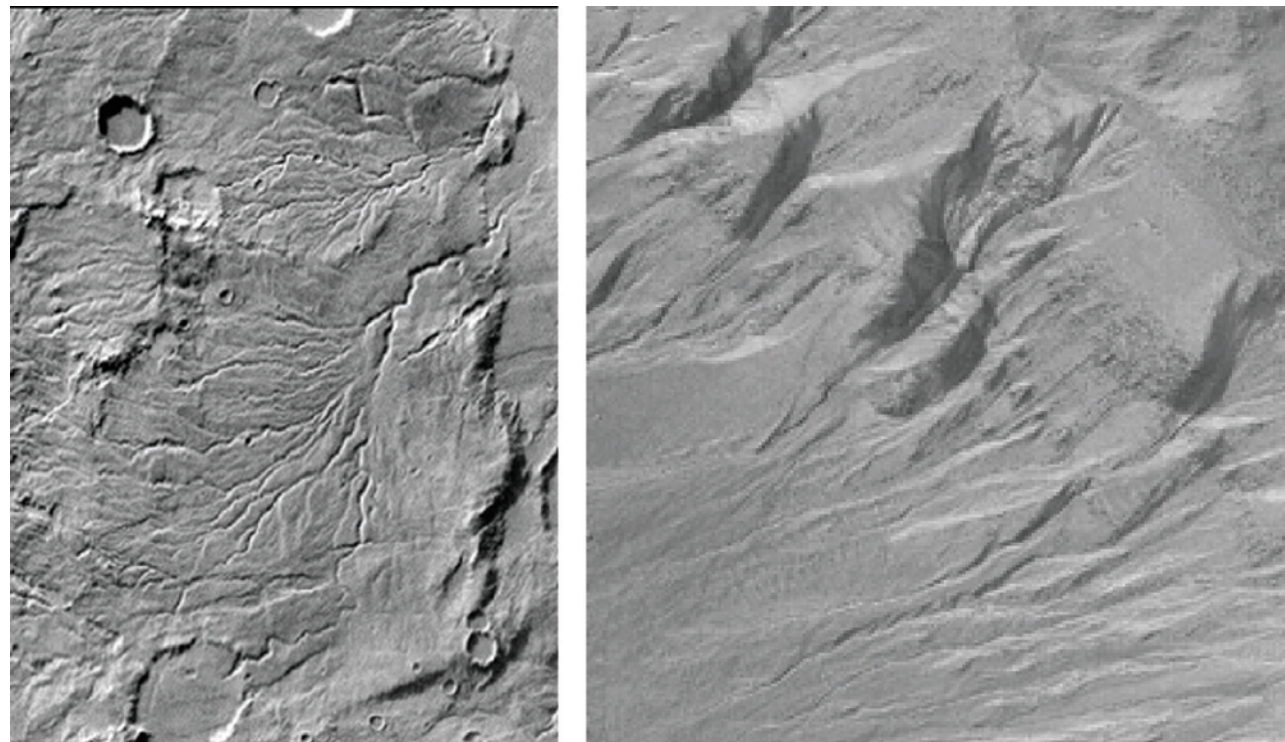


Figure 1. (Left) 3.5–4.0-billion-year-old networks of river-cut valleys incise the Martian southern highlands. (Image courtesy of NASA/JPL-Caltech.) (Right) Gullies formed on crater and valley walls during the planet's most recent history. (Image courtesy of NASA/JPL/Malin Space Science Systems.)

