by Michael H. Carr, Ruslan O. Kuzmin, and Philippe L. Masson

Geology of Mars

Mars has had a diverse geologic history. An ancient, heavily cratered surface preserves evidence of events of the planet's earliest history. Volcanic activity has continued until the recent geologic past and has resulted in the formation of huge shield volcanoes and extensive lava plains. Most of the volcanic activity was concentrated in Elysium and in the much larger Tharsis region, which is at the center of a 4,000-km-diameter, 10-km-high bulge on the planet's surface. Arrayed around the bulge are radial fractures that may be largely responsible for the immense canyons on the east flank of the bulge.

Massive floods have erupted periodically onto the surface of the planet, and most of the oldest surfaces are dissected by networks of branching valleys. The networks seemingly were formed by the slow erosion of running water and suggest warmer climates in the past. Evidence for ground ice is common at high latitudes. Although wind-deposited materials are common, the cumulative effect of wind erosion is small. The lack of plate tectonics and the ineffectiveness of wind, water, and ice in reducing relief have led both to the production of features of enormous size compared to those on Earth and to their nearly perfect preservation.

Introduction

Mars, the fourth planet from the Sun, has long been of special interest among the planets because of the potential for eventual human exploration and the possibility of indigenous life. The modern era of Mars exploration started on July 16, 1965, when the Mariner 4 spacecraft flew by the planet. Since that time, the USA and the USSR have sent numerous fly-bys, orbiters, and landers to Mars, the latest being the Viking orbiters and landers, which operated at the planet between 1976 and 1980, and the Soviet Phobos 2 spacecraft, which went into orbit around the planet in 1989. As a result of these missions, we have photographed from orbit almost all the surface at a resolution of 200 m/pixel and small fractions of the surface at resolutions as low as 8 m/pixel. In addition, we have closeup views of the surface and direct chemical measurements at the two Viking landing sites. The various missions have revealed a geologically diverse planet that has huge volcanoes, enormous canyons, extensive dune fields, and numerous channels seemingly eroded by running water (for comprehensive summaries, see Baker, 1982; Carr, 1981). The abundant evidence for water erosion is particularly intriguing as

the present climatic conditions are such that liquid water cannot exist at the surface. Water erosion suggests that the planet may have been warmer in the past and more hospitable to life.

Mars has a diameter of 6,788 km, which is intermediate between that of the Earth (12,756 km) and the Moon (3,476 km). The atmosphere is composed of 95.3 percent CO₂, 2.7 percent N₂, and 1.6 percent argon. The average atmospheric pressure is 7 millibars, but the pressure varies during the year because about 30 percent of the CO₂ in the atmosphere condenses on the winter pole and sublimates back into the atmosphere in summer. Surface temperatures range from 150°K at the winter pole to a daily average of 215°K at the equator. At low latitudes, the diurnal temperatures range from about 170°K to 290°K. Under these conditions, liquid water is unstable everywhere, and the planet has a permafrost zone that is several hundred meters thick at the equator and kilometers thick at the poles. At low latitudes (<40°), water ice is unstable at the surface and at all depths below the surface. It will sublime into the atmosphere at rates that are dependent on the permeability of the overlying rocks. Therefore, near-surface materials at low latitudes should have lost all their unbound water. At latitudes 40–80°, ice is stable at depths greater than about a meter below the surface. At the poles, water ice is stable at the surface and has been detected at the north pole, where it is exposed when the seasonal CO₂ cap sublimates in summer. The atmosphere contains very little water. On average, if all the water were to precipitate out of the atmosphere, it would form a layer only 1 micrometer deep. Nevertheless, the atmosphere is close to saturation for nighttime temperatures, and water-ice clouds are common. The opacity of the atmosphere varies considerably. During southern summers, dust storms are common; some reach global proportions and effectively obscure the surface from view for several months.

We have closeup views of the surface only at the two Viking landing sites. The Viking 1 lander is located at 22.5° N., 48° W. in a sparsely cratered area that has wrinkle ridges and, from the orbiter, looks like a lunar mare. The surface has a rolling topography and is strewn with rocks in the centimeter to meter size range. On and between the rocks is fine-grained material, which also is present as drifts ranging in size up to 10 m across. The surface of the drift material is partly cemented to form a duricrust, which indicates that the more volatile and soluble components have migrated within the soil profile. Several small areas, seemingly free of the drift material, appear to be bedrock exposures. Although volcanic, the blocks probably have been ejected from impact craters. They are more common than on lunar maria partly because the atmosphere protects the surface from the erosive effects of micrometeorite bombardment. The second Viking lander is located at 48° N., 225.6° W., seemingly on a debris flow from a large impact crater, Mie, 170 km to the east. The view from the lander shows a flat plain that is almost featureless except for numerous rocks, mostly in the 10–20 cm size range, that are distributed uniformly over the entire scene.

