

Himalayan Permafrost as a Martian Analogue: GPR Insights from the Tsokar Lake Basin of Cold-Arid Ladakh

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Abstract

Permafrost in high-altitude regions of the Himalaya represents a sensitive and understudied component of the global cryosphere, with significant implications for landscape evolution, hydrology, and climate change. The cold-arid region of Ladakh provides a unique natural setting for investigating permafrost dynamics due to its extreme climatic conditions resembling those operating on early Mars. This study employs Ground Penetrating Radar (GPR) to characterize the subsurface structure, stratigraphy, and active layer dynamics of permafrost in the Tso Kar basin located in the northwestern Himalayan region in Ladakh. The Tso Kar is a topographically closed basin underlain by unconsolidated, frozen sediments that are highly susceptible to both surface and subsurface frost-related processes. Three subsurface units identified from radargram include the active layer, permafrost table at varying depths and frozen subsurface. The permafrost thickness reaches up to ~ 12 m, overlain by buried snow (firn) of up to ~ 1.5 m, while the permafrost table lies about at depths of up to ~ 3 m from the surface. The Profile-1 demonstrate the stable permafrost with shallow active layer overlaying the well preserved frozen subsurface; Profile-2 represent an intermediate stage showing an increase in the thickness of active layer due to seasonal thaw resulting in the generation of transition zone and talik showing the partial degradation of permafrost and; Profile-3 represent the advanced stage of permafrost degradation reflected by the debris rich active layer over an discontinuous and irregular permafrost table. In addition, the study documents the presence of lithalsa landforms, suggesting recent permafrost degradation and localized thaw dynamics. These features provide geomorphic evidence of past permafrost conditions and ongoing cryogenic processes. In the context of accelerating global climate change, particularly in high-altitude and arid environments, this study underscores the urgent need to reassess the stability and spatial variability of permafrost in regions such as Ladakh. The results contribute to a better understanding of Himalayan permafrost systems and further explore the applicability of these observations in the context of planetary analogues by comparing the Ladakh permafrost system with ice-rich terrains identified on Mars, particularly in regions such as Utopia Planitia and Arcadia Planitia. Beyond its regional importance, the integrated field and GPR dataset presented here provides a process-based terrestrial calibration framework by relating the well-constrained geological evolution of the Tso-Kar Basin to its subsurface radar facies. Establishing this relationship enables a more robust assessment of the geological processes capable of producing analogous radar signatures on Mars, thereby reducing uncertainty in the interpretation of planetary radar observations.

1. Introduction

Permafrost, defined as ground that remains at or below 0°C for at least two consecutive years, is a critical component of the global cryosphere that exerts strong control on geomorphic processes, hydrology, and landscape evolution in cold regions (Brown and Kupsch, 1992; Haeberli, 2000; Dobinski, 2011; Haeberli et al., 2017). While extensive permafrost terrains are well documented in the Arctic and sub-Arctic regions, high-altitude permafrost in mountain environments, particularly those within the Himalaya, remain comparatively underexplored despite their sensitivity to climate change (Haeberli et al., 2017; Palazzi et al., 2017; Wang et al., 2023; Pepin et al., 2025). The Himalayan cryosphere, often referred

to as the “Third Pole,” hosts discontinuous and sporadic permafrost whose spatial distribution and subsurface characteristics are still poorly constrained, especially in cold-arid regions such as Ladakh (Allen et al., 2016; Gruber et al., 2017; Pant et al., 2018; Dimri et al., 2021; Khan et al., 2021). In the global context, the Himalayan cryosphere represents one of the largest repositories of snow and ice outside the polar regions, extending across high mountain region of Asia and influencing major river systems that sustain nearly one-fifth of the world’s population (Shrestha et al., 2015; Thakur et al., 2017; Mukherji et al., 2018; Dimri et al., 2021; Vishwakarma et al., 2022). Unlike the relatively continuous permafrost of polar regions, Himalayan permafrost is highly heterogeneous, governed by altitude, aspect, lithology, and microclimatic variability (Thakur et al., 2017; Mukherji et al., 2018; Dimri et al., 2021). Recent studies emphasize that high-mountain permafrost is particularly vulnerable to ongoing climatic warming, leading to slope instability, infrastructure hazards, and changes in hydrological regimes (Schmid et al., 2015; Gruber, 2012; Gurber et al., 2017; Bolch et al., 2019, 2022; Sah, 2025). Permafrost stratigraphy holds critical significance in Earth Sciences due to its integral role in understanding the cryosphere, climate dynamics, and geomorphological processes that shape polar and high-altitude regions. The stratigraphic composition of permafrost comprising distinct layers of sediments and ice provides essential records of past climatic conditions and informs on the stability of the ground as well as associated biogeochemical cycles (Ping et al., 2015). With the onset of global warming, rapid changes in permafrost systems have been observed, implicating critical consequences such as the alteration of ecosystem services, acceleration of landscape transformation through processes like thermokarst, and the release of large carbon stores as greenhouse gases (Ge et al., 2025; Mathys et al., 2025; Saintenoy and Leger, 2025). Hence, detailed investigation of subsurface ice stratigraphy is vital to predict and manage the environmental impacts linked to permafrost thawing and degradation. Despite its importance, systematic geophysical characterization of Himalayan permafrost remains limited compared to Arctic benchmarks (Frolov, 2003; Wu et al., 2005; Briggs et al., 2017; Wang et al., 2019; Ge et al., 2025; Mathys et al., 2025; Saintenoy and Leger, 2025).

Recent global studies have demonstrated the effectiveness of geophysical techniques in mapping and monitoring permafrost (Vonder et al., 2002; Kneisel et al., 2008; Hauck, 2001, 2013; Sjöberget al., 2015; Briggs et al., 2017; Tourei et al., 2024). In particular, Ground Penetrating Radar (GPR) has emerged as a powerful, high resolution non-invasive tool for imaging subsurface stratigraphy, identifying ice-rich layers, and delineating the active layer thickness (Arcone et al., 1998, 2002; Moorman et al., 2003; Brandt et al., 2007; Monnier et al., 2008; Campbell et al., 2018; Sudakova et al., 2021; Saintenoy & Leger, 2025; Muzalevski, 2025). GPR based investigations in regions such as Alaska, Svalbard, and Tibetan Plateau have successfully revealed permafrost thickness, ice lenses, thaw dynamics, and subsurface heterogeneities (Navarro et al., 2014; Edemsky et al., 2021; Zhang et al., 2024; Saintenoy & Leger, 2025; Kang et al., 2025; Ryazantsey, 2025; Muzalevski, 2025; Xiao et al., 2025). These studies highlight the utility of GPR in characterizing frozen ground and understanding its response to climatic forcing. In the Himalayan context, permafrost studies are relatively sparse and often limited to surface observations, thermal modeling, or indirect proxies. The cold-arid environment of the Ladakh region, characterized by low precipitation, high elevation, and extreme temperature variability, provides favorable conditions for

permafrost development. However, the subsurface architecture and dynamics of permafrost in this region remain inadequately understood due to logistical challenges and limited application of high-resolution geophysical methods. The use of GPR in Ladakh offers significant potential to bridge this knowledge gap by enabling detailed imaging of subsurface ice, sediment layering, and active layer processes.

Situated within this framework, the high-altitude permafrost environments of Ladakh in the Indian Himalayas are of special interest as terrestrial analogues for Martian subsurface ice systems (Pandey et al., 2020; Haq et al., 2022). Ladakh presents extreme environmental conditions including low temperatures, limited liquid water availability, and high salinity factors that closely resemble those hypothesized for Mars. The region features diverse and accessible periglacial landscapes such as glacial passes, salt rich lake shorelines, and permafrost related geomorphological features (Wünnemann et al., 2008, 2010; Pandey et al., 2019; Kumar et al., 2026). Investigations in Ladakh have revealed interactions between the diurnal water cycle and salts in the soil, that can create transient brine reservoirs, potentially analogous to habitable niches on Mars (Rastogi, 2009). These terrestrial analogues are essential for astrobiology research, providing insights into microbial survival strategies under cold, arid conditions and facilitating the development of life detection methods and exploration technologies applicable to the Martian environment (Sharma et al., 2024). The demonstrated resilience of cold adapted microorganisms isolated from permafrost supports the relevance of Ladakh's permafrost as a model for subsurface life on Mars (Pandey et al., 2020).

A major challenge in planetary geology is not the detection of the Martian subsurface, as orbital radar sounders such as SHARAD, MOSIR and MARSIS, together with the rover-mounted RIMFAX and RoPeR instruments during various missions have already revealed widespread subsurface reflectors, buried ice, and stratified sedimentary deposits (Hamran et al., 2020, 2022; Orosei et al., 2017; Fan et al. 2021, Mellon et al., 2008,2009; Cereti et al., 2007; Castaldo et al., 2017; Gupta et al., 2020; Chen et al., 2023; Raguso et al., 2024; Ciarletti, 2024) (Fig. 1a&b). Rather, the principal challenge lies in reliably interpreting these radar signatures to reconstruct the geological and environmental evolution of the Martian subsurface. Similar radar responses may result from different combinations of sedimentological characteristics, ice content, salinity, and cryogenic processes, rendering interpretations based solely on radar observations inherently uncertain (Casademont et al., 2024). Addressing this uncertainty requires well-characterized terrestrial analogue environments in which radar observations can be interpreted alongside independently constrained geological and geophysical data within a robust geological framework (Leuschen et al., 2003). The present GPR investigation of the Tso-Kar Basin is undertaken within this process-based analogue framework.

The cold desert of Ladakh exhibits striking similarities with selected Martian terrains, particularly in regions such as Utopia Planitia, Arcadia Planitia, and Gale Crater (Jangir & Dutta, 2025; Pandey et al., 2020; Ansari et al., 2025). These similarities include hyper-arid climatic conditions, dominance of aeolian and periglacial processes, and the presence of patterned ground, polygonal networks, and debris covered surfaces indicative of freeze-thaw activity (Pandey et al., 2020; Haq et al., 2022). Additionally,

both environments exhibit strong diurnal temperature variations and subsurface ice stability under thin atmospheric conditions (on Mars), making Ladakh an effective terrestrial analogue for studying Martian cryospheric and sedimentary processes (Pandey et al., 2020). Such analogues are critical for interpreting radar signatures and geomorphic features observed on Mars. Beyond terrestrial significance, permafrost studies in Ladakh hold increasing importance in the context of planetary science (Jangir & Dutta, 2025; Pandey et al., 2020; Ansari et al., 2025). Observations from missions such as Mars Reconnaissance Orbiter and Mars Odyssey have provided compelling evidence for the presence of ground ice and permafrost like conditions on Mars (Orosei et al., 2025; Yu et al., 2025; Mellon et al., 2008; Wainstein et al., 2008). Orbital radar instruments like SHARAD and MARSIS have detected subsurface reflectors interpreted as ice-rich layers, drawing strong parallels with GPR investigations on Earth (Cereti et al., 2007; Castaldo et al., 2017; Giuppi S. 2015; Gupta et al., 2020; Raguso et al., 2024; Ciarletti, V. 2024). In this context, the Ladakh region provides a unique natural laboratory to investigate permafrost processes and their geophysical signatures under conditions analogous to those on Mars. Ground Penetrating Radar (GPR) stands out as a highly effective geophysical tool for probing subsurface ice systems both on Earth and as an analogue for planetary studies. By integrating GPR based subsurface imaging with geomorphic and sedimentological observations, it is possible to develop improved models for interpreting Martian radar data and understanding cryospheric evolution on planetary bodies. The present study aims to (i) characterize the subsurface structure and dynamics of permafrost in the Tso Kar basin of Ladakh using GPR, (ii) identify key stratigraphic and cryogenic features such as ice lenses and active layer thickness, permafrost table and (iii) evaluate the suitability of the Ladakh permafrost system as a terrestrial analogue for Martian permafrost environments. This work not only contributes to the limited database on Himalayan permafrost but also provides valuable insights for comparative planetology and future exploration of extraterrestrial cryospheres.

The significance of the Tso-Kar Basin as a planetary analogue extends beyond its morphological similarity to Mars. Its Late Quaternary climatic, lacustrine, and permafrost evolution has been independently constrained through geomorphological, sedimentological, and palynological investigations (Wünnemann et al., 2008, 2010), providing a robust geological framework for relating environmental evolution to subsurface radar facies. Consequently, the GPR dataset can be interpreted within the context of basin evolution, allowing the observed radar facies to be associated with specific geological processes rather than being considered solely as morphological analogues of the Martian subsurface.

2. Regional Setup of the Study Area

Ladakh is a high altitude cold-arid desert, situated in the Trans-Himalayan range of the northwestern Himalaya in northern India (Figs. 2 and 3). Geomorphologically, the region is characterized by a combination of fluvio-glacial, lacustrine, and periglacial landscapes, including alluvial fans, moraines, outwash plains, and high-altitude saline lake basins such as Tso Kar (Wünnemann et al., 2008, 2010; Kumar et al., 2022; Singh et al., 2010; Mukherji et al., 2018; Dimri et al., 2021). The topography is rugged and highly dissected, with elevations typically ranging between ~ 4,000 to 6,000 m above sea level,

interspersed with broad intermontane valleys and plateau-like surfaces (Lal and Singh, 2025). Climatically, Ladakh experiences a cold desert environment with extremely low precipitation (< 100 mm annually), largely due to its location in the rain shadow of the Greater Himalaya (Philip and Mazari, 2000). The region is marked by strong diurnal and seasonal temperature variations, exhibits markedly extreme climatic conditions, with temperatures ranging from approximately – 40°C during winter to > 30°C in summer, alongside pronounced diurnal variability from below 0°C to above 30°C within a single day (Pandey et al., 2023). The region is an excellent natural laboratory encompassing a wide spectrum of largely pristine extreme environments, including glacial deposits, hyper-arid terrains, aeolian dune fields with interdunal ponds, hydrothermal springs, saline lakes, and extensive permafrost domains (Bhattacharyya, 1989; Philip and Mazary, 2000; Pandey et al., 2022). Tectonically, Ladakh occupies a complex zone influenced by the ongoing convergence between the Indian Plate and the Eurasian Plate, resulting in active deformation, faulting, and uplift that shape the present-day landscape (Sinha, 1981; Searle et al., 1987, 1988; Valdya, 1988; Nag et al., 2021; Petterson, 2023; Mir et al., 2024). These tectonically formed young high latitude landscape, combined with extreme climatic conditions, favor the development of discontinuous to sporadic permafrost across the Higher Himalayan and Trans-Himalayan domains.

