14 Mars Reconnaissance

The success of Pathfinder trail blazed a new era in Mars exploration. As Sojourner worked upon the surface of Mars, a series of reconnaissance orbiters, set on analysing the entire planet in unprecedented detail, was being developed. The first, called Mars Global Surveyor (MGS), arrived in September 1997 just as the Pathfinder mission was coming to an end. In 1999 the Mars Climate Observer (MCO) was lost on its approach to Mars, but MGS was joined by NASA's Odyssey orbiter in 2001, by ESA's Mars Express in 2003 and by NASA's Mars Reconnaissance Orbiter (MRO) in 2006—giving a total of four robotic reconnaissance spacecraft orbiting Mars, three of which are still delivering images, geological, topological, mineralogical, and other data. Together they represent the first comprehensive survey of another planet and are set on addressing the great unknowns about Mars' long and complex history.

Mars Global Surveyor

As the first of the new generation of Mars orbiters, Mars Global Surveyor was a worthy successor to Viking (Figure 40). Its objectives were ambitious: to image the entire planet and characterize its surface morphology at unprecedented resolutions; to determine the global composition and distribution of minerals; to create a three-dimensional topological map of the entire planet; to monitor surface–atmospheric interactions; and to act as a communications satellite for future lander missions, among other functions (Figure 41).

To achieve all this, MGS was equipped with a sophisticated array of instruments. First is the Mars Orbital Camera (MOC)—a spectacular optical camera designed by Mike Malin and Ken Edgett of Malin Space Science Systems (MSSS) with two resolution modes: a wide-angle mode with a 280-meter resolution providing regional context views of the planet, and a narrow-angle mode with maximum pixel resolution of just 1.5 meters (and

K. Nolan, *Mars, A Cosmic Stepping Stone*,
DOI: 10.1007/978-0-387-49981-9_14, © Praxis Publishing, Ltd. 2008

Figure 40: Mars Global Surveyor (MGS), which in 1997 heralded a new era of Mars exploration based on a long-term, phased strategy. [Credit: NASA/JPL/Corby Waste]

with a recent adaptation providing 0.5-meter pixel resolution, allowing surface objects as small as 2 meters to be identified). Using both modes, it has been possible to examine both regional-context geology as well as individual features with sufficient clarity to infer their underlying process of formation. Equally important on MGS is its Thermal Emission Spectrometer (TES) designed by Phil Christensen. This camera is capable of looking at the surface across many thermal (infrared) frequency bands, from which the surface mineralogy can be determined. With a resolution of 3×6 kilometers, TES was specifically designed to produce a mineralogical map of the entire

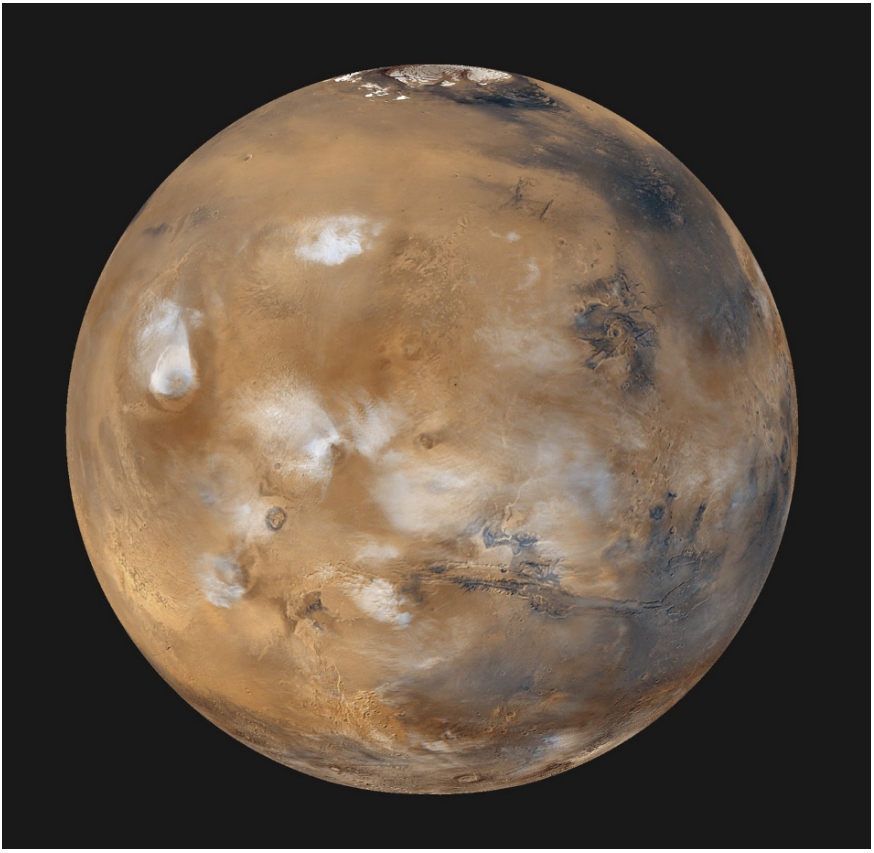

Figure 41: A global image of Mars from Mars Global Surveyor revealing water clouds. Scenes such as this can only be captured through long-term reconnaissance of the planet. See Plate 15 in the color section. [Credit: NASA/JPL/MSSS]

planet. A third instrument, arguably the most enigmatic on board, is the Mars Orbital Laser Altimeter, or MOLA. Using an onboard laser, MOLA fired laser-light pulses at the surface and observes their reflection. By measuring the time delay of each reflection from a given point on the surface, MOLA could determine the distance to that location. With a horizontal resolution of 100 meters and a vertical resolution of just 1 meter, MOLA has been able to construct the first three-dimensional topological map of Mars. Also of major importance was the onboard Magnetometer/Electrometer, capable of measuring the magnetic properties of the planet and the movement of electrons in any detected planetary magnetic fields, telling us about Mars' past and present magnetic properties, and from which the internal structure and dynamics of the planet can be inferred.

Morphology

From its arrival at Mars in late 1997 to its eventual failure in late 2006, MGS's various instruments produced enormous datasets that will take decades to fully analyze. The MOC image set alone comprises in excess of 240,000 images—far greater than the Viking orbital image set in both coverage and detail. From Tharsis in the west to Elysium in the far-east, from the ancient southern highlands to the younger northern lowland plains, all have been photographed in unprecedented detail. Of major significance, for example, has been the discovery of vast tracts of deep sedimentary layering at hundreds of locations across the planet, and from the equator to the poles (Figures 42–44). While both Mariner 9 and the Viking orbiters had photographed sedimentary layering at several locations, MGS has revealed that it is a planetwide phenomenon, pointing to massive transport and deposition of material in Mars' distant past.

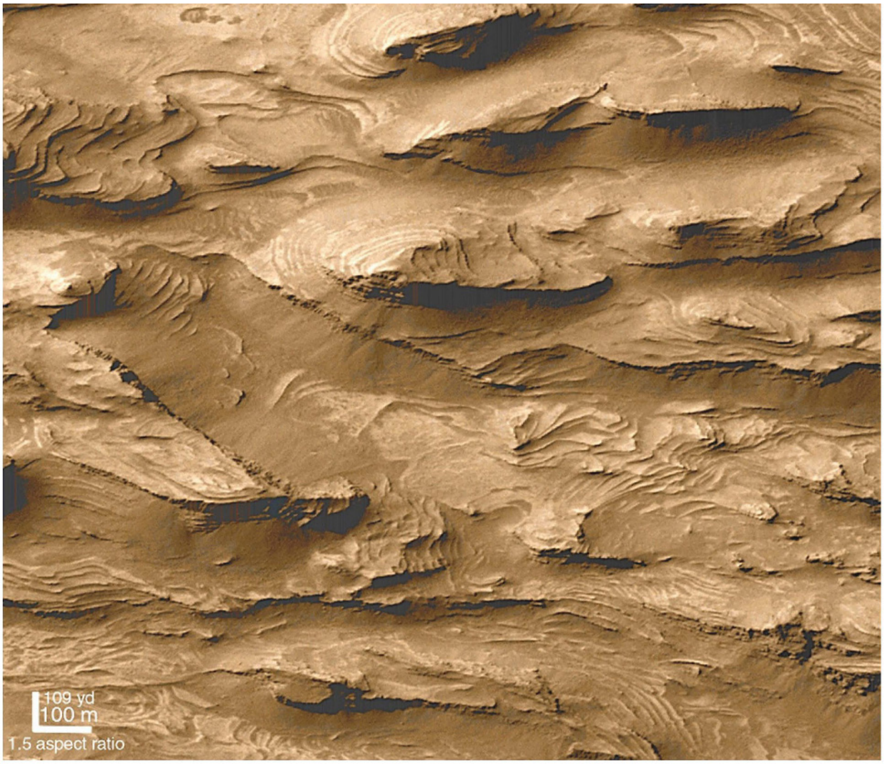

Figure 42: Mars Global Surveyor's Mars Orbiter Camera (MOC) confirms the presence of layered outcrops within Valles Marineris. This high-resolution image reveals extensive layering on the floor of western Candor Chasma. See Plate 16 in the color section. [Credit: NASA/JPL/MSSS]

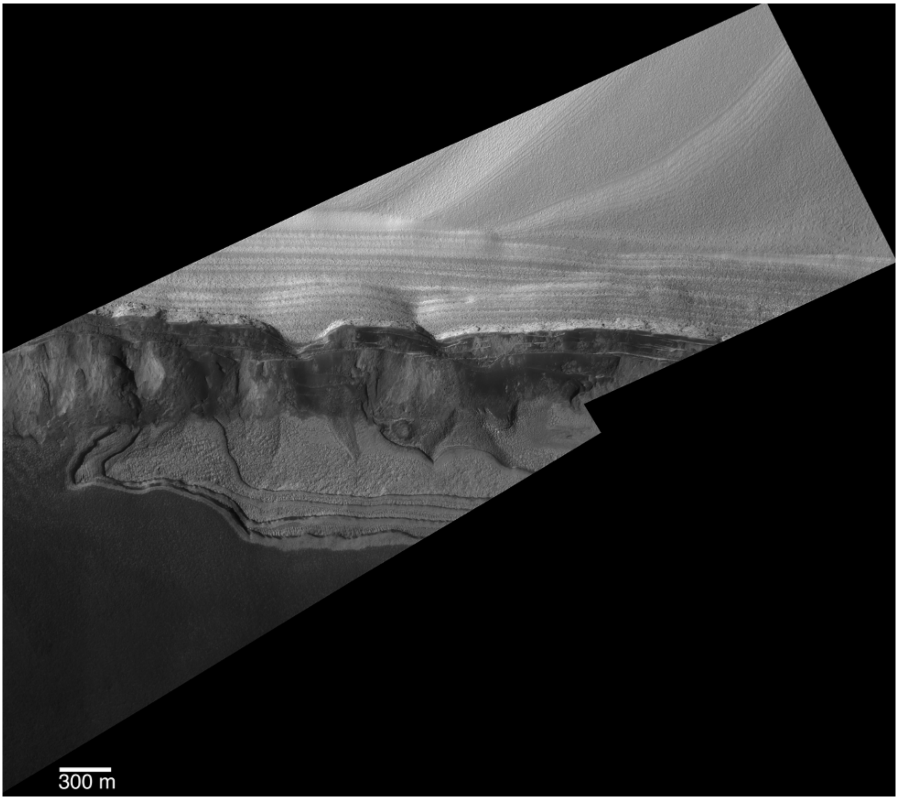

Figure 43: MGS/MOC view of a scarp at the head of Chasma Boreale, a large trough cut by erosion into the Martian north polar cap and revealing layered material beneath the ice cap. The picture was taken using a resolution-enhancing technique called ''compensated pitch and roll targeted observation (cPROTO).'' [Credit: NASA/JPL/MSSS]

Three distinctly different types of sedimentation have been identified—light-colored layers that are in the order of tens to hundreds of meters thick, massive layers approximately 1 kilometer in thickness, and thin messa or darker thin layers found on top of the other types of layering. MGS has also identified four types of terrain within which sedimentation can be found: within craters, for example at Arabia Terra; on inter-crater terrain, as found at northern Terra Meridiani; upon chaotic terrains, such as at Margaritifer Terra; and within chasm interiors, most notably within the walls and on the floor of Valles Marineris.

Such widespread sedimentary layering constitutes substantial evidence of a once active planet. Often spread over hundreds of kilometers and several kilometers in depth, the processes involved must have occurred on a

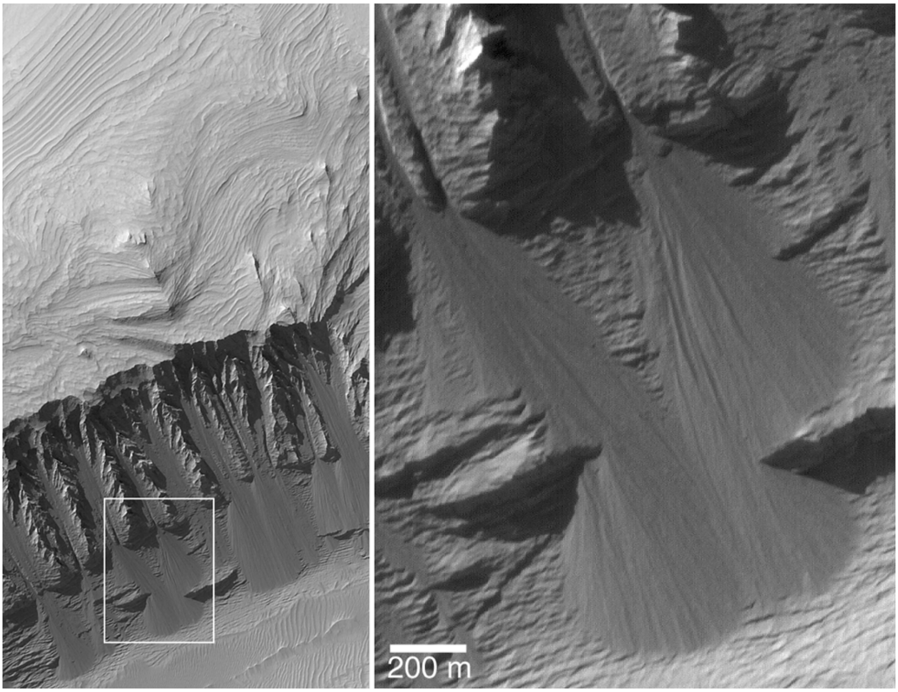

Figure 44: MGS/MOC/cPROTO image showing sedimentary layers in Candor Chasma, Valles Marineris. On the slope in the lower half of the image, fine-grained material has slid down the slope to create fan-shaped talus accumulations. [Credit: NASA/JPL/MSSS]

planetary scale that lasted for many millions of years. Also, in the particular case of the Valles Marineris rift, we know that the plain within which the rift resides was formed during the Hesperian period, therefore the several-kilometer deep sedimentary layering seen within its walls must have been laid down during the Noachian period, indicating that sedimentary layering occurred most prominently in Mars' earliest history. While there can be little doubt that much of the sedimentation was due to volcanic and tectonic activity, there are other possibilities. Eolian (wind) based erosion, transport and deposition, for example, may have been responsible for much of the observed layering, especially if Mars had a dense atmosphere at one time. There are also several types of aqueous activity—such as alluvial (flowing water), lacustrian (standing water as in lakes) and deltaic (running water flowing into a standing body of water)—that can give rise to sedimentation. At Hellas, Meridiani Planum, and the floor of Valles Marineris, for example, MGS/MOC has revealed extensive sedimentation that could well have been laid down by the action of water. Indeed MGS/MOC images provide

