# 9 Polar Lakes, Streams, and Springs as Analogs for the Hydrological Cycle on Mars

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The extensive fluvial features seen on the surface of Mars attest to the stable flow of water on that planet at some time in the past. However the low erosion rates, the sporadic distribution of the fluvial features, and computer simulations of the climate of early Mars all suggest that Mars was quite cold even when it was wet. Thus, the polar regions of the Earth provide potentially important analogs to conditions on Mars during its wet, but cold, early phase. Here we review studies of polar lakes, streams, and springs and compare the physical and geological aspects of these features with their possible Martian counterparts. Fundamentally, liquid water produced by summer melts can persist even when the mean annual temperature is below freezing because ice floats over liquid and provides an insulating barrier. Life flourishes in these liquid water habitats in Earth's polar regions and similarly life may have been present in ice-covered lakes and permafrost springs on Mars. Evidence for past life on Mars may therefore be preserved in the sediments and mineral precipitates associated with these features.

## 9.1 Polar Hydrology

There are several regions on Earth where mean annual temperatures are well below freezing and yet liquid water persists in these locales. Such polar regions provide an excellent analog to study the hydrological cycle under conditions that have prevailed in the polar desert environment of Mars. In this review we will focus on two areas including Axel Heiberg Island in the Canadian High Arctic and the McMurdo Dry Valleys of Antarctica. In both locations the mean annual air temperatures are extremely low and range from –15°C to –20°C on Axel Heiberg Island and from –15°C to –30°C at the dry valley bottoms in Antarctica [1, 2]. At both the Arctic and Antarctic sites the precipitation is low creating desert conditions. The site on Axel Heiberg Island lies within a region of thick, continuous permafrost and two sets of springs flow throughout the year with constant temperature and flow rates. In the McMurdo Dry Valleys of Antarctica, summer streams of glacial meltwater create large perennially ice-covered lakes. Important lessons regarding the search for life on Mars, past or present, are gleaned from studies of these terrestrial ecosystems.

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### 9.1.1 Arctic Springs

There are two sets of cold saline springs on Axel Heiberg Island located at approximately 79°N, 90°W [3] (Fig. 9.1). One group, located at the base of Colour Peak, consists of approximately 20 spring outlets 30–40 m above sea level that flow via a series of mineralized pipes and troughs down the south-facing slope of Colour Peak into Expedition Fiord. The second group is located at the base of Gypsum Hill 11 km east of Colour Peak. At Gypsum Hill the springs and seeps discharge from approximately 40 outlets along a band nearly 300 m long and 30 m wide and flow onto the Expedition River floodplain. The individual spring outlets are tens of centimeters in diameter.

