Investigates the subsurface habitable zone on Mars, defined as the depth range where water can remain liquid, considering pressure and temperature conditions according to the water phase diagram. Also includes the impact of water salinity on this range.

The depth range where liquid water can exist on Mars varies from surface-level to 310 km depending on local temperature, pressure, and compositional conditions, with salt content extending these habitable zones.

Abstract

Liquid water on Mars appears viable within a widely varying subsurface depth range that depends on local thermal, pressure, and compositional conditions. Jones et al. (2011) report that global computational models yield habitable volumes spanning from the surface to depths of up to 310 km when pressure–temperature conditions and salt-induced freezing point depression are considered. In the south polar region, radar observations combined with modeling (Egea-González et al., 2022; Orosei et al., 2018) indicate stable liquid water near 1.3–1.5 km depth. Clifford et al. (2010) demonstrate that in low-latitude, low-elevation regions, the relatively thinner cryosphere permits a liquid water zone from about 2.3 to 4.7 km, while cooler polar regions may harbor such zones between 6.5 and 12.5 km. In addition, Travis et al. (2003) and related work note that local permafrost thinning may restrict habitable conditions to the upper few hundred meters. Across studies, increased salinity consistently expands the depth range for liquid water by lowering the freezing point, thereby enhancing subsurface habitability under Martian conditions.

Paper search

Using your research question "Investigates the subsurface habitable zone on Mars, defined as the depth range where water can remain liquid, considering pressure and temperature conditions according to the water phase diagram. Also includes the impact of water salinity on this range.", we searched across over 126 million academic papers from the Semantic Scholar corpus. We retrieved the 50 papers most relevant to the query.

Screening

We screened in papers that met these criteria:

- **Martian Subsurface Focus**: Does the study analyze temperature and/or pressure conditions beneath the Martian surface?
- **Water Phase Analysis**: Does the study examine liquid water stability conditions (including potential effects of dissolved salts)?
- **Depth Parameters**: Does the study include data or models that analyze conditions at different depths below the Martian surface?
- **Research Methodology**: Does the study employ at least one of the following: theoretical models/simulations, laboratory experiments simulating Martian conditions, or Mars mission observational data?
- **Data Type**: Does the study include quantitative data analysis (not purely descriptive or speculative content)?

- **Mars Relevance**: Is Mars' subsurface environment the primary focus of the study (not primarily about other planetary bodies or only surface/atmospheric conditions)?

We considered all screening questions together and made a holistic judgement about whether to screen in each paper.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Research Methodology**:

  Describe the primary research methodology used in the study:

- Identify the type of study (e.g., theoretical modeling, radar observation, experimental simulation)
- Specify the key analytical techniques or instruments used
- Note any computational or simulation approaches

If multiple methodological approaches are used, list them in order of prominence. If the methodology is not clearly stated, write "Methodology not clearly specified" and provide any contextual details available.

Examples of acceptable answers:

- "Radar measurements using MARSIS instrument on Mars Express spacecraft"
- "Computational phase space modeling of Mars pressure-temperature conditions"
- "Experimental brine thermodynamics combined with global circulation modeling"

- **Depth and Spatial Scope of Analysis**:

  Extract the specific depth range or spatial extent of the study's investigation:

- Record the minimum and maximum depths studied
- Note any geographic or regional specificity
- Include units of measurement (km, meters)

If multiple depth ranges are discussed, prioritize those most directly related to liquid water potential. If no specific depth is mentioned, write "Depth not specified".

Examples of acceptable answers:

- "0-310 km depth range"
- "Planum Australe region, centered at 193°E, 81°S"
- "Subsurface extending to approximately 5 km depth"

- **Water State and Conditions**:

  Describe the specific conditions under which liquid water is considered possible:

- Note temperature range
- Record pressure conditions
- Specify any salinity or chemical factors enabling liquid water
- Identify any specific mechanisms preventing freezing (e.g., dissolved salts, pressure)

If multiple water states or conditions are discussed, list them in order of likelihood or prominence.

Examples of acceptable answers:

- ”Liquid water maintained by dissolved salts and ice pressure, temperature below 0°C”
- ”Water activity below 0.6, eutectic temperatures of calcium perchlorate brines”

- **Habitability Assessment**:

  Extract the study's assessment of potential habitability:

- Quantify the estimated habitable volume or percentage
- Note any comparisons to terrestrial habitable zones
- Specify the type of life or biological conditions considered

Focus on direct statements about habitability potential. If no explicit habitability assessment is made, write ”No direct habitability assessment provided”.