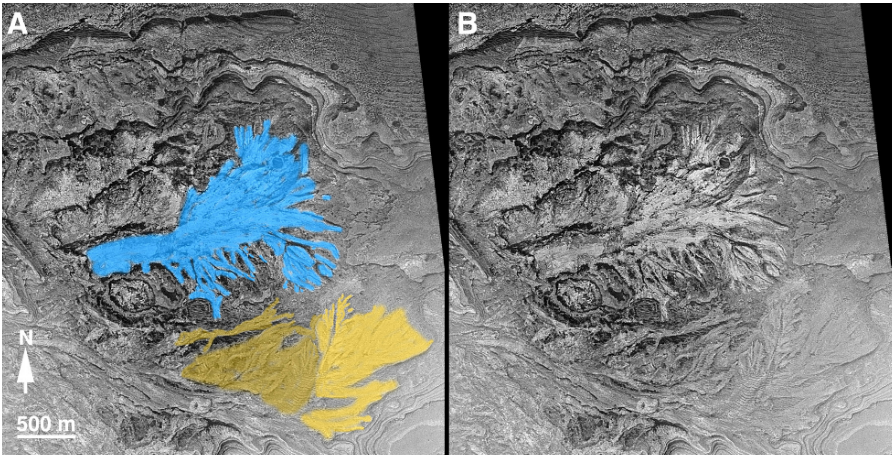

Figure 45: MGS/MOC image of alluvial sedimentation in Melas Chasma, Valles Marineris. The water-based ''fan-shaped'' sedimentation is highlighted in panel A (left). See Plate 18 in the color section. [Credit: NASA/JPL/MSSS]

intriguing evidence of alluvial sedimentation at Melas Chasma, one of the large troughs of the Valles Marineris system (Figure 45), revealing two sets of alluvial activity where the water sedimentation process created fans of debris with finger-like protrusions and with the channels through which the water flowed actually preserved to the present day. Among the most compelling evidence of persistent water flows and aqueous sedimentation was spotted by MGS at a site known as Holden Crater, in the Erythraeum region at 260°S, 340°W (Figure 46). The entire region covers an area of 4,000 square kilometers, with several valleys feeding into a fan-like layered landform covering about 100 square kilometers—unequivocal evidence of long-term, persistent surface water flows from river channels into a large standing body of water, within which a fan-shaped delta with layered sedimentation formed. The rhythmical layering also indicates episodic changes in environmental conditions.

Despite the extent of sedimentation identified by MGS, there are many questions that cannot be answered from MGS data alone. For example, many supposed dried river networks in the south of the planet show no evidence of sedimentary layering. And at many layered sites there is no obvious transport mechanism into or out of the region. Further, as sharp as the MOC images are, they are not quite good enough to definitively identify the processes that gave rise to the layering seen at many locations, and for this we need the sub-meter resolving power of the Mars Reconnaissance Orbiter with possibly lander missions being sent to those regions in the future.

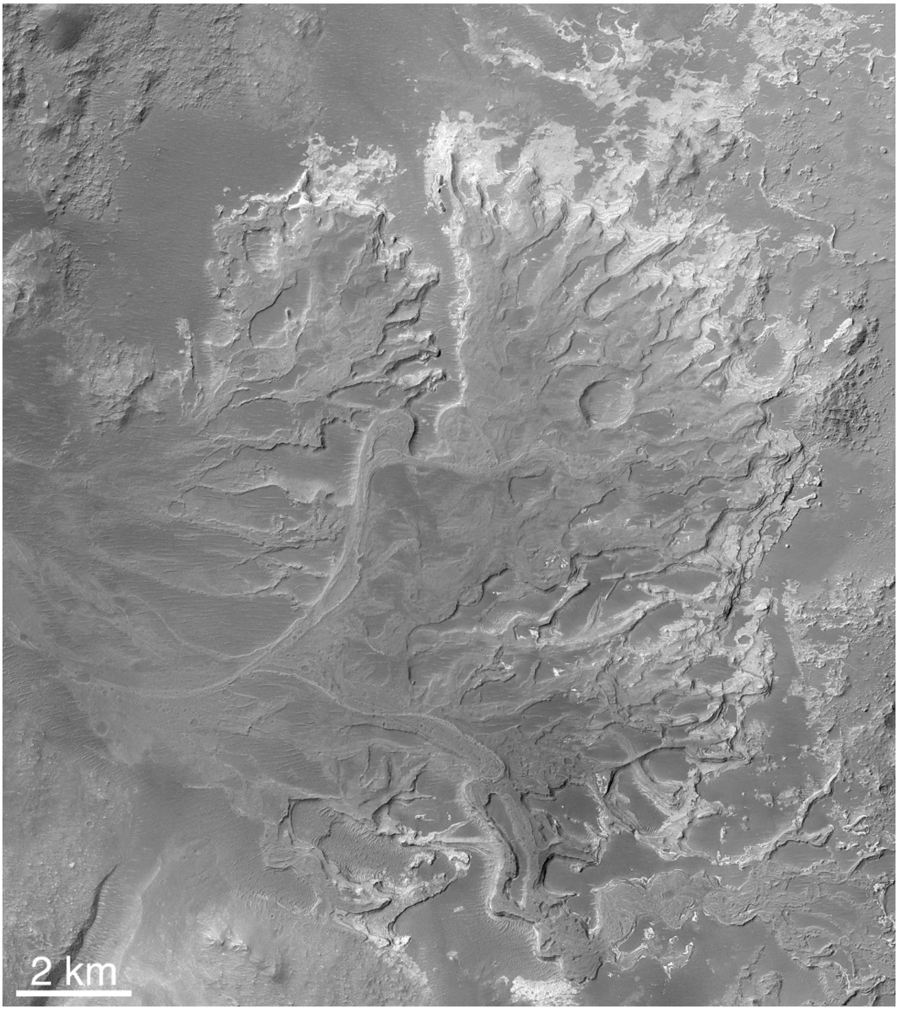

Figure 46: MGS/MOC image of Eberswalde Delta, located northeast of Holden Crater—unequivocal evidence of surface liquid water activity on Mars in the past. [Credit: NASA/JPL/MSSS]

Whatever the processes involved however, the identification of planetwide sedimentary layering firmly indicates that Mars was active in its past, probably involving a range of deposition processes including tectonic, volcanic, eolian, and even aqueous activity over long periods of time.

Global Topology

Another of Mars Global Surveyor's crowning achievements has been the production of a three-dimensional (3D) map of the surface of Mars with its

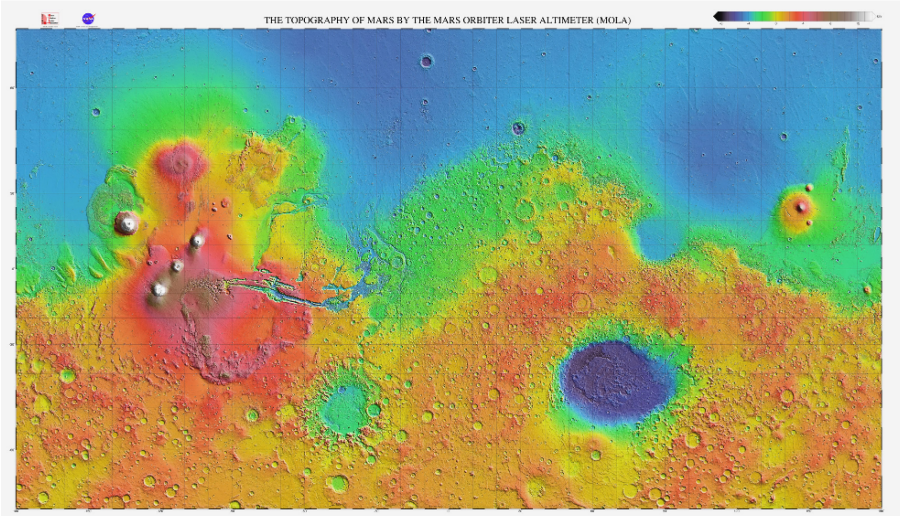

Figure 47: MGS MOLA 3D Topological Map of Mars. Of note is the north–south planetary dichotomy, with the northern hemisphere both lower and smoother than the cratered plains of the south. See Plate 17 in the color section. [Credit: NASA/JPL/USGS]

laser altimeter—MOLA. Between 1999 and 2001, MOLA fired over 670 million pulses at virtually every location on the planet, building a 3D topological map of the surface with a vertical resolution of just 1 meter (Figure 47). This has allowed the true relief of surface features to be seen for the first time, and greatly improves our understanding of the geological processes that give rise to them. The MOLA map is the best topological map of any world—including Earth, where the construction of such a detailed map of the entire surface is inhibited by a thicker atmosphere and the presence of trees, artificial structures, and water.

Among the most important results from MOLA is verification of a significant difference in the mean elevation of the northern and southern hemispheres; with the southern hemisphere about 3 kilometers higher. Such a difference points to significant yet currently unknown events in Mars' distant past that must be explained if we are to understand how such a dichotomy arose. MOLA has also indicated a general difference in geology between the north and south, where the south is dominated by older cratered terrain while the north is composed of a less cratered and younger surface. MOLA has also revealed surface roughnesses, which are important to determining geological processes such as erosion and deposition. Here it has shown that while the southern hemisphere is generally composed of rough terrain, the equatorial region is even rougher. By contrast, however, the northern lowlands have been shown to contain the smoothest surface in the entire Solar System.

MOLA has also provided a vital new approach to investigating possible water activity on Mars long ago. Because most of Mars' features were created during the Noachian and Hesperian eras, the topology seen today relates back to the time when we think water activity may also have occurred. Hence the MOLA map can reveal the ancient drainage patterns across the planet—identifying where water may have originated, as well as its final destination. Furthermore, because of the superlative resolution of the MOLA data, we can even determine water and flood channel capacities, the quantities of water involved and the length of time such activity may have persisted. Indeed MOLA suggests that, because of the drop in elevation from the southern to the northern hemisphere, the dominant drainage pattern would have been from the southern highlands to the northern lowlands. This seems to correspond with photographic evidence where, for example, possible water channels lead all the way from the giant Argyre Basin in the south to the Chryse outflow region in the northern hemisphere. Further photographic evidence shows that virtually all the gigantic flood channels seen on the planet also point northward. If substantial bodies of water resided on Mars in its early history, MOLA suggests that upwards of 90% of that water would have found its way to the northern hemisphere over time, prompting some scientists to consider that Mars may have possessed a vast northern hemisphere ocean in its distant past (although this idea is not unanimous, nor does the available evidence strongly suggest such an ocean). Intriguingly, MOLA also poses a Martian puzzle. From all combined estimates, we suspect that Mars currently retains enough water (in non-liquid form) that, if it were liquid on the surface, would cover the planet to a depth of about 30 meters; yet MOLA (among other surveys) suggests that there were sufficient quantities of water in the past to cover the planet to a depth of perhaps 500 meters. If this is correct, where has Mars' water gone?

MOLA has also greatly enhanced our understanding of the geological processes that shaped Mars' surface. It has been shown unequivocally that Tharsis and Elysium are gigantic continent-sized bulges on the surface. Intriguingly, it has also revealed that Olympus Mons is not part of the Tharsis bulge as was originally thought, but instead sits on lower terrain further west. And with Tharsis and Elysium so clearly seen as significant seats of past tectonic and volcanic activity, there can be little doubt that both would have contributed to the outgassing of volatile and biogenic materials. MOLA has revealed the full magnificence of many other surface features, also verifying, for example, that Hellas is a gigantic impact basin over 9 kilometers deep—the deepest impact basin in the Solar System. Apart from contributing substantially to our understanding of Mars' distant past, MOLA has also told us about the current state of Mars. For example, it has revealed the volume of water-ice locked into the north and south poles, and can even measure changes in elevation of the polar surfaces when carbon dioxide freezes during the winter, pointing to the quantities of carbon dioxide involved.

Mineralogy

Another important instrument on board Mars Global Surveyor was its Thermal Emission Spectrometer (TES), which photographed thermal or infrared emissions from the surface. Because different minerals emit heat in different ways, TES could detect various surface materials by observing their unique thermal emission properties, and by comparing such values to known heat emissions from minerals on Earth, identify those same minerals on Mars. While TES had a relatively crude resolution, it is only with such a broad pixel size that a comprehensive mineralogical survey of the entire planet could be completed. Of all the instruments on board MGS, TES has arguably provided the most puzzling results, not only because they provided a deeper insight into the material make-up of the planet but also because they have exposed a hitherto unseen complexity to the history of the planet.

TES has shown, for example, that the surface of Mars is composed primarily of silicates, as on Earth. It also reveals that the global dichotomy on Mars, identified from its surface terrain, is also broadly reflected through its surface composition. While the southern hemisphere is made up of ancient basalts, the northern hemisphere is largely composed of andesite, which on Earth is associated with younger surfaces produced through plate tectonic activity. The detection of andesite is therefore significant, suggesting some ancient tectonic process on Mars that is not obvious from optical or topological mapping. Also of significance has been the detection of olivine-rich feldspar on much of the northern surface. On Earth, olivine turns quickly into clay on contact with water moisture, suggesting that since none of the olivine on Mars has lost its integrity, Mars has been a very dry planet for at least several billion years.

In the search for water-altered minerals, TES has provided some intriguing results. First, TES has only detected trace amounts of carbonates (which form when precipitated from water). Such a stark discovery might suggest that Mars was never dominated by water, but this does not tally with other evidence that has suggested substantial water activity at one time. However, the absence of carbonates (at least as seen by TES) suggests that either they were never created in the first place or have subsequently disappeared. It may be, for example, that Mars was characterized by a dense carbon dioxide atmosphere that was not lost through precipitation as carbonates but was instead lost to space or by chemical reactions with the crust. Or, it may be that some carbonates did at one time exist and have been subsequently covered or chemically eroded. Whatever the scenario for water and carbon dioxide on ancient Mars, the TES carbonate measurements already tell us that we are far from understanding their ancient context and that more sensitive measurements are required. Almost in contradiction, TES has detected significant quantities of hematite at locations on Mars within Valles Marineris and across Meridiani Planum, verifying the existence of water at or near the surface for long periods in its past. As we will see in the next chapter, the Mars Exploration Rover Opportunity subsequently visited Meridiani Planum in 2004 (the first lander mission based on mineralogical evidence) and found precipitated salts, verifying the existence of an ancient shallow sea at that location.

Magnetic Fields

Because MGS required a full year to settle into orbit, it passed much closer to Mars than originally intended, approaching to within 150 kilometers of the surface on some passes. Critically, it temporarily passed underneath Mars' ionosphere, permitting MGS's magnetometer and electrometer to directly measure whether Mars' crust is magnetized and to infer the polarity (direction) of any detected magnetic field. Intriguingly, magnetic anomalies were found in the crust of the ancient southern highlands. The observations revealed stripes of magnetized crust, with the direction of the magnetic field within alternating stripes pointing in opposite directions. This was a fabulous result in itself because it verified, to some extent, that, in its distant past, Mars possessed an internal dynamo that drove a magnetic field and probably surface tectonic activity. Furthermore, the striping also looked superficially like the magnetic striping that is also found on Earth and is associated with its internal dynamo and plate tectonic movement. Here, Earth's internal magnetic field changes direction every few million years causing new material emerging from diverging tectonic plates to become magnetized and retain a record of Earth's internal magnetism of that time. By observing the alternating direction of the magnetic properties along stripes of the Earth's crust, we are witnessing a record of both the internal alternating magnetic field and of plate tectonic movement of the crust.