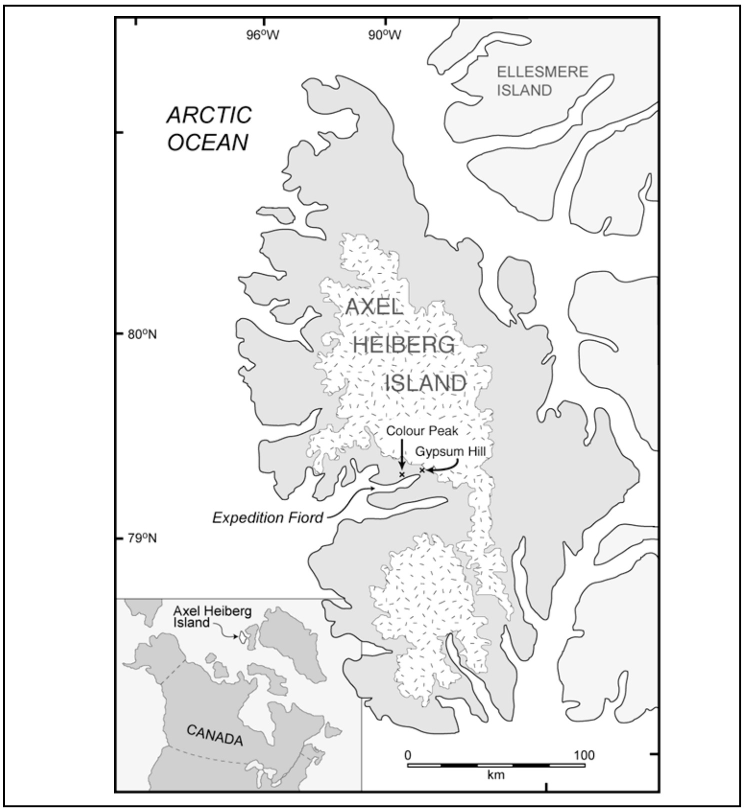


**Fig. 9.1** Study site location map for the Axel Heiberg spring sites.

The mean annual air temperature in the vicinity of the springs is –15°C and the region is characterized by thick, continuous permafrost reaching depths of nearly 600 m [1, 4]. Despite the cold conditions, the spring water flows at a constant temperature and rate all year (as shown in Fig. 9.2) discharging an anoxic brine with a near neutral pH and vent temperatures varying between –4°C and 7°C [3].

The combined flow of all outlets at Gypsum Hill and Colour Peak is 10–15 l/sec and 20–25 l/sec, respectively [3]. During the winter the Colour Peak discharge flows into the waters of the Expedition Fiord whereas the Gypsum Hill flow emerges from the springs and flows onto the Expedition River floodplain. Below freezing temperatures result in the formation of a residual icing that has reached 300,000 $m^2$ in size and the growth of numerous seasonal frost mound structures in the vicinity of the vents [3, 5]. Salts associated with the brine are deposited as a result of evaporative and freeze fractionation. During the summer months when air temperatures are above freezing the icing and mineral deposits are removed almost entirely by runoff and deflation.

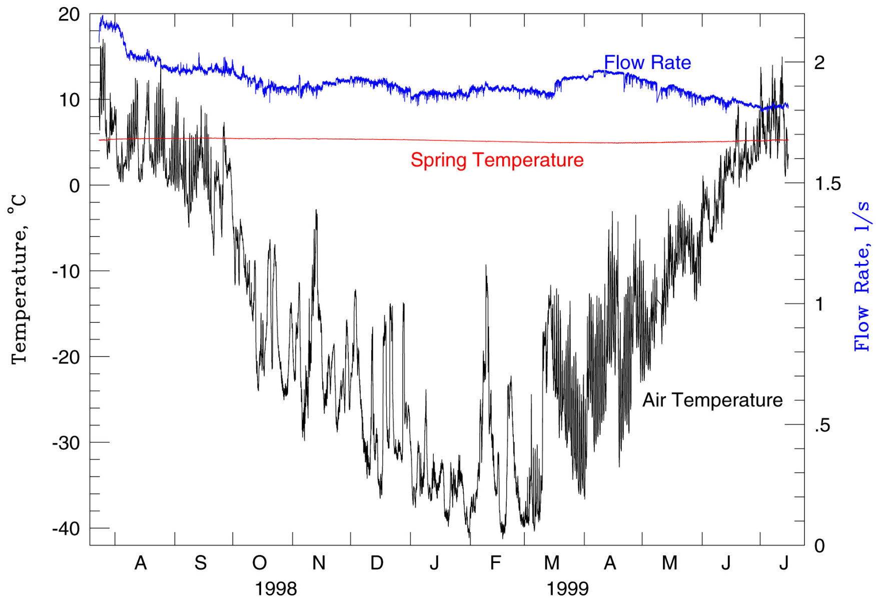


**Fig. 9.2** Temperature and flow rate of the cold saline springs on Axel Heiberg Island. Air temperature is shown as well [1].

Analysis of the dissolved gases and bubbles in the spring water indicates that the source of the water is a combination of subglacial melt and lake water. Two nearby glacially dammed alpine lakes, Phantom Lake and Astro Lake, provide large reservoirs of water and have basins residing upon gypsum-anhydrite piercement structures [1, 6]. Lake water is transported into the subsurface via permeable strata associated with the piercement structures. The water continues to flow along the subsurface salt strata and is transported to the spring sites. The water accumulates dissolved salts as it flows through this subsurface layer and emerges with a salinity value about five times that of seawater.

The composition of dissolved gases in the springs indicates that only 50 % of the water comes from lake water and that the other 50 % comes from glacial ice that has melted while isolated from the atmosphere [6]. The dissolved gases in lake water reflect the equilibrium with the atmosphere based on the relative solubility of each gas. In contrast, air trapped in glacial ice has an atmospheric composition other than for Ne and He. These latter two gases are soluble in ice and would therefore be expected to diffuse through the ice. As an example, the ratio of $N_2$/Ar in lake water in equilibrium with the atmosphere is 37 while for air it is 84.