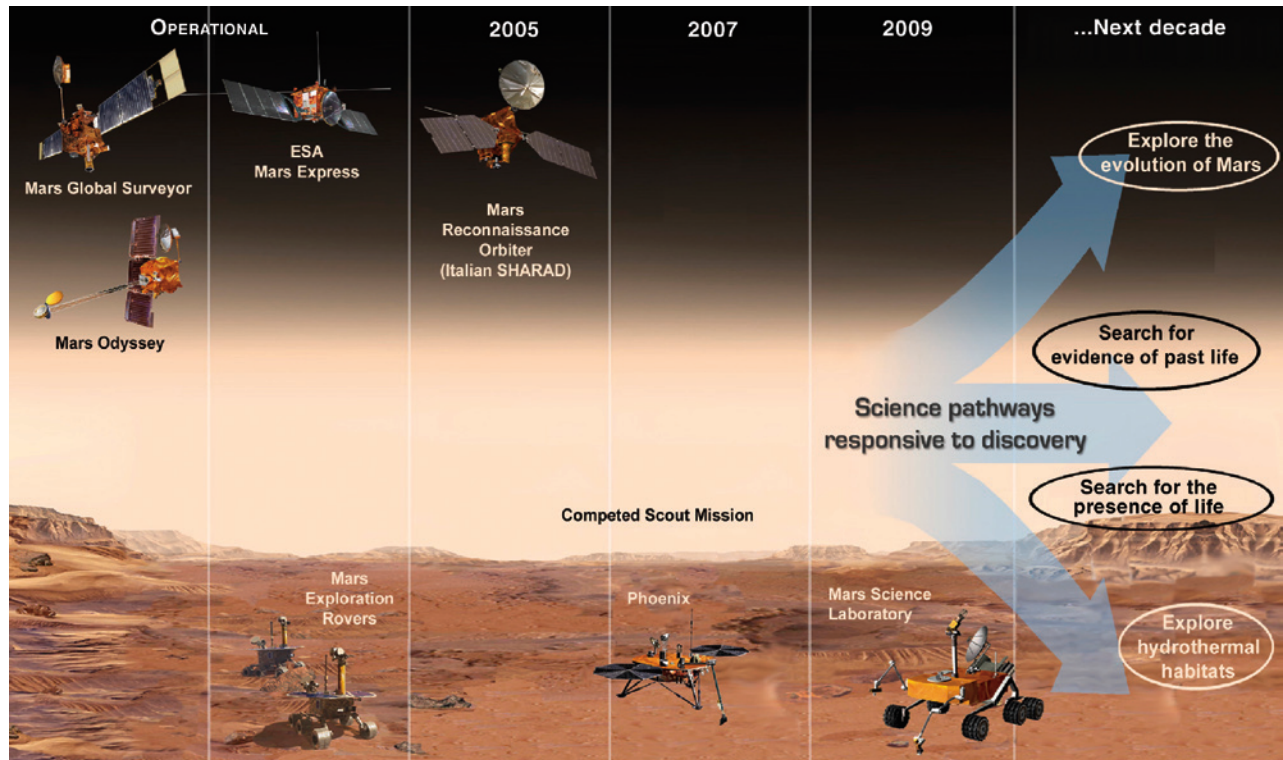


Figure 2. Recent and planned Mars spacecraft. All were or will be launched by NASA, except for Mars Express, which was launched by ESA.

3. Measuring seasonal variations in dust, ice clouds, and trace gases in Mars' atmosphere

CRISM consists of three assemblies (Fig. 3). The largest, the optical sensor unit (OSU), contains optics, detectors, radiators, and a cryogenic system, all of which can be gimbaled. A data processing unit (DPU) provides power, command and control, and data editing and compression, and gimbal motor electronics (GME) run the gimbal. The OSU is the heart of CRISM. A 10-cm-dia. Ritchey-Chretien telescope feeds a pair of Offner convex-grating spectrometers. In each spectrometer, a one-line spatial image is dispersed into the component wavelengths of reflected sunlight. One spectrometer, the visible/near IR (VNIR), uses an array of silicon photodiodes to capture its images. The other, an IR spectrometer, uses an array of HgCdTe diodes. Both detectors have a 640×480 (spatial \times spectral) format of $27 \mu\text{m}^2$ pixels bonded to a TMC 6604A read-out integrated circuit. As MRO moves along its orbit, CRISM points to nadir to take images. To remove smear, the pivoting capability is used to track a point on the surface and scan across it slowly. A cryogenic cooling system maintains the IR detector near -163°C for low noise, and the spectrometer is cooled by a passive radiator to maintain low background.

CRISM'S DESIGN AND FUNCTION

CRISM's design results from demanding engineering requirements that must be met to fulfill its science

objectives. One primary objective is high spatial resolution, better than 20 m/pixel. This is critical to seeing the layering of Mars' rocks, which tell us the sequence in which the rocks formed (younger rocks sit on top of older rocks). CRISM must also take its images at high spectral resolution, in hundreds of wavelengths, to determine which minerals make up the rocks. Electrons in mineral crystals preferentially absorb light at specific energy levels, and the spectrum of reflected sunlight exhibits absorption features at the corresponding wavelengths. Numerous rock-forming minerals have distinctive signatures in reflectance spectra, and the minerals present tell us about the environment in which the rocks formed (Fig. 4). For example, the iron- and magnesium-rich minerals olivine and pyroxene form in volcanic

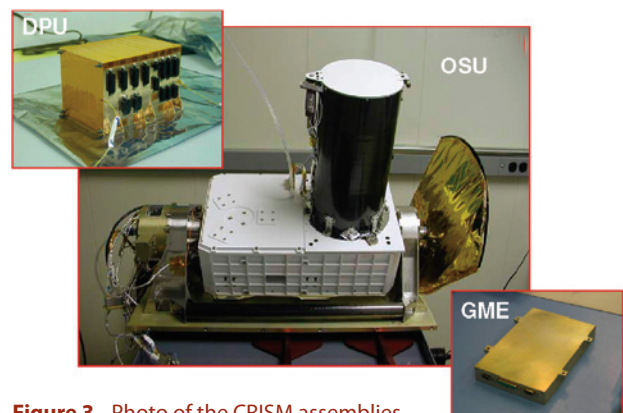


Figure 3. Photo of the CRISM assemblies.

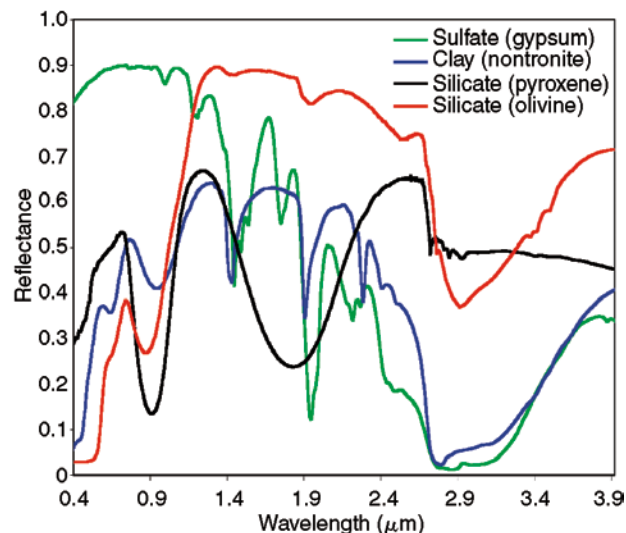


Figure 4. Major mineral indicators of the environments in which Martian rocks formed have distinctive spectral signatures at visible to IR wavelengths.

rock. Pyroxene persists in erosional debris, but olivine quickly weathers when water is present, so its presence indicates a dry environment. Clay minerals indicate the alteration of rock by water, and sulfates form where liquid water has evaporated. Thus imaging data with high spatial and high spectral resolution in many wavelengths can tell us about the history of environments in which Mars' rocks formed. To interpret these measurements, though, a high signal-to-noise ratio (SNR) is required, and dividing incoming photons into so many spatial and spectral bins degrades the SNR.