The initial magnetic striping on Mars seemed more elusive, however. It was not visibly associated with any feature that looked like a plate and indeed no evidence of tectonic plates could be seen across the planet.

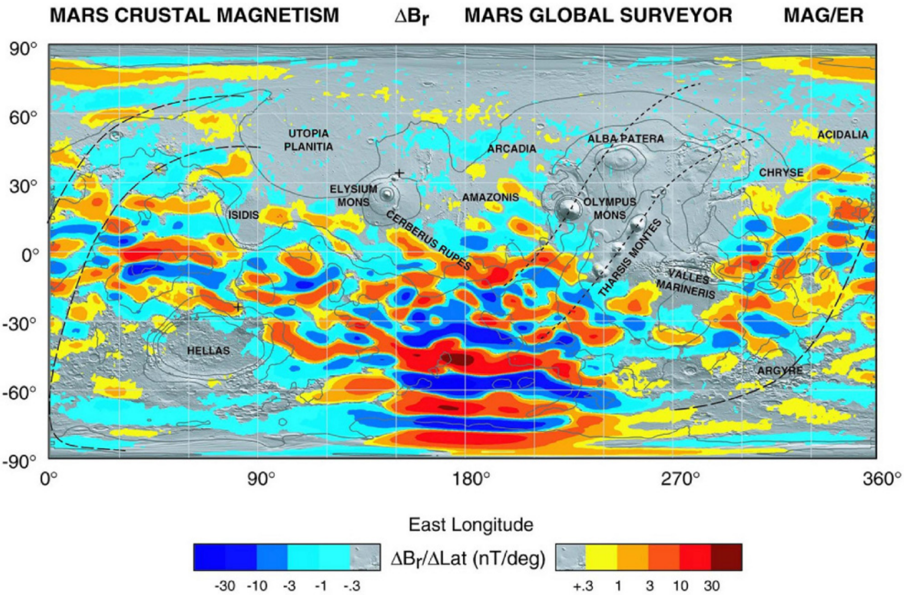

Figure 48: MGS map of the magnetic fields retained within Mars' crust. The widespread ''striping'' pattern suggests plate tectonic activity on Mars in its distant past. See Plate 19 in the color section. [Credit: MGS Magnetometer Team led by Mario Acuna at the Goddard Space Flight Center in Greenbelt, MD]

However, persistent and continuous magnetic mapping of the entire planet over the years by MGS has just recently yielded some of the most exciting results regarding Mars' distant past, and with far-reaching implications. As announced by J.E.P. Connerney, M.H. Acuna, and others at NASA's Goddard Space Flight Center in 2005, MGS has revealed significant magnetic striping across the entire globe of Mars, seen virtually everywhere except on younger terrain such as at Hellas in the south and Utopia Planitia in the north (Figure 48). The detection of such extensive striping suggests that Mars' surface was characterized by plate tectonic movement in it earliest history and that early Earth and Mars may have been quite similar in this respect. Indeed, this discovery may also clarify other features on Mars that, until now, have not been understood. For example, the three giant volcanoes on Tharsis all lie in a straight line. While this seemed curious, and unexplained, this new evidence points to the volcanoes having arisen on a moving tectonic plate sitting on an internal convective cell, as occurred with the Hawaiian Islands. Furthermore, while the gigantic scale of Valles Marineris has remained puzzling, the evidence of plate tectonics in Mars' distant past suggests that it may have been the result of two divergent tectonic plates.

Present Climate

Despite the importance of determining the nature of Mars in its early history, of emerging relevance is also the nature and dynamics of Mars today. For example, understanding the behavior of both water and carbon dioxide through their natural reservoirs—the polar ice caps, the planetary crust, and the atmosphere—will reveal much about the present climate as well as how it varies over periods of thousands or hundreds of thousands of years. And, of course, an up-to-date understanding of the planetary environment and climate are critical to the safety and success of all future orbital, aerial, lander, and human missions.

Once again, MGS has been pivotal in this respect. Through continuous monitoring on a daily basis and over several Martian years, MGS has provided valuable insight into Mars' climate. It has revealed, for example, that planetary wind patterns are dominated by a processes known as Hadley Circulation, where air from a cold winter hemisphere blows into the warmer summer hemisphere. Coupled to planetary rotation, trade winds similar to those on Earth, traveling at hundreds of kilometres per hour, blow eastward in the winter hemisphere and westward in the summer hemisphere. MGS has also provided some insight into one of the great mysteries about Mars: What is the source of its global dust storms? Dust storms on Mars can last for months or years and cover the entire planet, but their origin is currently unknown. MGS noticed, however, that local or regional dust storms most readily occur in the southern hemisphere during its summer and when Mars is closest to the Sun. It is possible, therefore, that a merger between local dust storms in the south and planetary trade winds may cause dust to circulate across the globe, while an amplification of solar heating within the accumulating dust storm may cause it to grow even larger.

MGS has also examined both polar regions of the planet in spectacular detail and over many seasonal changes. It has observed that both poles (but especially the North Pole) retain permanent caps of water-ice and ice-rich sediments that are several kilometers thick. It has also observed almost one-third of the planetary atmosphere freezing out as carbon-dioxide-ice on whichever pole is in winter, and being released again during spring thus radically affecting planetary winds and atmospheric pressure. MGS has also shown that each pole has a different climate, perhaps due to the fact that the South Pole resides at a higher elevation than the North Pole. Also seen, at the South Pole only, are permanent changes in the structure of carbon-dioxide-ice over an 8-year period, suggesting that Mars may be currently going through a period of climate change.

Yet another intriguing finding has been the discovery of near-surface gullies in tens of thousands of locations across Mars, especially on the flanks of crater walls in the southern hemisphere. Because liquid water cannot currently reside on or near the surface, some scientists are skeptical as to whether the phenomena involve running water and that flowing sand may be the cause. There is nevertheless growing consensus that liquid water containing salts that could lower the freezing point of water 60°C degree or more are the cause of these limited yet intriguing water flows. Furthermore, MGS has verified that they are possibly a current phenomenon by revealing new gullies in recent images where none was seen at the same location earlier in its mission (Figure 49). Irrespective of their underlying mechanism, the discovery of so many gullies is significant because they reveal surface activity that, hitherto, were not considered to occur on Mars today, and perhaps even point to micro-environments relevant to the search for evidence of life.

As already stated, Mars Global Surveyor failed in late 2006. It has been arguably the most successful mission to Mars to date and its legacy will certainly continue for decades to come. It has provided a far-reaching reconnaissance of the planet, the results from which have acted both as a vital reality check on our understanding of the planet and as a springboard to all current and future missions. Most of all, Mars Global Surveyor told us that Mars is far from understood and that there is a lot more to learn.

Figure 49: Gullies in the wall of a crater in Terra Sirenum, photographed in 2001 and 2005 by MGS/MOC, providing tantalizing evidence of recent water flows on or near the surface of Mars today. [Credit: NASA/JPL/MSSS]

Odyssey

As MGS was busily conducting its mission, NASA followed with a second reconnaissance orbiter in 1999—the Mars Climate Observer (MCO). It was not a coincidence that the Mars Climate Observer was timed to arrive at Mars two years after Global Surveyor. With the specific task of analyzing Mars' climate, atmosphere, polar, and volatile activity, MCO was timed to complement (and avail of) the significant survey carried out by its immediate forerunner. Similarly, in 2001, the aptly named Odyssey orbiter arrived after another two years, representing the third in a trio of orbiters set on comprehensively investigating the great mysteries of Mars. Odyssey was tasked with yet another unique series of analyses—to photograph the entire surface at a different and intermediate resolution between those of Viking and MGS, to conduct follow-up thermal mineralogical analyses of many specific sites at thousands of times the resolution of TES, to determine the abundances of over 20 elements upon the surface and, critically, to determine the global distribution of water in the top layer of Mars' crust.

With the loss of the Climate Observer and Polar Lander, the arrival of Odyssey in April 2001 was monitored very closely by all concerned. It is perhaps no exaggeration to say that the future of the Mars program rested on the success of Odyssey. Should a problem arise *en route* or while entering orbit, there would be serious repercussions. This time, however, everything worked to perfection. Odyssey used the same aerobraking procedure as MGS, but this time it worked perfectly and on October 24, 2001, Odyssey settled into its final science orbit about Mars, just a single kilometer off its targeted position. And to celebrate the mission, NASA even commissioned an original composition from the Greek composer Vangelis, whose music had been used to breath-taking effect in Carl Sagan's TV series "Cosmos." Titled *Mythodea*, Vangelis composed a major work for synthesizer, orchestra, choir, and two solo parts sung by world-renowned sopranos Kathleen Battle and Jessye Norman—exploring both the mythological legacy and the current space odyssey to the Red Planet. The work was performed live in Athens in June 2001 and was a resounding success, heralding the success to come for the space probe that had inspired the work.

Odyssey's Science Mission

Odyssey's science objectives are numerous and unprecedented. First, Odyssey has been tasked with photographing the planetary surface at a resolution of about 18 meters—which is of immense value when attempting to understand the planet's geology. While Viking had photographed some regions at a resolution of about 8 meter, general global mapping was at resolutions of between 150 to 300 meters, often insufficient to identify the underlying geological processes at work on the surface. Mars Global Surveyor's MOC addressed this problem in part with an ability to image interesting features to about 4 meters resolution; but even with its lengthy mission it has only been possible to image a small portion of the surface in such detail. And while in wide-angle mode, MOC has photographed virtually the entire planet at 250 meters resolution, but again these images are often of too low a resolution to provide defining answers on surface geology. So, with Odyssey photographing a far greater portion of the planet at an 18-meter resolution, it provides unprecedented views of much of the planet, finally providing us with the capability of interconnecting local-scale to regional and planetary-scale geology (Figure 50).

Using its onboard Gamma Ray Spectrometer (GRS), another of Odyssey's goals has been to map the global abundance and distribution of approximately 20 chemical elements, including hydrogen, silicon, iron, potassium, thorium, and chlorine, as well as the global distribution of water to a depth of about 1 meter. GRS is actually three instruments combined: two neutron detectors and a gamma-ray detector. Each instrument works by observing gamma rays or neutrons emitted from the Martian soil when

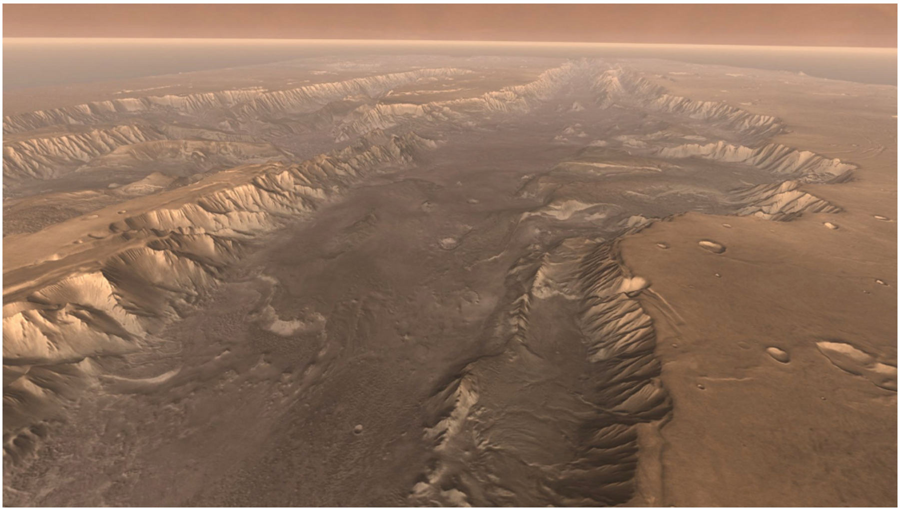

Figure 50: From high above Valles Marineris, this 2001 Mars Odyssey derived view looks down upon a sight resembling parts of the desert west of the United States. Here the canyon is 150 kilometers wide, with the floor composed of rocks, sediments, and landslide debris. Within the canyon walls lie hundreds of layers revealing Mars' geologic history. See Plate 20 in the color section. [Credit: NASA/JPL/Arizona State University]

bombarded by cosmic rays that reach the surface through Mars' tenuous atmosphere. With each element in the soil reacting uniquely to incoming cosmic rays and subsequently emitting its own particular gamma-ray or neutron signature, GRS can infer the composition of the soil by analyzing the patterns of the radiation emitted. In particular, the detection of gamma rays indicates the presence of hydrogen bound up in water within the soil, pointing to where water-ice or hydrated minerals may reside across the planet.

Another significant experiment being conducted by Odyssey is a planetary mineralogical survey using an onboard thermal imaging camera called THEMIS, also designed by Phil Christensen. Where MGS's TES camera had a low pixel resolution suited to global mapping, THEMIS' resolution is just 100 meters—1,800 times that of TES and capable of producing detailed local and regional level mineralogical images. Such resolution, coupled with excellent sensitivity and a large number of thermal frequencies has made THEMIS one of the defining instruments in our quest to understand the complex history of Mars and the search for life on that planet. With TES having already produced an exquisite global mineralogical map, THEMIS can now follow up on the multitude of interesting regions that TES identified. Further, THEMIS can identify a myriad of minerals—carbonates, sulfates, phosphates, silicates, oxides, and hydroxides, among others—all to near-trace levels. It is a powerful tool for determining the specific mineralogy and hence the geological evolution of each region examined.

Apart from determining surface mineralogy, THEMIS can also monitor surface reflectance and thermal inertia, from which surface compositions—sand, pebbles, boulders, solid rock, and so on (Figure 51)—can be determined. "Thermal inertia" means the resistance of a material to changes in temperature, and each surface type has its own thermal inertia. For example, dust and sand have a high thermal inertia as they heat up quickly during the day and cool down quickly at night. Conversely, large boulders and solid rock have a low thermal inertia as they are slow to warm up and equally slow to cool down. Hence, if THEMIS takes, for example, two or more thermal images of a given location during the day and at night, changes in temperature and hence the thermal inertia of the various surfaces in that location can be determined, from which their composition and petrology can be inferred.

Odyssey has also been tasked, with a radiation experiment called MARIE, to monitor solar and cosmic radiation both *en route* to Mars and in Mars orbit. Such measurements are critical to the wellbeing of all upcoming missions and most especially for any human mission. Finally, Odyssey has acted as an excellent communications satellite for both of the Mars

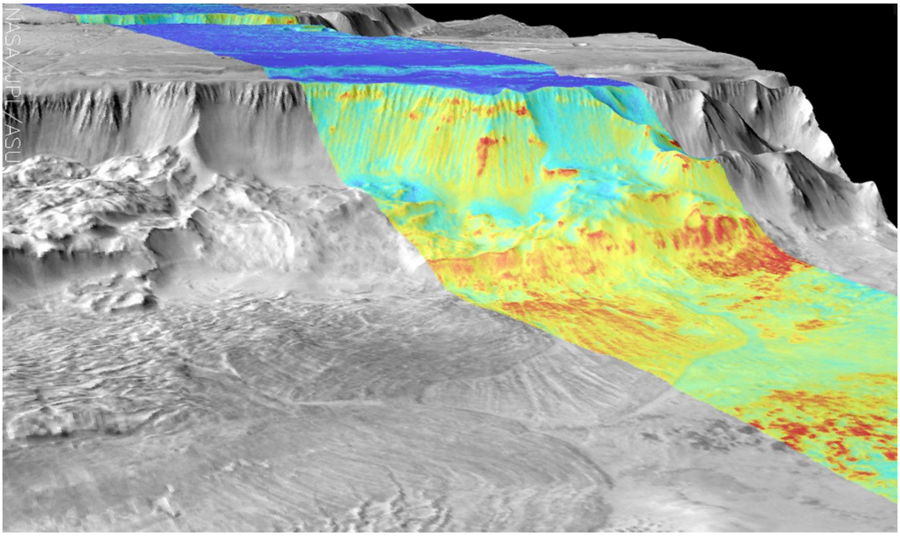

Figure 51: Odyssey/THEMIS infrared image of Melas Chasma at night, revealing the abundance and distribution of surface materials. Rocks retain their heat at night and stay warm, while dust and sand cool more rapidly. See Plate 21 in the color section. [Credit: NASA/JPL/Arizona State University]

Exploration rovers, relaying instructions from Earth to the rovers and scientific data from the rovers back to Earth.

