The Geohydrology of Mars

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ABSTRACT

The recent advances in space science have now made it possible to construct models of the existence, volume, and hydrologic cycle of the ground water of the planet Mars.

Outgassing models of water vapor indicate that the surface of Mars should be covered with water to a depth of 10 to 100 meters (1.4×10^{15} to 1.4×10^{16} m^3). Geomorphic evidence suggests a depth of at least 500 meters (7×10^{16} m^3) of water should occur over much of the planet, yet no surface water, other than glacial ice at the poles (2.3×10^{15} to 9×10^{15} m^3), exists today. Martian gravity, though only 40 percent of Earth's, would keep water from escaping the planet. A survey of surface and atmospheric water volumes indicates that the majority of water, 1.2×10^{16} to 6×10^{16} m^3, is hidden as ground water.

Hydrologic cycle models indicate that Mars has an active but near static hydrologic cycle, dominated by water discharge in desert lowlands and water recharge at the ice-covered poles. Ground-water flow plays a major role in this system.

INTRODUCTION

The hypothesis that water exists or has existed on the planet Mars is not new. The concept of Martian canals was first proposed by Giovanni Schiaparelli in 1879. In the late 19th century and early 20th centuries, with the aid of powerful telescopes, it became possible to view what was then interpreted as seasonal changes in Martian vegetation. The polar regions of Mars showed what appeared to be ice and snow which waxed and waned with Martian winter and summer. Yet, even with the most powerful telescopes, no surface water could be seen. Light from the Martian atmosphere, when spectrally analyzed, showed only little water vapor or traces of carbon dioxide. By the 1950s, Mars was concluded to be a lifeless planet. If water had existed on Mars, all moisture was believed to be trapped at the poles and mixed with frozen carbon dioxide: a desert world of little interest (Sagan, 1980).

This conclusion, based on Earth-bound observation, held until exploratory spacecraft began to photograph and then land on the planet in the late 1960s and mid-1970s. The abundance of data returned to Earth from these spacecraft along with new theories about the origin of the planets have called for a new understanding of the origin and fate of water on Mars.

GEOLOGY OF MARS

The planet Mars is the fourth planet in the solar system, some 230 million kilometers from the Sun. It takes 687 days for Mars to make one revolution about the Sun; the Martian day is equivalent to 1.026 Earth days. The total surface area of Mars is approximately 1.4×10^{14} m^2, while the Earth's surface area, by comparison, is about 5×10^{14} m^2. Mars' surface area is about the same as the total land area of Earth.

The present knowledge of Martian geology is restricted mostly to the interpretation of surface features, and the subsequent implications of these features to subsurface geology. This knowledge has been gathered by the Mariner and Viking-Orbiter series space probes launched during the early 1970s. The images transmitted to Earth from the Orbiters have allowed the mapping of the entire surface of Mars with a resolution of between 10 to 200 meters. In addition, measurements of the tempera-

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Received November 1987, revised February and July 1988, accepted July 1988.

Discussion open until September 1, 1989.

ture of the surface and atmosphere and water content of the atmosphere have been made. The two Viking Landers tested the soil for minerals and for life. No definite signs of life were detected. The last Viking Lander lost contact with Earth after six years of continuous data transmission (Carr *et al.*, 1984).

While Earth and Mars were formed in the same manner of planetary accretion, the images of Mars show a planet whose features lie somewhere between those of the Earth and the Moon plus some unique features of its own (Spitzer, ed. *et al.*, 1980). Over two-thirds of the planet is covered by craters produced by impacts. The many valleys indicate that running water was once present. The Tharsis Bulge region, a geological anomaly, is a huge area that extends over 7 kilometers above the Martian datum plain and is over 5500 kilometers across (Carr *et al.*, 1984). Here are found radial fractures, basaltic lava flows, canyons, and the largest and youngest volcanoes. One, Olympus Mons, stands 25 kilometers above the plain, and is the largest known volcano in the solar system (Francis, 1976).

