Dryden Lectureship in Research

Mars and the Remarkable Viking Results

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Introduction

THE Viking missions to Mars are the most extraordinary and complex remote effort ever performed by man. Four robots sent to Mars in 1975, several hundred million kilometers away, have continued to operate since their arrival in the summer of 1976 – taking pictures, recording spectroscopic and thermal data, following the Martian seasonal events, and performing chemical and biological analysis on samples of the surface. This triumphant achievement has become so routine and accepted that a major planetary event such as a global Martian dust storm or the first discovery of winter frost on the plains of Mars no longer draws a national press conference or is seen on the popular nightly news. The Vikings have snatched Mars from the romantic imagination of science fiction and psycho thrillers and placed it where it belongs in a technological society – into the scientific literature to join the rest of science. Mars is a planet in many ways like the Earth, while the atmosphere and surface are somewhat different from ours. Aside from the biological influence, its atmosphere has the same components as ours and its surface is made of elements quite common on Earth. There are no present-day oceans, lakes, or rivers and haven't been for millions of years, but signs of past flowing water are prominent. The question of life is enigmatic, but most biologists believe that if there is life on Mars it is either confined to some very local regions, e.g. polar, or is at an extremely low level of population; that it is somehow able to maintain an existence without developing the lavish abundance characteristic of the Earth. In any event, most scientists believe that Viking has not detected life and recognize that we have performed only a relatively simple experiment for the first time, and the profundity of the biological question will demand far more complex exploration for any credibly more definitive answer.

What made the Viking results so remarkable? Mainly three things: the technological engineering accomplishment, the voluminous scientific data about the planet, and the public interest. Each of these is both noteworthy and praiseworthy inasmuch as this is the first time a spacecraft has been successfully landed on Mars and has returned useful scientific data.

During the summer and fall of 1976 there were hundreds of newspaper and magazine articles, dozens of television reports and specials, numerous editorials and cartoons. Three complete editions of *Science*[1-3] were devoted to the Viking results. The *Journal of Geophysical Research*[4] had a special series on Viking. The reduction in the popular appeal is the normal course of events in our society. The public is bombarded with information about new discoveries, world affairs, local problems, new products, and social behavior. It was indeed remarkable that the Viking missions commanded the public interest for almost five months during the bicentennial and an election year. NASA has acknowledged that not since the Apollo missions has the public interest risen to the height as it did with Viking.

Engineering Achievements

The Viking Project is a NASA effort of the Office of Space Science, managed since its beginning in 1968 by the Langley Research Center. The goal was to land two spacecraft on Mars in order to increase man's knowledge about the planet; special emphasis was placed on the search for life on Mars. The initial goal was to use the 1974 Mars-Earth encounter, but fiscal replanning resulted in a delay until the 1976 encounter.

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The Soviets had also been planning Mars missions during this period. Their design consisted of separate Landers and Orbiters. They did not succeed in landing and carrying out their mission. From the outset, the two NASA spacecraft were designed to be identical, each consisting of an Orbiter and a soft Lander. The plan was to place the Orbiter/Lander into an orbit about Mars, to certify the landing site, and to release the Lander which would go through several braking steps for the soft landing on the surface. The experiments were to be conducted over the following several weeks and data returned to Earth. The launch vehicle selected was the Titan Centaur, a new combination that limited the weight to about 8000 pounds and the overall diameter to about 14 feet. The management goal of Viking was one of maximizing the scientific return while minimizing the risk and living within the constraints of money, time, weight, power, data, and the usual "politics." One new problem added was that of spacecraft sterilization. Because of the possibility of causing planetary contamination, and also because of the onboard life detection experiment, there was a requirement levied on the project to sterilize the entire Lander and all parts of the spacecraft that might land on the surface. The method selected was dry heat. The Lander, within its bioshield, and all of its components were placed in an oven at 113° C for 40 hours. The encapsulated Lander was not opened until after the launch; hence no repairs or last-minute adjustments after sterilization were possible.

The teams that were responsible cut across all of NASA's Centers, other Government agencies, industries, and the universities. The Martin-Marietta Corporation was responsible for building the Lander and integrating the spacecraft. Jet Propulsion Laboratory built the Orbiter and maintained the data and tracking system. Lewis Research Center provided the launch vehicle, Kennedy Space Center carried out the launch. Johnson Space Center, Ames Research Center, and Goddard Space Flight Center each provided incalculable technical assistance. Project management from conception to mission operation has been Langley Research Center's responsibility.

The 13 scientific teams were assembled by NASA Headquarters, each team in charge of a different experiment. These teams, consisting of 71 scientists, became an integral part of the project and reported through the project scientist to the project manager. The project, with the collaboration of the science teams, was responsible for conducting the experiments and publishing the data.

At the outset a "Mission Definition" was established which was periodically reviewed and revised. It was the single guiding document that described the experiments. It spelled out the quantity and quality of the data to be obtained and the error limits and frequency of the measurements. It became the central focal point for all requirements and compromises.

Planning was done in 1970-72. The hardware design was initiated in 1972, built and tested in 1973, integrated into the spacecraft in 1974, launched in 1975, and will be used through 1978. Some components have been used for as much as 10 times their design lifetimes. In general there was a policy established early to avoid any single-point failure. Through redundancy and clever design this policy was carried out strictly and has proved to be largely responsible for the endurance of the four spacecraft over the years.

Mars was by far the most difficult problem. Aside from some general knowledge about the celestial mechanics and some physical limitations, little was known about the planet at the outset. With the success of the Mariners, knowledge of the surface grew enormously, but some of the more important parameters for landing, such as the profile of the atmospheric components, its density, and the nature of the surface, were largely conjecture until the moment of the Viking 1 touchdown.