Odyssey's Findings

Central to our investigations on Mars is the detection of water. While ancient river and flood channels indicate that water once flowed there, many fundamental questions regarding its ancient and current context remain unanswered. In particular, we have been uncertain of the amount of water, if any, that remains on Mars today, of its chemical and physical state, or of its location on the planet. While Viking verified the existence of water-ice at the poles, it was not until the arrival of Odyssey that the full extent of water on Mars could be robustly addressed. In true spectacular fashion, within just 10 days of operation, Odyssey's GRS experiment put beyond all doubt the existence of vast quantities of water-ice at both the North and South Poles. Furthermore, it found that at above 60 degrees latitude in each hemisphere, the topmost layer of the crust is composed of upwards of 50% water-ice, suggesting that vast quantities of Mars' water has been locked into the crust as a permanent permafrost lasting billions of years (Figure 52). Indeed, even

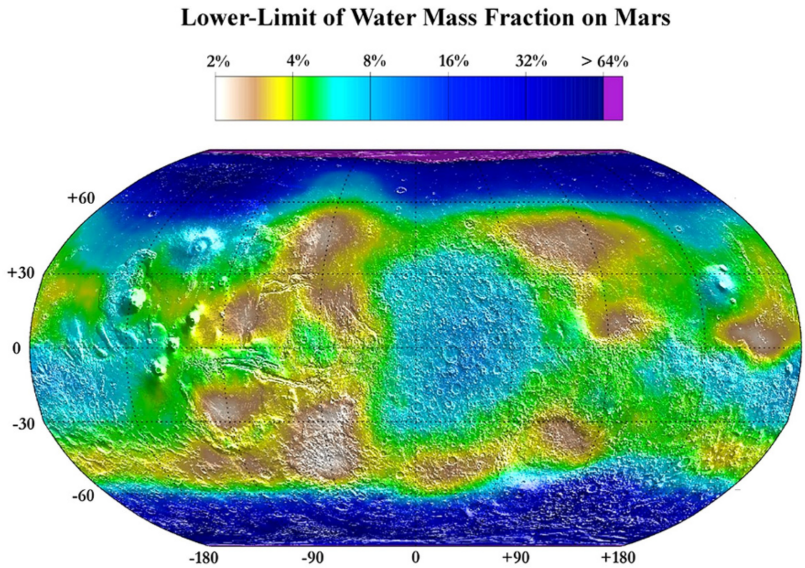

Figure 52: Mars Odyssey map showing the lower limit of the water content of the upper meter of Martian soil. The highest water–mass fractions, exceeding 60% in places, are found in the high latitudes and polar regions. See Plate 22 in the color section. [Credit: NASA/JPL/Los Alamos National Laboratory]

in the equatorial regions GRS found that the crust consists of several percent water—quantities too great to be in equilibrium with the current environment—perhaps suggesting that Mars' climate is gradually changing. GRS has also been busy determining the global distribution of various chemical elements, from which we will be able to better determine the composition and evolution of the crust as well as initial stocks of volatile and biogenic materials in Mars' distant past (Figure 53).

Odyssey's THEMIS instrument has also provided significant results to date. It has transmitted back to Earth spectacular optical and thermal maps of literally tens of thousands of sites on Mars. Many of the optical images are the best available of those regions, while the thermal images are proving to be of importance in studying Mars' ancient geology (Figure 54). First, THEMIS has verified TES findings, showing that the southern highlands are dominated by ancient basalt rocks while much of the northern lowlands are composed of andesite. Significantly, however, THEMIS has also identified isolated andesite in the southern hemisphere, indicating that even during Mars' earliest history at least some crustal recycling was occurring. THEMIS has also turned to the sites at which hematite was found and has constructed detailed maps of each region. These are critical if we are to determine the precise nature and extent of the

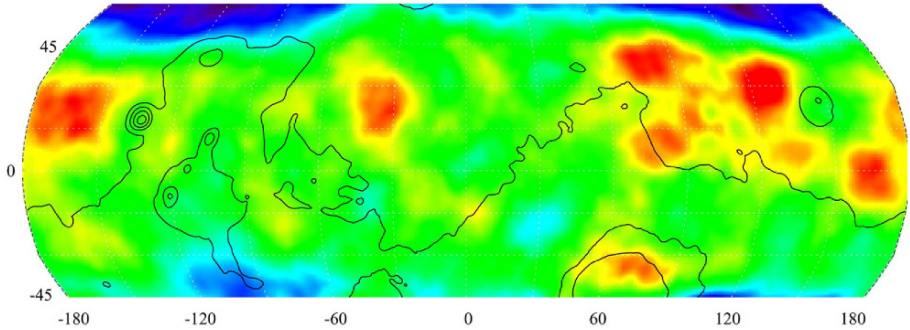

Figure 53: A Mars Odyssey gamma-ray spectrometer map of the mid-latitude region of Mars for the element iron. Regions of highest iron content are found at latitudes above 45°N and below 45°S. Regions of highest iron content are found nearer the Equator. Similar maps have been constructed for other elements. See Plate 23 in the color section. [Credit: NASA/JPL/Arizona State University]

hematite and, hence, the specific water activity from which it originated. The true power of THEMIS is in its detailed examination of the surface petrology and mineralogy of a given region. Although it will require the analysis of thousands of sites to gain a global context into the ancient processes shaping Mars, there have already been some significant results. For example, not only has THEMIS verified the presence of hematite at Meridiani Planum, but it has also been able to identify widespread sedimentary layering across the region, strengthening the case for past surface water activity at that location. No less than eight types of material have been identified within the sedimentary layers across the region, from ancient volcanic materials to hematite. Through THEMIS we can also see their stratigrapic relationship—that is, the chronological order in which they were laid down. Also, the nature of the layering in the region shows episodic erosion and deposition, as if Mars' early environment changed in a cyclical fashion (at least in that region). In particular, rhythmic variations in the layering observed suggest that one layer in particular was laid down by burial or cementation by percolating fluids, perhaps compacted by about a 1-kilometer-thick overburden that was subsequently eroded, pointing to significant activity in the region over a very long time.

Another important yet paradoxical discovery by THEMIS has been the identification of unweathered olivine layers at a depth of 5 kilometers within the walls of Valles Marineris. Since olivine is reduced to clay on contact with water, such a discovery would seem to suggest that Mars was incredibly dry even during the Noachian period. Such apparently contradictory evidence is an indication of both the incompleteness of our surveys

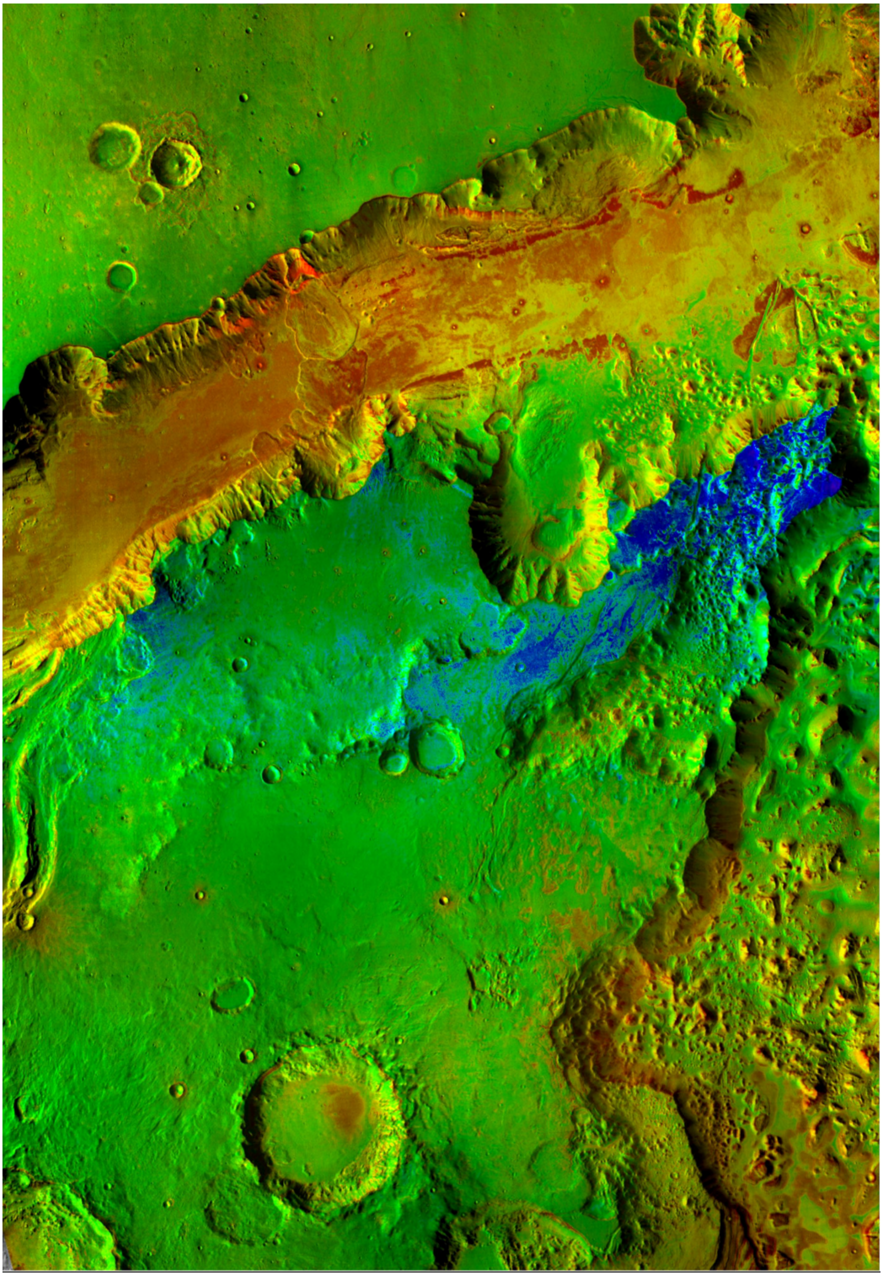

Figure 54: Ganges Chasma, part of the Valles Marineris, showing layering in the canyon walls to a depth of 5 kilometers. Outcrops of olivine, seen along the base of the canyon, suggest that the region has been dry for billons of years. See Plate 24 in the color section. [Credit: NASA/JPL/Arizona State University]

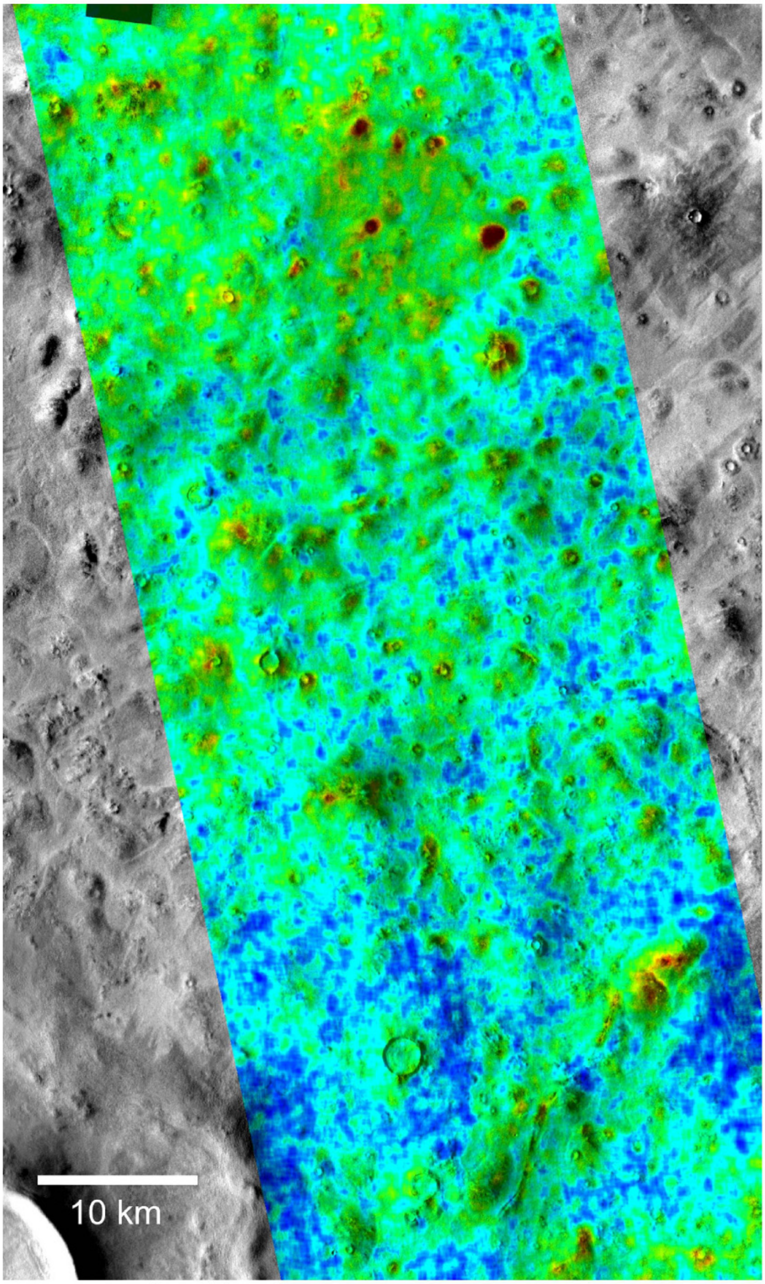

Figure 55: 2001 Mars Odyssey THEMIS image of near-surface water-ice in a region on Mars approximately 70°N. The instrument is able to reveal ice lying at depths from 4 centimeters to more than 18 centimeters. See Plate 25 in the color section. [Credit: NASA/JPL/Arizona State University]

of Mars and of our understanding of its complex history. None the less, we are now confident that, as with the spectacular analysis the Meridiani Planum, THEMIS will allow us to strip away the layers of time at site after site and reconstruct the detailed history of the planet.

