# Use of spacecraft data to derive regions on Mars where liquid water would be stable

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**Combining Viking pressure and temperature data with Mars Orbital Laser Altimeter topography data, we have computed the fraction of the martian year during which pressure and temperature allow for liquid water to be stable on the martian surface. We find that liquid water would be stable within the Hellas and Argyre basin and over the northern lowlands equatorward of about 40°. The location with the maximum period of stable conditions for liquid water is in the southeastern portion of Utopia Planitia, where 34% of the year liquid water would be stable if it were present. Locations of stability appear to correlate with the distribution of valley networks.**

The search for extinct or extant life on Mars is the search for past or present liquid water, respectively. There are numerous signs of past liquid water on Mars in the form of dry river valleys, paleolakes, and their associated flow and sediment patterns. Although some of these features are recent (Amazonian, 1.8 billion years ago to present), there is no evidence that any are currently flowing. Recent images from Mars Global Surveyor (MGS) indicate geologically very recent flows in the southern highlands (1). Any extant flows would have associated water ice, because the surface temperature is so low. Liquid water on the surface would be possible only at those sites with sufficiently high temperatures and pressure. The key to the selection of Mars sites for the search for evidence of life is the search for the presence of water.

An approach to this problem is the use of remotely sensed data incorporated in a Geographic Information System (GIS). A GIS is a computer-based system capable of assembling, storing, manipulating, and displaying geographically referenced information, i.e., data identified according to their locations. These data are layered and areas on these layers selected as a function of the information desired. The current study used existing data layers from the Viking and MGS missions to determine where water could be possible in liquid form on the martian surface, on the basis of the phase diagram for water.

Mars has water as ice in the polar caps and as vapor in the atmosphere. The atmosphere often contains enough water to be saturated at nighttime temperatures. Frost was observed on the ground at the Viking 2 Lander site at 48°N and presumably forms at other high-latitude sites as well (2). Water as liquid on the surface of Mars has not been observed, and theoretical considerations suggest liquid water would not form on the surface because of low pressures and temperatures (3, 4). However, the pressures (5) at the Viking sites were always above the triple point of liquid water [6.1 millibar (1 millibar = 100 Pa)], and surface temperatures on Mars have been observed to rise above freezing (6). Thus it is expected that pressure and temperature combinations exist on Mars that would allow liquid water. A map of such sites might reveal locations of the most recent liquid water activity or sites of possible transient liquid formation at the present epoch.

We have determined the locations and periods on Mars in which pressure and temperature conditions are thermodynamically consistent with liquid water. The pressure at each location throughout the martian orbit was determined from the Viking 2 Lander pressure record and extrapolated to other locations by using the Mars Orbital Laser Altimeter (MOLA) topographic data assuming hydrostatic equilibrium. Temperature throughout the year was determined by fitting a solar insolation function to the temperature maximum and minimum reported for each location based on the Viking Orbital thermal mapper (6, 7).

In *Methodology*, we describe the procedures used to determine the pressure and temperature over the year on the martian surface and use these to compute the cumulative time at each site that conditions would allow for liquid water. Clearly, temperature and pressure control the thermodynamic conditions that allow for liquid water but do not determine whether sufficient water will be present for liquid to form. We also explore correlations between the existence conditions and the amount of atmospheric water vapor at any site, also with the observed distribution of channel networks. Such correlations do not indicate that liquid water would be present at these sites but may indicate that such sites are locations of interest in terms of possible geochemical and biological activity of liquid water. Improved data from future Mars missions may provide better, more refined data layers that could be used to improve the analysis.