Interestingly, the springs on Axel Heiberg Island flow all year with little variation in their temperature and are not associated with volcanic activity [1]. Andersen et al. [1] show that this can be explained by considering the flow through the subsurface salt layers. The flow enters the subsurface via the permeable strata associated with the salt diapirs that reside beneath the lakes, glaciers and ice-cap. At this depth the groundwater temperature is 0°C. The flow then proceeds below the surface to depths of at least 600 m and is warmed by the local geothermal gradient to temperatures up to 6°C. The flow rate to the surface is rapid enough that the temperature of the emerging groundwater does not change significantly from its initial value at depth.

Fluvial spring systems in a polar desert environment likewise may exist on Mars (Fig. 9.3). Geologically young small-scale features resembling terrestrial water-carved gullies were observed by the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) and first reported by Malin and Edgett [7]. The superposition of the gullies on geologically young surfaces such as dunes and polygons as well as the extreme scarcity of superposed impact craters indicate the relative youth of the gullies, suggesting that the gullies formed within the past few million years [7, 8, 9]. These features exhibit a characteristic morphology indicative of fluid-type erosion of the surficial material and liquid water has been suggested as a likely fluid [7, 9–22]. The gullies are found exclusively poleward of 30° latitude in both the northern and southern hemispheres [8, 18]. These regions correspond with the areas of ground ice stability on Mars [23], suggesting that gully formation may be intrinsically tied to the presence of subsurface ice in the Martian polar desert environment.

Generally, gully morphology can be divided into alcove, channel, and depositional apron regions [7]. The theater-shaped alcove generally tapers downslope and may represent a fluid source region. The channels typically begin at the base of the alcove. Channels appear incised into the slope surface, having steep walls with a distinctive V-shaped cross section [7, 18]. Near the alcove-channel transition there is sometimes evidence of channels streamlining around obstacles and anastomosing channel patterns [7, 18]. The depositional aprons typically have a triangular shape which broadens downslope. The aprons appear smooth on a decameter scale but smaller swells and swales are observed that are oriented downslope along the long axis of the gully [7, 18]. The aprons sometimes extend beyond the base of the gully slope, and channels sometimes cut into the apron structure [7, 18].