CRISM's highest-resolution images will cover less than 1% of Mars' surface, so to put them into context CRISM also must take a global, lower-resolution contextual map. The best previous data at VNIR wavelengths, from the Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA) instrument on ESA's Mars Express, are 30 to 50 times lower in spatial resolution than CRISM's high-resolution measurements. This is too low to put high-resolution images fully into context, so an intermediate-resolution product is essential.

Finally, CRISM must meet its objectives while the MRO points to its measurement targets. The spacecraft's guidance and control system is designed to aim for a latitude and longitude during a targeted time span, and the exact timing and pointing geometry are determined by onboard ephemeris. Many targets do not fall exactly along the ground track, so the spacecraft points up to 30° off nadir. Also, for its targets to be adequately illuminated, MRO uses a 3 p.m. local solar time orbit. CRISM's IR detector must operate at cryogenic temperatures, and the optics must be cooled to -75°C or colder to limit background radiation inside the instrument. MRO's orbit and the requirement for flexibility

in spacecraft attitude preclude passive cooling of the IR detector because a radiator would not have a consistent view to cold space. At the same time, a long-life pulse tube cooler would not fit into the instrument's mass allocation.

Meeting the instrument's science requirements drove several technical innovations that solved these engineering challenges and allowed CRISM to double as a high-resolution imager and global mapper while maintaining the high quality of both data types.⁵

- When CRISM observes a target at high resolution, the gimbal actively tracks the target while simultaneously scanning across it slowly. In this way longer exposure times can be used to build up a high SNR without smearing the image.
- An internal integrating sphere (a sandblasted aluminum sphere containing an internal lamp with a small aperture through which the illuminated interior is viewed) provides a stable radiometric reference that allows instrument artifacts to be calibrated out.
- The DPU performs data editing and compression. CRISM takes its lower-resolution contextual map by parking the gimbal at nadir, spatially binning the images, and returning only selected wavelengths. This enables a global spectral map to fit into MRO's downlink bandwidth.
- A novel cryogenic system⁶ cools the IR detector using three RICOR K508 Integral Stirling cryocoolers connected in parallel with cryogenic diode heat pipes. The system provides a long life with low mass while avoiding the limitations on passive cooling imposed by the spacecraft's orbit and pointing. To minimize the heat lift required from the coolers, an innovative focal plane mounting⁷ was developed that holds the detector in place while minimizing its conductive coupling to the rest of the instrument. The coolers and heat pipe assembly are both mounted to minimize their coupling to noncryogenic surfaces.
- MRO's orbit does provide a sufficient view of cold space to cool the optics passively using a "duck-foot"-shaped radiator on the side of the OSU that points in the anti-sunward direction. However the required amount of cooling is accomplished using a relatively small radiator constructed from an oriented-strand carbon-fiber composite having three times the thermal conductivity of aluminum.

CRISM builds up its hyperspectral images one line at a time (Fig. 5) by taking an image frame through its long, narrow slit. The length of the slit determines the spatial width of the image, and for each spatial pixel, the optics disperse the light into a spectrum that fills out the second dimension of the frame. A three-dimensional spatial/spectral image of a target is built up by taking successive data frames as the spectrometer slit sweeps over a region.