**Data.** Data layers from the Viking and MGS missions were used for this project. Viking data included lander (surface) pressures [Planetary Data System Geosciences Node (1999) MGS and Viking Orbiter and Lander data and services (http://wundow.wustl.edu/wwwpds/dataserv/html)]. Annual maximum and minimum surface temperature derived from Viking Orbiter Infrared Thermal Mapper (IRTM) were used (7) to define the temperature ranges at each point. These IRTM images had a spatial resolution of 2° in aerographic latitude and longitude coordinates and defined the minimum spatial grid that could be considered in this study. MOLA topography data (8) and entry occultation pressure profile data (9) [MGS Radio Science Team (1999)Atmospheric Temperature and Pressure Profiles (http://nova.stanford.edu/projects/mgs)] were used to determine the surface pressure variations with altitude. Mars Atmospheric Water Detector (MAWD) data from the Viking Orbiters were also used as a global annual water vapor distribution [Planetary Data System Atmospheres Data Set Catalog (1999) Viking Orbiter Mars Atmospheric Water Detector data, Vol. 3001 (http://atmos.nmsu.edu/catalog.html)]. A map of channels (adapted from ref. 10) was included as well to relate the results to the existing network of channels.

**Methodology.** Liquid water is possible when the temperature is above 0°C and below the boiling point. No equilibrium is possible for pressures less than 6.1 millibar. To determine which locations

Abbreviations: GIS, Geographical Information System; MOLA, Mars Orbital Laser Altimeter; MGS, Mars Global Surveyor; IRTM, Infrared Thermal Mapper; MAWD, Mars Atmospheric Water Detector.

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match these criteria during the course of the martian year, we need the temperature and pressure at each point on the surface during the year. Simple models of suitable surface temperatures and suitable pressures were developed, and the intersection of these determines the spatial locations where liquid water would be possible. The first step in determining what locations match these criteria during the course of the martian orbit was to estimate the temperature and pressure at each point on the surface. A simple model of surface temperatures and pressures was developed to get estimates of these variables at each location in the martian orbit. The intersection of these data layers determined the spatial locations where liquid water would be possible. This calculation was then repeated at 1° steps of solar longitude ($L_s$), and the total segment of the orbit where these conditions were met was compiled. This result was then combined with the remaining data layers listed in the previous section in a few additional GIS functions, primarily the cross tabulation of several layers. GIS functions allow one to obtain further information from geographically coded data. The intersection of suitable temperatures and pressures is a GIS task: finding the spatial locations where some set of conditions is met. The relationship between the possible locations of liquid water on the surface of Mars and water vapor concentration and channel distribution was investigated by overlaying, masking, or intersecting several data layers.

**Temperature.** IRTM-derived annual maximum and minimum surface temperatures (7) were the basis for the temperature cycle (Fig. 1). Surface temperature depends on the thermal properties of the surface (thermal inertia and conductivity) but is determined by the amount of solar insolation at the martian surface. At a given latitude ($\alpha$), the solar insolation ($E$) is a function of solar longitude ($L_s$), the inclination of the planet relative to the Sun ($\beta$), and the distance to the sun. The latter is determined by the eccentricity of the planet's orbit ($e$), 0.093 for Mars, and the inclination of Mars's equator to its orbit, $i$, is 25.2° (11). The planet's inclination relative to the Sun at any point in its orbit can be written

$$\beta(L_s) = i \sin(L_s).$$

The polar equation of an ellipse (12) was used for the relative Sun–Mars distance,

$$r(L_s) = a(1 - e^2)/(1 + e \cos(L_s + 90°)),$$

where $a$ is the semimajor axis, and 90° has to be added to $L_s$ so 0° is northern hemisphere spring.

Solar insolation is also a function of incidence angle ($\theta$), so $E \propto r^{-2} \cos(\theta)$, where $\theta$ is the total angle between the point where sunlight is normal to the surface and the point under consideration. By using the Pythagorean theorem, this angle, $\theta$, can be written

$$\theta^2 = (\alpha - \beta)^2 + \varphi^2.$$

When the total is computed for 360° of longitude, $\varphi$, the solar radiation at Mars can be seen as a band that moves north and south with the seasons and peaks in the southern hemisphere summer. Because minimum and maximum insolation should correspond to minimum and maximum surface temperatures, the temperature at any position in the orbit can be scaled from the comparative value within the insolation range.