The Tso-Kar basin where the present study has been carried out is located at a distance of about 160km southeast of Leh town at an altitude of 4500 m (Figs. 2 and 3). Tso Kar is a large structural depression which is occupied with two prominent lakes (Tso-Kar and Startsapuk Tso) with no outlet drainage. The Tso-Kar is a brackish shallow lake having an area of 19km² whereas, the Startsapuk Tso is relatively deep freshwater lake covering an area of 4km². Geologically, the Tso-Kar basin is situated within the Taglang La Formation of the Tso Moriri Crystalline Complex, which is interpreted as an accreted terrain associated with the Indo-Tsangpo Suture Zone (Thakur and Viridi, 1979). The Taglang La Formation comprises metamorphosed calcareous, marly, and argillaceous metasedimentary sequences interlayered with concordant bands of amphibolites, forming the crystalline basement of the Tso Kar basin (Thakur & Mishra, 1984; Thakur, 1992). This basement is overlain by substantial accumulations of Quaternary lacustrine sediments that constitute the principal basin-fill deposits. The basin represents ongoing Himalayan mountain-building processes resulting in dislocation of many landforms such as streams, ridges, formation and shrinking of lakes and deformation of Quaternary landforms. Structurally, the basin is tectonically constrained by the north-south trending Tso-Kar Fault along its western margin and the Tso Moriri Fault along its eastern boundary (Fig. 3a-c). Hydrologically, Tso Kar is sustained by a shallow overflow from Startsapuk Tso, a river-fed lake within the same catchment. Tso Kar is hypersaline with an ephemeral salt crust dominated by thenardite and mirabilite. Permafrost occurrence in this region is strongly controlled by elevation, slope orientation, ground material, and microclimatic variability, often manifesting in the form of active layer dynamics, ice-rich sediments, and periglacial landforms such as patterned ground and frost mounds (Wünnemann et al., 2008, 2010; Kumar et al., 2022). The cold desert of Ladakh thus provides an ideal natural laboratory for investigating high-altitude permafrost systems and their sensitivity to climatic and tectonic forcing. The active tectonics of the study area has been deciphered by the streams perturbation imparted on the drainage system, particularly the 1st order

streams are sensitive to the ongoing deformation. The Tso Kar Basin has evolved within a tectonically controlled closed depression that experienced alternating lake highstands and regressive, salinizing phases throughout the Late Quaternary. This history exerted a first-order control on permafrost development, with permafrost aggradation favoured during low lake stands and inferred to have been largely absent during the mid-Holocene highstand (Wünnemann et al., 2008, 2010). Consequently, the subsurface radar facies imaged by GPR in this study preserve the cumulative imprint of climatic, hydrological, and cryogenic evolution rather than reflecting a single stage of basin development.

3. Martian Analogue Characteristics (Earth-Planetary Resemblances)

Owing to the elevated topography of Ladakh region, the area is characterized by reduced atmospheric pressure (typically 540 hPa), intense ultraviolet radiation (twice sea level), and minimal precipitation (mean annual precipitation < 90mm). This unique environmental setting is particularly conducive to multidisciplinary geological and astrobiological investigations, including ongoing surface processes, sub-surface stratigraphy, paleoenvironments, and technology test as a preparation for extraterrestrial exploration (Pandey et al., 2020; Haq et al., 2022; Phartiyal et al., 2021, 2025). Notably, the high mountain passes exhibit striking geomorphic and environmental analogues to early Martian conditions, marked by low atmospheric pressure, elevated UV flux exceeding those currently observed on Mars, active periglacial processes, permafrost dynamics, and glacial–meltwater interactions (Pandey et al., 2020; Phartiyal et al., 2025). At an elevation of approximately 4500 m, the atmospheric density is $\sim 0.64 \text{ kg m}^{-3}$, significantly lower than the $\sim 1.2 \text{ kg m}^{-3}$ typical at sea level, further reinforcing its relevance as a Mars analogue environment (Pandey et al., 2020; Kumar et al., 2022). The Hesperian epoch on Mars is inferred to have been associated with an atmospheric density of at least $\sim 0.4 \text{ kg m}^{-3}$. Tso Kar is a shallow, hydrologically fluctuating saline lake distinguished by elevated salinity levels, reaching hypersaline conditions ($> 50\%$; $\text{TDS} \approx 190.5 \text{ g L}^{-1}$), with a dominant Na–K– SO_4 –Cl geochemical composition and annual evaporation rates between 400 to 600 mm, substantially exceeding precipitation, particularly during the summer months when evaporation peaks and results in the formation of dense brines (Yu et al., 2001). Despite these harsh conditions, the lake supports a community of highly halo tolerant ostracod species adapted to extreme salinity regimes (Yu et al., 2001).

The basin preserves a well-developed assemblage of glacial geomorphic features, like small cirques and moraines and exhibits hummocky topography characterized by polished and striated clasts, indicative of past glacial activity. A particularly notable geomorphic attribute is the presence of elevated palaeo-shorelines, reaching up to + 98 m above the current lake level, prominently developed along the northern and southern margins and encircling the basin (Wünnemann et al., 2008; 2010). The Tso-Kar basin exhibits a diverse suite of permafrost-related geomorphic features, including thermokarst depressions, frost mounds, thermal contraction crack polygons, permafrost mounds characterized by thick ice lenses and reticulate cryostructures, and putative lithalsas reaching heights of up to $\sim 10 \text{ m}$ (Dimri et al., 1983; Wünnemann et al., 2008; 2010). These landforms represent the active periglacial dynamics and ongoing

geomorphic modification driven by permafrost processes. Numerous small to medium-sized ponds associated with frost mounds, as well as larger water bodies occupying isolated thermokarst depressions forms the discontinuous permafrost (Wünnemann et al., 2008; 2010). Cryostructural analyses revealed the presence of clear ice lenses embedded within a matrix of dark grey icy mud interspersed with patches of yellowish silt–clay–ice aggregates (Pandey et al., 2022). These matrices host significant concentrations of biomarkers, with reported values ranging from 10^3 to 10^4 orders of magnitude, including 4.9×10^2 to 4.33×10^5 ng g⁻¹ lipopolysaccharides (LPSs; N = 2) and 8.6 to $\sim 2 \times 10^4$ fmol mL⁻¹ adenosine triphosphate (ATP; N = 5) (Pandey et al., 2022). The detection of such biomarkers within ice-bound fine-grained sediments in permafrost-associated reticulate cryostructures underscores the astrobiological significance of these environments. These analogues provide valuable opportunities for developing and testing life detection strategies applicable to the polar and mid-latitude regions of Mars, as well as to ice-dominated surfaces on the earth, where similar ice-sediment mixtures may serve as repositories of concentrated biosignatures. In this context, geophysical investigations, particularly using Ground Penetrating Radar (GPR), offer a robust, non-destructive approach for subsurface characterization. GPR enables high-resolution mapping of stratigraphy and the delineation of permafrost structures, thereby providing critical insights into the internal architecture and evolution of these cryogenic systems. Because these ice-rich sedimentary sequences reflect the basin's long-term lake regression and salinization history rather than isolated permafrost processes (Wünnemann et al., 2008, 2010), their internal cryostratigraphy must be characterized using methods capable of resolving subsurface stratigraphy without disturbing the fragile permafrost-hosted biomarker record. GPR provides this capability (Moorman et al., 2003; French & Shur, 2010) and is therefore employed in this study to relate surface geomorphic features to the underlying cryostratigraphic framework.

4. Material and Methods

Subsurface imaging forms a critical component of this investigation, as characterization of the active layer, ice-rich horizons, and permafrost table allows surface geomorphic features to be linked with the underlying cryostratigraphic record of basin evolution. Cold-region environments, characterized by mean annual ground temperatures at or below 0°C, host a wide spectrum of cryospheric features including continuous to sporadic permafrost, a seasonally thawing active layer, ice wedges, taliks, and thermokarst landforms. These environments present strong contrasts in dielectric permittivity and electrical conductivity due to phase changes between ice and liquid water, making them particularly suitable for Ground Penetrating Radar (GPR) investigations (Bradford et al., 2005; Nakano and Sakai, 2008; Torn et al., 2025). The active layer, which undergoes annual freeze-thaw cycles, is a key focus in permafrost studies as its thickness, thermal regime, and liquid/solid water proportions act as proxies for permafrost stability, near-surface hydrology, and biogeochemical fluxes such as CO₂ and CH₄ emissions (Ehrlich et al., 2021; Torn et al., 2025). GPR provides critical information on active layer thickness, internal stratigraphy, and phase distribution through analysis of travel-time variations, reflection amplitudes, and signal attenuation (Harris et al., 2025).

During the present study, the data was collected using a 200 MHz antenna manufactured by GSSI (Geophysical Survey Systems Inc.) coupled with a SIR-4000 control unit. Prior to data acquisition, the equipment was calibrated under site-specific conditions, considering the relatively flat and dry surface characteristics of the study area. Several trial surveys were performed using different acquisition prompts and custom settings to optimize data quality and ensure reliable subsurface imaging. During data acquisition, varying dielectric constants representing the anticipated subsurface materials were incorporated in the custom survey settings to improve signal penetration and depth estimation. The acquired radar profiles were processed using RADAN 7 software. Data processing involved the application of a sequence of filters and corrections, including 600 MHz low-pass and 50 MHz high-pass Infinite Impulse Rate (IIR) filters, background removal, migration, horizontal and vertical scaling, and appropriate time-range adjustments. To preserve the integrity of the original radar reflections, only minimal filtering and gain enhancement (artificial energy amplification) were applied, thereby reducing processing induced artefacts and maintaining the authenticity of the recorded subsurface signatures.

5. Results

5.1. Permafrost Landforms and Sub-surface Imaging

The previous studies (Wünnemann et al., 2008; 2010) as well as the current field work in the study area reveals the basin exhibits a variety of well-preserved glacial and periglacial geomorphic features, including terminal and lateral moraines, hummocky mounds, V-shaped valleys, fan surfaces, terraces, paleolake-shorelines, and regression shorelines, reflecting the evidence of former glaciation and subsequent permafrost activity (Wünnemann et al., 2008, 2010). During the present study three sites were selected along the eastern margin of the Tso-Kar basin due to easy accessibility and site conditions for GPR survey to target the permafrost layers, including the depth of permafrost table, sub-surface sediment characteristics and structures (Fig. 4a,b). These include (a) Site-1 at the southern margin of Tso Kar (North of Startsapuk lake) with dry surface conditions, (b) Site-2 at the northern margin of the lake basin where the geomorphic features representing thermokarst activity, lithalsas and frost mounds are prominent features (Fig. 5a,b), Site-3 lies in between the Site-1 and 2 where the surface condition changes from prominent lake features to a relatively coarse surface material like slope fragments such as pebble and gravels (Fig. 4b). The elevation of the sites increases from site-1 to site-3 suggesting stratigraphically younging from site 3 to site 1 (Fig. 4b). At the western margin of the lake basin the topographic expression of Tso-Kar fault is prominently displayed representing a part of ongoing active tectonics in the Himalaya (Fig. 5b). The Tso-Kar fault is a part of the ITSZ deformation with strike slip environment, representing both compressional and extensional region due to structural step tectonics along Karakoram fault system.

Site-1

The Site-1 is located along the eastern margin of Tso Kar, where a 150 m survey transect extended from the shoreline towards the basin interior. The site was selected to characterize permafrost architecture

across lake-margin sediments influenced by sediment exposure and salinization, which have been identified as primary controls on permafrost development within the basin (Wünnemann et al., 2008, 2010). The site represents stratified permafrost architecture under cold-arid high altitude cryostratigraphy. The uppermost ~ 1–2.5 m profile shows a well-developed, laterally continuous reflectors that represent the active layer, which thaws and freezes seasonally (Fig. 7). The sharp contrast occurs due to a change in dielectric permittivity in thawed (wet) versus frozen (ice-rich) sediments. There are minor undulations due to micro-topographic or moisture variations. Repeated thaw freeze cycles result in rhythmic layering similar to that observed in annual or multi-annual climate fluctuations. Underneath active layer, the transition zone, representing moderately diffused reflective zone is marked as permafrost layer (Fig. 7). This zone represents intermediate climatic phases, where snow sublimation, and compaction occurs. A distinct, strong reflector at the top of permafrost zone is represented as permafrost table, a boundary between seasonally thawed layer above, and permanently frozen ground below. Its continuity along the profile indicates stable permafrost (Fig. 7). The variation in depth reflects local thermal anomalies and differences in sediment composition or moisture content. Ice-rich Permafrost layer has strong continuous sub-horizontal reflectors, layered ice lenses, and Ice segregation structures. The dipping reflector implies that buried paleo-surfaces or deformation related to solifluction or cryoturbation occurred as high and low reflectivity alternate bands, indicating cold periods of ice accumulation and warm periods of sediment deposition or ice melting.

The heterogeneous, discontinuous reflections consist of debris layers, colluvium, and freeze. These layers break the continuity, and represent event marker in stratigraphy in general, and in permafrost stratigraphy in the present study (Fig. 7). The weaker signal penetration of the weak, chaotic reflections corresponds to lower ice content and higher radar signal attenuation due to unfrozen or partially thawed ground (talik) (Fig. 7). The rhythmic layering of alternating reflectors may represent cyclic freeze-thaw events related to seasonal and/or longer-term climate fluctuations. The results are an important climatic archive with ice-rich layers representing cold and stable periods and debris-rich layers representing warm and unstable periods with sediment influx. The internal deformation in the sediments have also been examined where the dipping reflectors suggest the deformational features probably caused by cryoturbation, or periglacial mass movement.