In order to design a single set of parameters, a "Mars Engineering Model" was developed which set the boundaries for design. It prescribed the atmospheric envelope, the variety of possible surfaces, range of textures, radiation environment, etc. This working manual was constantly reviewed by all the scientists both within and outside of the project and used by all engineers for their particular subsystem. The Mars Engineering Model was an excellent crossroads for scientists and engineers at the working level. Together with the Mission Definition, this truly spelled out what the project was trying to do and the planetary constraints anticipated.

The overall design of the mission was to launch two spacecraft to orbit and land in the summer of 1976. The first would arrive as early as possible and be injected into an eliptical orbit around Mars. The period of the orbit selected was equal to one Martian day, so that the periapsis point would be over the candidate landing site which was selected prior to launch. The periapsis distance was kept to 1500 km as a result of the planetary quarantine requirements, to keep from inadvertantly crashing unsterilized components on the Martian surface. The certification of the landing site as "safe" would be carried out by two high-resolution TV cameras, a spectrometer, and a radiometer on board the Orbiter. The Lander would be released from the Orbiter, slowed first by an aeroshell, then by a high-velocity parachute, and lastly by terminal retro-rockets to permit the soft landing. Data were taken on the descent phase and stored on board the Lander, as well as transmitted directly to Earth via the Orbiter. Upon landing a camera was immediately activated and the first data from the surface were sent back to Earth via the Orbiter, which provided the relay link. The second spacecraft was to arrive considerably later in order to maximize the reaction time, should there have been a failure on Viking 1. It was slated to land at a different site and to perform the same experiments.

Three comments about time.

One, the time for the telemetry roundtrip was about 40 minutes. This meant that every command sent up and played back for verification was delayed. Unlike the Moon, there is no way of operating in near-real time between Mars and Earth. The time from deciding on a command, developing the sequence, checking it, and carrying it out is up to 2 weeks. During critical times involving the health of the spacecraft, it could be done in 24 hours.

Another temporal aspect of Mars is the season. Viking arrived at Mars at the beginning of Martian summer in the northern hemisphere and at aphelion. This was very fortunate since global Martian dust storms have been recorded during every perihelion, and a noteable one was observed during the Mariner 1971-72 encounter. The surface was seen very clearly when Viking arrived. Several months later the surface was so obscured by a global dust storm that even prominent features a hundred kilometers in size were obscured.

Lastly, a celestial event that was known to effect the mission was superior solar conjunction, which prevented transmission of data to Earth from mid-November to mid-December. While this was a welcome rest period for mission control, it meant loss of some data and the likely chance that the spacecraft would not survive the long period of silence.

After considerable study of Mariner and ground-based data, both candidate sites were selected in the northern hemisphere. Landing safety was an absolute criteria for the Viking 1 site; scientific interest played a larger role in Viking 2. The main constraints on the sites were elevation, roughness, latitudinal boundaries, the accumulation of adequate Mariner data, and the requirement that every candidate site have a backup candidate at the same latitude. Once injected into orbit the spacecraft could be maneuvered to different longitudes by changing the period; the latitude was essentially fixed. The first site selected was at 20° N latitude in a low valley to the east of the largest volcanic field. The candidate site for Viking 2 was selected primarily for its biological interest in a more northerly region up at 45° N latitude where it was expected that more water might be found.

The design of the Orbiter was patterned after the Mariner series. It is a solar-powered, three-axis-stabilized vehicle with a large propulsion capability for placing itself and the attached Lander into a Mars orbit. There is sufficient fuel for additional maneuvers, such as changing the period, orbit inclination, or lowering and raising the periapsis. A computer and data processor deal with signals and commands sent via a two-way communication system to the Earth. Another receiver is used to obtain data from the Landers. Attached to the Orbiter is a scanning platform that can be pointed towards the planet, its satellites, or to space. Three scientific instruments sighted along a common axis are mounted on the scanning platform so that the area covered is the same. One instrument is a pair of TV cameras, mounted side by side, that take high-resolution pictures. The pictures are taken consecutively so that the motion of the spacecraft results in a swath of pictures several hundred kilometers long and two pictures wide (40 km at periapsis). The cameras can take color pictures as well as black and white. The second instrument is an atmospheric water mapper. This is an infrared spectrometer operating at the 1.38-micron band. Since water is a highly variable constituent of the Martian atmosphere, and of enormous biological interest, it played a large role in the selection of the landing sites. The instrument was used for monitoring the site, and the planetary distribution and movement of water during the Mars diurnal and seasonal changes. The third instrument is an infrared thermal radiometer. This is a mapping instrument for determining the surface temperature of a scanned area, used in part to help determine the size of the surface rocks through thermal inertia, and also to measure thermal events and anomalies.

The design of the Lander was based on fresh concepts, with a few ideas borrowed from the lunar landers. The low density of the Martian atmosphere (about one percent that of the Earth's) presents a serious problem during the landing. There is enough atmosphere to overheat a spacecraft during entry, but not enough to totally decelerate it. The spacecraft was traveling at 4 km/s at entry. After release from the Orbiter and orientation, rockets were fired to deorbit. The Lander coasted for about 3 hours towards the Martian atmosphere, and at 300 km above the surface it was reoriented for entry. By adjusting the angle of attack, some aerodynamic lift was obtained. The aeroshell with an ablative heat shield was designed to take out most of the kinetic energy and to operate down to 6 km. The descent of the Lander was controlled by a landing radar system that located the surface, and a computer system that commanded the events during descent. Accelerometer data were used to determine the rate of fall and the descent profile. Gyros were used as an inertial reference of orientation. At an altitude of 6 km (descending at 250 m/s) a 16-m-diameter parachute was deployed by a mortar that was fired automatically, and 7 seconds later the aeroshell was jettisoned. The Lander has three retractable legs, each with a footpad. Eight seconds after parachute deployment, these were extended. The parachute operated for 45 seconds and slowed the Lander to 60 m/s. The terminal descent occurred during the last 1.5 km. Three retro-rockets using hydrazine were ignited for the final 40 seconds. The parachute was released and the engines were throttled by a command from the computer, the signals coming from a terminal descent landing radar. The final landing velocity was only a few feet per second (Fig. 1).