THEMIS is also providing unrivaled insight into the present nature Mars. It can, for example, closely monitor changes in frost and ice covering both poles and as the seasons pass, allowing for accurate monitoring of changes in carbon dioxide and water at sub-kilometer resolutions. In particular, THEMIS images, coupled to advanced computer modeling of the thermal inertia of rock, dust and ice on the surface of Mars, have allowed Phil Christensen and his colleague Joshua Banfield at Arizona State University Tempe, to determine the depth of near-surface ice in the polar regions over scales of just hundreds of meters, revealing that water-ice is likely to reside closer to the surface when covered by dust than by rock (Figure 55). Such measurements will prove critical to future missions, in particular for the Phoenix Lander, whose 2008 mission involves landing in the far north in search of near-surface ice. Furthermore, THEMIS thermal inertia measurements of near-surface ice reveal the precise ground patterns of water-ice retained under the surface, providing insight both into quasi-periodic climate change that is now thought to occur on Mars over timescales of tens of thousands of years, and into the cycling of water between the atmosphere and the crust over various timescales. Finally, with its extraordinary temperature-measuring capability, THEMIS can already tell us, at least to the limits of its resolution and sensitivity, that there are no high-temperature anomalies such as volcanoes or hydrothermal vents on Mars today. Fumaroles and hot springs may well exist, but we can now be confident that, if they do, they are on a small scale. Overall, THEMIS has turned out to be a monumental instrument for studying the mineralogy, past geology, and current environment on Mars (Figures 56 and 57).

Mars Express

With a legacy of unsuccessful Soviet Mars missions and a more limited European Space Agency (ESA) space science program, Mars exploration remained exclusive to the United States of America through the second half of the twentieth century. That changed in 2003, however, with the launch to Mars of ESA's reconnaissance orbiter Mars Express.

Mars Express, so named because it was designed, built, and launched in record time, was just one of a number of missions commissioned by ESA as part of its new Cosmic Vision program of space-science exploration.

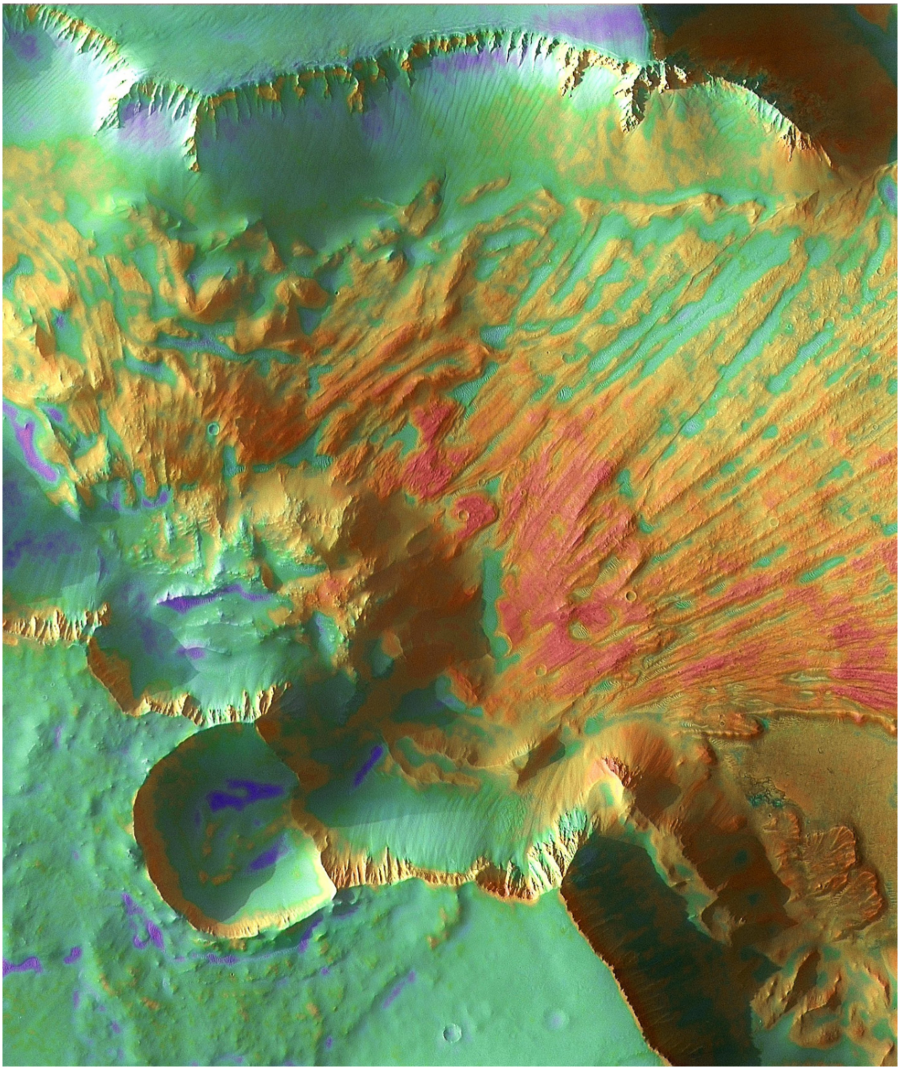

Figure 56: 2001 Mars Odyssey THEMIS image of a landslide in Juventae Chasma, part of the vast Noctis Labyrinthus (the Labyrinth of Night) in west Valles Marineris, perhaps created when tectonic faults opened and allowed subsurface water to escape, causing the ground to collapse. See Plate 26 in the color section. [Credit: NASA/JPL/Arizona State University]

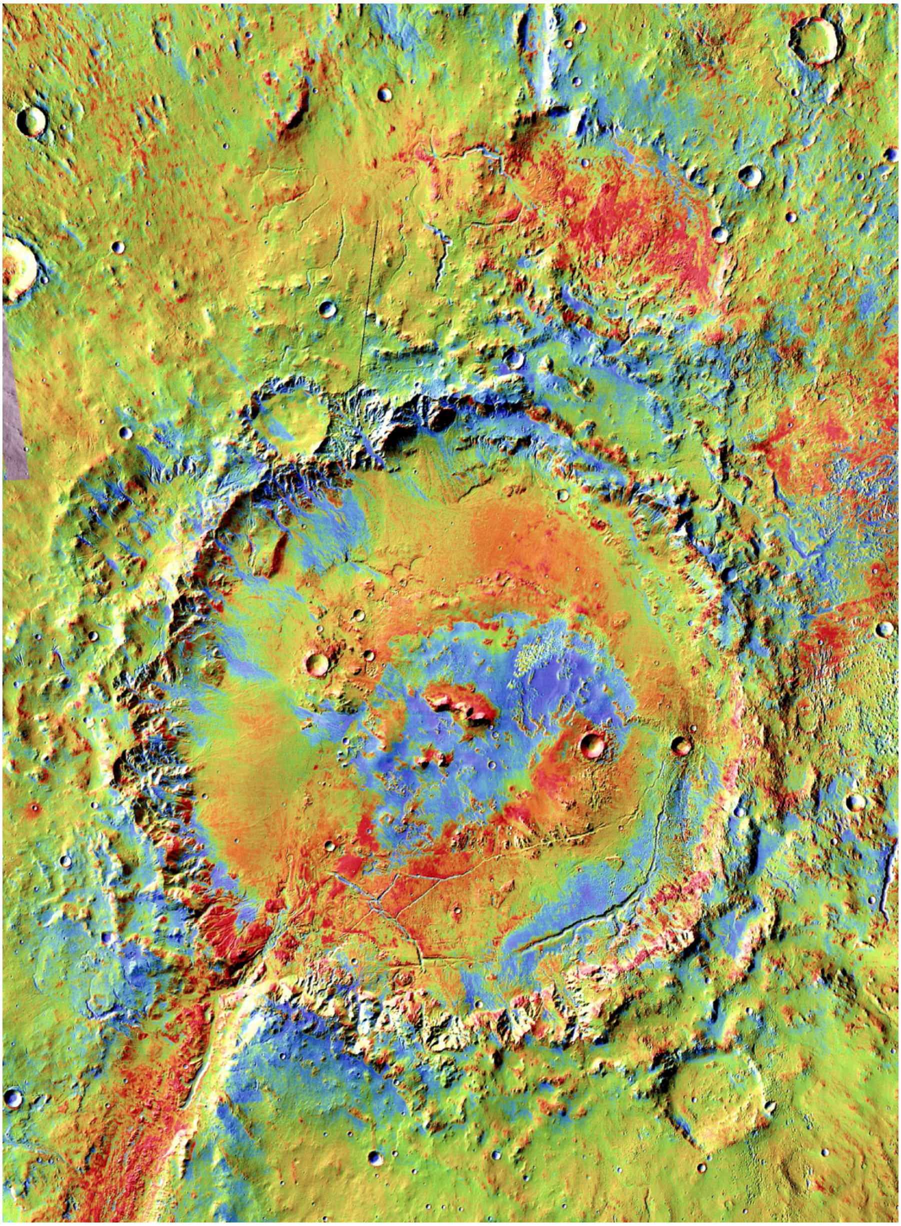

Figure 57: 2001 Mars Odyssey THEMIS image of Holden Crater, which formed on what may be the longest watercourse on Mars—the Uzboi–Ladon–Margaritifer valleys—stretching from the Argyre Basin in the south to Chryse Planitia in the north. See Plate 27 in the color section. [Credit: NASA/JPL/Arizona State University]

Mindful of (and learning from) the US Mars program, Mars Express was built both to complement US efforts by carrying out follow-on surveys based on MGS and Odyssey findings, as well as to conduct surveys specific to ESA's own emerging Mars program. The result was yet another exquisite robotic space probe equipped with an array of instruments designed to pursue new investigations at Mars. Mars Express—accompanied by its ill-fated passenger, the Beagle 2 Mars lander—was launched in June 2003 to avail of the extraordinarily close opposition of Mars that year; and with NASA's two Mars Exploration Rovers also *en route*, no less than four space probes were heading toward Mars at the same time. In December 2003, Beagle 2 was unfortunately lost on arrival, although Mars Express itself successfully settled into orbit and immediately began its reconnaissance mission. With the successful landing of the two Exploration Rovers in January 2004, no less than five robotic explorers were at work on and around the planet.

As with MGS and Odyssey, Mars Express is a multifaceted orbiter. First, its spectacular optical camera—the High Resolution Stereo Camera (HRSC)—is capable of mapping the planet at about 10 meters resolution (surpassing Odyssey), while a special super-high resolution mode can even photograph selected sites to 2 meters resolution. Furthermore, the HRSC can also take true stereo images, providing unprecedented three-dimensional views of Mars that are radically improving our understanding of the planet's topology, morphology, and geology.

Mars Express is also tasked with conducting an extensive mineralogical survey with OMEGA, its infrared spectrometer. While the spatial resolution of OMEGA is lower than that of THEMIS, its sensitivity is higher, meaning that it can identify even lower levels of minerals that are crucial to a complete picture of Mars' mineralogy and the processes by which they originated. For example, OMEGA can identify the various classes of silicates—whether feldspar, olivine, pyroxene, etc. OMEGA can also identify the iron content and oxidation state of iron-based minerals, locate clays and hydrated minerals, and detect carbonates and nitrates to abundances of just a few percent. While the mantra for NASA has become follow the water, ESA have aptly decided to prioritize tracing the history, evolution and current planetary cycling of carbon—and in this search, OMEGA should provide many answers.

Unique to Mars Express are a number of instruments whose aim is to determine the make-up and circulation of the planet's atmosphere, as well as to investigate how the atmosphere interacts with the crust and solar wind. Such information is critical to understanding Mars' current climate, the nature of its ancient atmosphere, and the mechanisms that may have caused it to dissipate over time. The energetic neutral atom analyzer, ASPERA, examines how the uppermost region of the atmosphere interacts with the solar wind, revealing the escape (or leakage) of the atmosphere to space over time. A Planetary Fourier Spectrometer (PFS) measures the global atmospheric distribution of water vapor (among other atmospheric constituents); an optical and ultra-violet camera called SPICAM can look through Mars' atmosphere to determine its composition; while a radio transceiver called MARS uses radio waves to measure both the temperature and pressure within the atmosphere and on the surface.

Mars Express carries another enigmatic instrument called MARSIS (Figure 58). This radio-sounding instrument consists of two radio booms, each 20 meters in length, which transmit radio waves at the planet and subsequently detect their reflections. The characteristics of each reflection are analyzed to reveal the underground structure to a depth of about

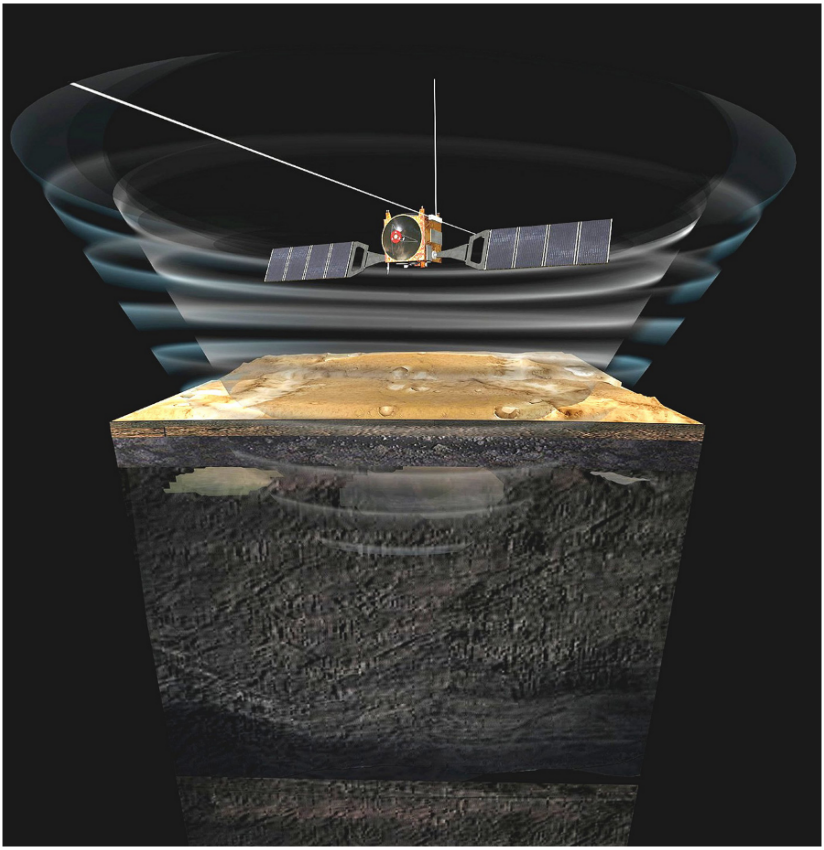

Figure 58: Image depicting Mars Express' MARSIS Radio Sounding instrument scanning for underground reservoirs of water and other buried geological features. See Plate 28a in the color section. [Credit: ESA]

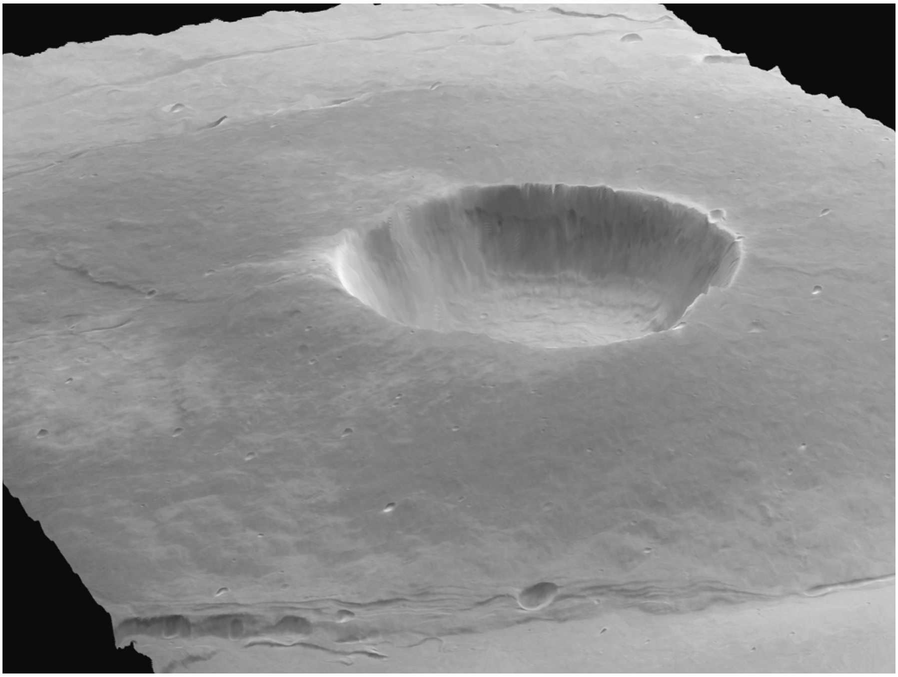

Figure 59: Mars Express/HRSC 3D view of the summit of Albor Tholus, a volcano on Elysium. The caldera is 30 kilometers across and 3 kilometers deep. On the rim, a bright ''dust fall'' triggered my Martian winds flows from the surrounding plateau into the caldera. [Credit: ESA/DLR/FU Berlin (G. Neukum)]

5 kilometers. In a similar manner to how a submarine uses sonar to detect otherwise invisible structures, MARSIS uses radio waves to reveal both ancient geological structures now covered over, as well as any remaining underground reservoirs of water or water-ice.