Mars has undergone definite tectonic activity such as volcanism and formation of the Tharsis Bulge region, yet no evidence of plate tectonics can be found. Fault grabens can be seen, but separate plates have not developed. Features and materials are, therefore, distinctly preserved from Mars' past since they cannot be recycled or destroyed by the collision or separation of continents. Materials that are buried deep in the Martian subsurface stay buried and cannot be recycled as they are on Earth (Haberle, 1986). This has important implications for the recycling of materials such as water.

The impact craters of Mars are, for the most part, still preserved. Like all the planets and their moons, Mars has had a history of meteor impacts. Almost the entire surface of the planet shows craters. The craters are indicators of the very slow process of weathering and great age of about half of the surface of Mars, about 4 billion years old (Carr, 1981).

Figure 1 shows a generalized stratigraphic column for Mars. The subsurface of Mars is probably composed of impact crater ejecta, mixed with lava flows from volcanic events. These lavas appear to be basaltic (Masursky, 1973). The subsurface is also believed to be fractured and brecciated to a depth of 10 to 20 kilometers (km) by the force of impacts and tectonic extension. Since the crust cannot be recycled by plate tectonics, these fractures would still be present to serve as reservoirs for water. Permafrost is believed to exist and is estimated to be about 8 km thick at the poles and about 3 km thick at the equator (Anderson, 1982).

Results of the two Viking Lander surface chemistry experiments indicate a soil composed of iron and magnesium clays, iron hydroxides, sulfate, and carbonate minerals. When heated, the soil samples produced about 1 percent water by weight (Arvidson *et al.*, 1983).

PRESENT ATMOSPHERE AND CLIMATE

The atmospheric pressure of Mars is much less than Earth's, 7 millibars on average. Earth's 1013 millibars is crushing by comparison (Haberle, 1986). Earth atmosphere is mostly nitrogen, oxygen, carbon dioxide, water vapor, and traces of noble gases. What little atmosphere Mars has is carbon dioxide (95 percent) and traces of nitrogen, argon, oxygen, carbon monoxide, water vapor (0.03 percent), and noble gases which can be

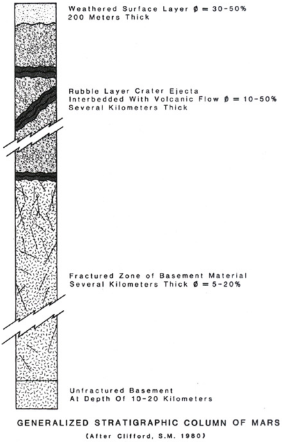

Fig. 1. A stratigraphic column of Mars.

measured only in parts per million. The maximum amount of water in the atmosphere is about 1.3×10^9 m^3 (Owen *et al.*, 1977).

Data from the Viking Orbiters' spectrometers concludes that the Martian atmosphere is saturated, given its temperature and pressure, with water vapor several times Earth atmosphere levels (Leovy, 1983). Images taken at the Viking Lander areas show frost which formed during the night. Images from the Orbiters show daily fog in the deep valley regions of Coprates Chasma. It is difficult to find an analogy on Earth to compare with this phenomenon of a desert constantly at the dew point. Perhaps the fog-bound area of the Chilean desert of South America is the closest analogy. There the water vapor comes from the Pacific Ocean while on Mars the water vapor must, at least in part, come from ground-water sources.

THE ORIGIN OF WATER ON MARS

The origin of the planets occurred when the solar system condensed out of the cloud of gas that surrounded the proto-sun. This cloud contained mostly hydrogen and helium but also had all the other elements and many of the simple chemical compounds found in the present solar system, including an abundance of water (Frazier, 1985). As the planets accreted by gravity and began to generate heat from this formation and by meteor impacts, outgassing of water vapor and other gaseous compounds and elements occurred.

This process formed the primitive atmospheres of the planets. The process was probably repeated several times for the Earth-sized planets since large meteor impacts would tend to blow away the atmosphere of any planet this size. No doubt much of the original water of Earth and Mars was lost during the first billion years or so of planet evolution. During this same period some water was provided by comet impacts but probably not enough to replace that which was lost. The models used to predict the present amounts of water can only be useful for the period of time that followed the early meteor impacts.