The Lander was designed to perform nine different investigations. During the 3-hour descent, a retarding potential analyzer, mass spectrometer, and pressure, temperature, and accelerometer sensors were used consecutively for measuring the atmospheric profiles of structure and chemical composition. The other experiments were to be performed simultaneously or intermittently throughout the mission. Each Lander was planned for a 60-day operation preceding the period of solar conjunction. The most extensive investigation was the imaging experiment. Two fascimile cameras, capable of color or black-and-white pictures were mounted atop the Lander. Each could operate in a complete panoramic mode from sky to foreground, and could be commanded to taken any segment of a picture. They could be used for stereo imaging, and also in a scanning mode for detecting motion. Mounted at 1.5 meters above the surface, they could see out to several kilometers and were focused as close as the footpad. Resolution was a couple of millimeters in the immediate vicinity of the Lander. The cameras were used constantly for verification of mechanical motion of other components, e.g., antenna movement and boom deployment.

Another Lander experiment was a meteorological station consisting of pressure, temperature, windspeed, and wind direction sensors. Due to the interference from the Lander, these sensors were mounted on a deployable arm held about 1 meter from the spacecraft. These atmospheric measurements were made periodically throughout every diurnal cycle for almost 2 years. Also mounted on the external part of the Lander was a three-axis seismometer for recording and measuring Mars quakes. This instrument operates in three modes: the normal mode records four samples per minute on each channel; a high data rate increases the sampling by a factor of five; in the trigger or event mode the sampling rate goes to one per second for each channel. The event mode can be initiated either by command from the Earth or automatically to record seismic events that are transient.

There are three analytical experiments on board the Lander, each requiring small samples from the surface. They are supplied by a scoop at the end of a retractable boom that can reach out to 3 meters away from the spacecraft. The boom can be swung in a 120 deg arc to allow the selection of the specific sample desired. It has been used for pushing rocks aside, and for digging and trenching the surface. Over a dozen samples have been obtained from each of the Mars surface locations. The sampler has withstood the large daily temperature excursions of 150-250 K for many months and is still operating (April 1978).

The most complex of the instruments is the biology experiment. This 40-pound device performs three complex physiological tests for growth, metabolism, and photosyn-

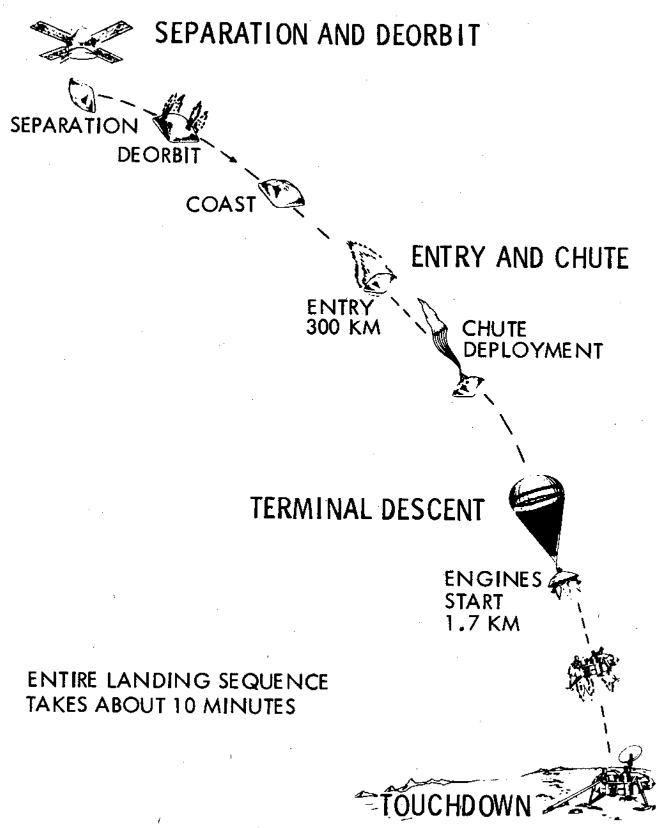

Fig. 1 Viking landing sequence.

thesis. There is no such device available commercially or in developmental laboratories. This instrument required the development of special helium leakproof valves, a long-time-storable biological nutrient system, a highly miniaturized xenon lamp, sterilizable beta radition detectors, storage of radioactive carbon compounds, a sample delivery system, special absorption cohesions, an energy-efficient heating and cooling system, pyrolytic units, and most important, a logic and data system to carry out the complex instructions for each of the steps. An average sequence for biology – the delivery of the sample, opening and closing of valves, turning a light on and off, the delivery of some nutrient, heating and cooling, collecting a gas sample and reading it out – is likely to utilize several hundred command operations for performing one experiment a single time over the several weeks it might take for a biological sequence. It has been commented that the biology instrument is of the same complexity as a small complete spacecraft with several tens of thousands of components, most having to operate perfectly to do one complete experiment. Each spacecraft has carried out about 10 experiments over a 9-month period, one long experiment lasting several months. Special sterilization procedures beyond that required by the rest of the instruments were employed for the biology instrument. Sterile assembly and additional heat cycles were used to assure the absence of terrestrial microbes which could have yielded a false positive result.