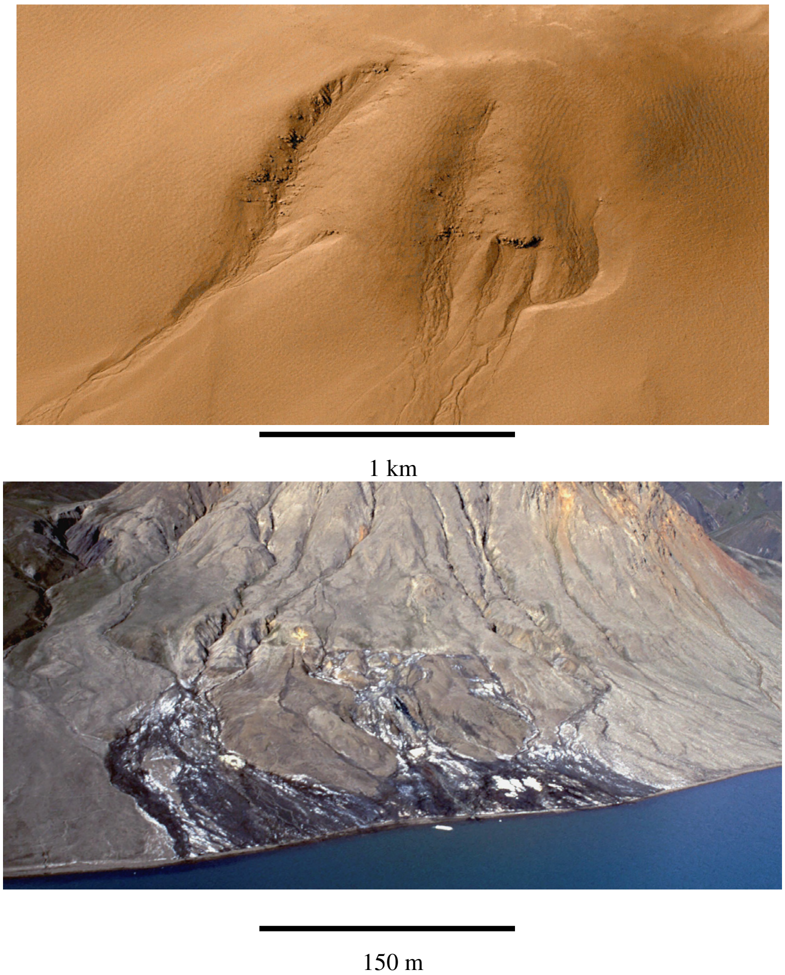


**Fig. 9.3** Top: Gullies on Mars (MGS MOC Release No. MOC2-238). Bottom: Cold permafrost springs on Axel Heiberg Island.

Numerous models have been proposed which invoke various physical processes, as well as various agents of erosion, to explain the origin of the Martian gullies and the origin of the erosive agents. Musselwhite et al. [24] proposed that a liquid $CO_2$ aquifer could form capped by a dry-ice barrier which seasonally breaks out rapidly releasing the liquid $CO_2$ from the side of the slope. Malin and Edgett [7] and Mellon and Phillips [21] suggested that a shallow aquifer several hundred meters deep could be the source of liquid water that ultimately carves the gully features, while Gaidos [13] argued for a deep aquifer. Costard et al. [12] likewise proposed liquid water as the principle agent of erosion, but suggested that melting shallow ground ice is the source of the water. Gilmore and Phillips [14] also rely on the melting of near-surface ground ice and proposed that meltwater would percolate to an impermeable layer that dips towards an exposed slope wall. Lee et al. [20], Hartmann et al. [15] and Christensen [11] suggested that the gullies may be formed by liquid water from dissipating snowpacks. In addition, Treiman [25] proposed that mass-wasting is also a candidate mechanism of gully formation.

However, a thorough analysis of Mars Global Surveyor (MGS) spacecraft data from the Mars Orbiter Camera (MOC), Mars Orbiter Laser Altimeter (MOLA), and Thermal Emission Spectrometer (TES), as well as an analysis of terrestrial springs in polar desert environments suggests that liquid water emanating from an underground aquifer is the most robust explanation regarding the formation of the Martian gullies [18]. A shallow aquifer can occur where competent rock layers can trap water below ground upslope from a ridge, while maintaining an overlying dry and thermally insulating soil layer. The dry insulating overburden allows geothermal heat to maintain liquid water within the confined aquifer at only a few hundred meters depth [18]. An ice-cemented-soil plug between the aquifer and slope surface develops where ground ice is generally stable. Freezing cycles induced by obliquity variations cause increased fluid pressure in the aquifer to fracture the ground ice plug and allow liquid water to emerge from the side of a slope to create the gully [21].

### 9.1.2 Antarctic Lakes

The McMurdo Dry Valleys of Antarctica are the largest ice-free region on the continent. Mean annual valley bottom temperatures range from −15 to −30°C and summer maximum temperatures are a few degrees above freezing [2]. The precipitation is low at 1−2 cm water equivalent and occurs almost entirely as snow. This is the most Mars-like environment on Earth. Despite these conditions there is an active hydrological cycle in these valleys which supports the presence of large ice-covered lakes with rich microbial communities on the lake bottom [26−29], in the water column [27, 30] and within the ice cover [31, 32]. A few percent of the light incident on the surface of the lake penetrates the ice cover [33, 34] but this is adequate for photosynthesis. The perennial ice cover inhibits the exchange of gases between the water column and the atmosphere. As a result gases carried into the lake in solution in the meltwater are concentrated, including $O_2$ [35], $N_2$ [36], and Ar [37] and biologically produced gases such as $O_2$ [38] and $N_2O$ [39].