WATER VAPOR OUTGASSING MODELS OF MARS

Several methods of modeling the amount of water outgassed during planet formation have been used (Squyres, 1984). These have included determining the argon/water, potassium/water, and nitrogen/water ratios. These models are based on the assumption that when water vapor is outgassed from the planet, other gases are outgassed also. On Earth it is possible to measure water volume to the volume of those gases that are chemically inactive and too heavy to escape the gravity of the planet. In theory these ratios of gases to water should then provide a method of estimating the volume of water outgassed from a planet that is of similar size and formation as the Earth.

The Ar/H_2O ratios for Mars yield a figure of about 10^{15} m^3 or enough to cover Mars with 10 meters (m) of water (Owen and Biemann, 1976). The K/H_2O ratios give about 10^{16} m^3 of water (Pollack and Black, 1979), and the N_2/H_2O ratios yield water of over 1.4×10^{16} m^3 (McElroy *et al.*, 1976, 1977). A major problem with these models is that large meteor impacts would have blown away some amounts of the gases, a process called impact erosion. This, in turn, would have yielded low gas to water ratios and therefore lower than actual water outgassing volumes (Carr, 1987).

GEOMORPHIC EVIDENCE OF WATER

When the Mariner 9 spacecraft went into orbit above Mars in November 1971, the images transmitted back to Earth showed that at some time in Mars' early history, liquid water and ice had been present and active on the surface (McCauley *et al.*, 1972). River and stream channels, areas of runoff, and surface features of fluvial deposition have been discovered, and yet clearly could not have been formed under the present desert climatic conditions.

The river and stream features have been divided into two categories: outflow and runoff channels (Sharp and Malin, 1975). The outflow channels are very dramatic in that they seem to be fully formed with little or no tributaries. The runoff channels are similar to those of Earth-type drainage systems but may not reflect actual Earth-type river systems that were once filled with water (Squyres, 1984).

Outflow Channels

One of the most striking features of the outflow channels, Figure 2, is the apparent removal of subsurface material and the collapse of the surface topography (Squyres, 1984). These channels are very large features, generally 1,000 to 1,500 km long, 20 to 180 km wide, and 500 to 2,500 m deep (Mars Channel Working Group, 1983). The major agent of erosion is clearly water, and the catastrophic flooding must have been enormous. One flood that originated in the Juventae Chasma had an estimated peak discharge of 7×10^6 to 5×10^8 m^3/second (Carr, 1979).

Volcanic eruptions beneath glaciers have been proposed to explain the volume of flood water

Fig. 2. Martian outflow channel near the Simund Vallis. NASA, Viking 1, P-16983. Scale is 1.5 cm = 20 km.

(McCauley *et al.*, 1972; Masursky *et al.*, 1977). The warming of subsurface ice and permafrost has been suggested by McCauley *et al.* (1972) and Sharp and Malin (1975). Glacial ice movement that would have carved the channels has been proposed by Lucchitta *et al.* (1981). Perhaps the most interesting from the point of view of a ground-water hydrologist is the model proposed by Carr (1979). This theory states that water was suddenly released from an extensive ground-water system that exists beneath a thick confining layer of impermeable permafrost. The water is under artesian conditions, and any thickening of the confining layer or crustal warping would create areas of high hydrostatic pressures. Once this pressure exceeds the lithostatic pressure, a flood of catastrophic proportions would occur. When the flooding stopped, the water would seep back into the ground or evaporate and later precipitate as snow on the poles.

When the flooding events occurred is debatable—one model estimates 4 billion years ago (Malin, 1976), and another model says 2.5 to 1.0 billion years ago (Masursky *et al.*, 1977). All that can be certain is that the flooding events occurred in the early history of Mars.

Runoff Channels or Martian Valleys

Runoff channels or Martian valley features, like the outflow channels, give indications of the presence of water. They are more analogous to terrestrial features than the outflow channels; however, they give no definite evidence of stream or river flow (Sharp and Malin, 1975). Images of these channels show no evidence of fluid erosion or runoff from surrounding areas into the channels; thus, the term "runoff channels" may not be appropriate. Some investigators prefer the term Martian valleys to describe them. Little evidence of fluid flow is seen as in the outflow channels. This could mean that the flow event was small or that resolution of the images is not great enough to detect flow evidence (Squyres, 1984). The channels are not as large as the outflow channels, ranging from less than 5 km to 1000 km in length and have widths from less than 1 km to 10 km.