**Pressure.** The other parameter modeled was the surface pressure. Although the surface altitude largely determines the surface pressures on Mars, annual variations are driven primarily by the heating and cooling of the polar caps (5, 13, 14). Viking 2 Lander pressure data (5) in combination with the MOLA topography data (Fig. 2) were used to derive altitude-dependent surface pressures. From the integrated hydrostatic equation (14), the pressure at an altitude, $z$, can be written

$$P(z, L_s) = P_{VL2}(L_s)\exp(-(z - z_{VL2})/H),$$

where $H$ is the scale height for Mars, 10.8 km (13), $P_{VL2}(L_s)$ is the surface pressure at the Viking 2 Lander site at solar longitude $L_s$ (fit to a polynomial curve), and $z_{VL2}$ is the MOLA-derived altitude at the Viking 2 Lander site (−4 km).

**Analysis Through an Orbit.** These calculations were repeated at 1° steps of solar longitude to compute the temperature and pressure layers throughout a typical martian orbit. The data layers were then combined by using the phase diagram, leaving those areas where liquid water would be possible at the surface and would be stable indefinitely if the relative humidity were 100%. These intersection areas are those where the surface pressure is high (topography low) and the surface temperature is also high. The period where these conditions were met was then totaled. This intersection and summing process is illustrated for $L_s = 0°$, 90°, 180°, and 270° in Fig. 3. The total image at the bottom of this figure indicates the fraction of the martian orbit where the liquid water conditions were met, shown in more detail in Fig. 4. The maximum period was 34% and occurred in the southeastern portion of Utopia Planitia. The spatial extent of the regions is restricted by temperature (solar insolation) to the north and altitude in the south. Only the northern lowlands and the plains are geographically low enough to have high surface pressures. Two locations identified in the southern hemisphere were the Argyre and Hellas Planitas.

**Comparison to Atmospheric Water Vapor.** This map of where liquid water may be possible was then overlaid on the water vapor concentration data. Before the map was overlaid, however, the raw Viking MAWD water vapor concentration point data were spatially averaged. The raw MAWD data were sparse over much of the martian surface, and only one measurement was available for most of locations where there were data, so the data were spatially averaged before they were resampled to the 2° spatial grid. The result of this smoothing was an image with more continuous data coverage. Water vapor concentrations on Mars were generally higher in the northern hemisphere throughout the period the orbiters collected data except around areas that are topographically high. When the maps of the stability of liquid water and water vapor were combined (Fig. 5), two regions of overlap can be seen, one in the northern plains: Arcadia Planitia (on the left and far right of the image) and the second in Acidalia Planitia (in the center). The seasonal variation was not included in this analysis because there were insufficient MAWD data points to generate seasonal imagery; because of this, the correspondence between the water vapor and temperature and pressure is not known.

**Comparison to Fluvial Features.** More interestingly, when the map of the stability of liquid water liquid was overlaid on a channel map (Fig. 6, adapted from ref. 10), most of the major martian channels were found to lie within the areas identified as possible locations where liquid water could be stable at the present.

## Discussion

On the basis of temperature data from the Viking orbiter mission and year-round pressure readings from the Viking Lander coupled with recent topography data, we have computed the locations and times on Mars that water is stable in liquid form. Water is stable over large areas on the edge of the northern lowlands and in the Isidis, Argyre, and Hellas plains. Moreover, in about 50% of these areas, liquid water may be possible during