The hydrological cycle in the dry valleys begins with snow carried in primarily from the coast. The snow that falls at low elevations sublimes away without creating any appreciable flow. At high elevations the snow accumulates and then flows downward as glaciers, as can be seen in Fig. 9.4. These glaciers provide the source of meltwater in the summer when air temperatures rise above freezing. With air temperatures above freezing, and of course with total pressure well above the triple point of water, the flow from the glaciers can travel a considerable distance. This process has formed the Onyx River in Antarctica (Fig. 9.4). The rivers and streams flow into the lowest point in the valleys and form lakes. Due to the lower temperatures the lakes are perennially ice-covered. However the lakes are not frozen solid. Indeed the ice covers are only 4−5 m thick and overlie 30−70 m of the water column. The thickness of the ice cover was explained by McKay et al. [40] by a simple annually averaged energy balance shown schematically in Fig. 9.5. The energy balance equation is

$$k\mathrm{d}T/\mathrm{d}z = (1-r)(1-a)S\mathrm{e}^{-z/h} + Fg + vL\rho\,, \qquad (1)$$

where $k$ is the thermal conductivity of the ice cover, $T$ is the temperature, $z$ is the depth measured downward, $r$ is the fraction of the surface covered by dirt, $a$ is the albedo of the ice cover, $S$ is the solar energy reaching the surface, $h$ is the extinction length for light, $Fg$ is the geothermal flux, $v$ is the rate of ablation from the top of the ice cover, $L$ is the latent heat of fusion for water, and $\rho$ is the density of ice. For the dry valley lakes [40, 41] the nominal values of these parameters are $r$ = 0.1, $a$ = 0.3, $S$ = 90 W m$^{-2}$ but considering only the visible portion of the sunlight which is capable of penetrating the ice cover $S$ = 45 W m$^{-2}$ [41], $Fg$ is negligible at ~0.08 W m$^{-2}$, $v$ = 30 cm/year. If Eq. 1 is integrated across the ice cover, the steady state annual average thickness of the ice can be computed and agrees with the observed ice cover thickness on the lakes.

The primary energy input into the lake is the latent heat carried by the inflowing meltwater. This latent heat is released when the water freezes at the bottom of the ice cover. In steady state the rate of freezing at the bottom of the ice cover equals the rate of ablation from the top of the ice cover ($v$). The ice cover thickness then adjusts so that, in steady state, the energy loss by conduction balances the energy input.

The key to the existence of such ice covered lakes is summer temperatures above freezing. In the dry valleys the value of the yearly degree days above freezing varies from 40 to 90°C-days [2, 42, 43]. If the temperature in the dry valleys were to fall such that the summer temperature no longer rose above freezing then the lakes would no longer be resupplied with liquid and would sublime away, maintaining liquid water under an ice cover of approximately the same thickness.

The energy balance model of the ice cover has also been applied to the thick ice cover of Lake Vida (19 m) [41]. There the ice is sealed and no meltwater flows below the ice cover in the summer. The ice cover overlies a brine solution and so the temperature of the bottom of the ice is not constant at 0°C as is the case for the other dry valley lakes. Instead the ice-brine interface varies with the concentration of the brine.

**Fig. 9.4** Perennially ice-covered Lake Vanda in Wright Valley, Antarctica. The Onyx River flows into the lake for a few weeks each summer. The lake is about 5 km across. Photo by J. Robie Vestal.

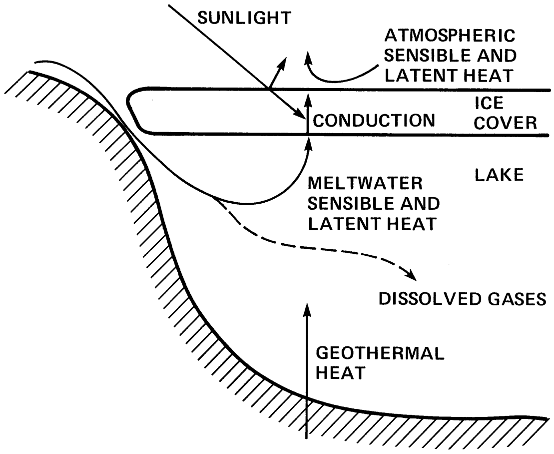


**Fig. 9.5** Energy balance of the ice cover on dry valley lakes.

When the ice becomes thicker the underlying brine becomes more concentrated, which lowers the equilibrium temperature at which the brine and ice coexist. The lowering of the temperature at the lower boundary of the ice decreases the steady state thickness of the ice. The net result is a negative feedback which stabilizes the ice cover thickness [41].