Highlands and plains

The surface of Mars can be divided into two main components: ancient cratered highlands, covering most of the southern hemisphere, and low-lying plains, which are mostly at high northern

Figure 1.—Impact craters, fractures, and volcanoes in Tharsis. Ejecta around the 30-km-diameter impact crater at the bottom of the picture is arrayed in lobes, each of which is outlined by a low ridge, as is typical of impact craters on Mars. The grabens in the upper left are formed by faults that are radial to the Tharsis bulge. Numerous small channels on the surface of the volcano Ceraunius Tholus, to the right, suggest an easily erodible, ash-covered surface.

latitudes. Superimposed on these two components are the high-standing volcanic provinces of Tharsis and Elysium.

The cratered highlands cover almost two-thirds of the planet. They are mostly at altitudes of 1–3 km above the datum, in contrast to the northern plains, which are mostly 1–2 km below the datum. The cause of the division between the highlands and plains is unclear, but it may be the result of a very large impact at the end of accretion (Wilhelms and Squyres, 1984). The density of impact craters in the martian highlands is comparable to that of the lunar highlands. The surface clearly dates back to the very earliest history of the planet when impact rates were high. On the Moon, the transition from very high impact rates to rates comparable to the present took place at about 3.8 Giga-annum, and the transition probably took place at the same time on Mars. The martian highlands differ from the lunar highlands in three main ways. The first difference is that sparsely cratered plains are more common between the larger craters in the martian highlands. These plains may be volcanic, as indicated by the presence in a few places of flow fronts and wrinkle ridges that resemble those on the lunar maria. On the other hand, many of the plains could be of impact or sedimentary origin. The second difference between the lunar and martian highlands concerns the impact ejecta. The ejecta around lunar craters generally

has a coarse, hummocky texture at the rim crest and grades outward into a finer, randomly hummocky or radial texture. On Mars, the ejecta around craters 5–100 km in diameter is arrayed commonly in discrete lobes, each lobe being outlined by a low ridge (fig. 1). This is true of almost all martian impact craters in this size range, irrespective of location. Two reasons have been suggested for the characteristic martian ejecta patterns. The first suggestion is that impact craters above a certain size penetrate the permafrost zone and eject water-laden, or ice-laden, materials that tend to flow across the surface following ejection from the crater (Carr and others, 1977). The second suggestion, based on wind-tunnel experiments, is that the interaction between the ejecta and the atmosphere causes the flowlike patterns (Schultz and Gault, 1984). The third difference between the lunar and martian highlands is the presence, within the martian highlands, of numerous networks of branching valleys. At low latitudes, these are almost everywhere within the highlands. They superficially resemble terrestrial river valleys and are believed to be formed by running water. They will be discussed more fully below in the section on “Water Erosion.”

The plains are located mostly in the northern hemisphere. The number of craters superimposed on them varies substantially and indicates that they continued to form throughout the history of the

planet. The plains are diverse in origin. The most unambiguous in origin are those on which numerous flow fronts are visible. They clearly formed from lava flows superimposed one on another, and they are most common around the volcanic centers of Tharsis and Elysium. On other plains, such as Lunae Planum, flows are rare, but wrinkle ridges like those on the Moon are common. These also are assumed to be volcanic. However, the vast majority of the low-lying northern plains lack obvious volcanic features. Instead, they are curiously textured and fractured. Many of their characteristics have been attributed to the action of ground ice or to their location at the ends of large flood features, where lakes must have formed and sediments must have been deposited. In some areas, particularly around the north pole, dune fields are visible. In yet other areas are features that have been attributed to the interaction of volcanism and ground ice. Thus, the plains appear to be complex in origin; they formed variously by volcanism and different forms of sedimentation and then subsequently were modified by tectonism and by wind, water, and ice.