The most likely mechanism for the formation of runoff channels involves the sapping away of the cliffs as ground water flows from them (Pieri, 1980). As ground water flowed from the base of the cliffs, the cliffs were undermined and then collapsed. This sapping continued farther into the plateaus until the source of water was exhausted or conditions for flow changed. The discharge need not have been great, just constant over a period of time. Examples of this process can be found on Earth in the high plateau areas of Utah in the U.S. (Laity, 1980).

The sapping process implies modest water flow at best which, unlike a catastrophic flood, would be difficult to maintain under present climatic conditions. The present temperatures and pressures would freeze and vaporize a modest water flow, and the sapping would have ceased almost immediately. Sapping could only have occurred when the temperatures and pressures were great enough to allow liquid water to flow easily. These conditions have not existed on Mars for billions of years. This implies a distant past for these conditions to be present. All of these channels are found only in areas estimated to be 3.5 to 4 billion years old (Masursky *et al.,* 1980a). The temperatures and atmospheric pressures must have lowered after this time so the sapping process stopped.

OTHER SURFACE FEATURES INDICATIVE OF GROUND WATER

Several other surface features are found on Mars that give indirect evidence of water or at least ground ice. Among these are fretted terrains, thermokarst, rampart craters, and playa lake deposits.

Fretted Terrain

These features are smooth, flat lowlands separated from the cratered uplands by abrupt escarpments (Sharp, 1973), which may reach 1 to 2 km in height. These flat plains may have been formed as the escarpments retreated into the uplands. This retreat may have resulted from the discharge of ground water at the base of the escarpment or by evaporation of exposed ground ice and the subsequent collapse of escarpment (Gatto and Anderson, 1975).

Thermokarst Areas

Thermokarsts are smaller in scale than the fretted terrains and usually involve smaller scale collapse of the surrounding area forming tablelands with scalloped edges (Carr and Schaber, 1977). These landforms are analogous to the thermokarst features found at high latitudes on Earth and are the result of disequilibrium in ground ice (Czudek and Demek, 1970). In thermokarst regions on Earth, the volume of water amounts to 80 to 90 percent of the deposit (Washburn, 1973).

Rampart Craters

The rampart craters look like the result of a stone thrown into thick mud but on a much larger scale. Figure 3 shows the rampart crater Yuty which has a crater diameter of about 19 km with the ejecta "splat" lobes thrown out for at least that distance and more. This type of crater is found all over Mars and appears to have occurred throughout all of Martian history (Allen, 1978).

The most unusual feature is the apparent fluidized ejecta lobes resulting from the impact of a meteor (Carr *et al.,* 1977). The Martian atmosphere has been too thin for the past 3 billion years to act as the fluidizing agent. Ground water is the only likely agent. Ground ice or permafrost only would have liquefied locally near the meteor impact and so could not have transported so much material (Squyres, 1984). Liquid ground water is the mostly likely agent of ejecta material transport. Rampart craters can thus be indicators that liquid subsurface water existed at the time of impact.

Playa Lakes

Evidence of standing water has been shown in the Valles Marineris. Deposits of sediments show layering of materials that are finely and evenly layered. This fine and even bedding is consistent with deposition in playas or lakes (Lucchitta, 1982). During an early wet period of Mars, this valley may well have had permanent lakes which received deposition from the surrounding area.