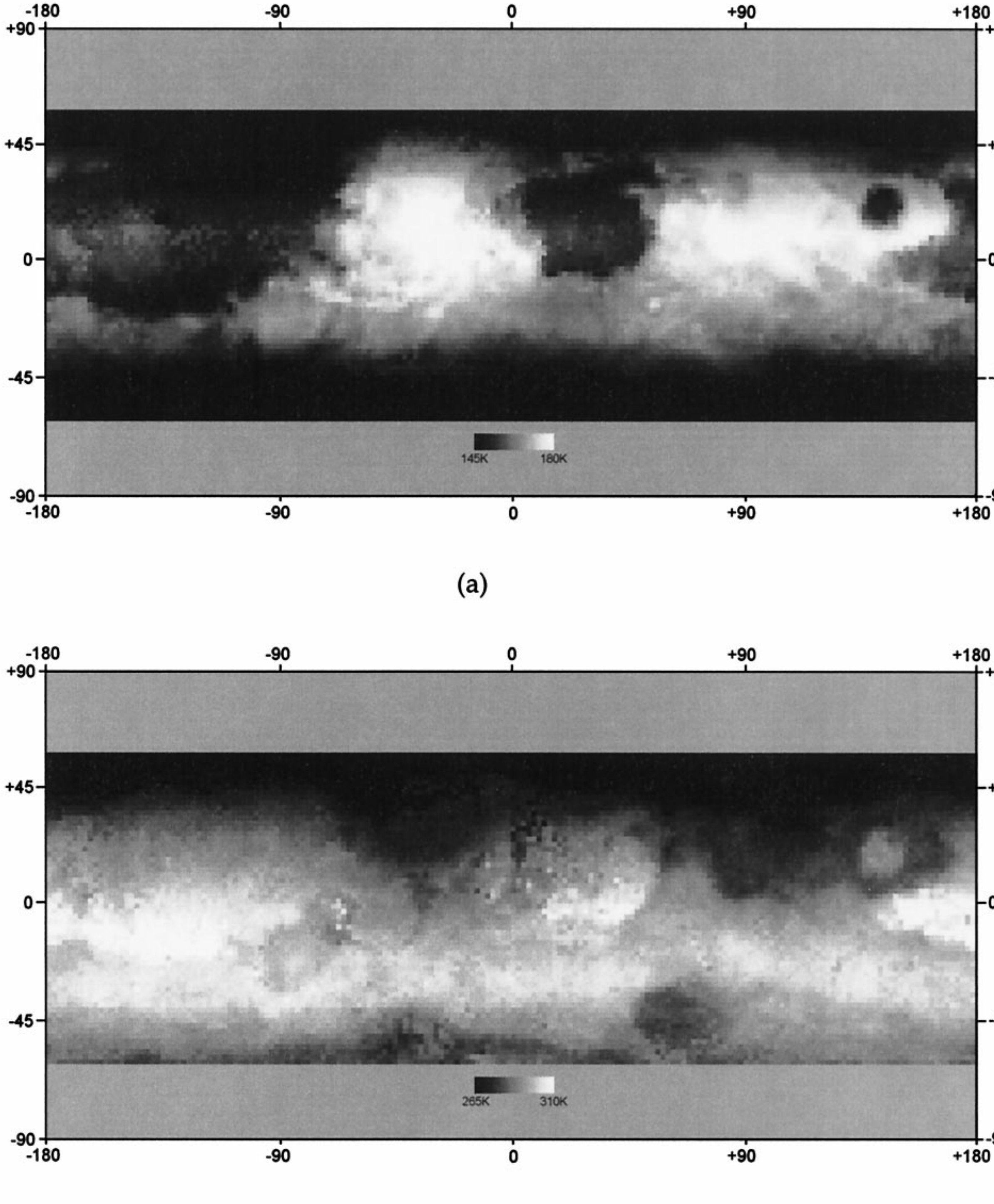


**Fig. 1.** IRTM annual minimum (*a*) and maximum (*b*) surface temperatures (7). Data were not available poleward of 60°N and S.

more than 5% of the martian orbit. These results do not indicate that water is present at these locations, only that, if it were present and heat sources were sufficient to bring the water in thermal equilibrium with the surface, the resulting liquid would be stable against freezing or boiling.