Data through Mars Express

The findings of Mars Express have been dramatic. The HRSC, for example, is providing new ways of looking at the planet through high-resolution color perspective images as well as true stereo 3D images (Figures 59–61; see also Figures 62 and 63). Mars Express scientists can now look at the relief of Mars in all three dimensions, gaining a unique insight into the underlying geology. MGS's MOLA also provides spectacular 3D perspectives of course, though its resolution is lower and was designed to produce a global topological map. With the HRSC's stereo images being of higher lateral resolution and revealing incredibly fine relief of individual surface features, both instruments complement each other in providing exquisite regional and local 3D views.

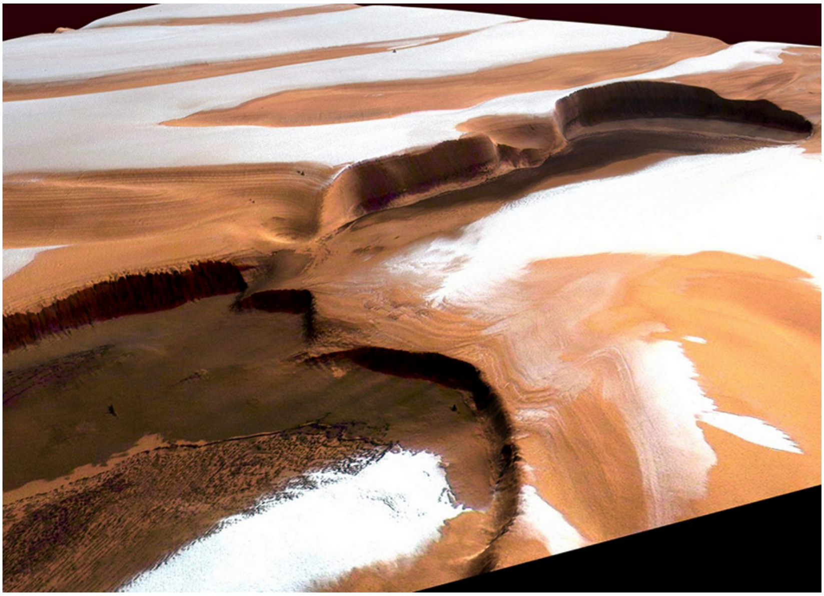

Figure 60: Mars Express/HRSC 3D perspective view of the Martian north polar ice cap, showing layers of water-ice and dust. The cliffs are 2 kilometers high. See Plate 29 in the color section. [Credit: ESA/DLR/FU Berlin (G. Neukum)]

Figure 61: Mars Express/HRSC 3D perspective view of Nicholson Crater located at Amazonis Planitia. This view shows the central part of the crater, measuring 100 kilometers across. See Plate 30 in the color section. [Credit: ESA/DLR/FU Berlin (G. Neukum)]

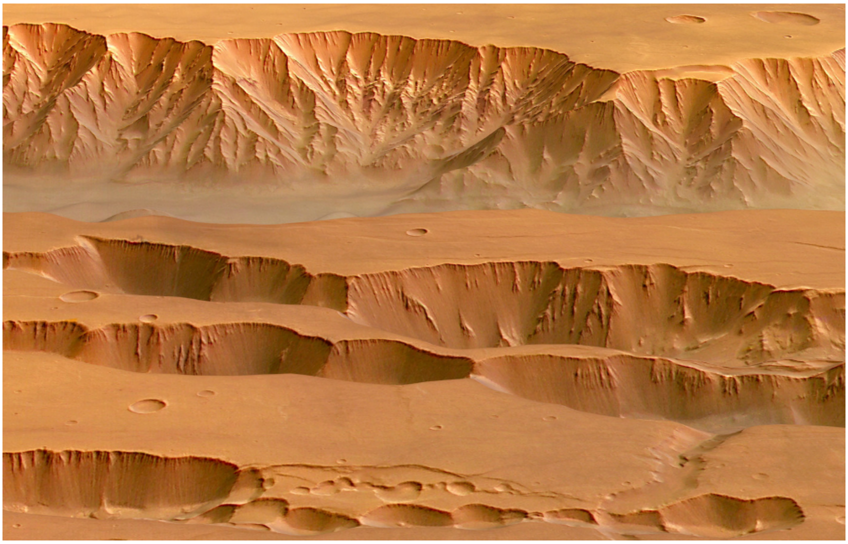

Figure 62: Mars Express/HRSC 3D perspective view of Coprates Chasma and Catena in Valles Marineris, with a ground resolution of approximately 48 meters. The main trough, appearing in the north (top half) of this image, ranges from 60 kilometers to 100 kilometers wide and extends 9 kilometers below the surrounding plains. See Plate 31 in the color section. [Credit: ESA/DLR/FU Berlin (G. Neukum)]

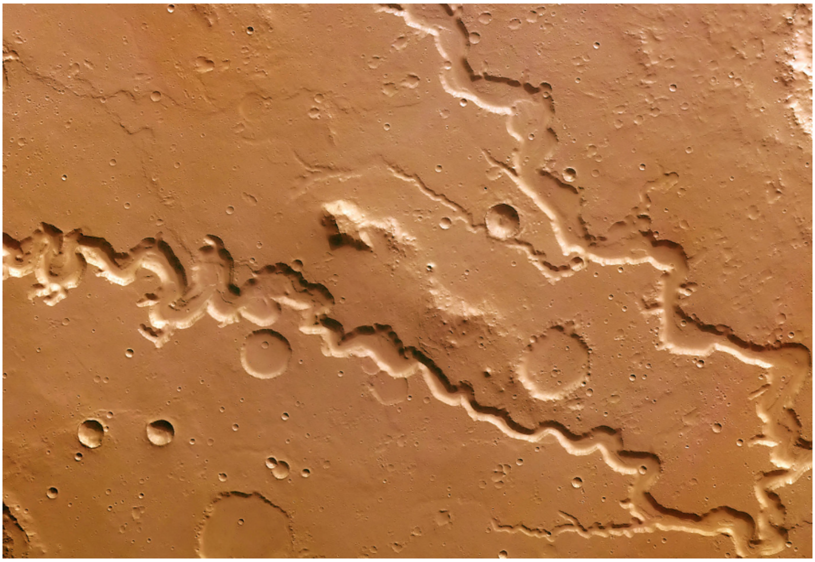

Figure 63: Mars Express/HRSC image of Nanedi Valles valley, extending 800 kilometers diagonally across Xanthe Terra, southwest of Chryse Planitia. The valley exhibits meanders and a merging of two branches in the north. Erosion was perhaps caused by ground-water outflow, flow of liquid beneath an ice cover or collapse of the surface in association with liquid flow. See Plate 32 in the color section. [Credit: ESA/DLR/FU Berlin (G. Neukum)]

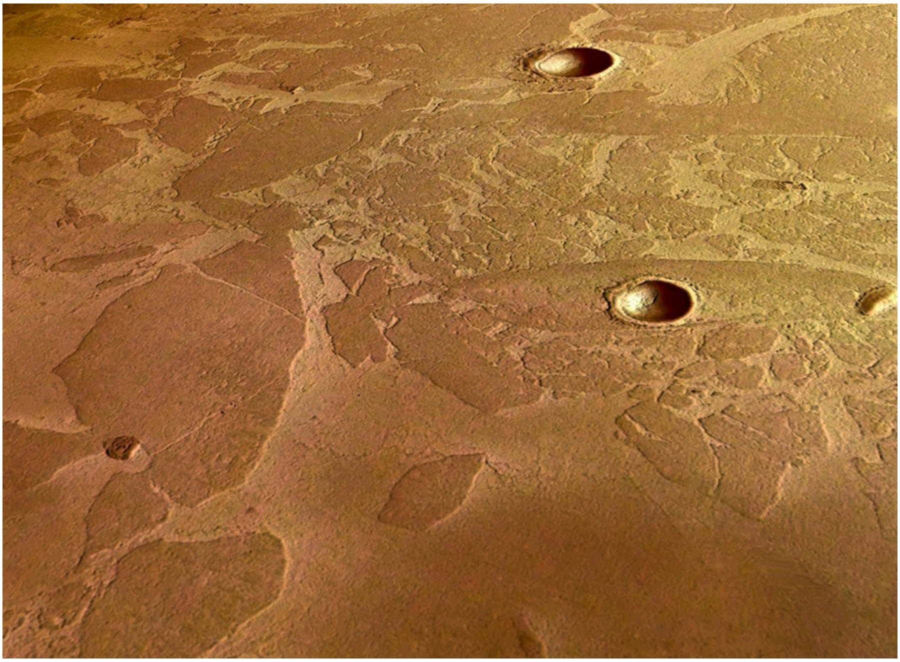

Figure 64: Pack-ice on Mars? This image, taken by the HRSC, shows what appears to be a dust-covered frozen sea at Elysium Planitia near the Martian equator. This scene is tens of kilometers across, centered on latitude 5°N and longitude 150°E. See Plate 33 in the color section. [Credit: ESA/DLR/FU Berlin (G. Neukum)]

One of the most dramatic results has been the discovery in 2004 by John B. Murray, Jan-Peter Muller, Gerhard Neukum, and others of what looks like a frozen sea on Mars today (Figure 64). A region south of Elysium, known as Cerberus Fossae, had previously been identified as having undergone tectonic-based lava and water flows within the last five million years or so. It was assumed that all water in the region would have long since disappeared. However, on photographing the area, HRSC images revealed what appears to be a frozen sea actually residing there today, measuring approximately 800 by 900 kilometers (about the size of the North Sea); and about 45 meters deep. Also seen within the region is what looks like broken glaciers that drifted apart before the sea froze and locked them into their current positions. The sea may have arisen due to tectonic and/or volcanic activity within Cerberus Fossae fissures, releasing enormous quantities of underground water which then flowed down for hundreds of kilometers, filling a vast area that then froze. The water may originally have come from underground ice that melted during the event, or it might even have originated as liquid water residing underground where the geothermal gradient prevented it from freezing and it burst onto the surface during the cracking of the fissures. Subsequent to the creation of the sea, volcanic ash falling on the freezing sea may have formed a protective layer, inhibiting all of the ice from sublimating into the atmosphere. Even so, it is clear that the water level in the region has dropped about 20 metres since it first formed due to sublimation. This discovery is significant. It reveals for the first time dramatic events occurring on Mars in the current geological era, indicating that the planet is certainly not dead. Also, in the search for past and present life, this discovery tells us that environments conducive to basic life as we know it may have persisted on Mars for the past four billion years and until several million years ago. If underground water reservoirs still exist, life could survive well there, protected from ultraviolet radiation and oxidation and availing of geothermal energy and geochemical nutrients.

HRSC has also provided unprecedented insight into the movement of water and ice across the surface of Mars both in its distant past and perhaps even today. For example, images of the Kasei Valles outflow channel which connects the southern Echus Chasma to Chryse Planitia in the east over a distance 2,500 kilometers reveal evidence of a vast flood on Mars billions of years ago, followed by the rapid freezing of much of the flood waters into a colossal glacier that subsequently carved out much of the valley and which may have persisted for as long as a thousand million years (Figures 65 and 66).

James Head of Brown University and Ernst Hauber of the German Aerospace Center have also used HRSC to identify recent glaciation on the planet, even in its equatorial regions. For example, glacial deposits can be seen at the base of Olympus Mons, pointing to glaciers in that region about four million years ago. Above 7,000 meters, glaciers may currently exist on the flanks of Olympus Mons and be disguised by a layer of dust. Further evidence of glaciation has been found at five other volcanoes. For example, HRSC images also reveal that Hecates Tholus (which erupted explosively about 350 million years ago) contained glacial deposits inside depressions within its caldera about four million years ago. And evidence of snow-ice accumulation, flow, and glaciation can also be found on the eastern side of Hellas Basin. Here, numerous concentrically ridged lobate and pitted surface features could only have been created by glaciation in the last few million years.