Site-2

Site-2 is located within the vegetated permafrost terrain of the northern Tso-Kar Basin, where lithals and segregated-ice mounds are widespread. The site was selected because it represents the characteristic geomorphic setting of permafrost development within the basin (Wünnemann et al., 2008). The GPR profile at site-2 also display well-defined cryostratigraphic layering within the permafrost, which can be related to climatic cyclicity and freeze-thaw. The upper portion of the profile (to about 1–2.5 m) has strong lateral reflectors, representing the active layer, which thaws and freezes seasonally (Fig. 8). The pronounced reflections are caused by contrasts in dielectric permittivity in thawed, moisture-rich sediments, and underlying frozen ice. Minor undulations on these reflectors represent micro-topographic variations and spatial moisture differences related to seasonal thaw variations. Several cycles of freeze-

thaw have induced rhythmic stratification. A moderately reflective and slightly stratified zone of signatures lies beneath the active layer, representing transitional permafrost undergoing progressive densification and ice segregation (Fig. 8). These stratified layers represent intermediate climatic stages with changes in snow accumulation, sublimation, compaction and ground ice. A large, strong-amplitude reflector at 1.5m depth separates the permafrost table from the active layer, which thaws seasonally beneath the permanently frozen ground (Fig. 8). This lateral continuity indicates relatively stable permafrost conditions across the area with localized thermal anomalies, and heterogeneities in sediment composition and moisture. The strong, continuous sub-horizontal reflections in layered reflectors represent ice lenses and ice segregation associated with ice-rich permafrost. Locally-developed dipping reflectors are interpreted as buried palaeo-surfaces or deformation features associated with solifluction, cryoturbation or other periglacial features (Fig. 8). Alternating zones of high and low reflectivity are interpreted to represent cycles of increased ice accumulation during colder periods and sediment deposition or warmer periods with less ground-ice. Heterogeneous and discontinuous reflections are interpreted as debris rich horizons consisting of colluvium and freeze-thaw (Fig. 8). These units disrupt the continuity of the cryostratigraphic sequence and are likely episodic depositional events that can act as important stratigraphic markers in the permafrost succession. At greater depths, weak and disordered reflections indicate reduced ice content and increased radar-wave attenuation, consistent with talik areas. The rhythmic alternation of reflective horizons throughout the profiles further supports the existence of cyclic freeze-thaw regimes driven by seasonal processes and possibly longer-term climatic fluctuations.

Site-3

Site-3 is situated adjacent to Thukje Gompa, representing a topographically elevated paleoshorelines surface. The site was selected to assess how present depositional setting differs in response to the subsurface permafrost characteristics (Wünnemann et al., 2008, 2010). The GPR profile at site-3 has a well developed stratified permafrost with distinct cryostratigraphic units and minor deformation structures. The signal penetration decreased from desired 12m in dry conditions to 7m due to signal loss because of relatively more clayey horizon. The topmost ~1m of the profile is characterized by a strongly laterally continuous reflectors layer which is interpreted to represent the active layer undergoing seasonal freeze-thaw (Fig. 9). Beneath this, the interval from ~ 1 to 3m has weak to moderate discontinuous reflections representing a transition zone between the active layer and permanently frozen ground, where the sediment structure has been modified by variations in moisture content and freeze-thaw. A prominent, continuous, high-amplitude reflector at 3.5–4.0 m is the permafrost table that separates seasonally influenced surface sediments from the permanently frozen deposits (Fig. 9). The most prominent feature is located between 40 and 80 m in the profile at depths of about 3–6 m with a row of strong, parallel and laterally continuous reflections indicating a layer of ice-rich stratified permafrost (Fig. 9). This high-contrast zone probably consists of alternating ice-rich and sediment-rich layers, buried ice lenses, or segregation ice layers formed during different freezing events. The extremely high reflection amplitudes imply strong contrasts between the dielectric properties, ice content, porosity, and density of the sediments and the cryostratigraphic unit, which may represent a separate depositional

or palaeoclimatic phase. Localized disruptions and small undulations of reflectors occur in several points along the profile, indicating minor cryogenic deformation structures (cryoturbation, frost heave, differential thaw settlement) but the overall stratification is preserved. At depths > 6 m the radar signal is strongly attenuated and appears to be underlain by relatively homogeneous frozen sediments or massive ice-rich permafrost with limited dielectric contrasts (Fig. 9).

5.2.Implications for Permafrost Stratigraphy, Structure and Paleoclimate Inferences

Permafrost stratigraphy refers to the vertical and lateral arrangement, composition, and chronological sequence of frozen ground layers within perennially frozen terrain, integrating sedimentology, ground ice characteristics, and thermal history to reconstruct past environmental and climatic conditions (French and Shur, 2010). It encompasses the study of distinct stratigraphic units such as the active layer (seasonally thawed zone), transient layer, and the underlying perennially frozen layer, which may contain diverse forms of ground ice including pore ice, segregated ice, ice lenses, and massive ice bodies like ice wedges (Gilbert et al., 2016). These units are differentiated based on lithology, cryostructures, ice content, and depositional history, often reflecting processes such as fluvial, lacustrine, glacial, or aeolian sedimentation operating under cold-climate regimes. Permafrost stratigraphy is crucial for interpreting the evolution of periglacial landscapes, identifying paleoenvironmental signals, and understanding the response of frozen ground to climatic fluctuations over Quaternary timescales (Stroková L. 2019; Paul et al., 2021; Tumskey V.E. 2021). Techniques such as borehole logging, geophysical surveys, cryostratigraphic analysis, and radiometric dating (e.g., radiocarbon or optically stimulated luminescence) are commonly employed to delineate stratigraphic boundaries and establish temporal frameworks (Kneisel et al., 2008; Hauck, C. 2013; Gusmeroli et al., 2015). In regions like the Himalayan cryosphere, including high-altitude cold deserts such as Ladakh, permafrost stratigraphy provides valuable insights into the interplay between tectonics, climate variability, and geomorphic processes, and is increasingly important for assessing ground stability, infrastructure risk, and carbon dynamics in the context of ongoing climate warming (Wani et al., 2020, 2021; Dimri et al., 2021; Jangir and Dutta. 2025).

5.3.Implications for Mars Analogue Studies

Global permafrost studies have become central to identifying and characterizing Mars analogue environments, providing critical insights for planetary science, astrobiology, and future exploration strategies (Hayset al., 2017; Cassaro et al., 2021; Becch and Comte et al., 2021; Marcheselli, V. 2022; Miner et al., 2023; Sharma et al., 2024). Cold, arid regions on Earth that host perennially frozen ground such as the Antarctic Dry Valleys, the Arctic permafrost of Siberia and Alaska, the Canadian High Arctic, and high-altitude cold deserts like Ladakh and the Atacama are widely used as terrestrial analogues because they replicate key Martian conditions, including low temperatures, limited liquid water availability, freeze-thaw dynamics, and ice-cemented regolith (Callaghan et., 2005; Nagy et al., 2020; Loidi et al., 2022). Research in these regions has focused on cryostratigraphy, ground ice distribution, and geomorphic features such as polygonal patterned ground, ice wedges, thermokarst depressions, and

frost mounds, which closely resemble landforms observed on Mars through orbital and rover missions (Ulrich M. 2011; Balme et al., 2013; Dong et al., 2025). Studies from the Antarctic McMurdo Dry Valleys, for instance, have demonstrated how sublimation driven processes and hyper-arid permafrost conditions can preserve ancient ice and sediment structures, offering analogues for Martian mid-latitude ground ice stability and degradation (Bockheim et al., 2007; McKay C.P, 2009; Gooseff et al., 2010; Kerrigan M.C. 2013). In the Arctic, extensive investigations of ice-rich permafrost sequences particularly the organic-rich Yedoma deposits have improved understanding of long-term cryogenic processes, sediment accumulation, and preservation of biosignatures within frozen matrices (Strausset al., 2021; Schirrmeister et al., 2024). These findings are directly relevant to Mars, where subsurface ice-rich layers may similarly archive past climatic and possibly biological information. High-altitude permafrost regions such as Ladakh in the NW Himalaya have emerged as important mid-latitude analogues, combining intense solar radiation, seasonal freeze thaw cycles, and discontinuous permafrost conditions that resembles those inferred for equatorial and mid-latitude regions on Mars (Pandey et al., 2022, 2023). Such studies help refine models of permafrost distribution under varying thermal regimes and topographic controls. Permafrost analogue research has also significantly contributed to interpreting remote sensing data from Mars missions (Farr et al., 2002; Philipp et al., 2021; Terhorst and Dowling, 2022). Features such as thermal contraction polygons, lobate debris aprons, and scalloped depressions identified on Mars have been better understood through comparative studies with terrestrial periglacial landscapes (Koutnik and Pathare, 2021; Hauber et al., 2011; Balme et al., 2013).

Furthermore, subsurface investigations using ground-penetrating radar in analogue terrains have informed the design and calibration of instruments used in missions like Mars Express and Mars Reconnaissance orbiters, especially the Perseverance and Zhurong Rovers. These missions have confirmed the presence of shallow subsurface ice, validating hypotheses derived from Earth-based permafrost studies (Leuschen et al., 2003; Farley et al., 2020; Hamran et al., 2020, 2022; Lavagna et al., 2022; Mellon and Sizemore, 2022; Pettinelli et al., 2022; Sheppard and Skinner, 2025; Briones et al., 2025). From an astrobiological perspective, permafrost analogue sites are invaluable for studying the survival and preservation of microbial life under extreme conditions. Investigations in Antarctic and Arctic permafrost have revealed viable microorganisms and preserved organic matter within frozen sediments, suggesting that similar environments on Mars could potentially harbor biosignatures (Hoover and Gilichinsky, 2001; Gilichinsky D.A. 2002; Yaminsky and Mulyukin, 2005; Mukhopadhyay et al., 2025). Consequently, these studies guide sampling strategies, contamination control protocols, and life-detection experiments for future missions. The research in Mars analogue environments has advanced planetary science by bridging terrestrial cryospheric processes with extraterrestrial geology. It provides a robust framework for interpreting Martian surface and subsurface features, constraining paleoclimate evolution, assessing habitability, and supporting the development of exploration technologies, thereby reinforcing the role of Earth analogues as natural laboratories for understanding Mars.

6. Discussion

The GPR data from the Tso Kar Basin offers a valuable window into the internal structure, cryostratigraphy, and climatic importance of high-altitude permafrost in northwest west higher himalayan cold desert of Ladakh. The study shows that Ground Penetrating Radar is a useful non-intrusive technique for mapping permafrost boundaries, cryogenic features, and palaeoenvironmental reconstructive in cold desert areas where direct subsurface access is impractical. The presence of well-defined stratified horizons, laterally continuous reflectors, ice-rich layers and transition zones in all of the studied sites confirm the presence of well-developed discontinuous permafrost and the complexity of periglacial processes. The GPR profiles from Sites 1, 2, and 3 consistently indicate a shallow active layer overlying frozen ground. The active layer, consisting of strong and continuous reflectors in the upper 1–2.5 m, is the zone subjected to annual freeze-thaw cycles. Similar active layer thicknesses have been reported from other high altitude permafrost areas of the Himalaya and Tibetan Plateau; Tso Kar Basin seasonal thaw depth is primarily controlled by altitude, surface moisture, sediment texture, snow cover and local topography (Gruber et al., 2017; Sah, K. 2025).

The variations in the depth and continuity of the active layer on the profiles are consistent with spatial heterogeneity in thermal conditions resulting from ground moisture, vegetation cover, sediment type, and micro-relief related to thermokarst and frost mound activity (Fig. 10). Such heterogeneity is critical in the context of ongoing climate warming because localized thickening of the active layer can exacerbate permafrost degradation and landscape instability. One of the main results of this investigation is the discovery of large permafrost tables with high amplitude reflectors at depths of 1.5 to 4 m. The continuity of these reflectors imply relatively stable permafrost conditions over much of the area. However, local variations in depth of the permafrost table indicate the presence of thermal anomalies and that permafrost distribution in the basin is discontinuous. Similar observations from Arctic, Antarctic, and Tibetan Plateau permafrost terrains suggest that local geomorphic and hydrological processes play a dominant role in controlling permafrost thickness and thermal regime (Bockheim, J. G. 2015; Smith et al., 2022) In the Tso Kar Basin, thermokarst depressions, frost mounds, lithalsas and variable sedimentary facies exert significant controls on ground thermal conditions and permafrost preservation.

The internal cryostratigraphy of GPR images consisted of cyclical high and low amplitude reflections. Such rhythmic stratification reflects repeated episodes of ground ice formation, sediment deposition, and freeze-thaw reworking. The layered ice lenses, segregation ice and debris rich horizons imply that the permafrost developed in a series of climatic and geomorphic episodes. The alternation of highly reflective ice-rich layers and weakly reflective sedimentary layers may represent periods of increased moisture availability and colder periods alternating with relatively warmer periods of enhanced sediment influx and reduced ground ice. Consequently, the permafrost sequence of the Tso Kar Basin may preserve an important archive of Quaternary climatic fluctuations in the NW Himalaya. The existence of transitional zones beneath the active layer in profile-2 highlights a dynamic permafrost evolution in the basin. Such transitional layers may serve as indicators of changing moisture regimes and past climatic variability (Fig. 10).

The localized deformation structures inferred from dipping reflectors in data, disrupted stratification, and undulating horizons demonstrate ongoing cryogenic and geomorphic processes. These features are considered to be the result of cryoturbation, frost heave, differential thaw settlement, solifluction, and other periglacial mass movement processes. Similar deformation features have been reported from Arctic and alpine permafrost terrains and are generally related to freeze-thaw and ground ice dynamics (Haeberli et al., 2006; Hu et al., 2025; Streletskiy et al., 2025). In the Tso Kar Basin, these structures may also reflect the influence of active tectonics along the nearby Tso Kar Fault and the Indus-Tsangpo Suture Zone. The discovery of weak and chaotic reflections at deeper levels interpreted as taliks or partially thawed ground is of particular importance under current climate conditions. Talik formation in discontinuous permafrost regions is a symptom of permafrost degradation due to warming and hydrological changes (Chen et al. 2020; Streletskiy et al. 2025). Expansion of talik zones may alter groundwater flow pathways, enhance thermokarst activity, and increase slope instability (Jin et al., 2022; Ke et al., 2025). Therefore, continuous monitoring of talik evolution in the Tso Kar Basin is essential for assessing the future response of Himalayan permafrost to climate change.