Given the dryness of the martian atmosphere, any liquid water present at the sites we have located is likely to be in the form of thin films that result from the melting of seasonal or nighttime frost deposits. The low water content of the atmosphere implies that even if the liquid is stable, it would evaporate in the atmosphere on a relatively short time scale (e.g., refs. 3 and 4). However, even such transient films of water could have important geochemical implications. The few minutes each year during which a film of liquid water is present at these sites could

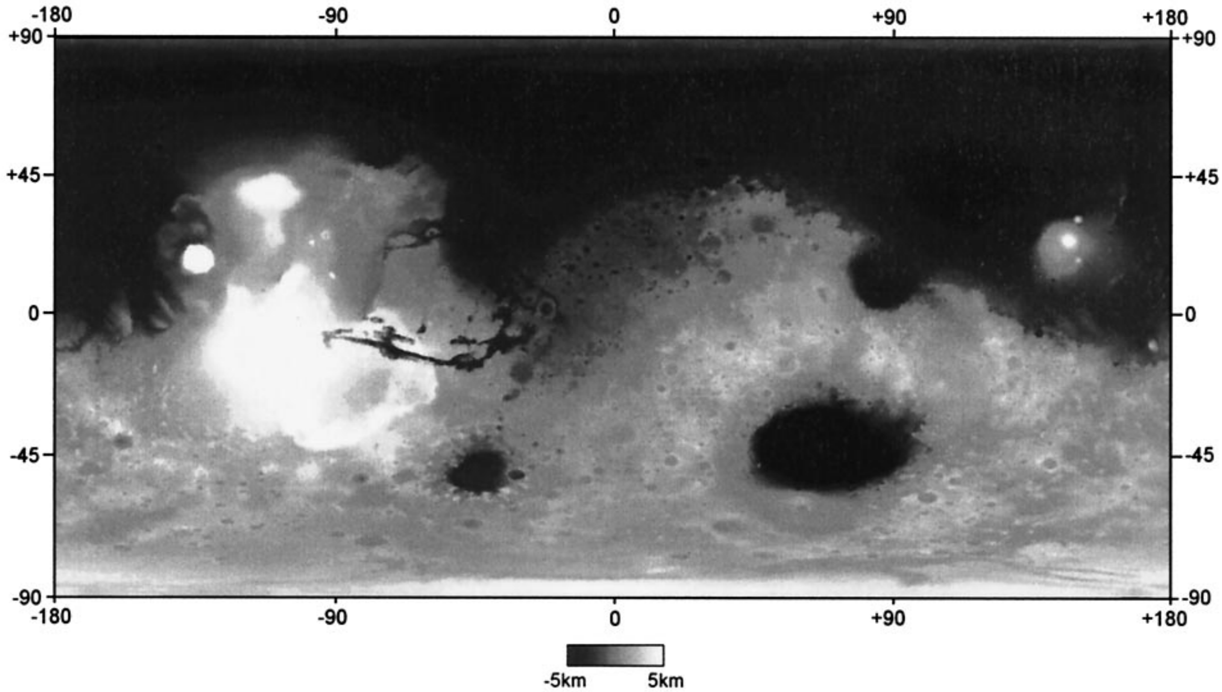


**Fig. 2.** MOLA topography data.

completely dominate the chemistry of the surface because of the importance of liquid water in mediating chemical weathering. Important reactions that might depend on the presence of liquid water include hematite formation, carbonate formation, and the acid weathering that appears to have occurred on Mars.

Thus, the sites we have identified as locations of liquid water stability may have high soil concentrations of hematite and carbonate. The analysis of samples from these sites could reveal the presence of these interesting minerals and test for the action of liquid water in the chemical weathering of Mars at the present.