A second analytical instrument of extraordinary development history is the gas chromatograph mass spectrometer (GCMS). This chemical analyzer was used to identify organic compounds in the soil and for minor constituents of the Martian atmosphere. The principle here is to volatilize a sample of soil by heating and then to analyze the vapors. This instrument, which does exist in the laboratory, usually occupies a full console with associated heavy pumps, valving racks, attendant chemical equipment, and an operator. The development of the miniaturized GCMS was a study in compactness. Besides the design ingenuity, there had to be a method for separating the bulky carrier gas, pyrolyzer sample ovens, special columns, control and data systems, and a method of processing and introducing a solid sample into a 100-mg heating chamber. A very unique problem of the GCMS was the restrictive use of organic material. Since the sensitivity sought was in the region of a few parts per million of Martian organics, even a small speck of organic paint or elastomer that inadvertantly got into the sample would completely destroy the determination. Special cleaning solvents for the instrument, purification of the retro-rocket fuel, nonorganic lubricants, methods of avoiding contamination by ablative materials such as the several hundred pound aeroshell and the parachute, were among the more difficult new problems for the spacecraft engineers. The instrument has performed beyond any expectation, yielding a crisp analysis of the samples that it took in.

The third analytical experiment is the x-ray fluorescence spectrometer. This device, which yields information about the elemental composition of the Martian samples, was added long after the payload had been selected. As a result of the intriguing Mariner results, the Project was directed to add this instrument in 1972. Redesign of an already tight spacecraft layout resulted in the movement of one box to the right, another to the left, and finally the slimmed-down XRFS was snuggled in between the biology and the GCMS instruments.

All of these instruments, as well as the communication system, data system, Lander computer, and thermal control system, require power. The global dust storms, the 12-hour Martian nights, and the distance from the Sun all argue against the use of solar panels on the Martian surface. The Viking Landers each carry two 35-watt radioisotope thermal electric generators that operate continuously on plutonium 238. Associated rechargeable batteries handle peak power.

Two other experiments should be mentioned even though they had no assigned instrument per se. One is a radio science experiment that uses the spacecraft telemetry system and the radar system signals to make certain measurements of Mars. Location of the Lander, ephemeris of the planet, occultation of the spacecraft by the planet or by the Sun to measure the atmosphere characteristics are some of the things that are done by the radio scientists.

Another experiment is done by a group of scientists whose work is called physical properties. This team has all rights to the engineering data and the job of squeezing out information about the Martian surface. For example, data on the stroke of the landing leg is translated into surface mechanical properties such as soil cohesion and angle of internal friction.

One last ingenious experiment onboard the Lander is called "magnetic property." This imaginative idea is to mount several small permanent magnets strategically around the spacecraft to come in contact with the surface. By taking pictures of the magnets, the magnetic properties of the soil and aerosols could be determined.

All of this is not to say that Viking has had no engineering failures. On a system so complexly built with tight fiscal policies, there must be some failure. The goal is to make sure that those failures are not critical links in the chain of success. The seismometer on Viking 1 failed to uncage and those 2 months of data were lost. On the other hand, almost 2 years of data on Viking 2 more than offsets the loss. On each of the GCMS, there was a loss of one out of three heating ovens, but this loss was made up by the strategy employed in using the remaining two ovens. And so it was throughout the operation. No matter what the problem, either a redundant subsystem or a work-around capability was always found.

The remarkably high overall score of the Viking engineering is revealed by the ultimate test: did it work? and how well? Both Vikings have already operated five times beyond their planned lifetimes. The returned data are several times that expected. Most of the original scientific and engineering personnel have left and been replaced by a younger and fresher team. The machines have virtually outlasted the people.

The Scientific Results

At the time of the Viking missions the knowledge of Mars was derived from three sources: ground-based telescopes, the Mariner missions, and the Soviet Mars missions. Telescopic data over the decades had given a good idea of the orbital mechanics, some early indications of Martian seasonal events, and a general map of the light and dark regions. The Mariner mission began to sketch in the wide variety of the surface, including the surprising discovery of volcanism. It confirmed a tenuous atmosphere made up mostly of carbon dioxide and revealed seasonal changes on the surface. The composition of the polar caps was established as mainly carbon dioxide.

Despite their ambitious but problematical Mars missions, the Soviets did succeed in taking some high-resolution pictures from orbit and had succeeded in landing and transmitting from the surface for 90 seconds.

During one mission the Soviets, in attempting to measure the composition of the atmosphere, obtained data that suggested the possibility of a large component of inert gas in the Martian atmosphere. This posed a unique last-minute problem for the Viking GCMS, which was not designed to operate under those conditions. A strategy was devised that allowed operation of the GCMS in any of several modes to protect it against the Martian atmosphere, should that atmosphere really contain the harmful inert gas. The data returned by Viking 1 only hours after landing revealed only a small amount of the inert gas and that the interpretation of the Soviet data as a higher value was wrong.

The two Vikings have delivered tens of thousands of pictures of Mars and its satellites. After the appropriate geometric and optical corrections have been made, the pictures are joined together into a mosaic. These mosaics are then made into coordinate maps. Since the pictures may be taken at different seasons, the maps are interpretive in nature. Generally, only a few percent of the planet has been mapped at the high Viking resolution (40 meters). The object of the visual imagery is not only to map the planet but to learn of its geological and its meteorological characteristics. By taking pictures of certain special objects of interest, and by use of color and stereoscopic photography, the details of the formation can be better understood. In almost all cases this translates into larger data requirements, so the imaging experiment is one in which the more data that comes back, or the longer the life of the Viking spacecraft, the more is learned. There is virtually an endless list of photographic desires of the regional heterogeneity and the seasonal changes of Mars.