From a broader cryospheric perspective, the study highlights the importance of Himalayan permafrost as a sensitive indicator of environmental change. Despite covering large areas of the high Himalaya, permafrost is poorly mapped and characterized when compared with the Arctic and Antarctic. The present study is one of the few detailed cryostratigraphic studies from Ladakh and the only study to provide valuable information on the spatial distribution and internal structure of Himalayan permafrost (Fig. 10). Such information is essential to assess the impacts of climate change on water resources, ecosystems, natural hazards and infrastructure in high mountain areas.

The primary implication of this study is to enhance our understanding for GPR data collection and processing for Mars analogue research. The cold-arid Ladakh environment, with discontinuous permafrost, thermokarsts, and ice-rich stratigraphy, is remarkably similar to that of Martian mid-latitudes. The radar signatures of active layers, permafrost tables, ice lenses, and cyclic cryostratigraphic sequences provide useful analogues for interpreting orbital and rover-based radar observations from Mars. The strong dielectric contrasts found in the GPR profiles are similar in nature to the radar contrasts measured by Mars radar instruments such as SHARAD, MARSIS, and RIMFAX. Therefore, the present study provides a process based framework for interpreting subsurface ice distribution, climatic cyclicity, and palaeoenvironmental archives on Mars. However, caution must be exercised while extrapolating terrestrial observations to Martian environments because of differences in gravity, atmospheric pressure, hydrological processes, and regolith properties.

The present preliminary investigation opens up several areas for future research to establish direct relationships between radar facies, sedimentology, cryostructures, and ground ice. Validation of this kind would revolutionize the confidence of cryostratigraphic interpretations. The long-term monitoring of active layer thickness, ground temperature and moisture may start to assess permafrost degradation. High-resolution remote sensing and UAV surveys should be used to map thermokarst landforms, frost mounds, lithalsas and active geomorphic processes at the landscape scale. Such datasets could be

used for regional-scale permafrost mapping and hazard assessment. The control of active tectonics on distribution of permafrost landform and cryogenic processes in the area in relation to the Tso Kar Fault and the Indus-Tsangpo Suture Zone should be studied. Knowledge of the tectonic controls on ground thermal regimes can offer new insights into the interaction between the cryosphere and the Himalayan tectonics. The Mars analogue potential of the Ladakh permafrost environment needs to be further explored by experimental investigations in radar calibration, dielectric property measurements, microbial survival, biosignature preservation, and rover scale investigations. Such studies would contribute substantially to planetary science, astrobiology, and the development of future Mars exploration missions.

7. Conclusion

The present study shows the potential of using GPR as a non-invasive, high-resolution tool for investigating the internal structure and cryostratigraphy of permafrost in the high-altitude cold desert of the Tso Kar Basin, Ladakh, NW Himalaya. The GPR investigations at three representative sites successfully mapped the active layer, transitional zone, permafrost table, ice-rich permafrost horizons, debris-rich zones, and deeper unfrozen or partially thawed (talik) zones. The GPR profiles indicate that the permafrost in the Tso Kar Basin is stratified and well-developed with cryostratigraphic sequences resulting from numerous freeze-thaw, ground-ice segregation, sediment deposition, and cryogenic reworking. We conclude that the increase in the thickness of active layers, and the development of transition zone and the presence of debris rich active layers in the GPR profiles reflect the progressive degradation of permafrost in the Ladakh Himalaya. The alternating high and low amplitude reflections in the GPR profiles further indicate cyclical changes in ice accumulation and sediment deposition, which implies that the permafrost past dynamics as well as the ongoing degradation due to climate change. The presence of ice lenses, debris horizons, and localized deformation features (cryoturbation and frost related disturbances) further emphasize the dynamic interplay between climatic, geomorphic, hydrological and possibly tectonic processes in shaping the permafrost landscape.

The discontinuous permafrost, spatially varied active layer, and deeper talik zones in the Tso Kar basin indicate the region is highly vulnerable to ongoing climate warming. These results have significant implications for the future permafrost degradation, thermokarst formation, ground instability, and related environmental hazards in the Himalayan cryosphere. The study accordingly makes a significant addition to the limited knowledge of distribution and subsurface characteristics of Himalayan permafrost, and serves as a baseline dataset for monitoring and climate change assessments.

Also, the cold arid climate of Ladakh, with well preserved cold permafrost stratigraphy and thermokarst features, makes it an important terrestrial analogue for Martian permafrost environments. The radar signatures presented here offer a process-based understanding of interpreting subsurface ice distribution, climatic cyclicity, and cryogenic structures imaged by Martian radar instruments like SHARAD, MARSIS, and RIMFAX. Although careful extrapolations are required due to the disparate

environments of Earth and Mars, this study shows the huge promise of Himalayan permafrost science for planetary science, astrobiology and future missions.

The current study from Ladakh will help to calibrate the equipment for survey in similar Martian conditions. The identification of permafrost table by sharp reflectors can indicate the ground ice stability zone in martian conditions. Layered deposits on Mars particularly in polar layered terrain may help in climate reconstruction that may represent the orbital-driven climate cycles such as Milankovitch. The cyclostratigraphic reconstruction from the present study represents a process-based analogue for interpreting martian stratified ice deposits. The frequency of GPR can be designed for a wide range to bridge the gap between resolution verses depth tradeoffs. Besides these results, there are number of challenges for Mars exploration, like uncertainty in signal attenuation, varying properties of martian regolith and poorly constrained dielectric constants. Contrastingly, the Mars may lack active hydrological cycling as the processes are dominated by sublimation and CO₂ frost dynamics that may pose significant challenges to understand the processes. Therefore, the processes active and working the martian environment needs to keep in mind while processing and interpreting the GPR signals. There may exist a resolution related problem in the martian GPR data, as the thinner layers need higher frequency antennas integrated with the rover setup. Thus, the GPR data with significant depth penetration and resolution may serve as important evidence to understand the seasonal to millennial cycle on Mars that although need careful comparison. The study further highlights the importance of integrating geophysical investigations with geomorphological, sedimentological, geochronological, and monitoring approaches to achieve a comprehensive understanding of permafrost evolution, climate interactions, and cryosphere dynamics in both terrestrial and planetary environments.

Declarations

Author Contribution

Ahsan Ul Haq: Data Acquisition, Data Processing and Manuscript writing
Binita Phartiyal: Data Acquisition
Yudhbir Singh: Data Interpretation
Bharti Sharma: Data Acquisition
Siddarth Pandey: Project design and Data Acquisition
S. K Pandita: Data Interpretation, Manuscript refining
G M Bhat: Data Interpretation
Jonathan D Clarke: Data Correlations with Martian Missions, Manuscript refining.
Rujal Pachhighar: Data Acquisition
Heet Joshi: Data Acquisition
Abdul Amir Khan: Data Acquisition
Mehnaz Jabeen: Data Acquisition

Funding Declaration:

The present study does not involve any specific research funding to carry out this work.

Data Availability:

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Consent to Publish Statement/Photographs:

We confirm that we have read and understood the above authorization and consent statement. We give our full permission for our identifiable image to be published in the manuscript under the Creative Commons Attribution (CC BY) open-access licence applicable to the article.

We understand that this consent relates specifically to the photograph/figure identified above and its publication as part of the scientific article.

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References

1. Andersen, M. L. et al. Toward a standardization of cryostructure and cryogenic soil structure terminology for the field description of permafrost-affected soils. *Soil Sci. Soc. Am. J.*, **90**(1), e70182. (2026).
2. Annan, A. P. GPR methods for hydrogeological studies. In *Hydrogeophysics* (185–213). Dordrecht: Springer Netherlands. (2005).
3. Ansari, A. H., Das, A., Ansari, N. G. & Sonker, A. Tracing early life on Mars: lessons from organics produced in high-altitude hot springs of Ladakh. *Progress Earth Planet. Sci.* **12** (1), 49 (2025).
4. Arcone, S. A., Lawson, D. E., Delaney, A. J., Strasser, J. C. & Strasser, J. D. Ground- penetrating radar reflection profiling of groundwater and bedrock in an area of discontinuous permafrost. *Geophysics* **63** (5), 1573–1584 (1998).
5. Arcone, S. A., Prentice, M. L. & Delaney, A. J. Stratigraphic profiling with ground-penetrating radar in permafrost: A review of possible analogs for Mars. *J. Geophys. Research: Planet.* **107** (E11), 18–11 (2002).
6. Balme, M. R., Gallagher, C. J. & Hauber, E. Morphological evidence for geologically young thaw of ice on Mars: A review of recent studies using high-resolution imaging data. *Prog. Phys. Geogr.* **37** (3), 289–324 (2013).
7. Beech, M. & Comte, M. Life on Mars: Past, Present, and Future. *Terraforming Mars*, 135–160. (2021).
8. Bockheim, J. G. *Cryopedology* p. 173 (Springer, 2015).

9. Bockheim, J. G., Campbell, I. B. & McLeod, M. Permafrost distribution and active- layer depths in the McMurdo Dry Valleys, Antarctica. *Permafrost Periglac. Process.* **18** (3), 217–227 (2007).
10. Bolch, T., Duethmann, D., Wortmann, M., Liu, S. & Disse, M. Declining glaciers endanger sustainable development of the oases along the Aksu-Tarim River (Central Asia). *Int. J. sustainable Dev. world Ecol.* **29** (3), 209–218 (2022).
11. Bolch, T. et al. Status and change of the cryosphere in the extended Hindu Kush Himalaya region. In *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people* (209–255). Cham: Springer International Publishing. (2019).
12. Bradford, J. H., McNamara, J. P., Bowden, W. & Gooseff, M. N. Measuring thaw depth beneath peat-lined arctic streams using ground-penetrating radar. *Hydrol. Processes: Int. J.* **19** (14), 2689–2699 (2005).
13. Brandt, O., Langley, K., Kohler, J. & Hamran, S. E. Detection of buried ice and sediment layers in permafrost using multi-frequency Ground Penetrating Radar: A case examination on Svalbard. *Remote Sens. Environ.* **111** (2–3), 212–227 (2007).
14. Briggs, M. A. et al. Surface geophysical methods for characterising frozen ground in transitional permafrost landscapes. *Permafrost Periglac. Process.* **28** (1), 52–65 (2017).
15. Briones, C., Rodríguez-Manfredi, J. A., Kereszturi, A. & Mangold, N. Robotic Missions to Mars. In *Mars and the Earthlings: A Realistic View on Mars Exploration and Settlement* (51–84). Cham: Springer Nature Switzerland. (2025).
16. Brown, R. J. & Kupsh, W. O. Permafrost terminology. *Biul. Peryglac.* **32**, 10–176 (1992).
17. Callaghan, T. V. et al. Arctic tundra and polar desert ecosystems. *Arct. Clim. impact Assess.* **1**, 243–352 (2005).
18. Campbell, S., Affleck, R. T. & Sinclair, S. Ground-penetrating radar studies of permafrost, periglacial, and near-surface geology at McMurdo Station, Antarctica. *Cold Reg. Sci. Technol.* **148**, 38–49 (2018).
19. Casademont, T. M., Dypvik, H., Eide, S., Berger, T. & Hamran, S. E. Martian ground penetrating radar: Toward automated diffraction detection for dielectric permittivity. *IEEE Trans. Geosci. Remote Sens.* **62**, 1–10 (2024).
20. Cassaro, A. et al. Antarctica as a reservoir of planetary analogue environments. *Extremophiles* **25** (5), 437–458 (2021).
21. Castaldo, L., Mège, D., Gurgurewicz, J., Orosei, R. & Alberti, G. Global permittivity mapping of the Martian surface from SHARAD. *Earth Planet. Sci. Lett.* **462**, 55–65 (2017).
22. Cereti, A., Vannaroni, G., Del Vento, D. & Pettinelli, E. Electromagnetic measurements on Martian soil analogs: Implications for MARSIS and SHARAD radars in detecting subsoil water. *Planet. Space Sci.* **55** (1–2), 193–202 (2007).
23. Chakraborty, T., Pandey, D. K., Singh, S. K., Phartiyal, B. & Putrevu, D. (December). *Characterization of Permafrost Active Layer using Polarimetric* (SAR and Ground Data over North-Western Indian Himalaya, 2023).

24. Chakraborty, T., Pandey, D. K., Singh, S. K., Phartiyal, B. & Putrevu, D. Characterization of Permafrost Active Layer using Polarimetric SAR and Ground Data over North-Western Indian Himalaya. In 2023 IEEE India Geoscience and Remote Sensing Symposium (InGARSS) (pp. 1–4). (2023), December.
25. Chen, A. et al. Ground-penetrating radar-derived measurements of active-layer thickness on the landscape scale with sparse calibration at Toolik and Happy Valley. *Alaska Geophys.* **81** (2), H9–H19 (2016).
26. Chen, R. et al. Martian soil as revealed by ground-penetrating radar at the Tianwen-1 landing. *siteGeology* **51** (3). 10.1130/G50632.1 (2023).
27. Ciarletti, V. Sounding Radars and Ground Penetrating Radars Designed for the Exploration of Our Solar System—Focus on Planet Mars. In *Ground Penetrating Radar: From Theoretical Endeavors to Computational Electromagnetics, Signal Processing, Antenna Design and Field Applications*. Wiley & Sons; ISTE. (2024).
28. Dimri, A. P. et al. Climate change, cryosphere and impacts in the Indian Himalayan Region. *Curr. Sci.* **120** (5), 774–790 (2021).
29. Dobinski, W., Grabiec, M. & Gądek, B. Spatial relationship in interaction between glacier and permafrost in different mountainous environments of high and mid latitudes, based on GPR research. *Geol. Q.* **55** (4), 375–388 (2011).
30. Dong, Z., Li, C. & Lü, P. *An Overview of Mars* An Introduction, 111–148 (Martian Aeolian Geomorphology, 2025).
31. Edemsky, D., Popov, A. & Prokopovich, I. Geophysical survey of Tunnug mound periphery, Tuva, Russia. *J. Appl. Geophys.* **189**, 104326 (2021).
32. Fan, M. et al. The Mars Orbiter Subsurface Investigation Radar (MOSIR) on China's Tianwen-1 Mission. *Space Sci. Rev.* **217** (8). <https://doi.org/10.1007/s11214-020-00786-4> (2021).
33. Farley, K. A. et al. Mars 2020 mission overview. *Space Sci. Rev.* **216** (8), 142 (2020).
34. Farr, T. G. et al. Terrestrial analogs to Mars. In *The Future of Solar System Exploration (2003–2013)—First Decadal Study contributions* (Vol. 272, pp. 35–76). (2002), August.
35. French, H. & Shur, Y. The principles of cryostratigraphy. *Earth Sci. Rev.* **101** (3–4), 190–206 (2010).
36. Frolov, A. D. A review of the nature and geophysical studies of the thick permafrost in Siberia: Relevance to exploration on Mars. *Journal Geophys. Research: Planets*, **108**(E4). (2003).
37. Ge, J. et al. Permafrost thawing characterization in engineering scale by multi-geophysical methods: A case study from the Tibet Plateau. *Eng. Geol.* **350**, 108012 (2025).
38. Gilbert, G. L., Kanevskiy, M. & Murton, J. B. Recent advances (2008–2015) in the study of ground ice and cryostratigraphy. *Permafrost Periglac. Process.* **27** (4), 377–389 (2016).
39. Gilichinsky, D. A. Permafrost model of extraterrestrial habitat. In *Astrobiology: the quest for the conditions of life* (125–142). Berlin, Heidelberg: Springer Berlin Heidelberg. (2002).
40. Giuppi, S. Radar Exploration of Mars: Recent Results and Progresses. In *Planetary Exploration and Science: Recent Results and Advances* (77–99). Berlin, Heidelberg: Springer Berlin Heidelberg.