Although chemically important, thin films of transient liquid water are not likely to provide suitable sites for life. However, there is clear evidence that in the past, climate conditions on Mars may have been more clement. Sites that are currently just

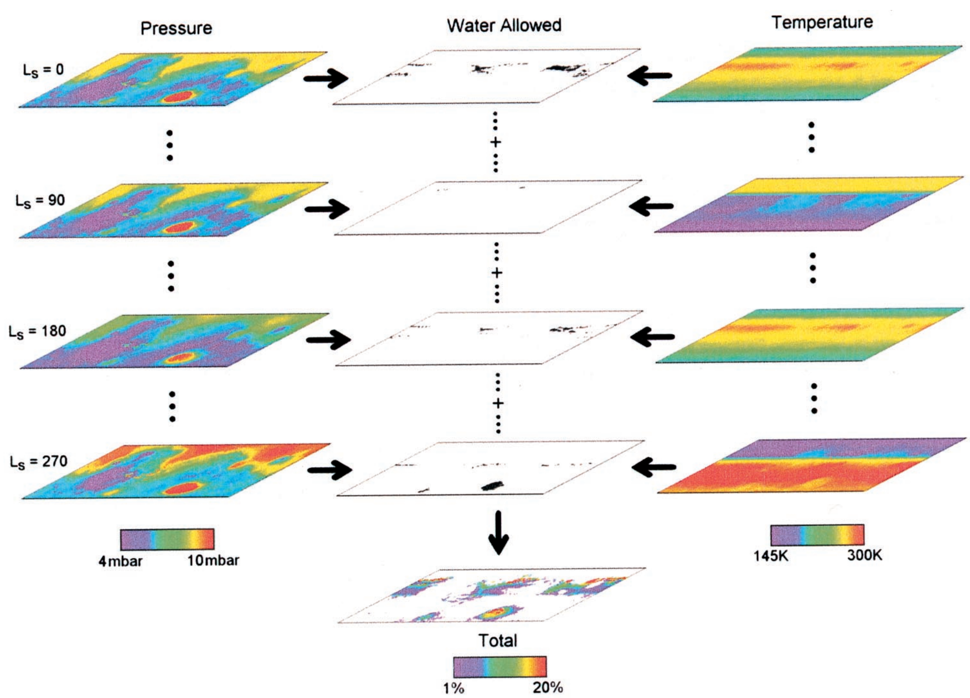


**Fig. 3.** At each degree of $L_s$, the pressure and temperature were combined to determine those areas where liquid water would be possible. The intersection regions were then aggregated to summarize at what fraction of the martian year the conditions were met.