ESTIMATES OF WATER FROM GEOMORPHIC FEATURES

The above discussion indicates that a vast amount of water must have been present to form the various geomorphic features described. The catastrophic flooding events alone would demand a large reservoir present in the subsurface. Based on such geomorphic features as catastrophic flooding and fretted terrains, Carr (1987) estimated that at least 7×10^{16} m^3 of water has been outgassed from

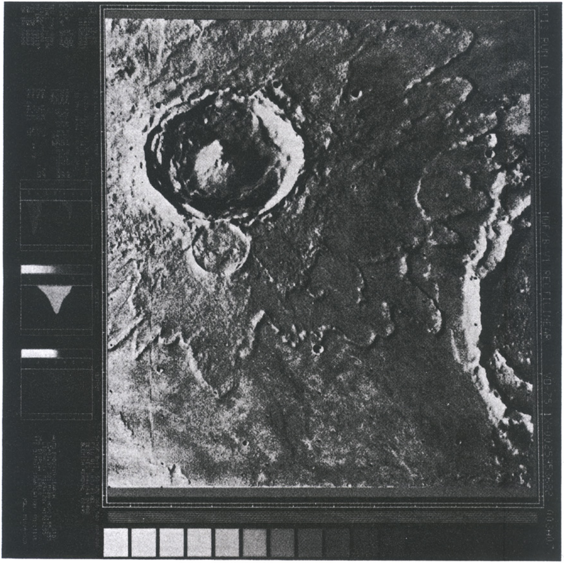

Fig. 3. Martian rampart crater Yuty. Note the fluidized ejecta lobes which surround the crater. NASA, Viking 1, 003A07. Scale is 1 cm = 5 km.

Mars which would cover Mars with 500 m of water. Most of this water is probably stored as ground water (Table 1).

Polar Water Deposits

The areas of Mars known to have water are the north and south poles. Unlike the poles of the Earth that are either frozen pack ice like the north pole or a continental glacier kilometers thick like the antarctic south pole, the Martian poles are more complex. The polar caps can be defined into three parts from top to bottom: the frost cap, the ice cap, and the layered deposits.

The seasonal frost cap appears during the winter at each pole. It is composed mostly of frozen CO_2 (Neugebauer *et al.*, 1971) and covers the poles to latitudes 45-40 degrees.

The ice caps are composed of water and dust in the north and CO_2, water, and dust in the south. The thickness at both poles is estimated at about 1 m (Davies *et al.*, 1977). The caps are not large reservoirs of Martian water.

Table 1. Distribution and Volumes of Water on Earth and Mars

Distribution	*Earth*	*Mars**
	Volume in m^3	
Atmosphere	1.3×10^{12}	1.3×10^{9}
Surface water as liquid	1.3×10^{18}	None present
Glaciers and polar ice	2.9×10^{16}	2.3×10^{15} to 9.0×10^{15}**
Ground water	8.4×10^{15}	1.2×10^{16} to 6.0×10^{16}
Total volume	1.4×10^{18}	1.4×10^{16} to 7.0×10^{16}***

* Estimates for Mars are based on planetary water vapor outgassing models, geomorphic features, measurements of the polar ice from Viking Orbiter images, and analyst of the atmosphere at the Viking Lander sites. These estimates may be conservative.

** This includes the Martian polar ice caps and the ice content of the layered deposits at the poles. The ice content estimates vary from 33% to 80%.

*** Based on an estimated outgassing of 100 to 500 m of water.

The layered deposits, found at the base of the poles, are called layered because of the interbedding of what appears to be dust and ice, some of which are 50 m thick. The total thickness of these deposits is about 2 km in the north and 4 to 6 km in the south (Dzurisin and Blasius, 1975). The layered deposits extend toward the equator to latitudes 80 to 85 degrees which amounts to about 1 percent of the surface (Squyres, 1984). Estimates of the ice content vary from 33 percent (Masursky *et al.*, 1980b) to as high as 80 percent (Clifford, 1982), and therefore must comprise one of the major reservoirs of water on Mars (Table 1).

HYDROLOGIC CYCLE AND GROUND-WATER FLOW

The hydrologic cycle of the Earth is a dynamic system of water movement powered by the thermal energy of the sun combined with the gravitational energy of Earth with the atmosphere, an important transportation medium. Water can thus be vaporized, moved by winds, precipitated as rain or snow, stored as surface water, ice, snow, ground water, and then moved again. As long as the Earth has an atmosphere and gravity and the sun's energy, this dynamic cycle will continue.