Volcanism

The most prominent volcanoes are in two regions, Tharsis and Elysium. Tharsis is at the center of a bulge in the planet's surface, the bulge being over 4,000 km across and 10 km high at the center. A similar bulge centered on Elysium is about 2,000 km across and 5 km high. Three large volcanoes are close to the summit of the bulge, and Olympus Mons, the tallest volcano on the planet, is on the northwest flank. All these volcanoes are enormous by terrestrial standards. Olympus Mons is 550 km across and 27 km high, and the three others have comparable dimensions. Lava flows and lava channels are clearly visible on their flanks, and each has a large, complex summit caldera. They all appear to have formed by the eruption of fluid lava with very little pyroclastic activity. The large size of the volcanoes has been attributed to the lack of plate tectonics on Mars and to the greater depths of their magma source, as compared to the depths for terrestrial volcanoes (Carr, 1973). The small number of superimposed impact craters on their flanks indicates that their surfaces are relatively young, although the volcanoes may have been growing throughout much of Mars' history. To the north of Tharsis is Alba Patera, the largest volcano in areal extent on the planet. It is roughly 1,500 km across but only a few kilometers high. Flows are visible on parts of its flank, but elsewhere, the volcano flanks are dissected by numerous branching channels. The easily eroded, channelled deposits have been interpreted as ash (Wilson and Mouginis-Mark, 1987). Densely dissected deposits on other volcanoes such as Ceraunius Tholus in Tharsis (fig. 1), Hecates Tholus in Elysium, and Tyrrhena Patera in the southern highlands also have been interpreted as ash. Thus, Mars seems to have experienced both the Hawaiian style of volcanism, involving the effusion of fluid lava, and more violent, pyroclastic eruptions, which have resulted in the deposition of extensive ash deposits.

Elysium Mons appears to be a shield volcano that formed largely from fluid lava (fig. 2). However, huge channels start at the periphery of the volcano and extend northward down the regional slope for hundreds of kilometers. The channels have streamlined forms and enclose teardrop-shaped islands. Similar large channels start adjacent to Hadriaca Patera on the rim of the large impact basin Hellas. They start at the volcano and extend for hundreds of kilometers down into the Hellas basin. All these channels show characteristics that result from large floods. They are thought to have formed by the massive release of water following melting of ground ice by the volcanoes. Numerous other features in the Elysium area and

elsewhere also have been interpreted to be the result of volcano-ice interactions (Squyres and others, 1987).

Tectonism

The most widespread indicators of surface deformation are normal faults, indicating extension, and wrinkle ridges, indicating compression. The most obvious deformational features are those associated with the Tharsis bulge. Around the bulge is a vast system of radial grabens (fig. 1) that affect about one-third of the planet's surface. The grabens are particularly prominent north of Tharsis, where many are diverted around the volcano Alba Patera and form a fracture ring. Circumferential wrinkle ridges also are present in places, particularly on the east side of the bulge in Lunae Planum. Both the fractures and the compressional ridges are believed to be the result of stresses caused in the lithosphere by the presence of the Tharsis bulge. No comparably extensive system of deformational features occurs around Elysium, but fractures are located in other places where the crust has been differentially loaded, as around large impact basins, such as Hellas and Isidis, and around large volcanoes, such as Elysium Mons (fig. 2) and Pavonis Mons.

The vast canyons on the east flanks of the Tharsis bulge are the most spectacular result of crustal deformation. The canyons extend from the summit of the Tharsis bulge eastward for 4,000 km, where they merge with the chaotic terrain and large channels south of the Chryse basin. In the central section, where several canyons merge, they form a depression that is 600 km across and several kilometers deep. Although the origin of the canyons is poorly understood, faulting clearly played a major role (Masson, 1977, 1985). The canyons are aligned along the Tharsis radial faults, and many of the canyon walls are straight cliffs or have triangularly faceted spurs, which clearly indicate faulting (fig. 3). In one location, a large impact crater is present on the canyon floor, as though the floor were a downfaulted section of the surrounding surface. Other processes also were involved in shaping the canyons. Parts of the walls have collapsed in huge landslides; other sections of the walls are deeply gullied. Fluvial sculpture is particularly common in the eastern sections. Faulting may have created most of the initial relief, and then the relief enabled other processes, such as mass wasting and fluvial action, to take place. Creation of massive fault scarps also may have exposed aquifers in the canyon walls and allowed ground water to leak into the canyons and thereby form temporary lakes.