Heterogeneity is indeed the most striking aspect of the planet. The types of terrain are vastly more variable than Mercury or the Moon. While Mariner discovered volcanism on Mars, Viking has measured the extent and variety of volcanism. A large part of the northern hemisphere is covered by volcanoes; some are broad volcanic lava fields, spreading for hundreds of kilometers. Other volcanoes of immense size show what appear to be deep-seated fractures and scarps with great lobate flows. Several types of flows are recognized including tubes, sheets, and channels. These suggest differing rates of flows. The geologists believe that they are seeing a process similar to one observed on the Earth – the movement of a basaltic low-viscosity lava. One kind of volcano unique to Mars is the patera or saucer shape, which does not have a counterpart of the Earth, Moon, or Mercury. These volcanoes have a low profile covering a vast area. The great central caldera is made up of coalescing crater vents with lava flows and tubes, and channels that radiate outward, indicating the volcanic origin. It has been suggested that these enormous shield volcanoes have this unusual profile because they have collapsed at the same time they were being formed over a long period of time.

Because of the low surface pressure on Mars, these are no contemporary large pools, rivers, or collection basins of liquid water on the surface. However, there is no shortage of water either in the atmosphere or within the surface; this has been measured by ground-based spectroscopy. The low atmospheric pressure on Mars results in the physical state of water being either solid or gaseous. Other than possibly on the microscale or in anomalous conditions, there simply is no liquid water on Mars today. However, Viking did gather a great deal of evidence of ancient fluvial activity caused by flowing water. Broad channels formed when subsurface water ice (permafrost) was melted by geothermal activity from deep volcanic centers. When the melting of the permafrost reached a slope, the interstitial water suddenly released great flows, sometimes a hundred kilometers wide, that modified the channels. In other cases spring sapping of the underground permafrost caused the melting and the flow of new water from the box-type canyon out onto the plains. Their distribution suggests the seasonal cause rather than internal heating. Still another kind of formation, a dendritic channel, also of widespread formation, suggests rainfall. Their filamentous appearance resembles our terrestrial river systems. But all of these fluvial features run for very short distances. Geologists suggest that this is because the water either percolated into the surface or quickly evaporated. How is it possible that these ancient rivers could have existed and yet there be none today? Obviously the atmospheric pressures must have been different during the time of their formation. As will be seen in the discussion of the atmosphere, this has been borne out. Mars did have a different atmosphere in the past, and the pressure was sufficient to cause the water to go into the liquid phase and form rivers. How long ago? This is still one of the unanswered problems. Based on the population of craters in the fluvial areas, there is some idea of the relative age. It appears that there were several episodes for the differing kinds of formations and that all of them occurred before the last 50 million years, some going back several billion years. In calculations of the flooding that took place, the rate is of the same order as some places on the Earth.

The permafrost in the surface of Mars is revealed by several kinds of features that resemble terrestrial features caused by frozen ice. Slow movement and subsequent freezing and thawing of the ground ice results in a kind of chaotic jumbled terrain seen over vast areas of Mars. Irregular depressions caused by local collapse result in flat-floored valleys also found in Siberia and appear as tablelands on Mars. Large polygonal patterned pieces resemble our ice wedges in the periglacial regions. The formations of a distinctively Martian type crater is highly suggestive of permafrost. Unlike the Lunar crater, with its typical radial sunburst pattern, the Martian ejection consists of discreet lobate layers ringed around the impact point. The interpretation is that, unlike the Moon which was explosive at the point of impact, these Martian craters were caused by an outward flow of material on the surface following the impact. The material was lubricated by the steam coming from the molten underlying permafrost which mobilizes the surface. Not all of the Martian craters are of this flow formation type. Some do resemble the Lunar or Mercurian type. Here it is believed that permafrost is either absent or too deep to be mobilized by the impact.

The great Martian canyon is one of the planet's most distinguishing features. This 5000-km-long feature is one of the youngest of the surface. It is cut by scraps and gullies and the regularity of the scraps appear to trace out the original fault lines. The canyon walls have great alluvial fresh falls and reveal a great deal of dry mass wasting. Old craters in the highlands above the canyon are erroded by this process. The floor of the canyon is very wide and shows vast plains with sand dunes, and fresh evidence of landslides, mass movement, tectonic activity, and wind action (Fig. 2).

Mars has two natural satellites, Phobos and Deimos, which have been extensively photographed by Viking from distances

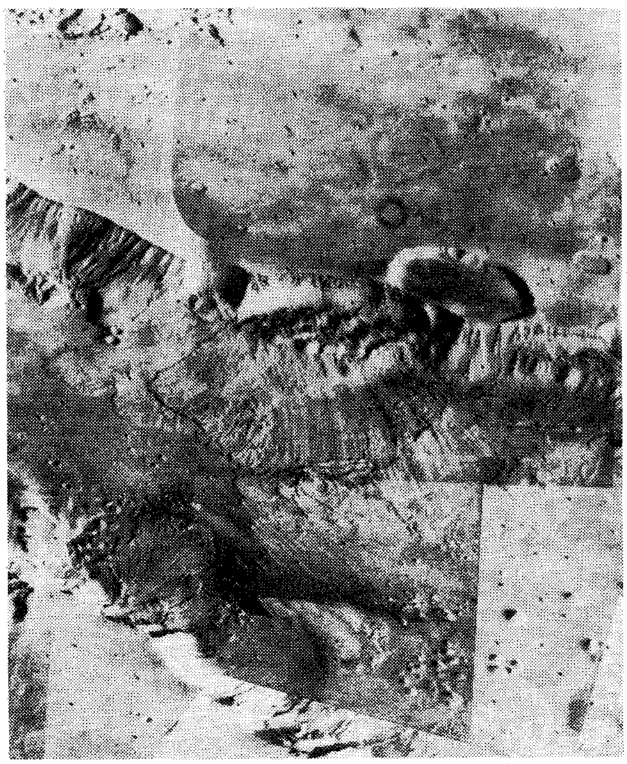

Fig. 2 This is a view taken by Viking 1 from a range of 2000 km looking southward across Valles Marineris (Marine Valley). This huge equatorial canyon of Mars, about 2 km deep, is 40 deg south of the landing site for Viking 2. The area shown is 70 km by 150 km.

as close as 30 km. The surfaces of each are quite different from one another. Phobos is very rough while Deimos looks more placid. This indicates that the two bodies have different histories. The surface of Phobos has numerous linear fracture features possibly caused by the impact of a large body. Both satellites have a low density and are of the gray color of carbonaceous chondrites. It has been suggested that these are captured astroids.