The conditions of Mars are quite different. Mars receives less than half of the thermal energy of the Earth, a force of gravity 40 percent of Earth's, and has little atmosphere to trap heat and transport water vapor. It would then appear that Mars would not have a hydrologic cycle since water cannot be moved. Yet, as argued above, water on Mars is in motion. Fog has been seen in the deserts far from the poles. It has been estimated that all of the permafrost and water near the surface should have evaporated within a few million years and precipitated at the poles (Clifford and Hillel, 1983). The rampart craters give evidence that throughout Martian history, water has existed near the surface. Some mechanism must be at work here to resupply the water which evaporates or sublimates. A hydrologic cycle must be at work, slow as it may be.

Due to the low temperatures involved, such a system would be a low energy or near static hydrologic cycle. This type of system has been described by Clifford and Haguenin (1980) and Clifford (1981). This model uses the process of basal melting of permafrost beneath the polar deposits which recharges the ground-water reservoirs. Ground water then migrates toward the equatorial regions of Mars. Figure 4 shows a generalized model of the system.

Solar input does not have to be great, just enough to allow a thin atmosphere to carry water vapor. Thermal energy for melting is supplied by the heat from the interior of Mars, estimated at 22 calories per cm^2 per year (Fanale, 1976) and compression of the polar cap.

GROUND-WATER FLOW

The Martian ground water moves from areas of high hydraulic head toward the areas of low hydraulic head. The poles with an average of 4 m of ice and dust and basal melting are areas of recharge, and the deserts are areas of discharge. As water sublimates as fog from the desert lowlands, a pressure difference is created and water then migrates upward toward this region of lower

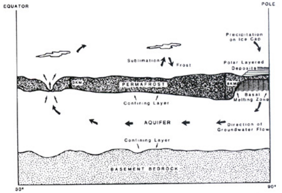

Fig. 4. Generalized model of the Martian hydrologic cycle.

hydraulic head. Water vapor is carried by the winds and is precipitated along with dust to form the layered deposits at the poles. The pressure from the weight of these thick ice/dust deposits and the accumulation of geothermal heat from the planet's interior melts the permafrost and ice and produces a region of higher hydraulic head. The water then migrates from this region of higher hydraulic head toward the desert lowlands where the hydraulic head is lower.

The volume of ground water is estimated to be between 1.2×10^{16} to 6×10^{16} m^3. This estimate is the result of the estimated volumes of known water reservoirs, such as the layered deposits at the poles, subtracted from the estimated total water volume. The ability of the subsurface to store this amount of water does not present any problem. The vast number of meteor impacts along with crustal warping and volcanism would have fractured the subsurface extensively. Due to the low Martian gravity, compaction of the subsurface would probably occur only at depths beyond 10 m. If the subsurface had an average porosity of only about 5 percent from the surface to this depth, this amount of water could be stored easily (Clifford, 1980).

The conditions of flow would be considered confined since the aquifer is overlain by permafrost that averages 8 m near the poles and 1 to 3 m near the equator and is in turn underlain by unfractured bedrock at 10 to 20 m beneath the surface.

CONCLUSIONS

The above discussion has been an overview of the current state of knowledge concerning Martian ground water. It was also an attempt to demonstrate that Mars has had and still has water which is now almost entirely ground water and permafrost. While the exact volume is open to debate, it is certainly possible to be well within an order of magnitude of Earth's ground-water volume.

Unlike the Earth with its dynamic ocean/atmosphere dominated hydrologic cycle, Mars is a near static ground-water/polar ice cap dominated cycle of slow water recycle time. This is due to the low solar energy input for rapid evaporation, very low atmospheric pressure and gas content to transport and precipitate water, lack of plate tectonics to recycle sediments containing water, and the slow movement of ground water due to the aquifer's thick confining layers which prevent rapid discharge and recharge. Much more research and modeling of Martian aquifers are needed.

Perhaps the most important conclusions may have to deal with the presence of life on Mars and mankind's eventual colonization of Mars, neither of which are possible without water being present. When the Viking Landers found no evidence of life, they looked only in the upper half meter or so of Mars where no water would be found. Only by exploring beneath the surface will definite results be found. When mankind arrives on Mars, ground water can be exploited for use. The first Martian hydrologists will have an entire planet's ground-water system to explore, measure, and model. Let us hope it will be soon.