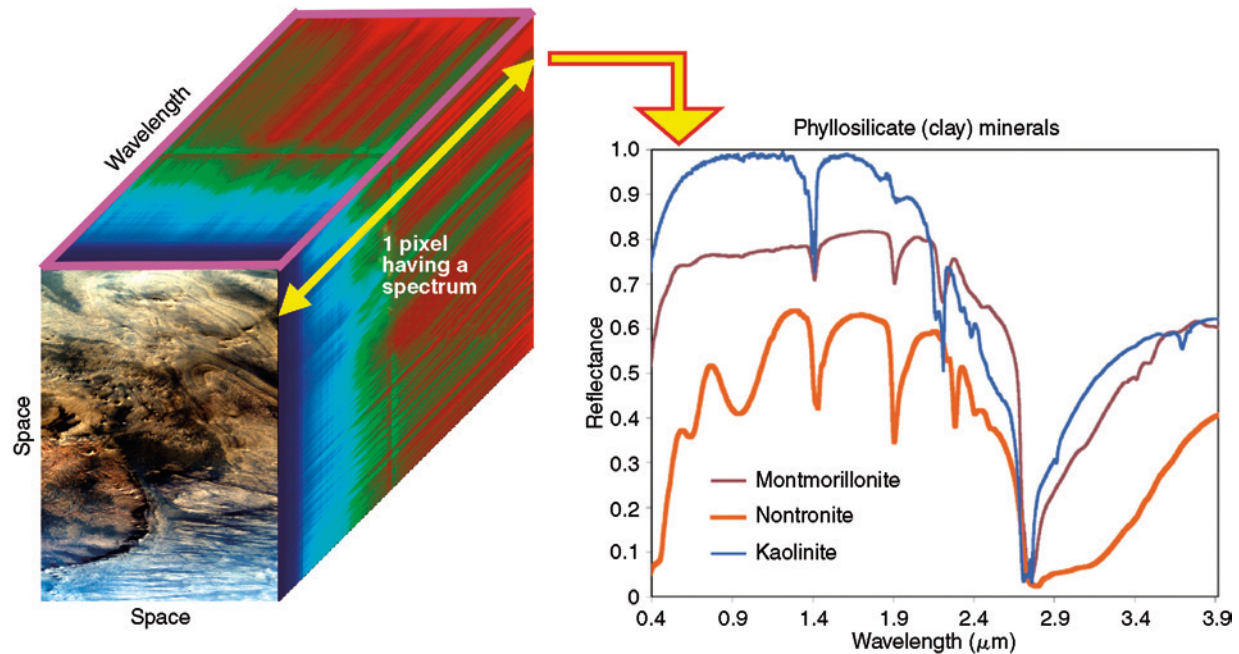


Figure 5. (Left) Schematic representation of CRISM data. A hyperspectral image “cube” is built from a series of single frames like the one outlined above in pink. A spatial image is built from a succession of data frames using one or more wavelengths. The sides of the cube show the relative intensity of the measured light on a color scale from blue (low) to red (high). The front face of the cube combines blue, green, and red light into a view similar to that which the human eye would see. (Right) The spectrum of a single spatial pixel contains features diagnostic of different minerals.

To take high-resolution images, CRISM operates in targeted mode. The instrument’s gimbal is scanned to track a point on the surface and compensate for the motion of the spacecraft. On top of that smooth curve, the gimbal superimposes a scan to cover a region approximately 10×10 km over 2–3 min. At 3.75 Hz, 350–540 image frames are acquired, yielding an image cube sampling the surface at about 18 m/pixel in 544 channels covering 0.36–3.92 μm . Ten additional abbreviated, spatially binned images are taken before and after the main image, providing measurements with different path lengths through the atmosphere while illumination remains nearly constant. This sequence of multiple measurements of the same target at different geometries—over a short time while the illumination is constant—is called an emission phase function (EPF). When analyzed using a radiative transfer model that incorporates a model of surface scattering and wavelength-dependent attenuation by atmospheric gases and aerosols, an EPF allows atmospheric scientists on CRISM’s team to study the atmosphere and to correct surface spectra for atmospheric effects. CRISM takes EPFs with each targeted measurement and also in a global grid of measurements every 2 weeks to study seasonal variations in the contents of dust, ice, and trace gases in the atmosphere.

CRISM can also build up images using passive, fixed pointing. The instrument points at nadir and images at 15 or 30 Hz. Because the spacecraft’s velocity relative to the surface along MRO’s orbit is about 3000 m/s, this

makes the along-track dimension of a pixel’s footprint 200 or 100 m, respectively. To “square off” the pixel footprint, data are binned spatially. When operating in this mode, CRISM returns data from only 72 wavelengths that have been selected carefully so that they cover the absorptions indicative of the minerals that the instrument is measuring. The 200-m/pixel mode is used to map Mars globally, and the 100-m/pixel mode is used to “ride along” with MRO’s other cameras when the available downlink or a crowded observing schedule limits the number of targeted observations.

GETTING CRISM TO MARS AND OPERATING IT

CRISM was selected for flight by NASA in response to an Announcement of Opportunity for the competitive selection of MRO’s mineral mapper. APL led an effort involving universities, NASA centers, and private industry, as well as the OMEGA instrument team at the Institut d’Astrophysique Spatiale in Orsay, France. This international partnership allows the CRISM team to aim its first round of targeted measurements at mineralogically interesting regions already discovered by OMEGA. In addition, the two instruments conduct coordinated observations from orbit, especially to monitor seasonal changes in the polar regions.

Following CRISM’s selection in November 2001, a preliminary design phase lasted through June 2002. Subcontractors selected to provide major subsystems

included SSG of Wilmington, Massachusetts, to build the optics; the Jet Propulsion Laboratory (JPL) of Pasadena, California, to provide the spectrometers' gratings; BEI Precision Systems of Maumelle, Arkansas, to provide the position encoder for the gimbal; Moog, Inc. of Chatsworth, California, to provide the gimbal motor; Swales Aerospace of Beltsville, Maryland, to provide the cryogenic heat pipe system; RICOR of Tel Aviv, Israel, to provide the coolers; XC Associates of Stephentown, New York, to provide the anti-sunward radiator; and Applied Coherent Technology (ACT) of Herndon, Virginia, to provide the ground data system for downlink processing. APL has provided the structure, all of the electronics, the internal calibration source, the telescope cover and baffle, flight software, integration and testing, calibration, the uplink operations system, management, and systems engineering. Fabrication of key components continued through early 2004, with instrument integration lasting through July 2004. Component- and system-level calibrations all took place at APL through late 2004. CRISM was integrated onto the MRO spacecraft and tested in January through February 2005 at Lockheed Martin Space Systems near Denver, Colorado. Finally,

MRO was mounted to its Atlas V launch vehicle, which lifted off from Cape Canaveral, Florida, on 12 August 2005.

During cruise to Mars, CRISM underwent four periods of in-flight calibration and checkout, but spent much of the time in "decontamination." With CRISM powered down, spacecraft-controlled heaters maintained the instrument at a temperature of 20°C–30°C, allowing adsorbed moisture to bake out of the instrument. This is crucial to the proper functioning of the cryogenic system as it minimizes radiative coupling between the cryogenic and warmer parts of CRISM.