The detection of recent glaciation on Mars is important as it points to significant climate change occurring on the planet over timescales of millions of years or less, where we suspect that periods of greater obliquity affect the planet's hydrological cycle and mobilize polar ice to micro-environments at lower latitudes. In response to the HRSC findings, a team

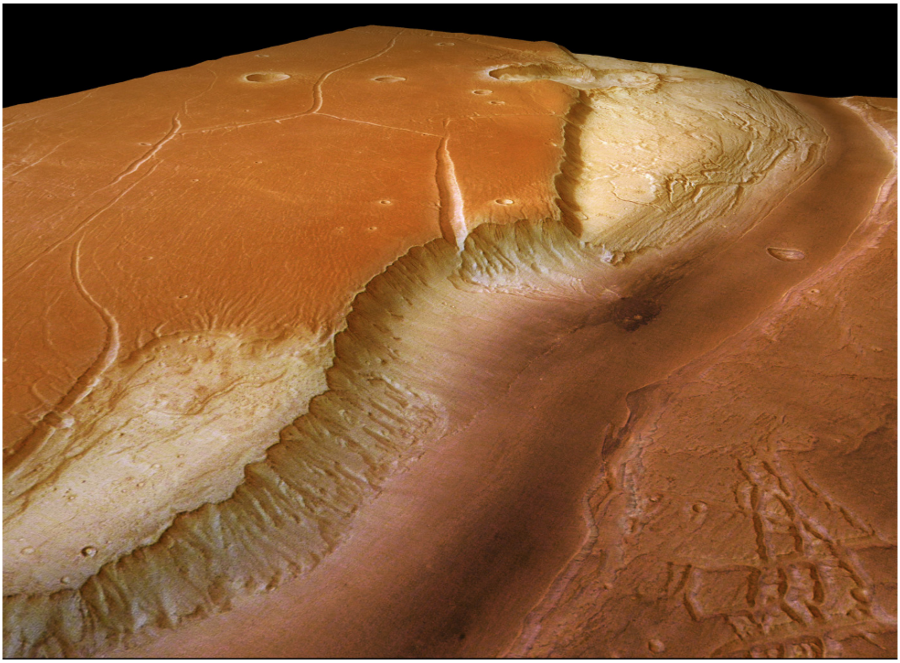

Figure 65: Mars Express/HRSC 3D perspective of the Kasei Valles outflow channel – a gigantic channel 2,900 kilometers long and 500 kilometers wide that may have persisted on Mars for upwards of a billion years. See Plate 34 in the color section. [Credit: ESA/DLR/FU Berlin (G. Neukum)]

led by Mars Express scientist François Forget at the University of Paris have even applied Mars meteorological computer simulations to the problem, yielding compelling results. By turning the clock back several million years and assuming an axial tilt of 45 degrees, Forget's simulations produce climatic conditions leading to glaciation at precisely the locations identified by the HRSC. With a greater tilt, increased solar illumination in the north polar summer increased the sublimation of the polar ice, leading to a more intense water cycle. The simulations show water-ice accumulating at a rate of 30 to 70 millimeters per year in localized areas on the flanks of the Elysium Mons, Olympus Mons, and the three Tharsis Montes volcanoes. After a few thousand years, the accumulated ice forms glaciers up to several hundreds of meters thick. Comparisons between the simulated and actual glacier deposits give excellent agreement. For example, simulations predict maximum deposition on the western flanks of the Arsia and Pavonis Montes of the Tharsis region and this is where the largest deposits are actually observed. Forget's simulations even reveal the manner in which ice accumulates on the flanks of mountains in the Tharsis region during such

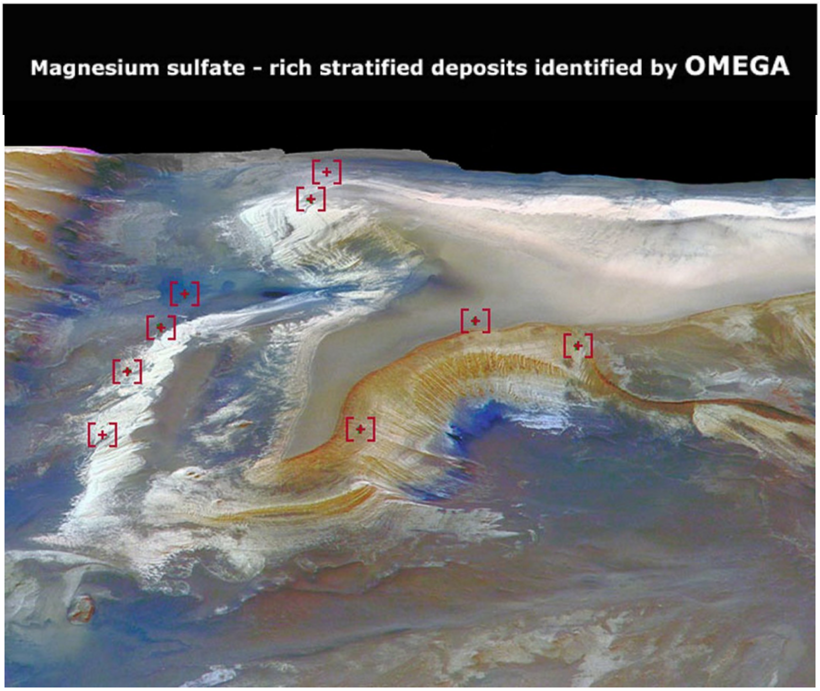

Figure 66: Mars Express/HRSC 3D perspective view of Candor Chasma with a superimposed infrared image from OMEGA. This image shows deposits of the mineral kieserite (hydrated magnesium sulfate). See Plate 35 in the color section. [Credit: ESA/OMEGA/HRSC]

periods of high obliquity. With year-round winds similar to Earth's monsoons, movement of moist air occurs particularly up the slopes of Arsia and Pavonis Montes; it then cools, leaving water condensation on the slopes as ice particles. Olympus Mons, on the other hand, experiences less deposition (as observed) because, even during high obliquity, monsoon-type winds and water condensation only occur during the northern summer and not all the year round. Simulations also reveal that water from the south polar cap accumulates at east Hellas Basin, which is so deep as to create a northward wind flow on its eastern side carrying water vapor sublimating from the south polar cap during summer. When the water-rich air meets the colder air mass over the eastern Hellas, the water condenses, precipitates, and forms glaciers over time.

Mineralogy

The OMEGA mineralogical detector has complemented the findings of both TES and THEMIS while also delivering unprecedented results of its own regarding Mars' distant past. First, OMEGA has further verified the broad presence of mafic materials (ancient and pristine basalts) in the south of the planet and felsic (andesite) to the north, corroborating the idea that the south is composed of the most ancient surface while the north is much younger. OMEGA has also found significant evidence of water-altered minerals. For example, it has found an area in the north polar region measuring 60 by 200 kilometers that is dominated by gypsum (calcium sulfate), revealing that water played a major role in altering the surface of the region. Also, hydrated minerals such as kieserite, gypsum, and polyhydrated sulfates have been found within the sedimentary layers of Valles Marineris, at Margaritifer Sinus, and Terra Meridiani, constituting significant evidence of ancient aqueous activity on Mars (Figures 67–69).

OMEGA has also re-examined the eastern Meridiani, where TES, THEMIS, and Opportunity have already verified the presence of hematite and precipitate salts. OMEGA has found widespread presence of water molecules within etched terrain in the region, overlying heavily cratered terrain but underlying the hematite-bearing plains explored by Opportunity.

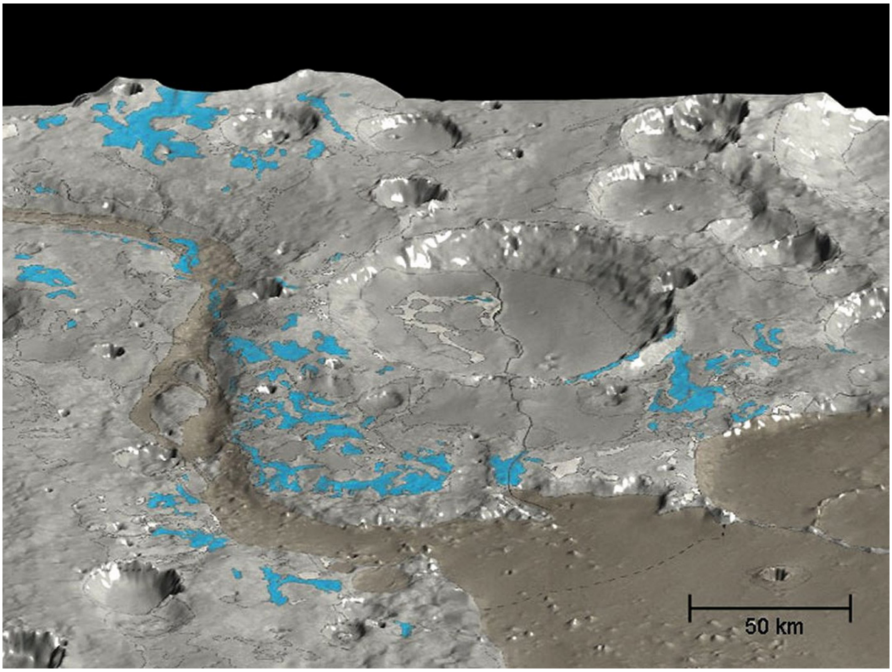

Figure 67: A Mars Express/HRSC 3D perspective view of Marwth Vallis, with a superimposed OMEGA map showing water-rich minerals. While no hydrated minerals are detected in the channel, the outflow was so violent as to expose ancient hydrated minerals, revealing an earlier era when water was present. See Plate 36 in the color section. [Credit: ESA/OMEGA/HRSC]

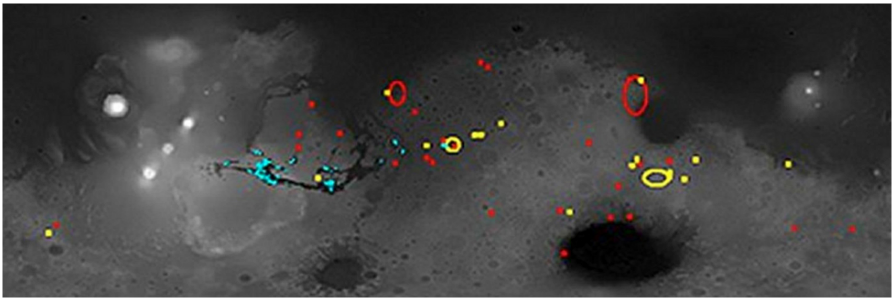

Figure 68: The global distribution of hydrated (water-rich) minerals as discovered by Mars Express/OMEGA. The map is superimposed on an MGS/MOLA map. Such maps indicate the distribution of phyllosilicates, sulfates, and other hydrated minerals. See Plate 37 in the color section. [Credit: IAS/OMEGA/ESA]

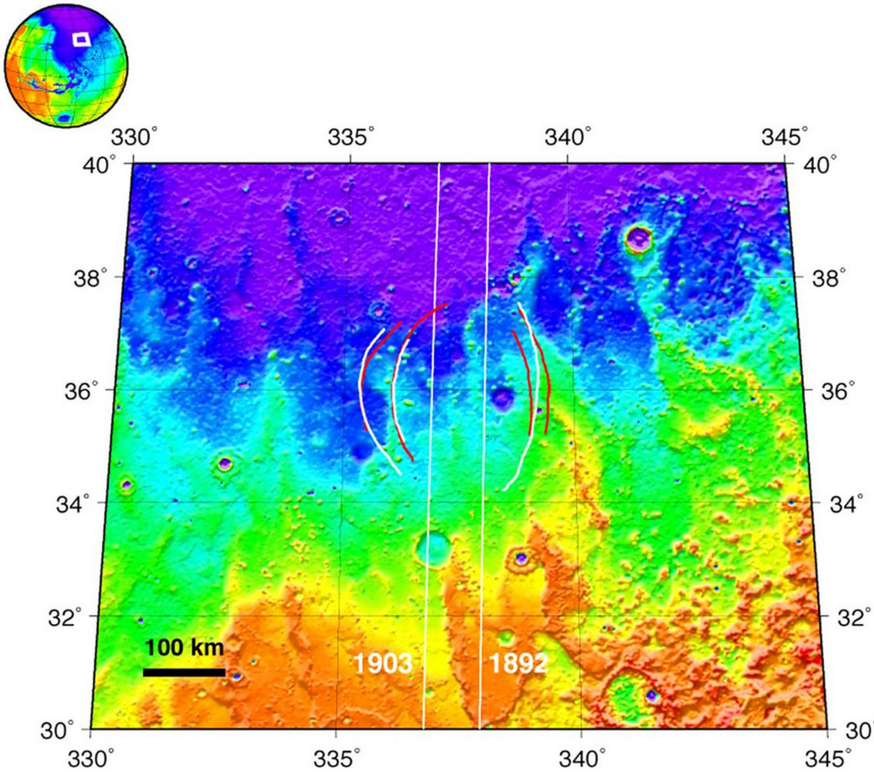

Figure 69: Mars Express/MARSIS identification of an ancient crater 250 kilometers in diameter buried under Chryse Planitia, superimposed on a MGS/MOLA topology map. See Plate 38 in the color section. [Credit: NASA/JPL/ASI/ESA/Uni. of Rome/MOLA Science Team]

This indicates that ancient aqueous environments inferred by Opportunity indeed extend over a large area, and corroborates the idea that an ancient sea once existed there. Of direct interest to the search for ancient prebiotic and life-related activity on Mars, OMEGA has also identified layered and water-altered terrain on Syrtis Major, suggesting the interaction between volcanism and volatile rich deposits and pointing to the possibility of ancient hydrothermal activity in the region.

Among some of the most intriguing discoveries has been the detection of methane in the atmosphere by the Mars Express PFS experiment at several specific locations on the planet, most notably from the Hellas Basin, from within Valles Marineris, and from Elysium. Since methane cannot reside within Mars' current atmosphere for long periods of time, it must have entered the atmosphere only recently. Measured at levels of about 10 parts per billion, an indigenous production rate of about 150 tonnes per year is suggested. Furthermore, the detection of formaldehyde—perhaps produced when methane is oxidized—points to a limit of methane production upwards of 20 times greater.

Currently, three natural mechanisms of methane production are envisaged—from active volcanism, from delivery by comet impacts, and as a by-product of life activity. Given how quiescent Mars is today, it is difficult to see how volcanism could give rise to such quantities; and while comet impact could deliver the detected methane, its localized nature suggests an indigenous source. Hence, while the detected methane may arise from a geochemical process, a biological source cannot be ruled out.

Finally, the Mars Express MARSIS radio sounding experiment has also probed below the surface to depths of up to 5 kilometers, identifying large impact basins, including one up to 250 kilometers across, buried beneath the smooth northern lowlands near Chryse Planitia. Such discovery suggests that even though the northern lowlands are younger than the southern highlands they are none the less extremely old and point to planet-wide water activity occurring only in Mars' earliest history. MARSIS radar maps have also detected what appear to be underground reservoirs of water-ice, while radar maps of the south polar region reveal the structure of the water-ice cap in exquisite detail, unequivocally verifying that enough water resides in the southern ice-cap alone to cover the entire planet to a depth of 11 meters (Figures 70 and 71).

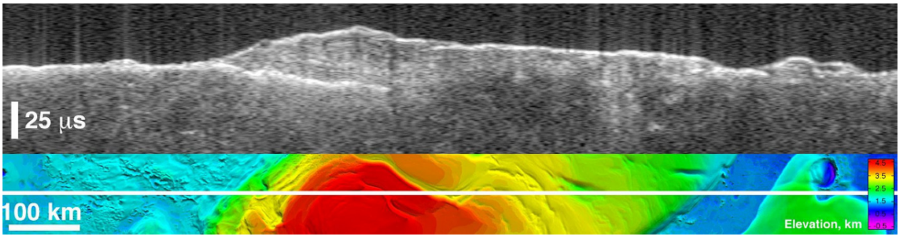

Figure 70: Mars Express/MARSIS subsurface map of the water-ice of the south polar region of Mars. The amount of water-ice in the region is equivalent to a layer 11 meters deep covering the entire planet. See Plate 28b in the color section. [Credit: NASA/JPL/ASI/ESA/Uni. of Rome/MOLA Science Team]

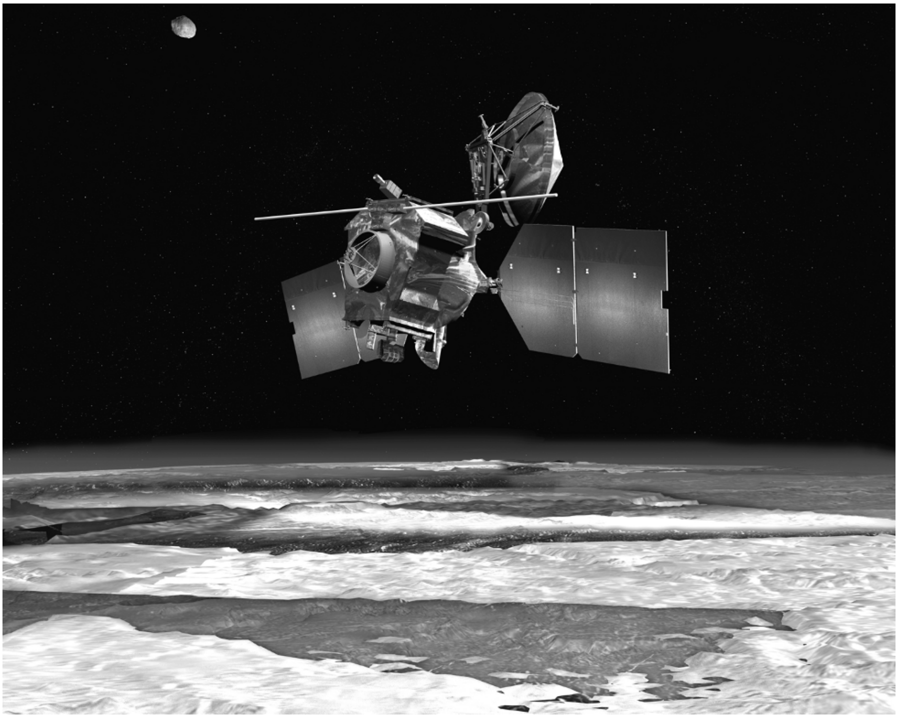

Figure 71: Mars Reconnaissance Orbiter (MRO), among the most sophisticated planetary probes ever sent to another planet. It will pave the way for continued Mars exploration well into the twenty-first century. [Credit: NASA/JPL]

The Future: Mars Reconnaissance Orbiter

In March 2006 yet another orbiter, NASA's Mars Reconnaissance Orbiter (MRO) arrived at Mars. This orbiter is set on gathering more data than all previous missions to Mars combined. MRO's onboard stereo camera—called HiRISE—is no less than half the diameter of the Hubble Space Telescope and has an extraordinary pixel resolution of just 30 centimeters, allowing it to resolve features on the surface less than 1 meter across. MRO will also use revolutionary navigation techniques to guide future landers to the surface of the planet with 10 times current precision, and will provide images of the surface of sufficient quality to allow safe human landings to be planned.