ACKNOWLEDGMENTS

I would like to thank Moid Ahmad, Damian Nance, and Geoffrey Smith, all of Ohio University's Department of Geological Sciences for their very helpful critical reviews and suggestions for this paper; Hubertus Bloemer of Ohio University's Geography Department for work on the diagrams; and Thomas Winn and Kenn Frieling for their grammatical criticisms.

I wish also to acknowledge and thank the Team Leader, Michael H. Carr, Patricia Ross, Manager, Request Coordination, and the National Space Science Data Center of the National Aeronautics and Space Administration for the Viking images.

REFERENCES

Allen, C. C. 1978. Areal distribution of rampart craters on Mars. National Aeronautics and Space Administration Technical Memorandum 79729. pp. 160-161.

Anderson, D. M. 1982. Physical and mechanical properties of permafrost on Mars. National Aeronautics and Space Administration Technical Memorandum 85127. p. 265.

Arvidson, R. E., *et al.* 1983. The Planets: The Surface of Mars. W. H. Freeman And Co., San Francisco. 132 pp.

Carr, M. H., L. S. Crumpler, J. A. Cutts, R. Greeley, J. E. Guest, and H. Masursky. 1977. Martian impact craters and emplacement of ejecta by surface flow. J. Geophys. Res. v. 82, pp. 4055-4065.

Carr, M. H. and G. G. Schaber. 1977. Martian permafrost features. J. Geophys. Res. v. 82, pp. 3985-4015.

Carr, M. H. 1979. Formation of Martian flood features by release of water from confined aquifers. J. Geophys. Res. v. 84, pp. 2995-3007.

Carr, M. H. 1981. The Surface of Mars. Yale University Press, New Haven, Conn. 232 pp.

Carr, M. H., *et al.* 1984. The Geology of the Terrestrial Planets. National Aeronautics and Space Administration. SP-469, pp. 207-263.

Carr, M. H. 1987. Water on Mars. Nature. v. 326, pp. 30-35.

Clifford, S. M. and R. L. Haguenin. 1980. The H_2O mass balance on Mars: implication for a global sub-permafrost ground water flow system. National Aeronautics and Space Administration Technical Memorandum 81776. pp. 144-146.

Clifford, S. M. 1980. A model for the removal and subsurface storage of a primitive Martian ice sheet. National Aeronautics and Space Administration Technical Memorandum 82385. pp. 405-407.

Clifford, S. M. 1981. A model for the climatic behavior of water on Mars. Proc. 3rd Int. Colloq. on Mars, Pasadena. Lunar Planet. Inst. Contrib. 441, Houston, Texas.

Clifford, S. M. 1982. Polar basal melting on Mars. National Aeronautics and Space Administration Technical Memorandum 85127. pp. 261-263.

Clifford, S. M. and D. Hillel. 1983. The stability of ground ice in equatorial region of Mars. J. Geophys. Res. v. 88, pp. 2456-2474.

Czudek, T. and J. Demek. 1970. Thermokarst in Siberia and its influence on the development of lowland relief. Quaternary Research. v. 1, pp. 103-120.

Davies, D. W., C. B. Farmer, and D. D. LaPorte. 1977. Behavior of volatiles in Mars polar areas: a model incorporating new experimental data. J. Geophys. Res. v. 84, pp. 3815-3822.

Dzurisin, D. and K. R. Blasius. 1975. Topography of the polar layered deposits of Mars. J. Geophys. Res. v. 82, pp. 4225-4248.

Fanale, F. P. 1976. Martian volatiles; their degassing history and geochemical fate. Icarus. v. 28, pp. 179-202.

Francis, P. 1976. Volcanoes. Pelican Books, New York. 368 pp.

Frazier, K. 1985. Solar System. Planet Earth Series, Time-Life Books, Alexandria, VA. 176 pp.

Gatto, L. W. and D. M. Anderson. 1975. Alaska thermokarst terrain and possible Martian analog. Science. v. 188, pp. 255-257.

Haberle, R. M. 1986. The climate of Mars. Sci. Am. v. 254, no. 5, pp. 54-62.