(2015).

41. Gooseff, M. N., Mcknight, D. M., Carr, M. H., Baeseman, J. & Lyons, W. B. Antarctic McMurdo Dry Valley stream ecosystems as analog to fluvial systems on Mars. *Life in Antarctic deserts and other cold dry environments*, 139–159. (2010).
42. Gruber, S. Derivation and analysis of a high-resolution estimate of global permafrost zonation. *Cryosphere* **6** (1), 221–233 (2012).
43. Gruber, S. et al. Inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region. *Cryosphere* **11** (1), 81–99 (2017).
44. Gupta, V., Gupta, S. K. & Kim, J. Automated discontinuity detection and reconstruction in subsurface environment of mars using deep learning: A case study of SHARAD observation. *Appl. Sci.* **10** (7), 2279 (2020).
45. Gusmeroli, A. et al. Active layer stratigraphy and organic layer thickness at a thermokarst site in Arctic Alaska identified using ground penetrating radar. *Arctic, Antarctic, and Alpine Research*, 47(2), 195–202. (2015).
46. Haeberli, W. Modern research perspectives relating to permafrost creep and rock glaciers: a discussion. *Permafrost Periglac. Process.* **11** (4), 290–293 (2000).
47. Haeberli, W. et al. Permafrost creep and rock glacier dynamics. *Permafrost Periglac. Process.* **17** (3), 189–214 (2006).
48. Haeberli, W., Schaub, Y. & Huggel, C. Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology* **293**, 405–417 (2017).
49. Hamran, S. E. et al. Ground penetrating radar observations of subsurface structures in the floor of Jezero crater. *Mars Sci. Adv.* **8** (34), eabp8564 (2022).
50. Hamran, S. E. et al. ... yan, M. J. Radar imager for Mars' subsurface experiment—RIMFAX. *Space Science Reviews*, 216(8), 128. (2020).
51. Harris, R. H., Evans, S. G., Marshall, S. T., Godsey, S. E. & Parsekian, A. D. Using ground-penetrating radar to infer ice wedge characteristics proximal to water tracks. *Journal Geophys. Research: Earth Surface*, **130**(1), (2025). e2024JF007832.
52. Hauber, E. et al. *Periglacial landscapes on Svalbard* (Terrestrial analogs for cold-climate landforms on Mars, 2011).
53. Hauck, C. *Geophysical methods for detecting permafrost in high mountains*. Eigenverl. d. Versuchsanst. f. Wasserbau, Hydrologie u. Glaziologie, 171, p. 204. (2001).
54. Hauck, C. New concepts in geophysical surveying and data interpretation for permafrost terrain. *Permafrost Periglac. Process.* **24** (2), 131–137 (2013).
55. Hoover, R. B. & Gilichinsky, D. Significance to astrobiology of micro-organisms in permafrost and ice. In *Permafrost response on economic development, environmental security and natural resources* (553–579). Dordrecht: Springer Netherlands. (2001).

56. Hu, X., Jiang, G. & Wang, Z. Quaternary studies: Disciplinary review, technical methods, and future prospects. *Geographical Res. Bull.* **4**, 473–490 (2025).
57. Jangir, Y. & Dutta, S. *Planetary analog sites in the Indian subcontinent and the Indian Ocean* (Underexplored environments suited for astrobiological and space research, 2025).
58. Jin, H. et al. Permafrost degradation and its hydrogeological impacts. *Water* **14** (3), 372 (2022).
59. Jonard, F. et al. in *Ground-based soil moisture determination*. (eds Ecohydrology) (Observation and Measurement of Ecohydrological Processes, 2018).
60. Kang, S., Park, G., Kim, N., Tutumluer, E. & Lee, J. S. GPR-based depth estimation of ground interfaces in permafrost region: Electromagnetic method and cone penetration assessment. *Measurement* **242**, 116158 (2025).
61. Ke, X. et al. Thermokarst lakes disturb the permafrost structure and stimulate through-talik formation in the Qinghai–Tibet Plateau, China: A hydrogeophysical investigation. *Cryosphere* **19** (10), 4989–5002 (2025).
62. Kerrigan, M. C. *The Periglacial Landscape Of Utopia Planitia; Geologic Evidence For Recent Climate Change On Mars* (The University of Western Ontario (Canada), 2013).
63. Khan, M. A. R. et al. Modelling permafrost distribution in western Himalaya using remote sensing and field observations. *Remote Sens.* **13** (21), 4403 (2021).
64. Kneisel, C., Hauck, C., Fortier, R. & Moorman, B. Advances in geophysical methods for permafrost investigations. *Permafrost Periglac. Process.* **19** (2), 157–178 (2008).
65. Koutnik, M. R. & Pathare, A. V. Contextualizing lobate debris aprons and glacier-like forms on Mars with debris-covered glaciers on Earth. *Progress Phys. Geography: Earth Environ.* **45** (2), 130–186 (2021).
66. Krutskikh, N., Ryazantsev, P., Ignashov, P. & Kabonen, A. The spatial analysis of vegetation cover and permafrost degradation for a subarctic palsa mire based on UAS photogrammetry and GPR data in the Kola Peninsula. *Remote Sens.* **15** (7), 1896 (2023).
67. Kumar, A., Singh, A. K. & Deepankar, U. Extreme weather events and climate shifts in Ladakh: A multiparameter analysis. In *Building Resilient Water and Food Systems under Climate Change* (215–228). Academic. (2026).
68. Lal, R. & Singh, P. Lakes and Palaeolakes of Ladakh in Context of Geoheritage and Geotourism. In *Geoconservation and Geotourism Potential of India* (33–58). Cham: Springer Nature Switzerland. (2025).
69. Lavagna, M. et al. Final Report of the International Mars Ice Mapper Reconnaissance/Science Measurement Definition Team. (2022).
70. Leuschen, C., Kanagaratnam, P., Yoshikawa, K., Arcone, S. & Gogineni, P. Design and field experiments of a ground-penetrating radar for Mars exploration. *J. Geophys. Research: Planet.* **108**(E4). (2003).

71. Liljedahl, A. K. et al. Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nat. Geosci.* **9** (4), 312–318 (2016).
72. Liu, C. & Wang, Y. Sliding mode control strategy for grid-connected inverters based on boundary layer. In *Journal of Physics: Conference Series* (Vol. 2584, No. 1, p. 012084). IOP Publishing. (2023), September.
73. Loidi, J., Navarro-Sánchez, G. & Vynokurov, D. Climatic definitions of the world's terrestrial biomes. *Veg. Classif. Surv.* **3**, 231–271 (2022).
74. Marcheselli, V. The exploration of the earth subsurface as a Martian analogue. *Tecnoscienza–Italian J. Sci. Technol. Stud.* **13** (1), 25–45 (2022).
75. Mathys, T. et al. Quantifying permafrost ground ice contents in the Tien Shan and Pamir (Central Asia): a petrophysical joint inversion approach using a geometric mean model. *Cryosphere* **19** (12), 6591–6628 (2025).
76. McKay, C. P. Snow recurrence sets the depth of dry permafrost at high elevations in the McMurdo Dry Valleys of Antarctica. *Antarct. Sci.* **21** (1), 89–94 (2009).
77. Mellon, M. T. et al. A prelanding assessment of the ice table depth and ground ice characteristics in Martian permafrost at the Phoenix landing site. *J. Geophys. Research: Planet.* **113**, E3 (2008).
78. Mellon, M. T. et al. Ground ice at the Phoenix landing site: Stability state and origin. *J. Geophys. Research: Planet.* **114**, E1 (2009).
79. Mellon, M. T. & Sizemore, H. The history of ground ice at Jezero Crater Mars and other past, present, and future landing sites. *Icarus* **371**, 114667 (2022).
80. Miner, K. R. et al. Earth to mars: a protocol for characterizing permafrost in the context of climate change as an analog for extraplanetary exploration. *Astrobiology* **23** (9), 1006–1018 (2023).
81. Mir, S. A., Najar, M. M., Kumar, A. & Sharma, R. Geochemical and Provenance Studies of Trans-Himalayan Lake Sediments, Ladakh, India: Their Relationship with Catchment Geology, Geomorphology and Constraint with Different Tectonic Settings. *Geochem. Int.* **62** (13), 1421–1432 (2024).
82. Monnier, S., Camerlynck, C. & Rejiba, F. Ground penetrating radar survey and stratigraphic interpretation of the Plan du Lac rock glaciers, Vanoise Massif, northern French Alps. *Permafrost Periglac. Process.* **19** (1), 19–30 (2008).
83. Moorman, B. J., Robinson, S. D. & Burgess, M. M. Imaging periglacial conditions with ground-penetrating radar. *Permafrost Periglac. Process.* **14** (4), 319–329 (2003).
84. Moran, M. L., Greenfield, R. J., Arcone, S. A. & Delaney, A. J. Multidimensional GPR array processing using Kirchhoff migration. *J. Appl. Geophys.* **43** (2–4), 281–295 (2000).
85. Mukhopadhyay, S., Sarkar, S. & Sar, P. *Microbial life within the deep, hot subsurface biosphere and its implications in astrobiology* 433–461 (Mineral Transformation and Bioremediation by Geo-Microbes, 2025).

86. Nagy, B. et al. The thermal behavior of ice-bearing ground: the highest cold, dry desert on Earth as an analog for conditions on Mars, at Ojos del Salado, Puna de Atacama-Altiplano region. *Astrobiology* **20** (6), 701–722 (2020).
87. Orosei, R. et al. Radar sounding of LucusPlanum, Mars, by MARSIS. *J. Geophys. Research: Planet.* **122** (7), 1405–1418 (2017).
88. Pandey, S. et al. Ladakh: diverse, high-altitude extreme environments for off-earth analogue and astrobiology research. *Int. J. Astrobiol.* **19** (1), 78–98 (2020).
89. Pant, N. C., Ravindra, R., Srivastava, D. & Thompson, L. The Himalayan cryosphere: past and present variability of the ‘third pole’. (2018).
90. Paul, J. R., Kokelj, S. V. & Baltzer, J. L. Spatial and stratigraphic variation of near- surface ground ice in discontinuous permafrost of the taiga shield. *Permafrost Periglac. Process.* **32** (1), 3–18 (2021).
91. Pepin, N. et al. Elevation-dependent climate change in mountain environments. *Nature Reviews Earth & Environment*, 1–17. (2025).
92. Petterson, M. G. Overview of the Geology, Structure, and Tectonics of the Ladakh Batholith and Indus Suture Rocks. In *Himalayan Thick-Skin Basement Deformation of the Ladakh Batholith, Leh-Ladakh Region, NW India* (11–37). Cham: Springer Nature Switzerland. (2023).
93. Pettinelli, E., Cosciotti, B., Lauro, S. E. & Mattei, E. An overview of GPR subsurface exploration of planets and moons. *Lead. Edge.* **41** (10), 672–680 (2022).
94. Phartiyal, B., Clarke Jonathan, D. A. & Pandey, S. Prospects of Astrogeology and Astrobiology researches in India: Ladakh as an example. *J. Palaeosciences.* **70**, 326–337. <https://doi.org/10.54991/jop.2021.24> (2021).
95. Phartiyal, B., Kumar, A. & Shukla, S. Martian/Lunar Analogue Research Station in India: Ladakh as a potential site. *Curr. Sci.* **1** (28), 446–451. 10.18520/cs/v128/i5/446-451 (2025).
96. Philip, G. & Mazari, R. K. Shrinking lake basins in the proximity of the Indus Suture Zone of northwestern Himalaya: a case study of Tso Kar and Startsapuk Tso, using 1RS-1C data. *Int. J. Remote Sens.* **21** (16), 2973–2984 (2000).
97. Philipp, M., Dietz, A., Buchelt, S. & Kuenzer, C. Trends in satellite Earth observation for permafrost related analyses—A review. *Remote Sens.* **13** (6), 1217 (2021).
98. Ping, C. L., Jastrow, J. D., Jorgenson, M. T., Michaelson, G. J. & Shur, Y. L. Permafrost soils and carbon cycling. *Soil* **1** (1), 147–171 (2015).
99. Raguso, M. C. et al. D. A., Analysis of orbital sounding in context with in-situ ground penetrating Radar at Jezero Crater, Mars. *Geophys. Res. Lett.*, **51**(19), (2024). e2024GL109027.
100. Rastogi, S. P. Kar-Tso: A high altitude natural salt-pan in the Himalayas. In *Proceedings of the 2nd International Conference on the Ecological Importance of Solar Saltworks (CEISSA 2009)*. (2009).
101. Sah, K. *Understanding Permafrost Distribution and Degradation Dynamics in the HKH* (A Review of Current Research, 2025).

