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Communication

Mountain Permafrost: A Reflection on the Periglacial Environment in Mongolia

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Abstract: There are different ideas about the classification and distribution of permafrost in Mongolia. Terms such as continuous, discontinuous, sporadic, and isolated permafrost are inconsistently applied; hence, maps of permafrost display different distribution patterns. Particularly, the southern border of the Siberian permafrost in Mongolia is still debated. Furthermore, comparing these maps is challenging when studying impacts of climate change on permafrost. While, without a doubt, Mongolia's permafrost is in a stage of significant degradation and has receded from vast regions, telling this story is difficult when data are not easily comparable. Today, all permafrost is restricted to Mongolia's mountains. To better describe permafrost that depends on orography and elevation, we propose to use the more appropriate term 'mountain permafrost.' Surprisingly, the term 'periglacial' is mostly absent in the literature on Mongolia's permafrost. We here aim to clarify definitions of terms and hope that future studies will pay attention to both periglacial environments and mountain permafrost.

Keywords: Mongolia; mountains; periglacial; permafrost

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1. Introduction

While permafrost is widespread in Mongolia and systematically studied since the early 1960s, Kamp et al. (2022) [1] concluded in their review on 'Mongolia's Cryosphere':

> *"The extent and distribution of permafrost and its subtypes across Mongolia is still debated. Interestingly, authors do not agree if continuous permafrost even exists in Mongolia, or if its southern boundary is to be found in southern Siberia. One of the reasons for this uncertainty seems to be the misinterpretation of periglacial processes and landforms as proof of widespread extensive permafrost conditions. While their occurrence does prove frozen ground and related favorable conditions, it does not necessarily prove continuous permafrost. Consequently, some permafrost maps might overestimate the extent of (continuous) permafrost in Mongolia [. . .] Finally, in many Mongolian publications on permafrost, the term 'periglacial' does not appear, which might be a result of incorrect translations. A synchronization of permafrost key terms is necessary."*

We here intend to help clarify the definition and terminology related to permafrost and periglacial environments. In the case of Mongolia, we propose to use the terms continuous, discontinuous, sporadic, and isolated permafrost with caution and to substitute it with 'alpine permafrost' or 'mountain permafrost' as orography and elevation are key factors for the occurrence of permafrost in the Mongolian landscape.

2. Periglacial Environments

The original term 'periglacial', introduced by von Lozinski in 1909 (see [2]), means 'around glacial' and, thus, focuses on location. An entire research field of periglacial geomorphology particularly developed since the mid-1940s with a focus on Central Europe, and the first specialized book *The Periglacial Environment* was published by French (1976) [3] in the 1970s. A wide range of elements defined the periglacial environment, for example, cold climate, topography, frozen ground, morphodynamic processes, soil water, and human impacts.

Today, it is understood that periglacial is location-independent and rather focuses on process: frost action and/or permafrost-related processes are dominant and represent, besides glacial processes, the most influential factors shaping landscapes in cold polar zones and high mountains [4–7]. One conventional description is that periglacial environments include those in which frost action governs at a mean annual air temperature (MAAT) of below −2 °C, or those in which permafrost-related processes dominate at a MAAT of between −2 °C and +3 °C [6,8]. In areas of intensive frost activity and cryogenic weathering, processes such as heaving and sorting are common resulting in the formation of various types of patterned ground. Slow mass movements such as solifluction and gelifluction [9] rule, but also other geomorphological processes such as fluvial ones are involved in shaping the periglacial environment [10] (Figure 1). While these characteristics describe the periglacial environment, they do not necessarily define permafrost. In many permafrost maps of Mongolia, 'seasonal frozen ground' is included as a separate zone, which might lead to misinterpretations and an overestimation of the total permafrost coverage as seasonal frozen ground is part of the periglacial but not the permafrost environment.