Water erosion

One of the most puzzling aspects of martian geology is the role that water has played in the evolution of the planet. We have seen that liquid water is unstable at the surface under present climatic conditions, yet we see abundant evidence of water erosion. The most intriguing features are large, dry valleys, interpreted as having formed by large floods. Many of the valleys start in areas of what has been termed "chaotic terrain," in which the ground seemingly has collapsed to form a surface of jostled and tilted blocks that are 1–2 km below the surrounding terrain. The areas of chaotic terrain range in size up to several hundred kilometers across. The largest areas are in the Margaritifer Sinus region east of the canyons and south of the Chryse basin (fig. 4). In this area, large, dry valleys emerge from the chaotic terrain and extend northward down the regional slope for over 1,000 km. Several large channels to the north and east of the canyons converge on the Chryse basin and then continue farther north, where

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Figure 2.—In the upper right, the large volcano, Elysium Mons, with a 12-km-diameter central caldera, is surrounded by circular fractures that were caused by the flexure of the lithosphere under the weight of the volcano. At the upper left, several large channels start in grabens and extend northward, off the picture, for several hundred kilometers.

they merge into the low-lying northern plains. The valleys emerge full-size and have few, if any, tributaries. They have streamlined walls and scoured floors, and they commonly contain teardrop-shaped islands. All these characteristics suggest that they are the result of large floods, rather than the result of slow erosion by running water. Although most of the flood channels are around the Chryse basin, they are found elsewhere. Those near Elysium and Hellas have been mentioned already, and others occur in Memnonia and western Amazonis. Impact craters superimposed on the flood channels suggest that they have a wide range of ages.

The floods were enormous. The largest known terrestrial floods are those that cut the channeled scablands in eastern Washington State in the USA in the late Pleistocene. These are estimated to have had peak discharges of about 10^7 cubic meters per second (m^3/s), as compared with the average discharge of $10^5 \text{ m}^3/\text{s}$ for the USA's Mississippi River today. Discharges for the martian floods are estimated to have been as high as $10^9 \text{ m}^3/\text{s}$ (Baker, 1982). The amount of water that flowed through the channels around the Chryse basin is estimated to be the equivalent of 45 m spread over the whole planet (Carr and others, 1987). The cause of the large floods is unclear, and they may not all be of the same origin. We already have seen that the floods in Elysium and Hellas were, in some way, connected with volcanism. Volcanism may have resulted in the melting of ground ice, the migration of ground water beneath the permafrost, and ultimately, the catastrophic breakout of water. Similarly, volcanism in Tharsis may have resulted in the outward migration of ground

water to the lower lying regions around the edge of the Tharsis bulge, where repeated breakouts took place. Sediments within the large equatorial canyons suggest that the canyons contained lakes at one time, probably as a result of ground-water flow out from under the surrounding plateau. Catastrophic release of water from these lakes may have caused some of the large channels that connect with the canyons to the east. After the floods were over, large lakes must have been left at the ends of the channels. The fate of this water would have depended on the latitude of the lakes. Many of the Chryse channels and those in Elysium and Hellas end at high latitudes. If climatic conditions then were similar to present conditions, these lakes would have frozen and possibly formed permanent ice deposits, which may account for some of the peculiarities of the low-lying, high-latitude plains. Other channels, such as Mangala Vallis, end at low latitudes. In these cases, the water in the terminal lakes would have frozen and then sublimed into the atmosphere, to be frozen out ultimately at the poles.

Other fluvial features appear to be the result of slow erosion by running water (fig. 5). Networks of branching valleys are found throughout the heavily cratered terrain and in a few places on younger surfaces. They resemble terrestrial river valleys in that they have tributaries and increase in size downstream, although only rarely can a channel be observed within the valley. The valleys generally are short compared with terrestrial river systems, most being less than a few hundred kilometers in length, so rarely does one valley system dominate the drainage over a large area. The most

Figure 5.—Branching-valley networks in Thaumasia. An ancient cratered surface has been dissected by a dense network of valleys, which suggests slow erosion by running water. The large crater at the bottom of the picture is 50 km across.

plausible explanation for the valleys is that they formed by the slow erosion of running water. The open nature of some networks, the alcovelike terminations of tributaries, and the range of junction angles between branches all suggest ground-water sapping (Pieri, 1980). Other networks, however, lack these characteristics and more resemble valleys formed by surface runoff.