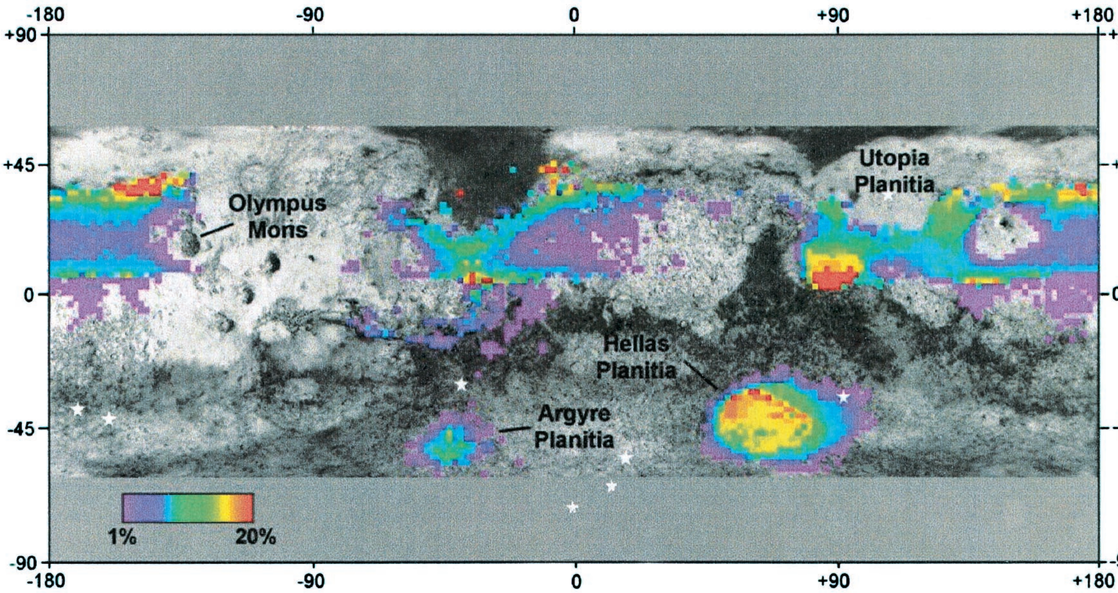


**Fig. 4.** Locations where liquid water could be possible by using the Viking Lander 2 surface pressure profile and Viking Orbiter IRTM temperature variations combined with MGS MOLA topography data. Purple areas were suitable for liquid water for 1% of the martian orbit and red areas for at least 20%, whereas the maximum, 34%, occurred in the southeastern portion of Utopia Planitia. Dao Vallis was the only region also identified by Malin and Edgett (ref. 1, sites indicated by stars).

able to support liquid water may have been more favorable in the past and are thus good targets for a search for evidence of past life.

The relation between present sites for liquid water and fluvial activity in the past may explain the favorable correlation between locations that allow for the existence of liquid water today and the distribution of fluvial channels. This correlation may indicate that the formation of fluvial features is controlled by the atmospheric conditions that allow for liquid water stability rather than by the distribution of geothermal sources of ground water. In locations where liquid water is unstable to freezing or boiling, the surface outflows do not propagate, and no fluvial feature is formed.

The fluvial features reported by Malin and Edgett (1) seem to be the youngest such features on the planet, and it is of interest to compare the distribution of these features (figure 1 of ref. 1) with our regions of liquid water stability (Fig. 4). With the exception of the Dao Vallis on the northeastern rim of the Hellas Basin, there is no overlap. Because our stability criteria were for pure water, we suggest that the liquid that formed the recent fluvial features was more stable than liquid water. This would be consistent with saturated brine solutions. For example, NaCl