The Mars Reconnaissance Orbiter represents a significant step forward in orbital reconnaissance, housing the most sophisticated computers and instruments ever sent to another planet. With its HiRISE camera capable of sub-metre resolutions and in stereo, MRO will finally bridge the gap between orbital imaging at the planetary level and lander-based imaging at centimeter and smaller scales. Such a seamless connection is already providing defining views of the planet that allow for underlying processes behind geological features to be determined. As an example, sub-meter resolution HiRISE images of layering within an exposed scarp at the head of Chasma Boreale in the north polar region reveal unprecedented detail of geologically recent climate variations recorded in the layers at 40 centimeters resolution (Figure 72). And with the prospect of obtaining tens of thousands of images of the surface at such resolutions, we will finally be able to unravel much of the vast and intricate geological history of the planet. Views of the surface from HiRISE will also reveal thousands of candidate sites for follow-up exobiological missions such as NASA's upcoming Phoenix and Mars Science Laboratory rover, and ESA's ExoMars rover.

MRO is also engaged in a mineralogical survey of the planet at no less than 10 times the resolution of THEMIS or OMEGA. Here, MRO's thermal imaging camera, called CRISM, will specifically look for water-altered minerals such as clays, carbonates, and precipitated salts beyond the detection threshold of THEMIS and OMEGA. In tandem with HiRISE, CRISM will reveal the history of water activity of the planet in unprecedented clarity, as well as unveil hitherto invisible small-scale recent or current activity. Both instruments will become the eyes through which an entirely new planet, currently invisible to us, will be revealed over the coming years. Indeed, results already received are proving to be extremely revealing. For example, sedimentary deposits in Candor Chasma (Figure 73), examined both by HiRISE and CRISM, reveal for the first time ancient fluid flows through cracks in the rocks of that region on the sub-meter level, suggesting possible ancient hydrothermal sites as habitats for microbial life.

MRO will also survey the planetary subsurface using the same radio sounding technique employed by MARSIS on board Mars Express. While

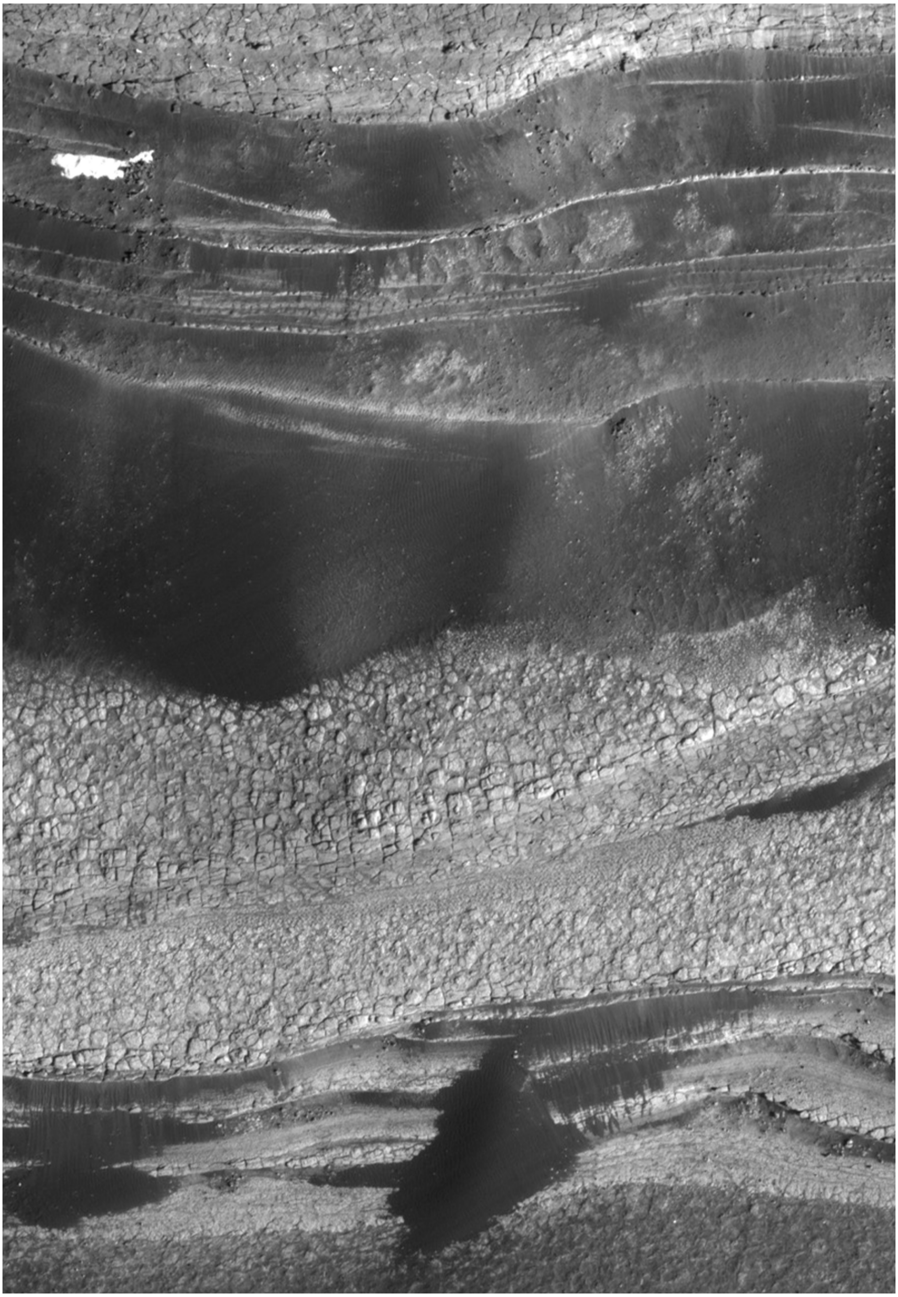

Figure 72: High-resolution MRO/HiRISE images of layering within an exposed scarp at the head of Chasma Boreale in the north polar region, revealing unprecedented detail of climate variations recorded in the layers. Pixel resolution is 38 centimeters. [Credit: NASA/JPL-Caltech/Univ. of Arizona]

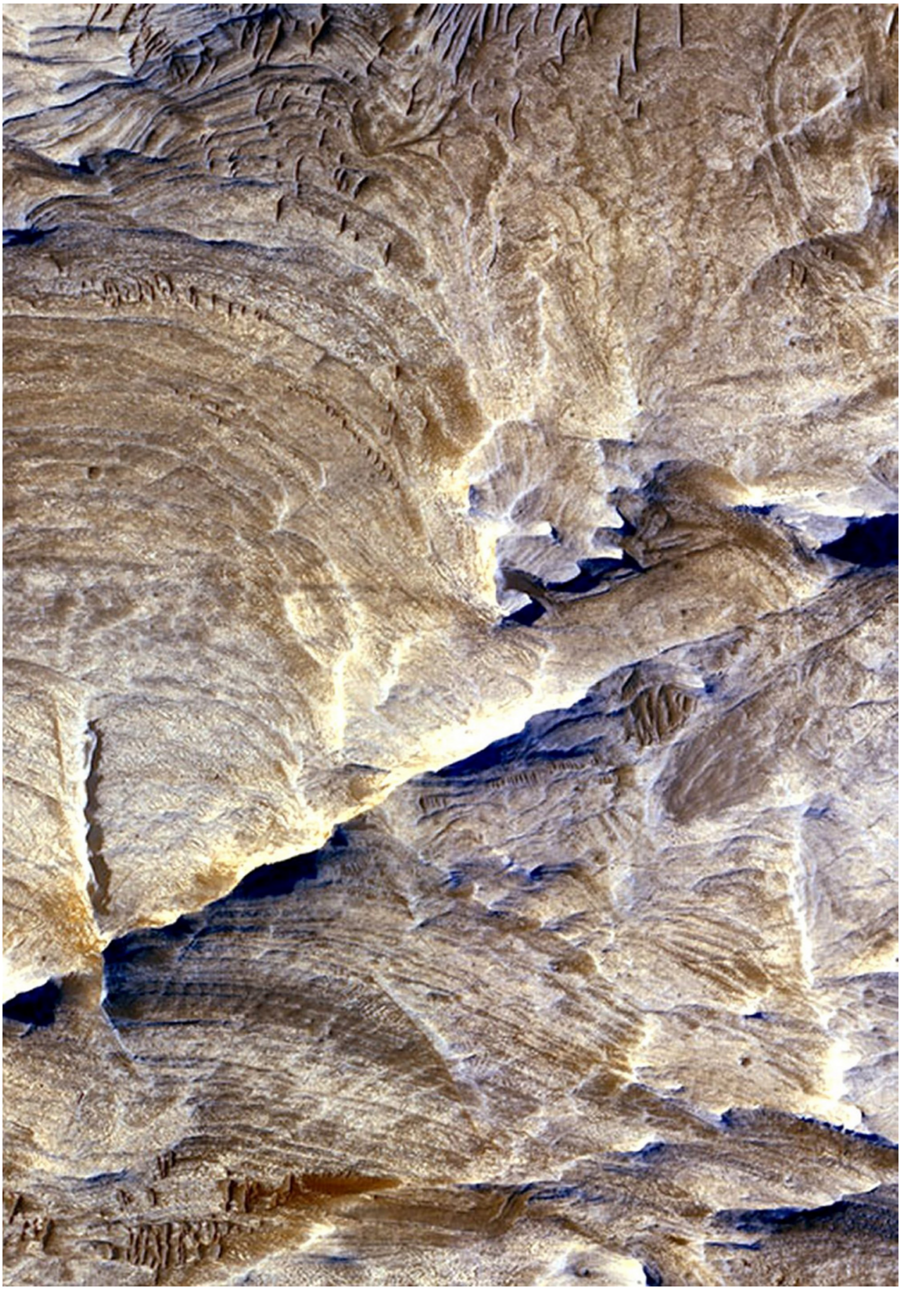

Figure 73: Sedimentary deposits in Candor Chasma examined by MRO's HiRISE and CRISM reveal ancient fluid flows through cracks in the rocks on the sub-meter level, suggesting a possible ancient hydrothermal site as habitats for microbial life. See Plate 39 in the color section. [Credit: NASA/JPL-Caltech/Univ. of Arizona]

MARSIS can probe to a depth of 5 kilometers and has a vertical resolution of 100 meters, MRO's SHARAD radio sounder will probe to a depth of just 1 kilometer but with a vertical resolution of 10 meters. With both instruments working in tandem, the subsurface structure of the planet can be probed in excellent detail, revealing whether underground reservoirs of water reside there today. Here again results already relayed back reveal a layered structure to Mars' southern ice cap that suggests past climate change and clearly defines the boundary between the underlying Martian surface and the ice cap above (Figure 74).

MRO will also conduct a number of other studies of the planet-atmospheric radio sounding to determine the three-dimensional structure of the atmosphere, seasonal and yearly climate monitoring, and a color full-planet imager providing daily planetary weather reports. Subsequent to its two-year primary science mission, MRO will enter a unique second two-year *relay mode* phase of operations, specifically designed to test a range of new technologies and help with the precision landing requirements of Phoenix, the Mars Science Laboratory, and ExoMars. Through its unique UFH communications facility called Electra, MRO will communicate with and guide all future spacecraft when approaching the planet, allowing them to accurately determine their celestial coordinates and trajectory. Similarly, landers and rovers on the surface will use Electra to better determine their position. A technology demonstration optical-navigation-camera will

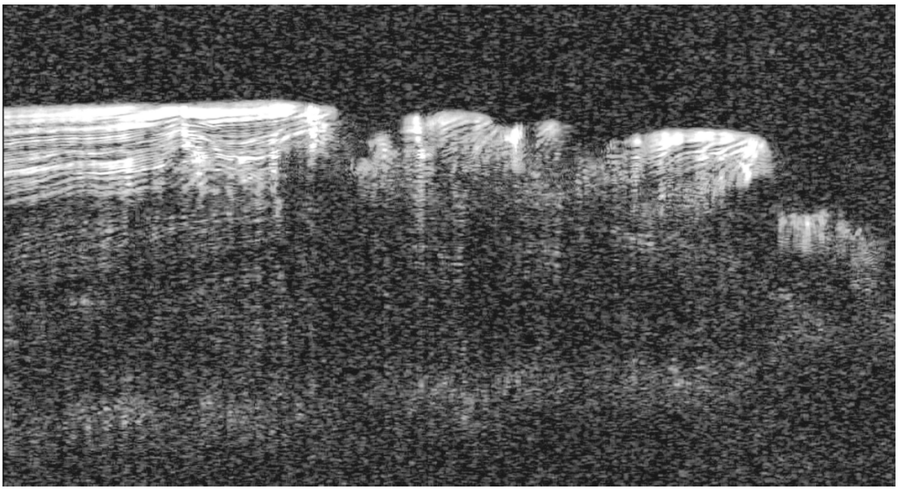

Figure 74: MRO/SHARAD radio 'sounding 'image' subsurface section of Mars' northern polar cap. The ice cap is approximately 2,000 meters deep, with horizontal layers in the upper 600 meters (brighter) of the ice cap suggesting cycles of climate change. [Credit: NASA/JPL-Caltech/ASI/University of Rome/Washington University in St. Louis]

accurately track the position of Mars' two satellites Phobos and Deimos, comparing their predicted positions with actual positions and hence provide improved navigation data. Finally, MRO will test a new mode of communications with Earth called Ka-Band Communications which demands less power than traditional X-band communications.

Combined, all four reconnaissance orbiters have radically altered our understanding of Mars, revealing it to be a complex world where significant volatile and water activity occurred both in its earliest history and episodically over billions of years. Our understanding is far from complete, but the picture emerging is of a planet with a vibrant ancient past in ways perhaps relevant to understanding the early history of our own planet and the emergence of life.