102. Saintenoy, A. & Léger, E. Studying cold regions with ground-penetrating radar: a review. *Comptes Rendus Géoscience*. **357** (G1), 283–298 (2025).
103. Schirrmeister, L. et al. *Yedoma: Late Pleistocene ice-rich syngenetic permafrost of Beringia* (Elsevier, 2024).
104. Schmid, M. O. et al. Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth. *Cryosphere* **9** (6), 2089–2099 (2015).
105. Searle, M. P. Structural evolution and sequence of thrusting in the High Himalayan, Tibetan-Tethys and Indus Suture zones of Zaskar and Ladakh, western Himalaya: Reply. *J. Struct. Geol.* **10** (1), 130–132 (1988).
106. Searle, M. P. et al. The closing of Tethys and the tectonics of the Himalaya. *Geol. Soc. Am. Bull.* **98** (6), 678–701 (1987).
107. Sharma, R. et al. Astrobiological Exploration: Cosmic Evolution, Martian Habitats, and Prospects. *Martian Habitats, and Prospects* (May 29, 2024). (2024).
108. Sheppard, A. & Skinner, K. A. *MarsLGPR: Mars rover localization with ground penetrating radar* (IEEE Transactions on Field Robotics, 2025).
109. Shrestha, A. B. et al. The Himalayan Climate and Water Atlas: impact of climate change on water resources in five of Asia's major river basins. (2015).
110. Singh, Y. et al. Deformation Characteristics and Mechanism of Pernote Landslide, Jammu India: Geomorphological, Geological and Geophysical Evidences. *J. Geol. Soc. India*. **102** (3), 350–359 (2026).
111. Sinha, A. K. Geology and Tectonics of the Himalayan Region of Ladakh, Himachal, Garwhal-Kumaun and Arunachal Pradesh: A Review. *Zagros Hindu. Kush Himalaya Geodynamic Evol.* **3**, 122–148 (1981).
112. Sjöberg, Y., Marklund, P., Pettersson, R. & Lyon, S. W. Geophysical mapping of palsa peatland permafrost. *Cryosphere* **9** (2), 465–478 (2015).
113. Smith, S. L., O'Neill, H. B., Isaksen, K., Noetzli, J. & Romanovsky, V. E. The changing thermal state of permafrost. *Nat. Reviews Earth Environ.* **3** (1), 10–23 (2022).
114. Strauss, J. et al. Circum-Arctic map of the Yedoma permafrost domain. *Front. Earth Sci.* **9**, 758360 (2021).
115. Streletskiy, D. A. et al. Thawing permafrost is subsiding in the Northern Hemisphere—review and perspectives. *Environ. Res. Lett.* **20** (1), 013006 (2025).
116. Strokova, L. Recognition of geological processes in permafrost conditions. *Bull. Eng. Geol. Environ.* **78** (8), 5517–5530 (2019).
117. Sudakova, M. et al. Using ground penetrating radar for permafrost monitoring from 2015–2017 at calm sites in the Pechora river delta. *Remote Sens.* **13** (16), 3271 (2021).
118. Terhorst, A. & Dowling, J. A. *Terrestrial analogue research to support human performance on Mars: A review and bibliographic analysis* (Science & Technology, 2022).

119. Thakur, P. K. et al. Cryospheric studies in indianhimalayan and polar region: current status, advances and future prospects of remote sensing. *Proceedings of the National Academy of Sciences, India Section A: Physical Sciences*, 87(4), 593–616. (2017).
120. Thakur, V. C. Geology of western Himalaya. *Phys. Chem. Earth*. **19**, 1–355 (1992).
121. Thakur, V. C. & Misra, D. K. Tectonic framework of the Indus and Shyok suture zones in eastern Ladakh, northwest Himalaya. *Tectonophysics* **101** (3–4), 207–220 (1984).
122. Thakur, V. C. & Viridi, N. S. Lithostratigraphy, structural framework, deformation and metamorphism of the southeastern region of Ladakh, Kashmir Himalaya, India. (1979).
123. Torn, M. S. et al. Large emissions of CO₂ and CH₄ due to active-layer warming in Arctic tundra. *Nat. Commun.* **16** (1), 124 (2025).
124. Tourei, A. et al. Mapping permafrost variability and degradation using seismic surface waves, electrical resistivity, and temperature sensing: A case study in Arctic Alaska. *Journal of Geophys. Research: Earth Surf.*, **129**(3), (2024). e2023JF007352.
125. Tumskey, V. E. Cryolithostratigraphy and cryofacies analysis. *Earth's Cryosphere*. **25** (4), 3–16 (2021).
126. Ul Haq, A. et al. Permafrost Mapping of sediments of Tso-Kar, Ladakh: Dynamics Inferred from Ground Penetrating Radar for a Mars Analogue Glacial Basin. In *The Astrobiology Science Conference (AbSciCon) 2022* (pp. 320-02). (2022), May.
127. Ulrich, M. Permafrost landform studies on Earth: Implications for periglacial landscape evolution and habitability on Mars (Doctoral dissertation). (2011).
128. Valdiya, K. S. Tectonics and evolution of the central sector of the Himalaya. *Philosophical Trans. Royal Soc. Lond. Ser. Math. Phys. Sci.* **326** (1589), 151–175 (1988).
129. Vishwakarma, B. D. et al. Challenges in understanding the variability of the cryosphere in the Himalaya and its impact on regional water resources. *Front. Water*. **4**, 909246 (2022).
130. VonderMühl, D., Hauck, C. & Gubler, H. Mapping of mountain permafrost using geophysical methods. *Prog. Phys. Geogr.* **26** (4), 643–660 (2002).
131. Wainstein, P. A., Tseung, J. M. W. B., Moorman, B. J. & Stevens, C. W. Integrating GPR and CCRI techniques: Implications for the identification and mapping of ground ice on Mars. *Mars J.* **4**, 1–13 (2008). address when accessed 29/08/2026
http://www.marsjournal.org/contents/2008/0001/files/wainstein_mars_2008_0001.pdf
132. Wang, J. et al. Landsat satellites observed dynamics of snowline altitude at the end of the melting season, Himalayas, 1991–2022. *Remote Sens.* **15** (10), 2534 (2023).
133. Wang, Y. et al. Imaging of the internal structure of permafrost in the Tibetan plateau using ground penetrating radar. *Electronics* **9** (1), 56 (2019).
134. Wani, J. M., Thayyen, R. J., Gruber, S., Ojha, C. S. P. & Stumm, D. Single-year thermal regime and inferred permafrost occurrence in the upper Ganglass catchment of the cold- arid Himalaya, Ladakh, India. *Science of the total environment*, 703, 134631. (2020).

135. Wani, J. M., Thayyen, R. J., Ojha, C. S. P. & Gruber, S. The surface energy balance in a cold and arid permafrost environment, Ladakh, Himalayas, India. *Cryosphere* **15** (5), 2273–2293 (2021).
136. Wrigley, C. *Earth, ice, bone, blood: Permafrost and extinction in the Russian Arctic* (U of ` Minnesota, 2023).
137. Wu, T., Li, S., Cheng, G. & Nan, Z. Using ground-penetrating radar to detect permafrost degradation in the northern limit of permafrost on the Tibetan Plateau. *Cold Reg. Sci. Technol.* **41** (3), 211–219 (2005).
138. Wünnemann, B. et al. Hydrological evolution during the last 15 kyr in the Tso Kar lake basin (Ladakh, India), derived from geomorphological, sedimentological and palynological records. *Q. Sci. Rev.* **29** (9–10), 1138–1155 (2010).
139. Wünnemann, B., Reinhardt, C., Kotlia, B. S. & Riedel, F. Observations on the relationship between lake formation, permafrost activity and lithalsa development during the last 20 000 years in the Tso Kar basin, Ladakh, India. *Permafrost Periglac. Process.* **19** (4), 341–358 (2008).
140. Xiao, Y. et al. Mapping Mountain Permafrost via GPR-Augmented Machine Learning in the Northeastern Qinghai–Tibet Plateau. *Remote Sensing*, 17(12), 2015. (2025).
141. Yaminsky, I. V. & Mulyukin, A. L. Living cells in permafrost as models for astrobiology research. *Life Anc. Ice.* **5653**, 277 (2005).
142. Yu, A., Wang, H., An, D. & Shi, H. Evolution of Mars Water-Ice Detection Research from 1990 to 2024. *Remote Sens.* **17** (6), 1023 (2025).
143. Yu, G., Harrison, S. P. & Xue, B. *Lake status records from China: data base documentation* pp. 1–243 (MPI-BGC, 2001).
144. Zheng, N., Ding, C., Su, Y. & Orosei, R. Water ice resources on the shallow subsurface of Mars: indications to rover-mounted radar observation. *Remote Sens.* **16** (5), 824 (2024).

Figures

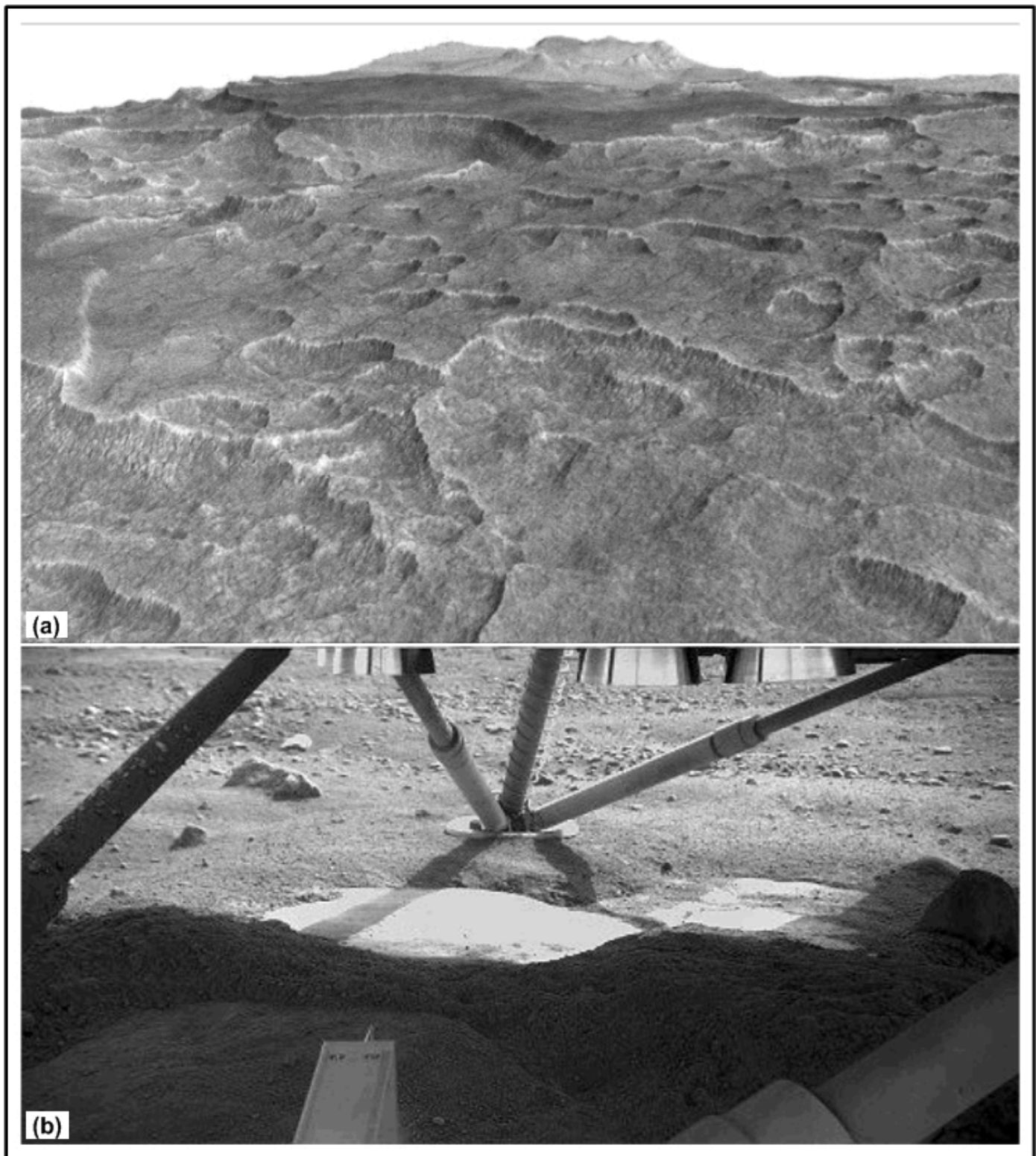


Figure 1

Vertically exaggerated view of martian permafrost from scalloped depressions in Mars' Utopia Planitia region with distinctive surface textures of the landform that reflects sub-surface permafrost (HiRISE image PSP_002439_2265), <https://science.nasa.gov/resource/scalloped-terrain-led-to-finding-of-buried-ice-on-mars>.(b) Ground ice at the Phoenix Landing Site exposed in 50 cm pits excavated by the descent thrusters under the lander (Phoenix image PIA11379) (Mellon et al., 2009).



Figure 2

Location map showing the study area at Tso Kar.