The origin of the valley networks is controversial. Their branching pattern and small size indicate that they were formed by the slow erosion of running water, but the precise mode of formation and the climatic conditions required are both unknown. Under present climatic conditions, small streams on Mars would freeze rapidly so that the source of water for the larger rivers downstream would be cut off. Most of the valley networks are in the cratered highlands, the oldest part of the planet's surface. The valley networks suggest, therefore, that early Mars was much warmer than now, and liquid water could flow across the surface. Greenhouse calculations indicate that, in order for surface temperatures on Mars to be above freezing, a CO₂

atmosphere of 1–3 bars thick is required (Pollack, 1979). If such a thick atmosphere were present, it would be inherently unstable because the CO₂ would react with the surface rocks in the presence of liquid water and would form carbonates. It has been suggested, therefore, that Mars had an early, thick atmosphere that kept Mars warm, but that early in the planet's history, this atmosphere largely dissipated as a result of carbonate formation, and the planet assumed today's cold, hostile conditions. This simple model is questionable, however, in view of the presence of younger valley networks, such as those on the volcano Alba Patera. Some of these younger valleys have been attributed to local hydrothermal recycling of water, but Baker and others (1991) claim that the younger valleys are also the result of climate change. They think that Mars has experienced repeated, massive changes in global climates and that these changes were triggered by the large floods. Another problem is that massive carbonate deposits have not been detected. If the valley networks are the result of global climate change, then the 1–3 bars of CO₂ should

Figure 6.—Debris flows at 45° N., 330° W. High-standing outliers of highlands are surrounded completely by debris flows that extend about 20 km away from the bases of the cliffs. Movement of the debris is believed to have been aided by the presence of ice in the flows. The scene is 200 km across.

be in carbonate deposits younger than the valley networks themselves, but remote sensing has failed to reveal them.

Ground ice

Several features of the martian surface are explained most plausibly as resulting from the presence of ground ice (Kuzmin, 1983; Lucchitta, 1981). We have seen that ice is unstable at all depths below the surface at low latitudes, but it is stable at depths deeper than a few meters at high latitudes. Although ice is unstable at low latitudes, it may be found at depths of a few meters to several hundred meters because of the slow rate of diffusion of water vapor away from the ice, through the overlying materials, into the atmosphere. Kuzmin (1980) attempted to measure the depth to the top of the ground-ice layer by studying the morphology of impact craters, on the assumption that petallike ejecta patterns were due to the presence of ground ice or ground water. He found that, in any given region, the petallike patterns were only around craters larger than a certain minimum size. The size decreased from 6–8 km in diameter at the equator to 2–4 km at 40° latitude. From this, he inferred that ice is

common at depths greater than about 300 m at the equator and at depths greater than about 100 m at 40° latitude.

Debris flows also may indicate the presence of ground ice. In the 35–50°-latitude band in both hemispheres, debris flows commonly are seen at the bases of cliffs (fig. 6). These are convex-upward flows that extend about 20 km away from the bases of the cliffs. Such features are rare, if present at all, at low latitudes. The simplest explanation is that at low latitudes where cliffs form, talus simply accumulates on the cliff slope and so inhibits further erosion. At high latitudes, however, because of the presence of ground ice, ice becomes incorporated in the talus and thereby enables the talus to flow away from the cliff, which exposes the slope to further erosion. Debris flows are particularly common in regions of what has been termed “fretted terrain,” in which flat-floored valleys, filled with debris flows, extend from low-lying plains far into the cratered uplands. The formation of these valleys appears to be connected in some way with the formation of the debris flows. A general softening of the terrain at high latitudes also has been attributed to ground ice. At low latitudes, many features, such as crater-rim crests, are crisply preserved, whereas poleward of about 40° latitude, similar features are rounded or softened in appearance. Squyres and Carr (1986) attributed the general softening at high latitudes to ice-abetted creep of the near-surface materials.

Figure 7.—Layered terrain at the north pole. The upper surface of the terrain is almost free of impact craters, which suggests a young age. The layers are clearly visible on the walls of valleys that are cut into the terrain. The image is 50 km across.

Poles

At each pole, and extending outward to about the 80°-latitude circle, is a thick stack of layered sediments (fig. 7). The sediments are at least 1–2 km thick in the north and at least 4–6 km thick in the south. Incised into the smooth, upper surface of the deposits are numerous valleys and low escarpments. These curl out from the pole in a counterclockwise direction in the north and in a predominantly clockwise direction in the south. Between the valleys, which are roughly equally spaced and 50 km apart, the surface of the deposits is very smooth and almost free of craters. For most of the year, the layered deposits are covered with CO₂ frost, but in summer, they become partly defrosted. The layering is seen best as a finely layered, horizontal banding on defrosted slopes. The deposits are believed to be composed of dust and ice and the layering to be caused by different proportions of the two components. The scarcity of impact craters indicates a relatively young age, although the age of the deposits could still be on the order of hundreds of millions of years.