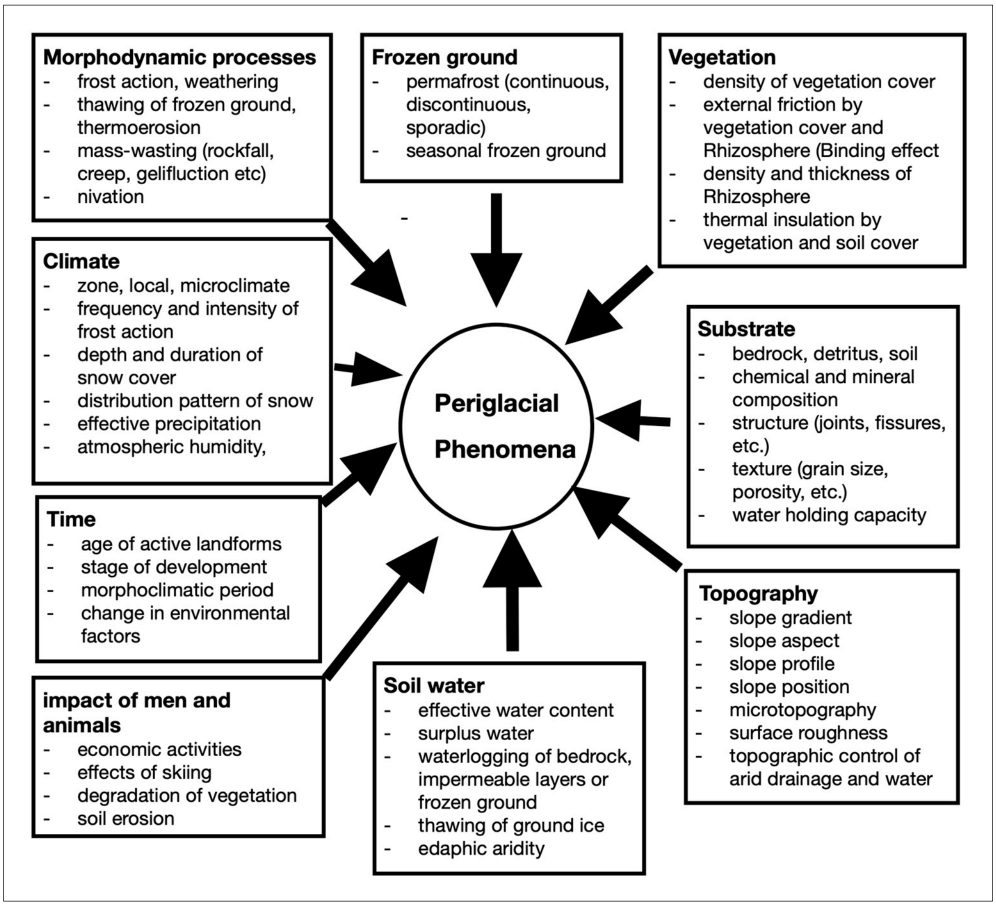

Figure 1. Elements that define the periglacial environment [10] (modified).

Höllermann (1985) [10] underscored the importance of altitudinal periglacial belts in mountains. He described the climatic conditions of the periglacial belt in Mongolia as of 'continental type or interior type' and gave the Tien Shan and Southern Khangai Mountains as regional examples. The MAAT in this periglacial belt was between −1 °C and −4 °C. Later, French (2006) [7] expanded on this idea and explained that, in addition to

MAAT, also the mean annual ground surface temperature (MAGST) and the temperature at the surface of the permafrost (TTOP), at the base of the active layer, are critical to define periglacial processes based on thermal conditions. While permafrost in High Arctic and continental periglacial environments is widespread, it may, or may not, be present in alpine mid-latitude environments [8].

While periglacial environments reach into the polar zones and high mountains, it is challenging to define the lowest latitudinal and altitudinal boundaries because regional and local topography, weather and climate, and other environmental conditions might favor periglacial processes or not. Without a doubt, the periglacial environment surrounds the glacial one, and, thus, the former is found at lower latitudes and elevations than the latter. Both glacial and periglacial conditions can be found in Mongolia's Altai mountains. One such environment, where periglacial but no glacial conditions exist, is the extensive arid steppes of continental Mongolia.

3. Permafrost

Permafrost covers 22–25% of the exposed land surface today, i.e., land that is not covered by glacial ice, in the Northern Hemisphere and around 65% in Eurasia [11].