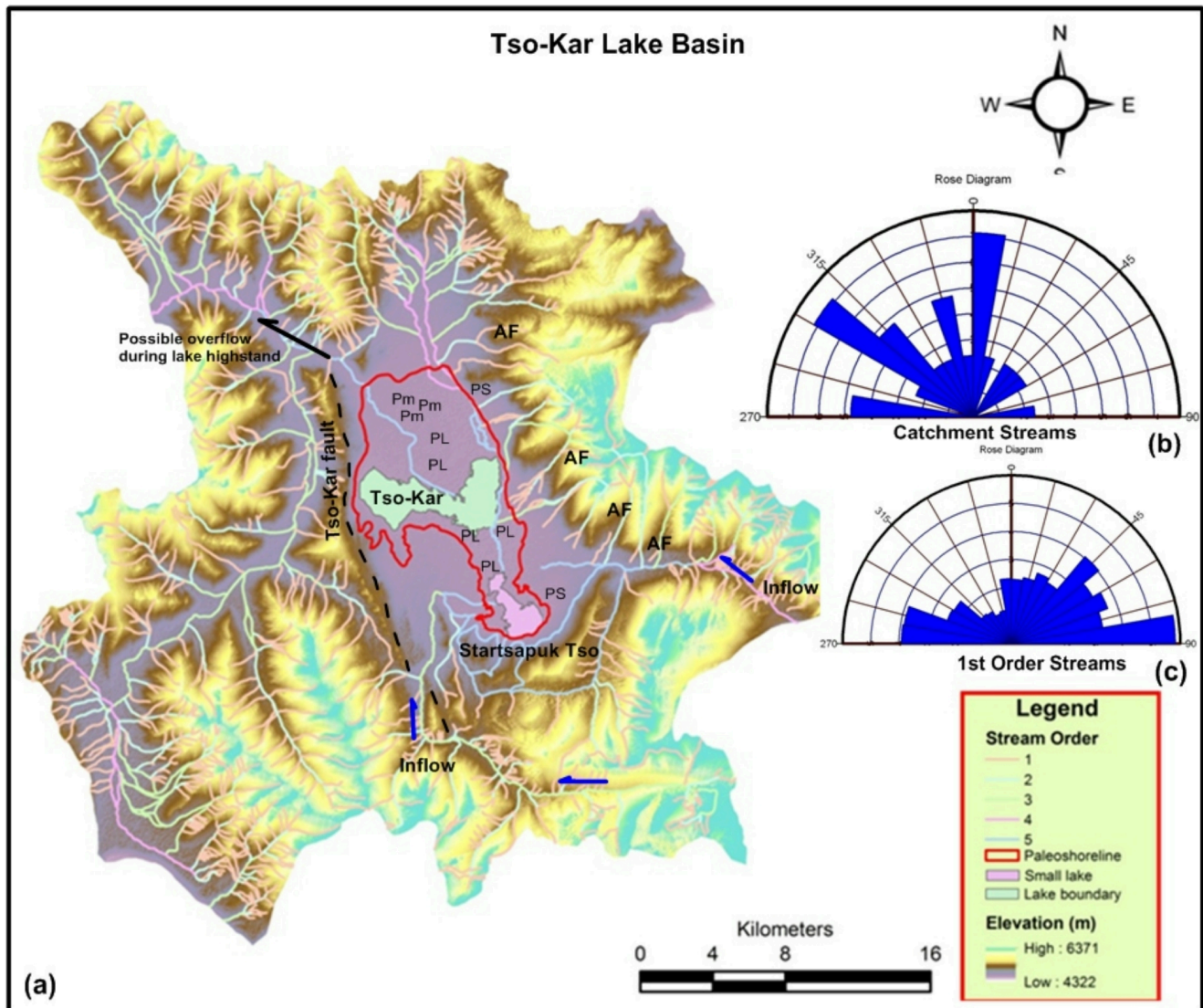


Figure 3

(a) Digital Elevation Map of Tso Kar showing both Tso Kar and Starsapuk lakes, lake catchment and streams orders and surface expression of Tso-Kar fault (b) Rose diagram showing major stream direction (N-S and NW-SE) (c) Rose diagram showing the trend of 1st order streams which are sensitive to the ongoing tectonic deformation.

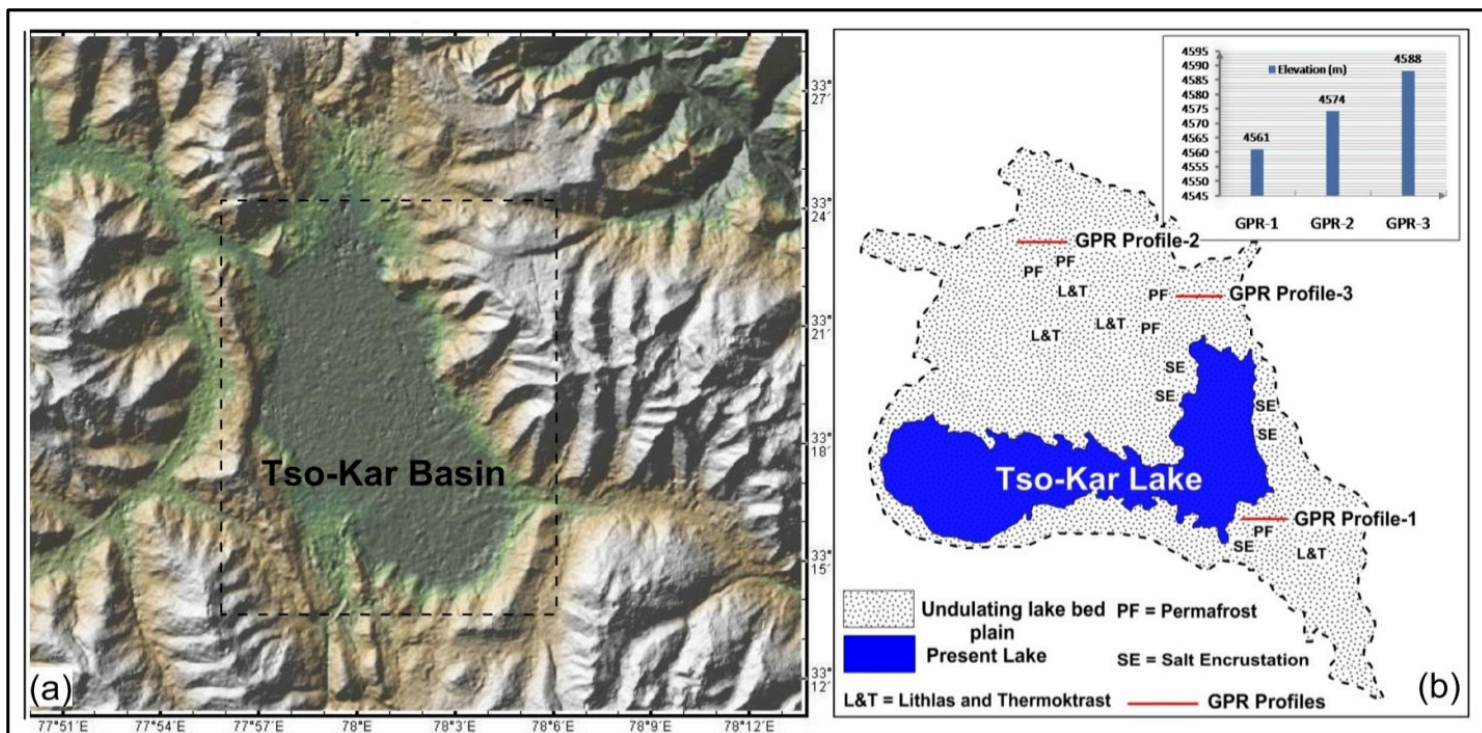


Figure 4

(a) Satellite image of the Tso-kar basin showing landscape pattern (b) Map showing the Tso Kar, surrounding periglacial landforms and the GPR traverses. The histogram shows elevation of the GPR profiles where the lower elevation corresponds to the stratigraphically younger strata and the highest elevation (paleoshorelines) corresponds to older strata.

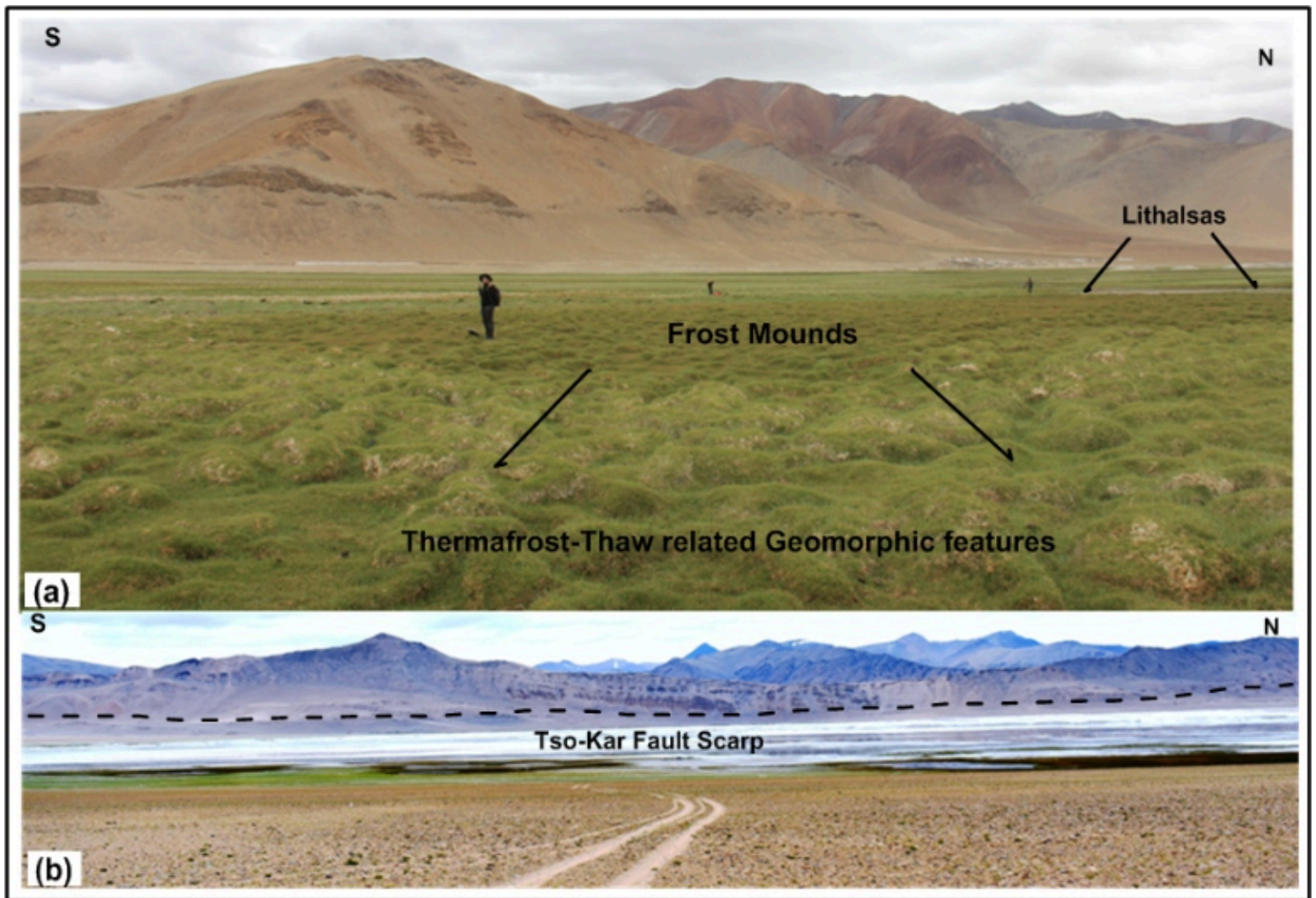


Figure 5

Field photographs showing (a) Geomorphic features (frost mounds and lithalsas), representing the thermokarst-thaw conditions (b) Prominent geomorphic expression of Tso-Kar fault representing the evidence of active tectonic deformation as a part of Himalayan mountain building and continuous collision.



Figure 6

Field photographs showing (a) Site condition and survey layout at site-1 (GPR Profile-1) showing the Antenna, and Control Unit and Survey Wheel for data acquisition the N-S represent the north and south directions (b) Survey layout at site-2 (GPR Profile-2) representing prominent peri-glacial landscape with surface expression of thermokarst (c) Survey layout at site-3 (GPR Profile-3) showing dry surface condition, representing favourable condition for GPR data acquisition.

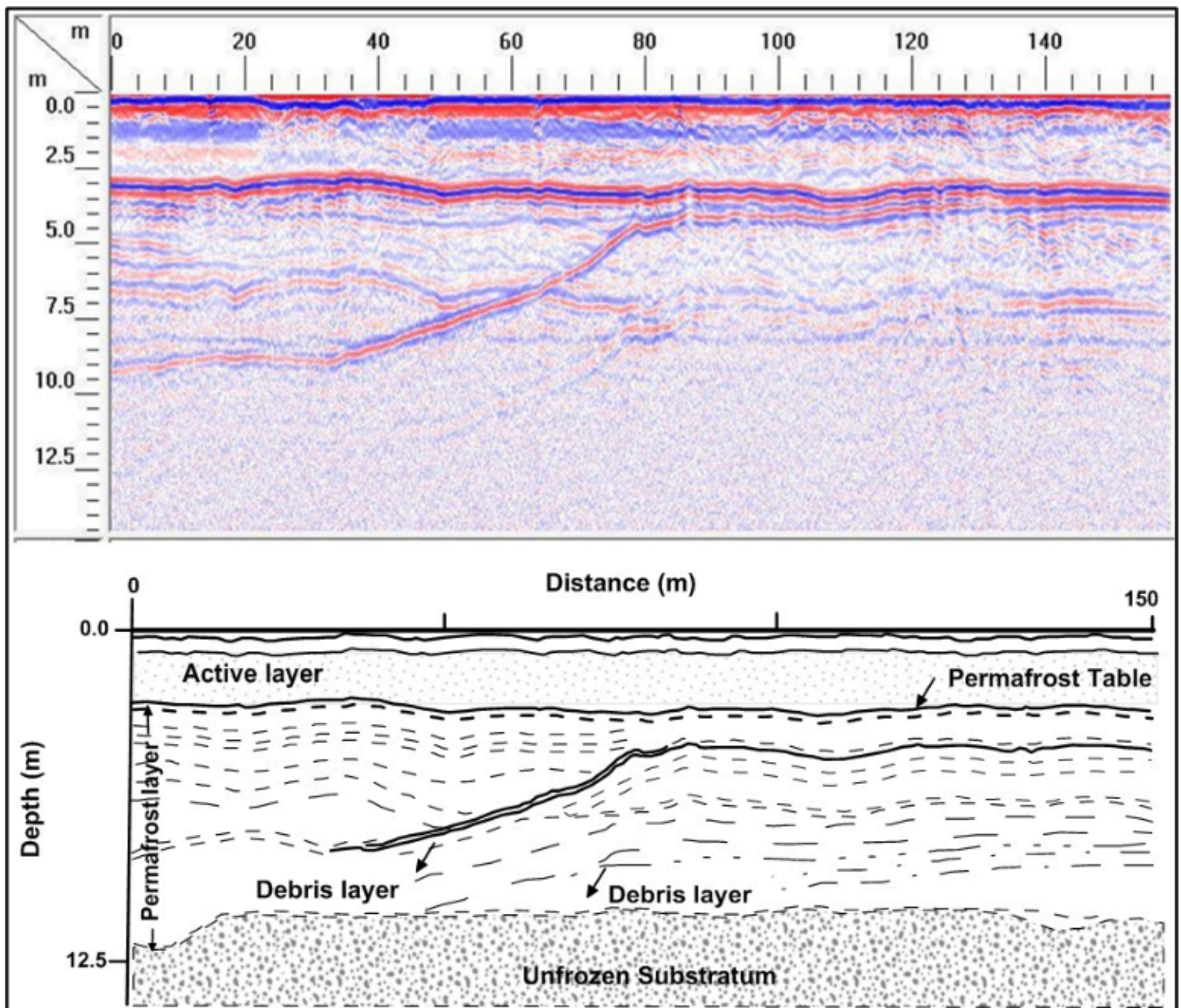


Figure 7

GPR profile of site-1 showing the lateral and vertical variability in the signal with sub-surface permafrost stratigraphy and structures. The sketch labeled to depict the interpretation without altering the GPR profile. The profile starts from lake shoreline to the hill side, showing the active layer, permafrost table, debris layer and unfrozen substratum. The sloping reflectors labeled in the sketch are the debris layer and represent flow of coarse sediments from the adjacent slope to the lake during warm period. The unfrozen substratum in the sketch represent the basement for this permafrost layers.