MRO's orbital mission began when the main engine fired to inject the spacecraft into Mars orbit on 10 March 2006. Following orbit insertion, the spacecraft conducted several hundred dips into the upper atmosphere for aerobraking to lower the initial apoapsis (the high point of the orbit). Aerobraking was completed by September 2006, and on 27 September CRISM's protective cover was deployed and Mars observations began (Fig. 6). During MRO's 2-year primary science phase, CRISM will downlink about 1.4 terabytes of data, which will expand on the ground into about 12 terabytes of data products for delivery to the science community. This

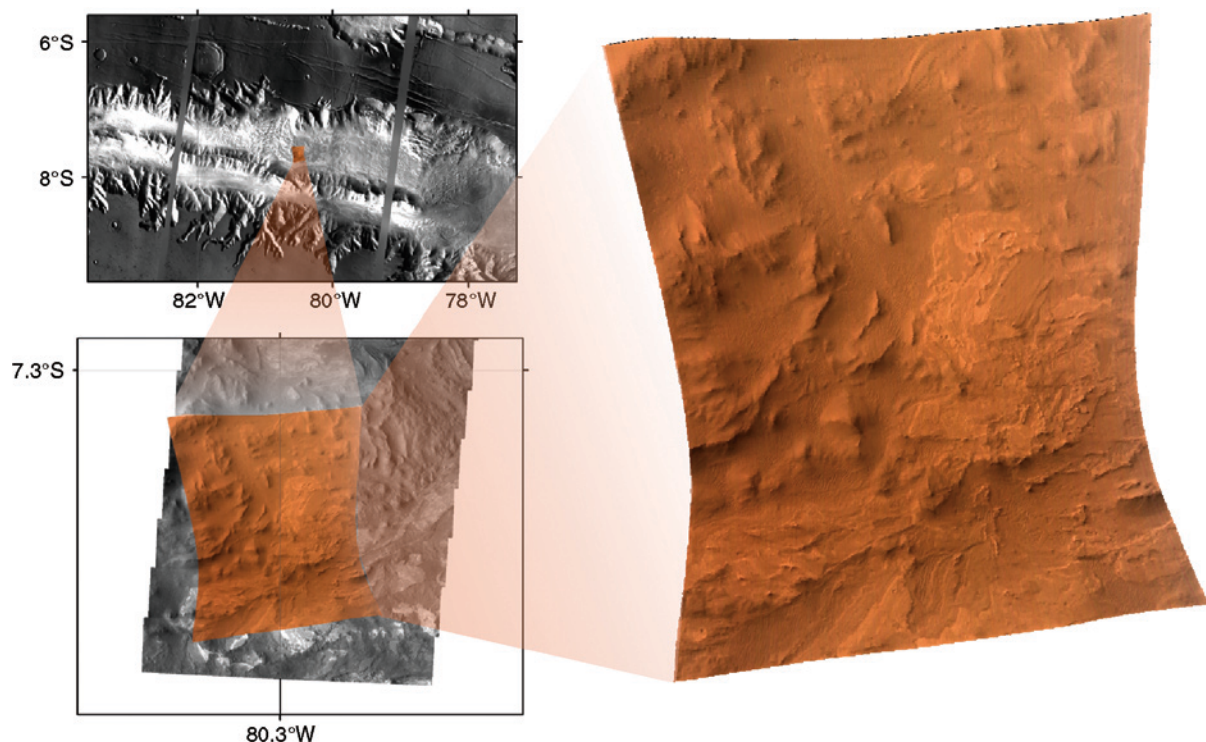


Figure 6. CRISM's first targeted image of Mars was acquired over western Valles Marineris. The image covers an area about 13 km north–south and 9 km east–west. The left panels show the image's regional context on a mosaic from the Mars Odyssey spacecraft's Thermal Emission Imaging System (THEMIS). The map-projected CRISM image at right shows that the site has bland color properties at visible wavelengths and is mostly reddened by Mars' pervasive dust. During image acquisition MRO's range to the target started at 410 km, decreased to about 290 km when the spacecraft made its closest approach, and increased again to 410 km. The change in geometry during image acquisition gives each CRISM-targeted image a characteristic hourglass shape. (Image centered at 7.7°S, 270.5°E.)

is a larger data volume than delivered by any planetary instrument to date.

CRISM is operated from the CRISM Science Operations Center (SOC) at APL. The MRO project passes through commands to the instrument and performs minimal monitoring of instrument health and status. The SOC must function concurrently as a mission operations center, a processing facility for an extremely large volume of data, and a center for science analysis of the returned data. CRISM's successful operation heavily leverages a division of labor and intelligent software design by APL and ACT. Outside science team members, most notably at Washington University in St. Louis, Missouri, Brown University in Providence, Rhode Island, NASA Ames Research Center in Moffett Field, California, and JPL in California, enter latitudes and longitudes and establish parameters for requested observations into an ACT-designed targeting database. For each 2-week uplink planning period, an APL-developed Java-based uplink planning system (JMRO) searches the database and finds the highest-priority targets that are visible to the spacecraft and have desirable illumination. JMRO fills time between these targeted observations with global mapping and internal calibrations and issues the commands required to execute each observation. This process uses very capable flight software, which includes 256 easily uploadable instrument command macros that reside in the DPU. Macros form the building blocks for all of CRISM's routine activities, including targeted images, mapping, internal calibrations, and regularly conducted subsystem tests. Using the macros, each Mars observation, calibration, or engineering checkout requires the actual issuance of only two commands from the SOC: an "observation load" containing a string of macro numbers and delay times between the macros, and a "scan profile load" of six coefficients that define a profile for the gimbal if scanning is required. Each activity commanded in this way is initiated by the spacecraft computer when the onboard ephemeris indicates that MRO is approaching the latitude and longitude over which the activity should occur. Flight software also continually compares currents, voltages, and temperatures against uploaded limits and, in case a limit is exceeded, selectively powers down the relevant subsystem without disrupting other internal instrument operations.