Shur et al. (2011) [12] described how Russian scientists used the term 'permanently frozen ground (soil)' at least since 1927 with the publication of the map by Sumgin (1927, 1940) [13,14]. Muller (1947) [15] then introduced 'permafrost' as the abbreviation of this term into the English literature. The International Permafrost Association (IPA), founded in 1983, stated that, while seasonally frozen ground is soil or rock and included ice or organic material that freezes for more than 15 days per year, permafrost is ground that remains at or below 0 °C (32 °F) for at least two years [16,17]. The IPA's definition implies that permafrost does not necessarily require the existence of ice lenses or layers. However, it should be assumed that many permafrost areas do contain ice. Furthermore, it must be understood that not all areas with an annual average air temperature below freezing have permafrost.

The IPA's permafrost definition is mirrored by the one commonly used in North America in which permafrost is solely identified by ground temperature and independent from location, snow cover, or any other environmental conditions, while, in contrast, in the Russian definition, permafrost must contain ice [12]. Of importance here is that many scientists concerned with permafrost in Mongolia are trained in the Russian tradition, which might be reflected in classifications and, even more, distribution maps that are based on ground ice occurrence. One might, thus, expect that Russian and probably also Mongolian permafrost maps should include a much smaller permafrost area because only areas in which ice occurs are mapped.

To facilitate the scientific conversation, the IPA/van Everdingen (2005) [17] published a multi-language glossary in 1998 and revised it in 2005 and defined as follows:

> Continuous: "*Permafrost occurring everywhere beneath the exposed land surface throughout a geographic region with the exception of widely scattered sites, such as newly deposited unconsolidated sediments, where the climate has just begun to impose its influence on the thermal regime of the ground, causing the development of continuous permafrost. The term [...] generally refers to areas where more than 90 percent of the ground surface is underlain by permafrost*."

> Discontinuous: "*Permafrost occurring in some areas beneath the exposed land surface throughout a geographic region where other areas are free of permafrost. Discontinuous permafrost occurs between the continuous permafrost zone and the southern latitudinal limit of permafrost in lowlands. Depending on the scale of mapping, several subzones can often be distinguished, based on the percentage of the land surface underlain by permafrost*."

According to the glossary, both English and Russian permafrost classifications separate at the first level into continuous (>90%) and discontinuous (<90%), and then add sub-classes to discontinuous. In the English literature, these are extensive (65–90%), intermediate

(35–65%), sporadic (10–35%), and isolated (<10%); the Russian literature uses massive island (70–80%), island (40–60%), and sporadic (5–30%) (Table 1). Irritating is the fact that the Russian classification lists three such sub-classes, but their coverage percentage brackets are inconclusive: 5–30%, 40–60%, and 70–80%, which excludes 30–40%, 60–70%, and 80–90%. In contrast, the Mongolian classification separates into continuous (>85%) and discontinuous (50–85%) but then adds two first-level classes, sporadic (10–50%) and isolated (<10%), i.e., the latter two are not sub-classes of discontinuous (Table 2). Similarly, it was also performed in the IPA's 'Circum-arctic Map of Permafrost and Ground Ice Conditions' by Brown et al. (1997) [18]: continuous (>90%), discontinuous (50–90%), sporadic (10–50%), and isolated (<10%). By comparing these classification systems, the class sporadic represents the following coverage percentages: 10–35% in the English literature, 5–30% in the Russian literature, and 10–50% in the Mongolian literature and the IPA's circum-arctic map. Considering such incompatibilities, direct comparisons of results from older studies are challenging and should be avoided. Assumingly as a reaction to these issues, today, the IPA (2023) [16] favors a three-class system by stating "*a typical classification recognizes continuous permafrost (underlying 90–100% of the landscape); discontinuous permafrost (50–90%); and sporadic permafrost (0–50%)*," i.e., the isolated class was dropped. Already earlier, the IPA/von Everdingen (2005) [17] recommended that the terms insular, island, and scattered should be discontinued.