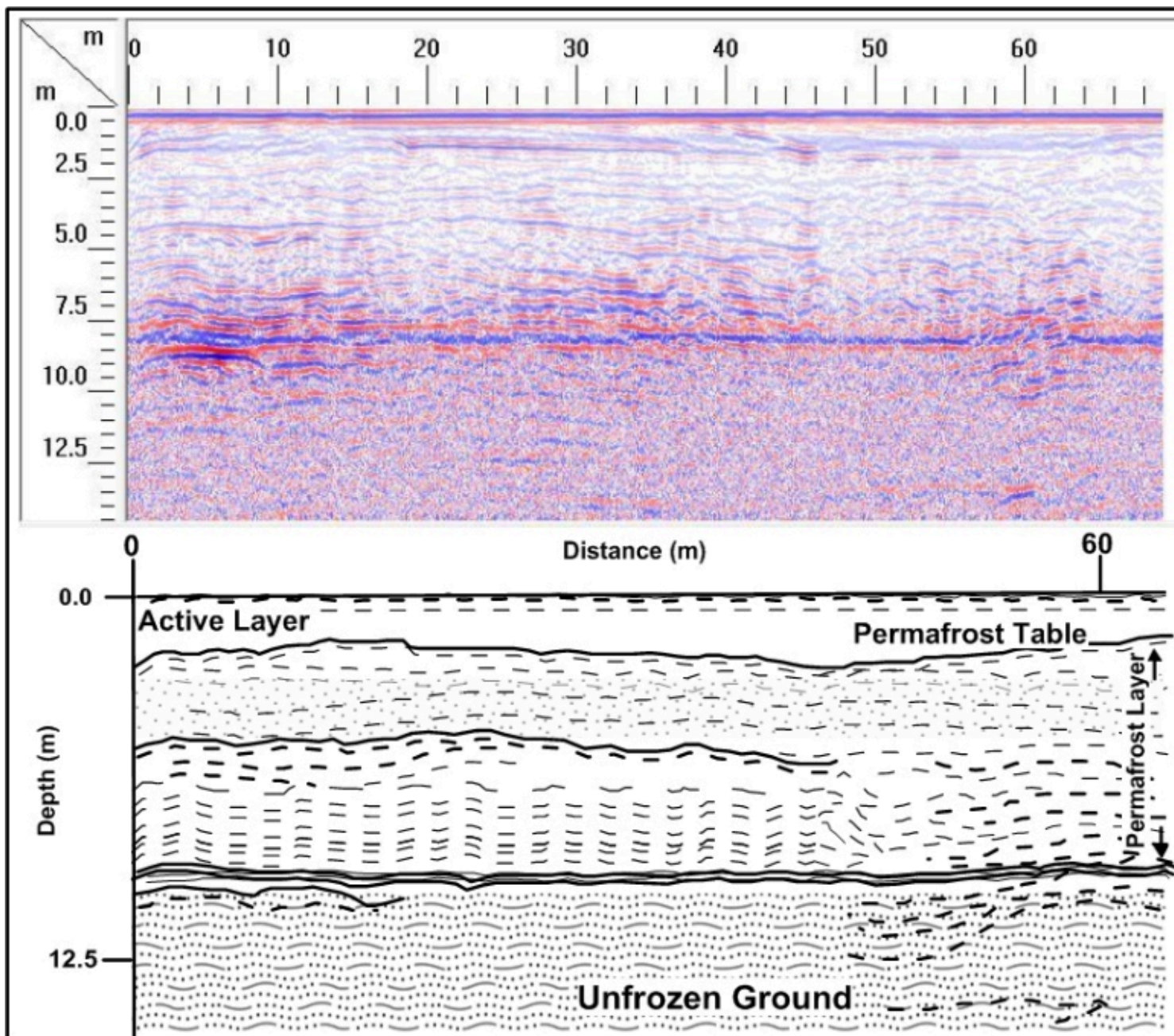


Figure 8

GPR profile of site-2 showing the lateral and vertical variability in the signal with sub-surface permafrost stratigraphy and structures. The sketch labeled to depict the interpretation without altering the GPR profile. The profile is taken on a flat surface, showing prominent stratified layers and cryogenic features like active layer, permafrost table, debris layer and unfrozen substratum. The profile shows small scale deformations structures induced by gravity flow or due to post depositional processes.

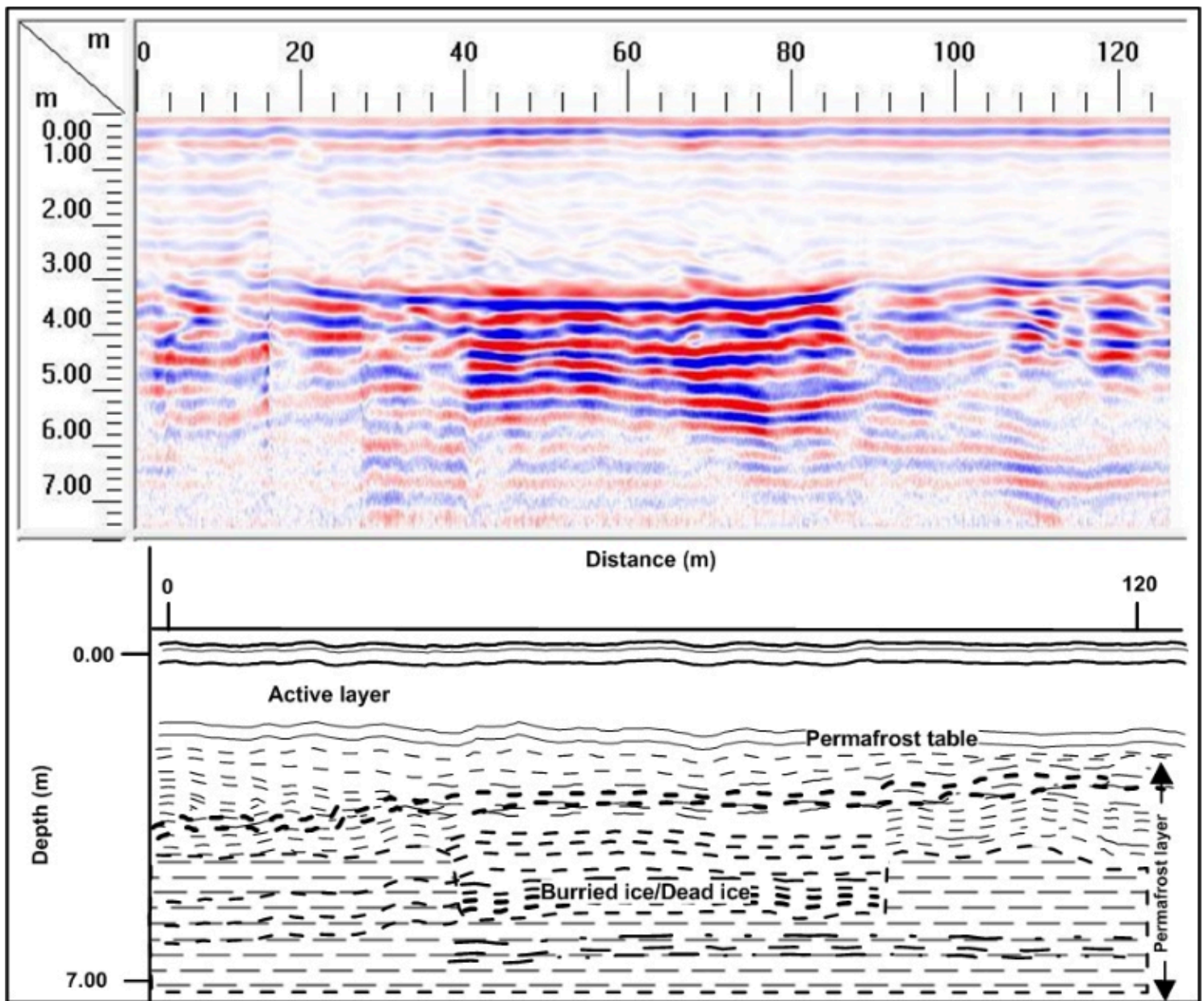


Figure 9

High-resolution GPR profile of Site-3 illustrating the vertical cryostratigraphic architecture comprising the firn layer, active layer, and permafrost table. The labeled sketch depicts the interpretation without altering the GPR profile. The alternating high and low amplitude reflections represent interbedded ice and sediment-rich layer formed under varying palaeoclimatic, geomorphic, and hydrological conditions. The high reflections at a depth of 3-6m represent the buried ice having high reflections and cause the signal loss.

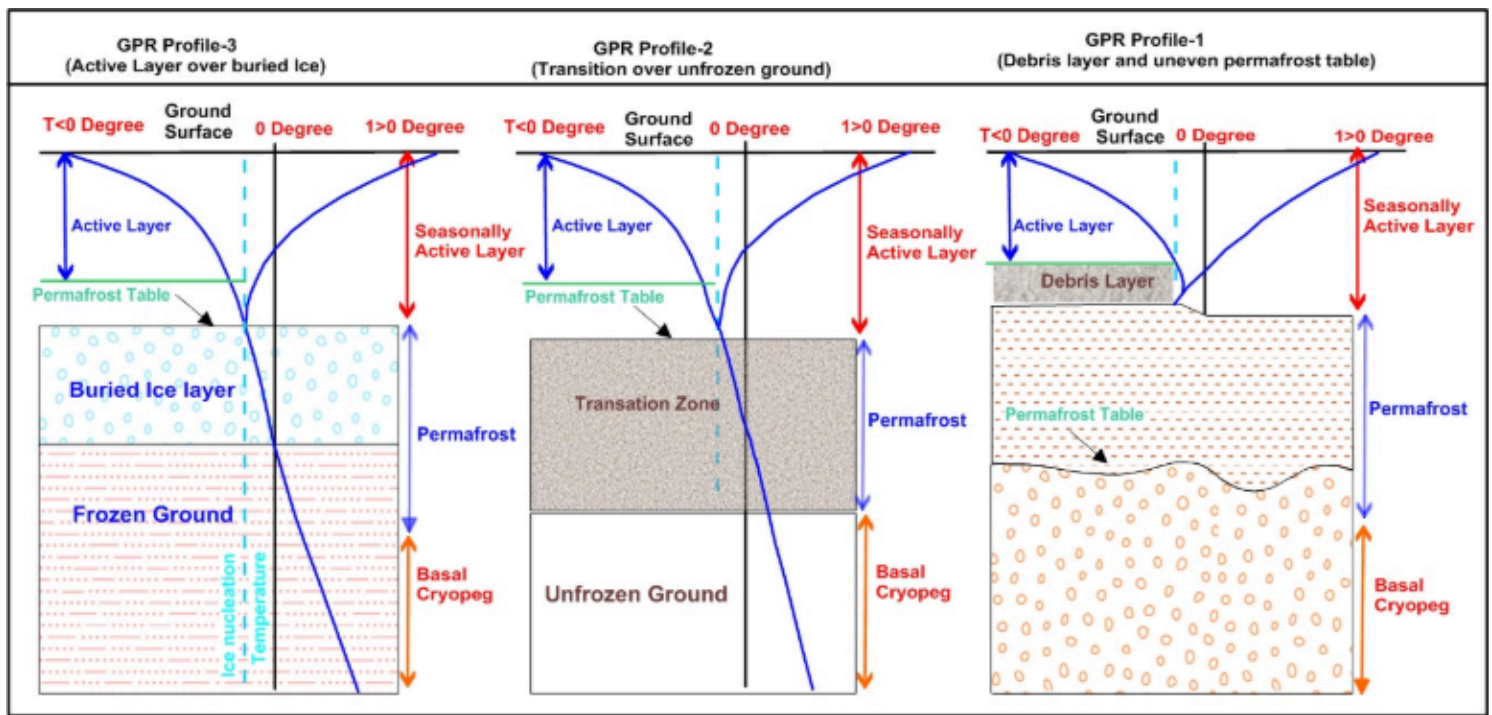


Figure 10

Schematic diagram illustrating the cryostratigraphic evidence and vertical cross-section of the three GPR profiles showing a progressive spatial variability of permafrost conditions. The Profile-1 demonstrate the stable permafrost with shallow active layer overlaying the well preserved frozen sub-surface; Profile-2 represent an intermediate stage showing an increase in the thickness of active layer due to seasonal thaw resulting in the generation of transition zone and talik showing the partial degradation of permafrost and; Profile-3 represent the advanced stage of permafrost degradation reflected by the debris rich active layer over an discontinuous and irregular permafrost table (Profile-1,2&3 corresponds to Site-1,2&3 respectively).