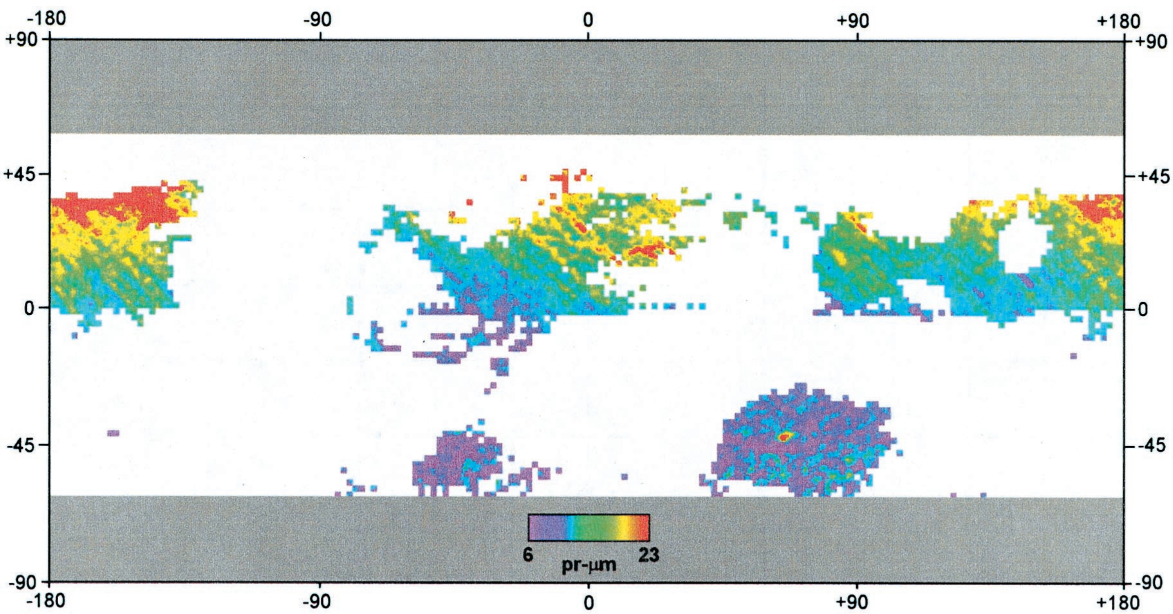


**Fig. 5.** Relatively high MAWD-measured water vapor concentration values were found to be located within the areas where liquid water was found to be possible.

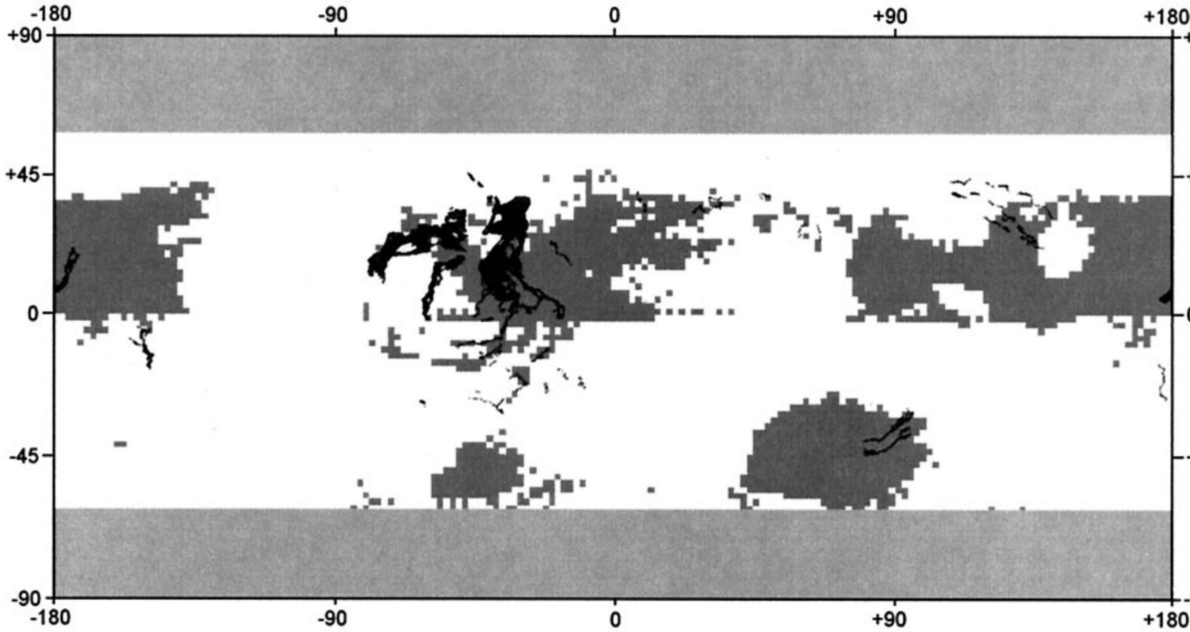


**Fig. 6.** Most of the major martian channels (black) lie within the areas identified as possible locations for liquid water (dark gray).

brines could flow for temperatures down to −20°C and pressures to 1 millibar. Interestingly, the only permafrost springs on Earth that are not driven by volcanic heat sources have salt-rich outflows (15). We would expect, therefore, that large salt accumulations may be associated with these young martian outflows.

Our preliminary analysis has pointed to the role of atmospheric pressure and surface temperature in controlling the stability of liquid water. Our analysis was based entirely on remote sensing data sets. Further analysis combining these data with martian global circulation models could produce more refined estimates of liquid water stability and more confident extrapolations to conditions under a thicker, warmer atmosphere in the past or future.

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ASTRONOMY

SPECIAL FEATURE

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