Table 1. Common definitions of permafrost terms in the (older) English and Russian literature [17].

English	% Permafrost	Russian	% Permafrost
Continuous	>90	Continuous	>90
Discontinuous	<90	Discontinuous	<90
- Extensive	65–90	- Massive island	70–80
- Intermediate	35–65	- Island	40–60
- Sporadic	10–35	- Sporadic	5–30
- Isolated	0–10	?	0–5

Table 2. Common definitions of permafrost terms in the (older) Mongolian literature [19] and in the IPA's 'Circum-arctic Map of Permafrost and Ground Ice Conditions' by Brown et al. (1997) [18].

Mongolian	% Permafrost	IPA	% Permafrost
Continuous	>85	Continuous	>90
Discontinuous	50–85	Discontinuous	50–90
Sporadic	10–50	Sporadic	10–50
Isolated	<10	Isolated	<10

4. Permafrost in Mongolia

Mongolia has the fifth largest permafrost area after Russia, Canada, China, and Alaska in the U.S. [20]. Sumgin (1927) [13] presented the first map of permafrost in Asia, in which the Siberian permafrost region reaches into Mongolia. Lonjid (1963) [21] then published a map of seasonally frozen ground. In the map by Gravis et al. (1971) [22], Mongolia's permafrost region was classified into five zones: continuous, intermittent (=discontinuous), island, sparsely island, and sporadic, and this model was later picked up by Tumurbaatar and Mijiddorj (2006) [23] and Ulaanbaatar and Legden 2015 [24] (Figure 2, Table 3). Gravis was part of a Mongolian–Soviet geocryology research program that carried out geomorphological field observations across Mongolia between 1967 and 1970. The so-called 'Gravis Map' also includes a zone of 'pereletok', which is a Russian term meaning 'survives over the summer' and represents an intergelisol, a seasonally frozen layer of ground at the base of the active layer that may persist for one or several summers and then thaws; as such, pereletok is part of the suprapermafrost rather than the actual permafrost, although it may easily be mistaken for it [25,26] (Figure 3). The IPA's 'Circum-arctic Map of Permafrost and Ground Ice Conditions' by Brown et al. (1997) [18] displays four permafrost zones within Mongolia: continuous, discontinuous, sporadic, and isolated patches, and this classification has been cited in several other studies [27,28]. The map by Jambaljav et al. (2016) [29] separates into four permafrost zones based on ground temperature regime: continuous (<−2 °C), discontinuous (−2 to −1 °C), sporadic (−1 to 0 °C), and isolated (0 to +1 °C).

Table 3. Permafrost classifications, methodologies, and coverage/year in Mongolia from different authors. In each classification, the permafrost coverage decreases from class to class. (Note: 'seasonally frozen ground' and 'pereletok' displayed in some maps are not part of the permafrost region).

Author/s	Permafrost Classification	Methodology	Coverage/Year
Gravis (1974) [30], Gravis et al. (1971) [22], Tumurbaatar and Mijiddorj (2006) [23], Ulaanbaatar and Legden (2015) [24]	5 zones: continuous, intermittent (=discontinuous), island, sparsely island, sporadic		63% in 1971
Lonjid and Tumburtaar (1977) [31]	3 zones: continuous and discontinuous, scattered, sporadic		
Sodnom and Yanshin (1990, 2005) [32,33]	3 zones: continuous and discontinuous, island and sparsely island, sporadic	Based on 'Gravis Map' from 1971 [22]	63% in 1971
Brown et al. (1997, 2001) [18,34], Saruulzaya et al. (2016, 2021) [28,35]	4 zones: continuous, discontinuous, sporadic, isolated		---
Sharkhuu (2003) [36]	3 zones: continuous and discontinuous, isolated, sporadic		---
Kynicky et al. (2009) [37]	---	Electrical and thermal soundings for 2003–2009; manual observations of air and ground temperatures, precipitation, and near-surface soil moisture and groundwater level for 2004–2005	51% in 2009
Jambaljav et al. (2016) [29]	4 zones continuous (<−2 °C), discontinuous (−2 to −1 °C), sporadic (−1 to 0 °C), isolated (0 to +1 °C).	Temperature at the top of the permafrost (TTOP) modeling	29% in 2015
Obu et al. (2019) [11]	4 zones: continuous, discontinuous, sporadic, isolated	Mean annual ground temperature (MAGT) at the top of the permafrost (TTOP) modeling at 1 km^2 scale for 2000–2016, validated against 36 measured borehole MAGT	2016
Zorigt et al. (2020) [38]	3 zones: −9.5 to −4 °C, −3.9 to −2 °C, >(?)−1.9 °C	Measured borehole mean annual ground temperature (MAGT)	26% in 2013
Jambaljav et al. (2022) [20]	4 zones: continuous, discontinuous, sporadic, isolated	Mean annual ground temperature (MAGT) at the top of the permafrost (TTOP) modeling for 2004–2013, validated against >100 measured borehole MAGT from 2014 to 2015	29% in 2013