Downlinked data and housekeeping are processed at the SOC using APL- and ACT-designed modules built around an ACT-designed system called PIPE (Planetary Image Processing Environment). A housekeeping database records all voltages, temperatures, and currents and formats them into easily monitored daily, weekly, and monthly health and status plots for trend analysis. An automated ground alarm is generated by the instrument if limits are exceeded, and when it is received on the ground, team members are notified via e-mail and

paggers. Image data are formatted upon downlink into files that are ready for archiving to the Planetary Data System, NASA's planetary data library. An automated data validation system checks each data file for integrity and compares downlinked against planned data so that corrupted or missing observations can be replanned if necessary. Image files are converted into similarly archive-ready calibrated form, and for each image the geometric information required for projecting the image into map format is generated in parallel. Global mapping observations are projected into a set of 1964 tiles that cover the planet at 256 pixels per degree. This is the same spatial resolution as Viking Orbiter monochrome image mosaics that supported Mars research for more than 20 years, except that CRISM's map is in 72 colors!

FIRST RESULTS: UNCOVERING MARS' COMPLEXITY

Early CRISM images cover representative examples of rock outcrops formed throughout Martian history and are already yielding surprising discoveries. Martian history is divided into three main eras, named for the locations of the rocks dating to those ages. The Noachian era, the oldest, dates to >3.8 billion years ago and corresponds to a part of Earth's history preserved mostly as stray fragments embedded in much younger rocks. The Hesperian era, from about 3 to 3.8 billion years ago, corresponds to the first part of Earth's Archean period when the oldest known fossils formed and the atmosphere still lacked free oxygen. Mars' youngest era, the Amazonian, corresponds to most of Earth's rock record. Our knowledge of Mars' evolution during these eras has been assembled from decades of study of Viking, Mars Global Surveyor, Mars Odyssey, Mars Express, and Mars Exploration Rover data.^{8,9} We know that during the Noachian era water flowed on the surface. Crustal rocks were partly altered to clay-like minerals called phyllosilicates, showing that they remained wet for prolonged periods. The Hesperian era included formation of vast volcanic plains and extensive deposits of layered rocks. Layering suggests that sedimentary rocks formed by wind or water-related processes. The layered rocks contain sulfates and certain ferric iron minerals, suggesting that when water was present it was acidic, extremely saline, and probably intermittent. Amazonian rocks show very little evidence of liquid water processes; instead, volcanic and wind processes mainly shaped the surface for the latter two-thirds of the planet's history. Mars' rock record suggests that an early, wetter period had already transitioned to the arid, frigid Mars of today while Earth's life still consisted of the most primitive single-celled prokaryotic forms (without cell nuclei). The question of life on Mars is thus mostly the search for past environments in which fossil evidence for life may be preserved.

CRISM's first returned data reveal evidence for environmental variability throughout Mars' history.

Noachian deposits exhibit diverse phyllosilicate compositions in more types of rock exposures than had previously been recognized. Different phyllosilicate compositions are sometimes separated only by hundreds of meters, indicating variations in alteration environments or in the parent rock on small time or spatial scales. Either signifies unexpectedly complex geologic environments during Mars' early history. Hesperian layered deposits exhibit strong vertical, compositional layering, with different abundances and compositions of sulfate and ferric iron minerals. This suggests local environmental variations on short geologic timescales. Brief wet episodes were probably separated by longer dry periods during which sediment traps accumulated dust, minimally altered sand, or volcanic materials. The polar layered deposits of the Amazonian north are a surprise. Their underlying sediment layers are rich in hydrated minerals that form in liquid water. This suggests possible past melting of a paleo-polar ice cap. The modern ice cap has vertical layering in the abundance and/or grain size of ice that records climate change on the thousands-of-years timescale. And despite the present harsh climate, eroded slopes of the polar caps may show evidence for deposition of icy sediment by geologically young fluid flow.

Figure 7 shows two targeted images of Noachian rock dating to Mars' earliest history, where phyllosilicate-rich rocks outcrop at the surface. Both images are displayed in IR false color, i.e., different minerals appear in different colors. The left panel shows a region known as Mawrth Vallis. Here, gray-colored basaltic rocks occur in layers that sandwich highly altered phyllosilicate-rich rock. The circular gray, basaltic region at the lower right is the highest-standing, youngest rock layer, most of which has been removed by erosion. Two types of phyllosilicate, in light blue and buff, occur below the upper basalt layer. Each phyllosilicate type records a different weathering environment, and most of the phyllosilicate has also been eroded away. The bottom, oldest rocks are the gray-colored basalt at the upper right and lower left.

The right panel of Fig. 7 shows a part of the Nili Fossae region. The reddish-gray basaltic layer in the center of the image has been largely eroded away by an ancient river valley, which extends to the lower right. Beneath the basalt is an older, reddish olivine layer whose debris accumulated as windblown sand dunes in the dry river valley. The bottom, oldest layer of rock is the light blue area rich in phyllosilicate. In both regions the phyllosilicate is among the oldest of the old rocks, and