Examples of acceptable answers:

- ”3.2% of present-day Mars potentially habitable for terrestrial-like life”
- ”Potential biosphere extending 7 times deeper than Earth's hot deep biosphere”

Results

Characteristics of Included Studies

Study	Study Type	Geographic Focus	Depth Range Investigated	Primary Parameters Studied	Full text retrieved
Jones et al., 2011	Computational phase space modeling	Global	0–310 km	Pressure-temperature phase space, habitable volume, salinity effects	Yes
Egea-González et al., 2022	Radar observation and computational analysis	Planum Australe (south polar cap)	1.3–1.5 km	Subglacial water stability, thermal properties, radar reflectivity	No
Travis et al., 2003	Computational 3D thermohydrologic modeling	Global (parameterized)	No mention found (permafrost thinned to 300 m)	Subsurface convection, permafrost thickness, hydrothermal processes	No

Study	Study Type	Geographic Focus	Depth Range Investigated	Primary Parameters Studied	Full text retrieved
Orosei et al., 2018	Radar observation and computational modeling	Planum Australe (193°E, 81°S)	~1.5 km	Subglacial lake detection, dielectric properties, radar signal analysis	Yes
Clifford et al., 2010	Theoretical modeling and radar observation	Global, focus on low latitude/low elevation	2.3–4.7 km (equator), 6.5–12.5 km (poles)	Cryosphere thickness, groundwater potential, heat flow, salt effects	No
Mellon and Phillips, 2001	Theoretical modeling	Global	Top few meters to (no mention found of full range)	No mention found	No

Study Type:

- Four studies used computational or theoretical modeling approaches.
- Three studies used radar observation, all in combination with computational or theoretical modeling.
- One study combined both theoretical modeling and radar observation.
- Some studies used multiple approaches.

Geographic Focus:

- Four studies had a global focus.
- Two studies focused on Planum Australe (south polar cap).
- One study specifically mentioned low latitude/low elevation regions as a subset of global.

Depth Range Investigated:

- Two studies investigated depths of 1–2 kilometers.
- One study investigated depths of 2–5 kilometers (equator) and 6–13 kilometers (poles).
- One study investigated depths of 0–310 kilometers.
- One study investigated permafrost thinned to approximately 300 meters.
- One study investigated the top few meters, but we didn't find mention of the full depth range for this study.
- We didn't find mention of a specified or complete depth range for two studies.

Primary Parameters Studied:

- Subglacial water or lake detection was investigated in two studies.
- Salinity or salt effects were investigated in two studies.
- Thermal properties or heat flow were investigated in two studies.

- Radar reflectivity, signal, or dielectric properties were investigated in two studies.
- Pressure-temperature phase space and habitable volume were investigated in one study.
- Subsurface convection or hydrothermal processes were investigated in one study.
- Permafrost thickness, cryosphere thickness, and groundwater potential were each investigated in one study.
- We didn't find mention of the primary parameters studied for one study.

Thematic Analysis

Regional Focus and Subsurface Water Detection

- Several studies (Orosei et al., 2018; Egea-González et al., 2022) focus on the south polar region (Planum Australe), where subglacial lakes have been detected by radar.
- These studies report that radar observations, combined with computational modeling, support the presence of stable subglacial water at depths of approximately 1.3–1.5 kilometers under the south polar cap.

Influence of Latitude, Elevation, and Surface Materials

- Clifford et al., 2010 report that low-latitude and low-elevation regions may have thinner cryospheres and shallower groundwater tables, which they suggest could increase the likelihood of habitable conditions.
- Chevrier et al., 2020 (referenced in the narrative, not included in the main table) also discuss the potential for habitable conditions in these regions.
- Jones, 2012 (referenced in the narrative) and Chevrier et al., 2020 suggest that equatorial and mid-latitude regions with specific surface materials, such as dark sand or duricrust, may support transient shallow liquid water.

Salinity and Water Stability

- Jones et al., 2011 and Clifford et al., 2010 both investigate the effects of salinity on the stability of subsurface water. Their modeling indicates that increased salinity can expand the depth range where liquid water is stable, due to the depression of the freezing point.
- The presence of salts is therefore a key factor in determining the potential habitable zone in the Martian subsurface.

Regional Variation in Habitable Zone Depth

- The spatial heterogeneity of heat flow, crustal composition, and salt distribution leads to significant regional variation in the depth and extent of the habitable zone, as reported by several studies.
- Abotalib and Heggy, 2019 (referenced in the narrative) identify the southern mid-latitudes and Valles Marineris as regions where deep briny aquifers may discharge to the surface, forming recurring slope lineae (RSL).

Summary of Key Insights

- The depth range for potential liquid water on Mars varies widely across studies, from the top few meters to over 300 kilometers, depending on local conditions and modeling assumptions.
- Salinity is consistently identified as a critical factor in expanding the habitable zone.

- There is substantial regional variation in the potential for habitable conditions, driven by differences in heat flow, crustal properties, and salt distribution.
- Most studies rely on modeling, with a smaller number incorporating radar observations to directly detect subsurface water.

: Jones et al., 2011, parameter details : Jones et al., 2011, salinity effects : Egea-González et al., 2022, subglacial water stability : Egea-González et al., 2022, radar reflectivity : Travis et al., 2003, subsurface convection : Travis et al., 2003, hydrothermal processes : Orosei et al., 2018, subglacial lake detection : Orosei et al., 2018, radar signal analysis : Clifford et al., 2010, cryosphere thickness : Clifford et al., 2010, salt effects

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