Subsurface Habitable Zone on Mars: Depth Ranges for Liquid Water and the Role of Salinity

Introduction

The search for liquid water on Mars is a cornerstone of astrobiology, as it is essential for potential habitability. The subsurface habitable zone is defined as the range of depths where temperature and pressure conditions allow water to exist in a liquid state, as governed by its phase diagram. This report compiles research on the depth ranges where liquid water may be found on Mars, considering temperature, pressure, and the critical role of water salinity, which lowers the freezing point and expands the habitable zone.

Martian Subsurface Conditions

Temperature and Geothermal Gradient

Mars' surface temperature averages around -60°C (213 K), with significant variations by latitude and season, ranging from -143°C at the polar caps to occasionally +27°C in equatorial soils (Mars Temperature Overview). Below the surface, the temperature increases due to the geothermal gradient, estimated at approximately 15 K/km based on a mean heat flow of 25–35 mW/m² and a crustal thermal conductivity of 2.0 W m⁻¹ K⁻¹. This gradient implies that temperatures reach the freezing point of pure water (273 K) at depths of about 3.5 kilometers, assuming a surface temperature of 213 K.

Pressure Considerations

On Mars' surface, the atmospheric pressure is approximately 600 Pa, below the triple point of water (611.657 Pa), making liquid water unstable. In the subsurface, pressure increases with depth due to the weight of overlying rock (density ~~3000 kg/m³, gravity ~3.71 m/s²). Calculations suggest that at just 10 meters depth, the lithostatic pressure reaches ~111,300 Pa (~~1.1 atm), sufficient for liquid water stability. However, the relevant pressure for liquid water is the pore pressure within subsurface aquifers or fractures, which may approximate lithostatic or hydrostatic conditions depending on the geological context.

The Martian Cryosphere

The Martian cryosphere is a layer of permanently frozen ground where temperatures remain below the freezing point of water or brines. Research by Clifford et al. (2010) provides revised estimates of its depth, influenced by heat flow, thermal conductivity, and salinity (Depth of Martian Cryosphere). For pure water (freezing point 273 K) and a heat flow of 15 mW/m², the cryosphere extends to:

- **Equator**: 0.5–4.5 km
- **Poles**: ~10.5 km

Below these depths, temperatures exceed 0°C, allowing liquid water if present. Regional variations, such as higher heat flow in volcanic areas (up to 200–300 mW/m²), can reduce these depths significantly.

Role of Water Salinity

Salts, particularly perchlorates, are abundant on Mars and lower the freezing point of water, enabling liquid brines at temperatures below 0°C. A study on the stability of liquid water under Martian conditions found that saturated sodium perchlorate ($NaClO_4$) solutions remain liquid between 240 K and 275 K, even at low pressures (Stability of Liquid Water). For brines with a freezing point of 252 K, the cryosphere base is shallower:

- **Equator**: 0.12–2.6 km (for 30 mW/m² heat flow)
- **Poles**: ~9.2 km

For highly saline perchlorate brines (eutectic temperature 203 K), the cryosphere may be absent equatorward of ~35° latitude, suggesting liquid brines could exist at very shallow depths, potentially less than 1 km, provided sufficient pore pressure. This significantly expands the subsurface habitable zone in warmer, equatorial regions.

Evidence of Subsurface Liquid Water

Seismic Data from InSight

Recent studies using seismic data from NASA's InSight lander indicate large reservoirs of liquid water in the Martian crust at depths of 11.5 to 20 kilometers (Scientists Find Oceans). These reservoirs, found in tiny cracks and pores within fractured igneous rock, could contain enough water to cover Mars to a depth of 1–2 kilometers. The high temperatures at these depths (likely >273 K) and sufficient pore pressure support liquid water stability.

Subglacial Water Detection

Radar data from the Mars Express spacecraft's MARSIS instrument detected subglacial liquid water at approximately 1.5 kilometers beneath the South polar cap (Global Search for Liquid Water). The high pressure from overlying ice and possible geothermal heating maintain liquid water, potentially as a brine due to the presence of salts, which lower the freezing point.

Regional Variations

The depth of the habitable zone varies with local geology. In areas with recent volcanism, such as Olympus Mons, higher heat flow reduces the cryosphere's thickness, allowing liquid water at shallower depths. Conversely, in polar regions, colder surface temperatures deepen the cryosphere, pushing the habitable zone to greater depths.

Depth Ranges for Liquid Water

The following table summarizes the depth ranges where liquid water may exist, based on freezing point and geothermal conditions:

Freezing Point (K)	Heat Flow (mW/m^2)	Equatorial Depth (km)	Polar Depth (km)
273 (Pure Water)	15	0.5–4.5	~10.5
273 (Pure Water)	30	0.25–2.25	~5.25
252 (Brine)	15	0.24–2.6	~9.2
252 (Brine)	30	0.12–1.3	~4.6
203 (Perchlorate Brine)	15	Absent (<35° latitude)	~9

These ranges assume a geothermal gradient of ~15 K/km and account for variations in thermal conductivity (0.1–1.0 $W\ m^{-1}\ K^{-1}$). Depths are shallower in regions with higher heat flow or lower thermal conductivity.

Implications for Habitability

The presence of liquid water at these depths suggests potential habitats for microbial life, particularly in regions where brines allow liquid water at shallower, more accessible depths. Low-latitude, low-elevation areas like Valles Marineris or Amazonis Planitia are optimal for detecting groundwater due to thinner cryospheres and higher temperatures. However, accessing water at depths of 11.5–20 km, as suggested by InSight data, poses significant technological challenges, as even on Earth, drilling beyond 12 km is difficult.

Conclusion

The subsurface habitable zone on Mars, where liquid water can exist, spans depths from approximately 0.5 to 20 kilometers, influenced by the geothermal gradient, local geology, and water salinity. Salts like perchlorates lower the freezing point, enabling liquid brines at shallower depths, potentially less than 1 kilometer in equatorial regions. Seismic and radar evidence confirms liquid water at specific depths, such as 1.5 km under the South polar cap and 11.5–20 km in the deep crust. These findings enhance our understanding of Mars' potential habitability and guide future exploration efforts.

Key Citations

- Depth of the Martian cryosphere: Revised estimates
- Radar evidence of subglacial liquid water on Mars
- Scientists find oceans of water on Mars
- Stability of the Liquid Water Phase on Mars
- Mars Temperature Overview