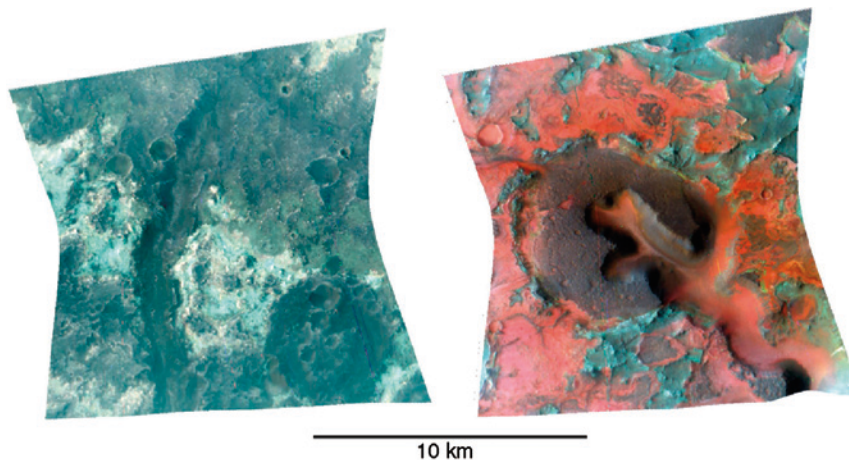


Figure 7. CRISM-targeted images of the Mawrth Vallis region (left) and the Nili Fossae region (right). The images are false-color composites constructed from 2.5-, 1.5-, and 1.1- μm wavelengths. Basaltic rock appears dark gray, olivine-rich rock and sand appear red, and different types of phyllosilicate appear in light blue or buff colors. (Left image centered at 22.5°N, 341.8°E; right image centered at 22.3°N, 77.1°E.)

in Nili Fossae it is overlaid by younger olivine whose presence shows that the clay-forming wet environment dried out early in Mars' history.

Figure 8 shows two targeted images covering an eroded plateau of layered rock in Valles Marineris. These rocks are typical of Hesperian-aged layered rocks that occur in many parts of Mars, and they have been interpreted variously as ancient lake sediments, layered volcanic rock, or accumulated windblown dust. The landforms alone are insufficient to distinguish among these possibilities, but the mineralogic layering of the deposits can help. The color images in Fig. 8 were constructed by measuring mineralogic absorptions, color-coding them, and draping the results over a topographic model to show how mineralogy is related to the underlying landforms. Each area shows a complicated set of layers that have been folded and turned on their sides by tectonic processes. Some of the layers are rich in dust or highly oxidized rock, which would appear similar, and are shown in red; some are rich in sulfate and appear in green; and some are dominated by minimally altered iron- and magnesium-rich igneous minerals and appear in blue. This interlayering of radically different compositions reveals a very complicated geologic history. One reason the rocks could have formed is a changeable environment in which long episodes of deposition of windblown dust and sand were punctuated by wet episodes during which lakes formed and evaporated, leaving behind sulfates. Alternatively, water circulating through permeable layers or fractures could have leached and oxidized volcanic rock and left behind sulfate-filled veins.

Figure 9 shows a mosaic of data taken by CRISM in its global mapping mode, covering the north polar ice cap and the underlying layered sediments. These materials are among the most recently formed on Mars during

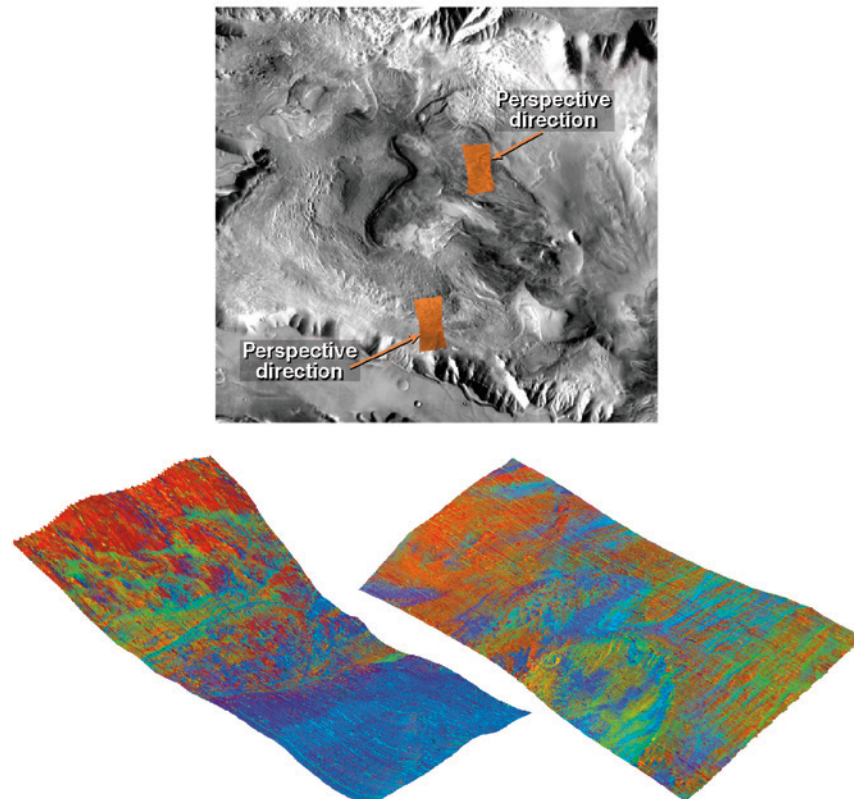


Figure 8. CRISM-targeted images of layered rock in the Candor Chasma segment of Valles Marineris. The top panel shows true-color versions of the data overlaid on a regional THEMIS image mosaic about 175 km across. The bottom two panels show IR false-color versions of the images, which have been draped over a terrain model with 4× vertical exaggeration. Dust and highly oxidized rock are shown in red, deposits of sulfate minerals are shown in green, and Mg- and Fe-rich volcanic rock is shown in blue. (Left image centered at 5.7°S, 284.6°E; right image centered at 6.7°S, 284.2°E.)

the late Amazonian era only several million years ago. To produce this figure more than 1400 images were processed to color-code mineral absorptions and projected to latitude and longitude locations to create a map. The individual images were then overlaid. Ice appears white; other materials are color-coded to show the strength of the spectral signature of water-containing minerals. One such mineral is gypsum, which forms by evaporation of saline water that leached from calcium-rich volcanic rock. OMEGA had shown that gypsum occurs in the region just above the polar ice, colored red and yellow in Fig. 9, where the dark sediment layers underlying the ice have been reworked by the wind into a vast field of sand dunes. CRISM's map is about 10 times higher in spatial resolution than OMEGA's and shows that water-containing minerals are much more pervasive in the dark sediments than had been thought, exposed even in small valleys in the polar ice. CRISM's new data support the idea, already suggested by some researchers, that the underlying dark sediments may have formed when a past polar ice cap melted.