The Martian polar caps change dramatically during the seasons. When Viking arrived, the northern cap had shrunk to its minimum size, revealing what is known as the permanent cap, while the southern cap was in its full winter formation extending all the way to 40°S latitude. The cap consists of extensive areas of terraced deposits influenced by rapid erosion and deposition. Frost deposits within the cap are patchy and nonuniform. This was likely caused by local winds and slopes. The southern and northern caps appear different, and most scientists believe that some long-term solar epochs are responsible for the differences.

The composition of the polar cap as measured by Mariner is mainly dry ice. Early in the mission, when the southern cap was at its maximum size, measurements of the surface temperature of the cap were made from orbit and found to be well below the equilibrium temperature of dry ice at the pressure of the atmosphere. This suggests some very dynamic event during winter solstice. The super-cooling of the pole results in a lowered vapor pressure of the volatile components, such as carbon dioxide and water, and a concentration of such nonvolatiles as nitrogen and the noble gases. There is then a movement of new air mass to make up the atmospheric loss. This was corroborated by the Lander measurements which revealed a steady drop in pressure during the southern winter period.

The permanent polar cap, the cap that remains during the summer season, turns out to be water ice. Its temperature was measured and found to be 200-215 K. These data were also consistent with the data showing the atmospheric water vapor to be saturated over the winter pole. The amount of water trapped in the pole is not known, since the depth can only be estimated. The estimates range from a layer only a few millimeters to several hundreds of meters thick. However, what is important is that there is more water (by many orders of magnitude) locked up in the polar regions than in the atmosphere.

Martian atmospheric water is variable depending on the location, the season, and the time of day. Water is correlated with topographic elevation, the region of minimum corresponding to the highest elevation. Water is heavily dominant in the summer hemisphere; the southern winter hemisphere has almost no water. Daily changes in atmospheric water take place where there are abrupt changes in elevation. These are probably due to local phenomena such as wind, dust, or a thin cloud or haze which is present at dawn but dissipates by noon. A thin layer of haze could obscure most of the water below.

During the descent through the Martian atmosphere, its physical and chemical composition was measured. Viking 1 entered during the Mars afternoon, Viking 2 in the mid-morning. Mars has an ionosphere made up mostly of O_2^+. The peak concentration is at 130 km altitude; above this a small amount of O^+ was detected. The principal constituent of the upper atmosphere is carbon dioxide, with small amounts of nitrogen, argon, carbon monoxide, oxygen, and nitric oxide (which is inferred). The isotopic ratios of carbon and oxygen were measured and found to be similar to terrestrial values; the nitorgen ratio differed, however (N^{15} is enriched relative to N^{14}). This is due to the separation and subsequent exothermic loss of the N^{14} preferentially over the course of time. By modeling the Martian atmosphere with these data, it appears that there was a considerably denser atmosphere in the past – somewhere between 10 and 50 times the present value of 7.5 millibars at the surface. This denser atmosphere would account for the possibility of the ancient rivers seen from the Orbiter. The atmosphere is well mixed to heights of about 120 km. The discovery of nitrogen for the first time was a major milestone of Viking. Attempts to detect nitrogen had previously failed and upper limits of at most a few percent were believed by most planetologists. The absence of nitrogen had been a real thorn in the side of biologists, who could not imagine an organic chemistry on Mars with no nitrogen. The discovery of 2.5% nitrogen in the Martian atmosphere opened the door to a good deal of organic speculation.

The Viking 1 landing site was a considerable surprise. While most scientists believed that the local Mars scene would somewhat resemble the Earth, no one was quite prepared for the similarity between Mars and the California desert a few hundred kilometers away from Mission Control. It looked like a rocky field and appeared as though one could almost get into a car and drive to the spot (Fig. 3). How strange that it should be on another planet 400 million km away on the other side of the Sun. The Viking 2 site was also a flat desert field dominated by rocks, although of a rather different texture. The Viking 1 site in the Chryse plains has many sizes of fine-grain rocks among a dusty wind-deposited overlay. One large rock 3 meters across dominates the scene (Fig. 4). The topography is undulating and drifts appear in the lee of large boulders, suggesting periodic deposition and deflation. The fine material has a great deal of cohesion.

The Martian surface material is firmer than the Lunar material, but during the landing one of the footpads was buried several centimeters beneath. Some of the rocks that could not be moved by the sampling arm are probably buried beneath the surface. Others sitting on top were easily pushed and rolled. Many of the small weakly cohesive clods are similar to a terrestrial material called duricrust formed by precipitation and evaporation. Attempts to collect pea-sized rocks have failed and reveal an absence of sizes 0.2-1.3 cm, a phenomenon still unclear. The tiny permanent magnets accumulated material from the aerosol as well as the surface. In fact, some 4-7% of the surface material is magnetic, interpreted by the scientists as a form of gamma maghemite. This is consistent with the reddish pigment.

At the Viking 1 site, the rocks are angular and highly pitted.