The layering suggests cyclic sedimentation, and the origin of the deposits may be connected in some way with the obliquity cycle. The obliquity is the angle between the equatorial plane of a planet and the

orbital plane. The obliquity of Mars oscillates between roughly 15° and 35° on a 1.2-million-year cycle. At the highest obliquity, twice as much insolation falls on the poles as at the lowest obliquity. As a consequence, the capacity of the high-latitude regolith to hold adsorbed CO₂, the size of the CO₂ cap, and the atmospheric pressure all may change as the obliquity changes. These changes could affect global wind regimes, dust storm activity, and sedimentation rates at the poles and thereby cause cyclic sedimentation. Layering also would be caused by any event that resulted in large amounts of water vapor's being introduced into the atmosphere. Such possible events are volcanic eruptions, large floods, and cometary impacts. These all would result in the deposition of an ice-rich layer at the poles.

Conclusions

Mars, like the Earth, has had a diverse geologic history. An ancient, heavily cratered surface preserves evidence of events in the planet's earliest history. Volcanic activity has continued throughout the planet's history, possibly to the present, and has resulted in the formation of extensive lava plains and large shield volcanoes. Most

volcanic activity has been in two provinces, Tharsis and Elysium, which are at the centers of large bulges in the planet's surface. The Tharsis bulge caused fracturing over about one-third of the planet's surface, and this fracturing may be largely responsible for the formation of enormous canyons down the east flank of the bulge. Massive floods of water have flowed periodically across the surface, and some of these may have been triggered somehow by volcanism. In addition, dissection of some surfaces by networks of small branching valleys, particularly in the ancient cratered highlands, indicates slow erosion by running water and possibly massive, global climate changes. The morphology of impact craters and the presence of numerous features suggesting ground ice together indicate that ground ice is abundant at shallow depths at high latitudes and at greater depths at low latitudes. Thus, Mars is a planet on which most of the geologic processes familiar to us here on Earth have operated. The two planets are, however, very different. The lack of plate tectonics on Mars has led to greater stability of the surface and to the development of enormous volcanoes and canyons. In addition, the ineffectiveness of water erosion in eliminating topographic relief has led to the almost perfect preservation of features widely ranging in age. Despite the excellent photographic coverage and nearly perfect preservation, the origin of many of the features remains obscure. We look forward to Mars Observer, Mars 94, and Mars 96 to help us unlock more of the planet's secrets.

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Michael H. Carr is a Geologist with the U.S. Geological Survey in Menlo Park, California. Since joining the Mariner 9 imaging team in 1970, he has worked on various martian problems including the planet's volcanic history, the origin of its channels and valleys, climate change, and the global inventory of water. As the leader of the Viking orbiter imaging team, he supervised the acquisition of over 55,000 pictures of the planet and coordinated their initial interpretation. He summarized the early Viking results in a widely used book entitled "The Surface of Mars."

Dr. R.O. Kuzmin is Senior Scientist of the Laboratory of Comparative Planetology and Meteoritics at the Vernadsky Institute, Russian Academy of Sciences, Moscow. His research interests have included the nature of permafrost on Mars and the geomorphic effects of fluvial-glacial processes on the martian surface. The study and selection of potential landing sites for different types of landers for the future Russian Mars 94 and Mars 96 missions have been important objectives of Dr. Kuzmin's work during last 2 years. He is a member of the USA-Russia Joint Working Group for selection of Mars landing sites and is updating the engineering model of the martian surface. Dr. Kuzmin is a participating scientist on the Thermal Emission Spectroscopy team on the Mars Observer mission and is a co-investigator on the TERMOSCAN and camera experiments on the Mars 94 mission.

Dr. Philippe L. Masson is a Professor of the Université Paris-Sud (Orsay, France), where he has been Chairman of the Department of Earth Sciences since 1991. He graduated from this department in 1973 and received his doctorate from the same university by studying comparative planetary geology and structural geology. In 1974, he joined the U.S. National Aeronautics and Space Administration's Planetary Geology Program, and over the last 19 years, his research interests have focused on the geologic evolution of the terrestrial planets and the exploration of the solar system.