Meltwater would have leached calcium and other soluble metals out of the sand and formed salts whose molecular structures contain water.

MORE TO COME

Over the first 100 days of its 2-year primary science phase, MRO downlinked enough data to fill nearly 1000 CDs, quickly matching the record for Mars data returned over 9 years by NASA's Mars Global Surveyor. About 30% of MRO's data have come from CRISM, which took more than 250 targeted images and nearly 500 ride-along images. CRISM also mapped nearly a quarter of the planet at 200 m/pixel and returned over 500 separate EPF measurements to track seasonal variations in the atmosphere. This was accomplished while MRO's data rate was relatively low. By the end of the primary science phase, CRISM is expected to have collected 6000 targeted images and 6500 EPFs, and to have completed its global map. Data volume will grow further if the MRO's science activities continue longer: the spacecraft presently has enough fuel to continue

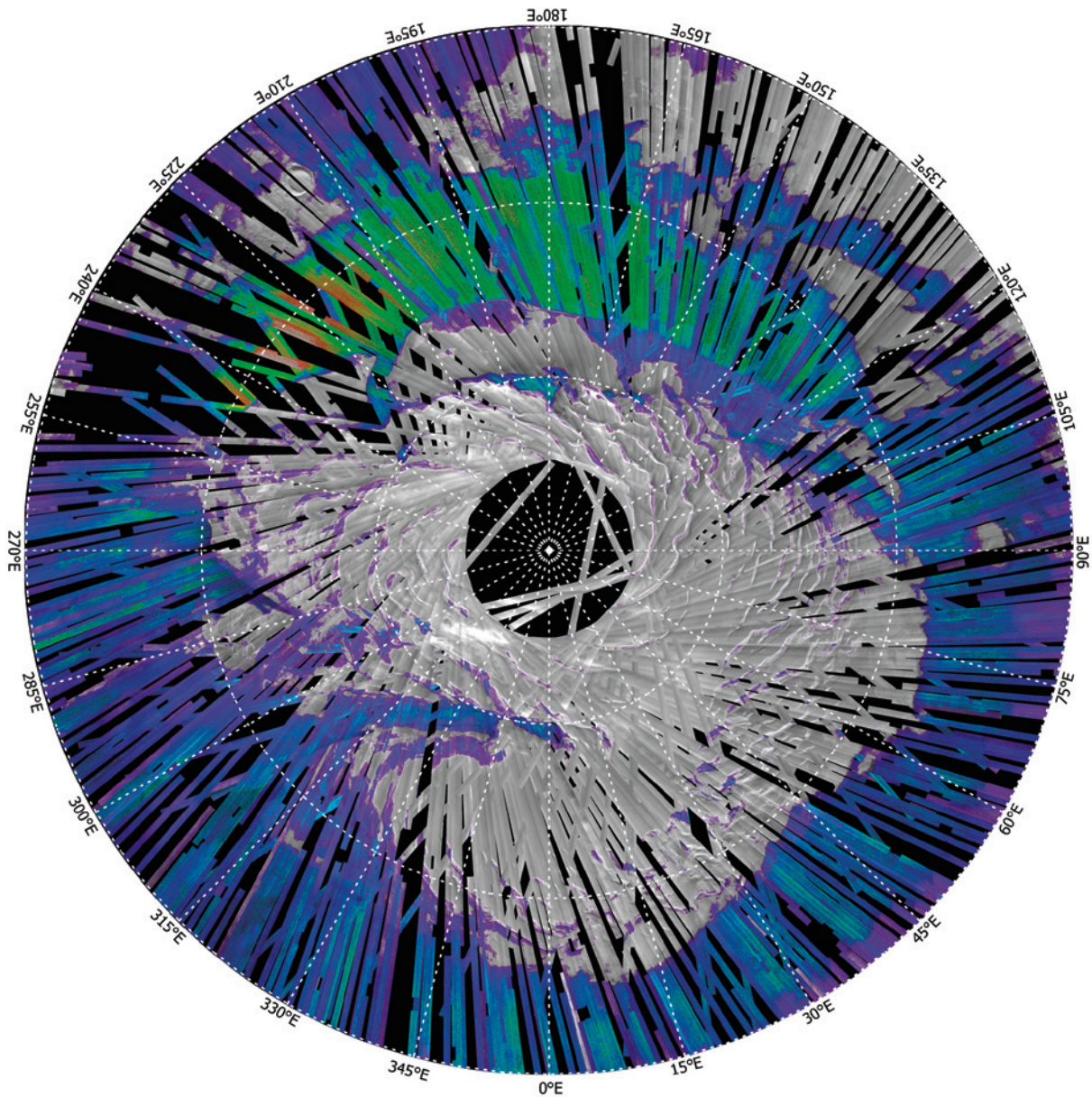


Figure 9. Polar stereographic-projected mosaic of CRISM mapping data taken poleward of 75°N latitude. Ice appears white; in non-ice regions, the content of hydrated minerals is shown in false color, where redder colors represent more hydrated minerals. The areas in green, yellow, and red contain gypsum.

operations through 2015 or later. CRISM's and MRO's other data sets will be analyzed by the science community for decades to come and will help to rewrite Martian history as it is currently understood. For more information on CRISM, visit <http://crism.jhuapl.edu/>.

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