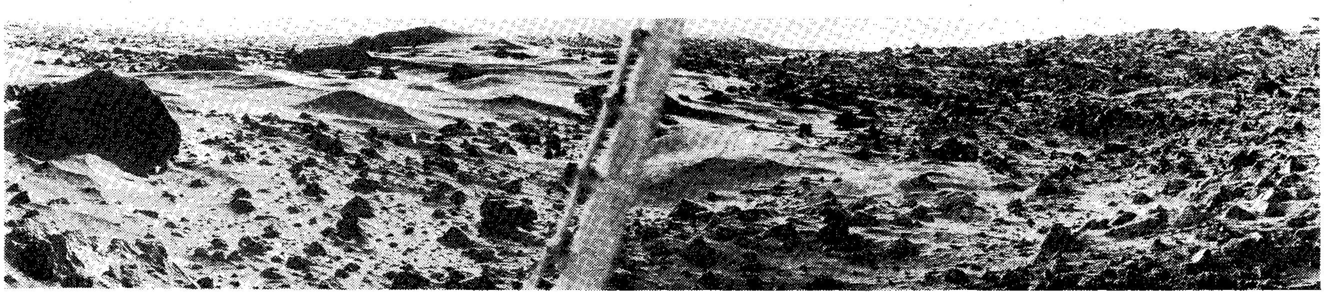

Fig. 3 This spectacular picture of the Martian landscape by the Viking 1 Lander shows a dune field with features remarkably similar to many seen in the deserts of Earth. The meteorology boom, which supports Viking's miniature weather station, cuts through the picture's center.

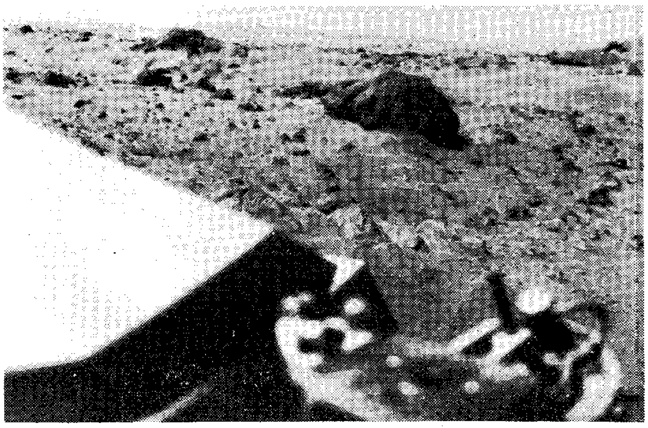

Fig. 4 This Mars view looks northeast from Viking 1 and completes the 360 deg panorama of the landing site begun earlier with the spacecraft's other camera. The largest boulder (center) is about 3 m wide and 1 m high.

In the horizon several outcrops are seen. The terrain is formed by chemical and mechanical destruction of the upper layer of a volcanic flow which exposed the jointed and fractured outcrop and left behind the angular rocks. Debris from impact material was added to this, and the wind also carried fine material and faceted the angular rocks. The Chryse sky is a faint orange due to the scattering by aerosols.

The Viking 2 site at Utopia is also a flat plain with many boulders of similar size and character. The rocks are mostly vesicular. The site is near a large crater, and the rocks are believed to be the ejecta of that feature. Fine-grain material, probably swept from the more northerly polar regions, is deposited among the rocks. The Utopia sky is also light orange.

Each of these sites has been photographed many hundreds of times to search for changes that take place on the surface or in the sky. The sky changes with the time of day. By monitoring the brightness of the twilight, the vertical distribution of the particles was measured. Suspended particles of dust a half micron in size are constantly present and make up the major source of atmospheric opacity during the afternoon and evening. This is probably of similar composition as the fine material of the surface. In the summer a ground fog of water ice particles about half a kilometer thick forms later at night and dissipates during the morning.

One of the most significant changes observed on the surface was the slumping of a handful of material poised on an incline. This change is important in interpreting the age of the scene. If in the few months that we were observing, this dramatic change can occur, it suggests that over the million of years there has been extensive change.

Another change on the surface was seen recently during the Martian winter in the deposition of ice on the surface. The rocks at the Utopia site had become ringed with a white material. The temperature of the surface is too warm for the material to be carbon dioxide, which suggests that is water ice (or snow) precipitating on the ground. An alternative idea is that the material is a clathrate, a mixture of water ice and dry ice bound physically, not seen too frequently on Earth but possibly common on Mars.

There has been a conscious search for any morphology, color, or motion that may suggest a biological origin. The scenes were scrutinized monoscopically, stereoscopically, in color, and by computurized differencing of pictures. "No evidence direct or indirect has been obtained for macroscopic biology at these sites." The scientists recognize the shortcomings of this aspect of searching for life inasmuch as the few square kilometers around the Viking Landers constitute an almost insignificant sampling of the Martian surface.

While no major seismic event has been detected on Mars during the Viking period, there has been the suggestion of a minor event. This local seism took place 110 km from the Viking 2 site and had a magnitude of 2.8 (on the Richter scale). The shear wave of this event indicates a crustal thickness of 15 km. The short duration of the signal suggests an Earthlike event rather than a Lunar type which rings for a long period. The low level of activity indicates that Mars is not as seismically active as the Earth, a result not too surprising to most.

The Martian atmosphere behaves in a very predictable manner. In the northern hemisphere in summer the pressure drops by about 30%, and then reverses itself due to the condensation of materials at the poles and on the surface. The diurnal and semidiurnal pressure oscillations are due to solar tides. Summer winds are relatively mild and highly repetitious, generated by global circulation and modified by the local terrain. Winter has more severe winds and, when coinciding with perihelion, generates a global dust storm. In 1977 the optical extinction rose from about 0.3 during summer to over 3.0 during the height of obscuration. Winds in excess of 30 m/s were recorded. The nighttime temperature is about 150 K. In the summer it rises to 240-260 K in the midafternoon. During the winter the daytime temperature falls to 150 K. The phase retardation of heating suggests that both convection and absorption of solar radiation play significant roles that affect the global atmospheric tides.