## 9.2 Martian Hydrology: Rivers and Lakes Without Rain

McKay and Davis [44] have applied this model to predict the existence of perennially ice-covered lakes on early Mars. For example, Gusev Crater may have once been an ice-covered lake (Fig. 9.6) (see also Chap. 10 by Cabrol and Grin). On Mars there would be seasonal variations even at the equator due to the relatively high eccentricity (0.1) of the Martian orbit. At higher latitudes the obliquity and eccentricity both cause seasonal effects. When the obliquity is at its maximum (45°) and perihelion occurs at summer then daily average temperatures above freezing can occur even if mean annual temperatures are as low as −40°C [44]. The modeling results suggest that ice-covered lakes on Mars could have persisted up to 500 Ma after mean annual temperatures fell below freezing. Indeed, even if mean annual temperatures on Mars were never above freezing and there was never any rain on Mars, large ice-covered lakes could have existed replenished by a snow-based hydrological cycle. As in Antarctica, these lakes could have provided a habitat for life (see Fig. 9.7). Moore et al. [45] developed a plausible regional scale hydrological cycle in the Chryse region of Mars patterned after the dry valleys. In their model moisture, which evaporated from the ice, covered northern plains accumulates to form glaciers which provide a source of meltwater. The biological perspective on the history of water on Mars [46] suggests that the evidence for life accessible on the surface would be in sediments from such lake deposits [47].

It is important to note that such lakes cannot exist on Mars today due to the low pressure. The pressure on Mars is close to the triple point pressure of water (610 Pa). At these low pressures meltwater is not generated from the heating of glacial ice and instead the ice sublimes [48, 49]. There are regions on Mars where conditions would allow for liquid water [50, 51] but no ice is present at these locations.

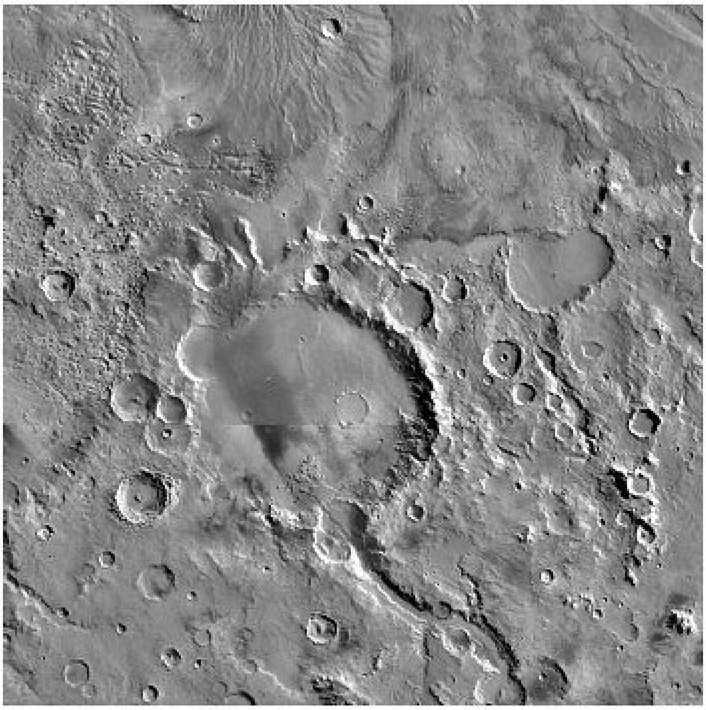

**Fig. 9.6** Gusev Crater on Mars could have been an ice-covered lake similar to those seen in the dry valleys of Antarctica. A river, Ma'adim Vallis, has entered the crater from the lower right. The heavily cratered terrain surrounding Gusev is inconsistent with rain - rivers and lakes without rain.

**Fig. 9.7** Benthic microbial mat communities beneath the ice covers of Lake Vanda (top) and Lake Hoare (bottom) in the McMurdo Dry Valleys. Microbial communities similar to these played a major role in shaping Earth's earliest biosphere. Similar communities may have evolved on Mars during a more clement period when liquid water was stable at the surface.

## 9.3 Conclusions

Even when Mars was wet it was probably cold. Thus the hydrological cycle in the coldest regions on Earth provides the best analogs for the possible Martian hydrology. From studies of springs, rivers and lakes in the polar regions we have developed quantitative models that show how liquid water could have persisted on Mars even if mean annual temperatures were below freezing. The fact that ice floats and the existence of even transient temperatures above freezing are the keys to liquid water, and possibly life, on Mars.

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