Laity, J. E. 1980. Ground water sapping on the Colorado Plateau. National Aeronautics and Space Administration Technical Memorandum 82385. pp. 358-360.

Leovy, C. B. 1983. The Planets: The Atmosphere of Mars. W. H. Freeman and Co., San Francisco. 132 pp.

Lucchitta, B. K. 1982. Lakes or playas in Valles Marineris. National Aeronautics and Space Administration Technical Memorandum 85127. pp. 233-234.

Lucchitta, B. K., D. M. Anderson, and H. Shoji. 1981. Did ice streams carve Martian outflow channels? Nature. v. 290, pp. 759-763.

Malin, M. C. 1976. Age of Martian channels. J. Geophys. Res. v. 81, pp. 4825-4845.

Mars Channel Working Group, Baker, V. R., ed. 1983. Channels and valleys of Mars. Geo. Soc. Am. Bull. v. 94, pp. 1035-1054.

Masursky, H. 1973. An overview of geologic results from Mariner 9. J. Geophys. Res. v. 78, pp. 4009-4030.

Masursky, H., J. M. Boyce, A. L. Dial, G. G. Schaber, and M. E. Strobell. 1977. Classification and time of formation of Martian channels based on Viking data. J. Geophys. Res. v. 82, pp. 4016-4038.

Masursky, H., A. L. Dial, and M. H. Strobell. 1980a. Martian channels—a late Viking View. National Aeronautics and Space Administration Technical Memorandum 82385. pp. 184-187.

Masursky, H., A. L. Dial, and M. H. Strobell. 1980b. Inventory of North Pole ice, Mars. National Aeronautics and Space Administration Technical Memorandum 82385. p. 383.

McCauley, J. F., M. H. Carr, J. A. Cutts, W. K. Hartman, H. Masursky, D. J. Milton, R. P. Sharp, and D. E. Wilhelms. 1972. Preliminary Mariner 9 report on the geology of Mars. Icarus. v. 17, pp. 289-327.

McElroy, M. B., Y. L. Yung, and A. O. Nier. 1976. Isotopic composition of nitrogen: implications for the past history of Mars' atmosphere. Science. v. 194, pp. 70-72.

McElroy, M. B., T. Y. Kong, and Y. L. Yung. 1977. Photochemistry and evolution of Mars' atmosphere: a Viking perspective. J. Geophys. Res. v. 82, pp. 4379-4388.

Neugebauer, G., G. Munch, H. H. Kieffer, S. C. Chase, and E. D. Miner. 1971. Mariner 1969 infrared radiometer results: temperature and thermal properties of Martian surface. Astron. J. v. 76, pp. 719-727.

Owen, T. and K. Biemann. 1976. Composition of the atmosphere at the surface of Mars: detection of argon-36 and preliminary analyses. Science. v. 193, pp. 801-803.

Owen, T. K., K. Biemann, D. R. Rushneck, J. E. Biller, D. W. Howarth, and A. L. Lafleur. 1977. The composition of the atmosphere at the surface of Mars. J. Geophys. Res. v. 82, pp. 4635-4639.

Pieri, D. 1980. Martian valleys, morphology, distribution, age, and origin. Science. v. 210, pp. 895-897.

Pollack, J. B. and D. C. Black. 1979. Implications of the gas compositional measurements of Pioneer Venus for the origin of planetary. Science. v. 205, pp. 56-59.

Sagan, C. 1980. Cosmos. Random House, New York. 365 pp.

Sharp, R. P. 1973. Mars: fretted and chaotic terrain. J. Geophys. Res. v. 78, pp. 4073-4083.

Sharp, R. P. and M. C. Malin. 1975. Channels on Mars. Geol. Soc. Am. Bull. v. 86, pp. 593-609.

Spitzer, C. R., editor, *et al.* 1980. Viking Orbiter views of Mars. National Aeronautics and Space Administration SP-441. 175 pp.

Squyres, S. W. 1984. The history of water on Mars. Ann. Rev. Earth Planet. Sci. pp. 83-106.

Washburn, A. L. 1973. Periglacial Processes and Environments. St. Martin's, NY. 320 pp.

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