The biological results and the chemical results are inextricably entertwined. Fortunately, most of the surface samples were taken of similar material on the same day for each of the analytical instruments. The only samples analyzed were of the fine-grained material lying between or beneath the rocks. For the most part, samples that were taken were analyzed immediately, except for portions of biology that were held back to be used as a control in a comparison experiment.

The chemical elements at Chryse and Utopia are of similar composition. The numerous samples taken of the surface and subsurface all showed roughly the same characteristics, an iron-rich clay with oxides of silica and iron predominating. Sulfur, in the form of sulfate probably associated with magnesium (similar to gypsum), makes up 8-10%. Water is about 5%. Aluminum is only about 5%, and the alkali metals are also low. The material is probably of mafic origin (less differentiated than the salic terrestrial rocks). A model that is used for laboratory studies is nontronite, a substance formed by hydrothermal conditions. On the Earth it is common as a weathering product of basaltic lava flows (reminescent of the extensive volcanism and permafrost seen by the Orbiters).

By far the biggest surprise of the Viking results was the absence of organic material in our samples. Besides the obvious biological source, there are at least two other important likely sources of organic compound that were anticipated: one is *de novo* synthesis, that is, made out of carbon in the atmosphere, and the other is from meteorites. The synthesis of organics from simple atmospheric compounds such as methane and ammonia is well established, and the team fully expected to find measurable quantities on the surface. The meteorites (carbonaceous chondrites) that land on the Earth contain several percent organic material, often of a fairly complex nature. Since the source of the chondrites is believed to be the astroid belt, closer to Mars, a rich source of organics was anticipated. Indeed, the problem anticipated was to sort out the possible sources of organics and to distinguish the biological from the nonbiological. What a great shock to find no organics on Mars! The instrument sensitivity is of the order of a part per billion for some common molecules, and none were found. One might ask about the reliability of the result, the performance of the instrument, errors in the data, etc. The results are indeed reliable. Everything has been double checked, down to measuring our own levels of contamination in the instrument (which proved that it worked) and the result is accurate, no measurable organics in any sample at either site. Water and carbonates have been measured at about the anticipated level, but no organics. The explanation for this is still not well understood. This may be explained by some of the results of the biological experiments.

Two of the three biological tests appear to be positive! It is imperative to discuss the prudence with which the biology data must be handled. Unlike the physical and chemical data, the biological result is in part an emotional one. With all of the imaginative stories, cartoons, and pseudoscientific films fed to the public, the issue of life on Mars cannot be treated as just another result. The speculative positive that is reversed within a week to a negative, while possibly accepted by the scientists, has a very shocking effect on the general public. The interpretation of science daily in full public view leads scientists to be as reasonably conservative as possible. Also, because the biology experiments require considerable time for their incubation, the results are not meaningful until the end of the experiment.

Now to return to the three biology experiments, two of which gave a positive type of results. One negative experiment was an attempt to test for terrestrial type organisms using a terrestrial type growth nutrient. Any surviving contaminant from Earth would certainly have caused this to be a resounding positive (one reason for the certainty of the effectiveness of the sterilization procedure). The experiment did however reveal a surprisingly oxidizing material in the surface. The addition of water vapor to the Mars surface sample resulted in the release of copious quantities of oxygen. This high level of oxidizing potential could be the reason for the absence of organics. It may be that all organics had been oxidized by some reactant in the soil.

In one of the positive experiments a small amount of dilute aqueous nutrient is used. The appearance of gaseous metabolites suggests the presence of microorganisms that convert the nutrient. Here the result was positive, but confusing and unconvincing. The time course of events and the level of utilization did not fit any known behavior of microorganisms. The reaction leveled off rapidly and additional nutrient neither stimulated nor repeated the results. The only supportive evidence is the thermal destruction of the process, which might suggest a biological cause. It is too easy to postulate chemical reaction that could mimic the results for it to be considered formidable evidence by itself.

In the third biological experiment, a true simulation of the Martian environment was used to innoculate the sample. No liquid water, an atmosphere of carbon dioxide and carbon monoxide, and a light source to simulate the Sun. Unfortunately, the results were not internally consistent. In some cases they appeared statistically positive and in other cases negative. The instability to reliably repeat the results may be due to the varying conditions of the experiment or to differences in the Martian samples. This too can be explained by chemistry. So the biological results remain ambiguous. While inorganic chemical reactions can be invoked to explain the results, biology cannot be ruled out.

A difficult aspect for the exobiologists is the combination of these biological data with the absence of organic chemistry, the very stuff of which all known life is made. Extensive laboratory experiments are currently underway to simulate some of these data in order to explain the results.

How remarkable! Chemical and biological experiments are being performed on Mars as though in our own laboratories. Taking pictures at will, listening for seismic shocks, and making measurements of the atmosphere and the surface. All of this from the first spacecraft ever to be landed successfully on Mars, and return useful scientific data.

An Afterthought

In a sense Viking has been too successful. Each mission must stand on the shoulders of the last. Our tireless, almost perfect machine is a model very hard to beat with the next mission. The thing that Viking cannot do is move. An analytical robot on wheels to carry the laboratory across the extensive regions of Mars from one geological unit to the next – that may be the goal. To last for more than a year and to determine which samples should be collected for ultimate return to Earth – that could be its strategy. Viking has solved some of the problems, set a remarkable example, and pointed the way for future explorers.

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