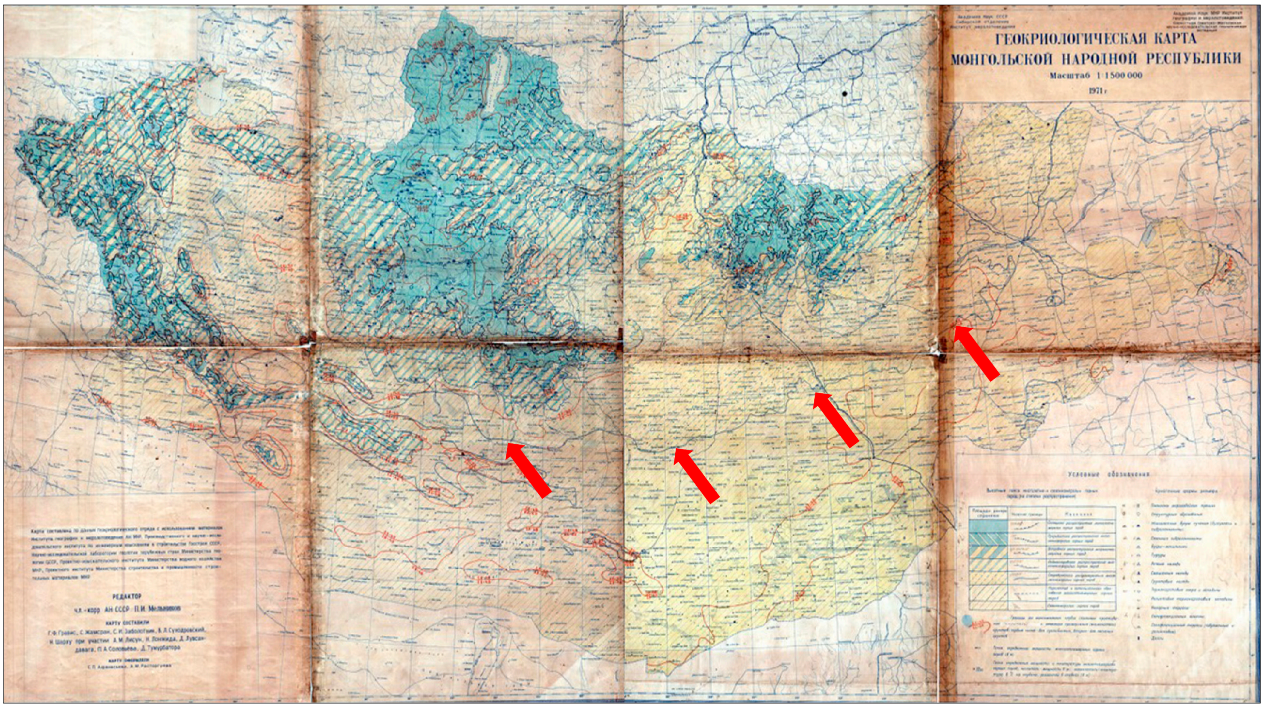

Figure 2. Permafrost zones in Mongolia after Gravis et al. (1971) [22]. The legend of the so-called 'Gravis Map' lists five permafrost zones: continuous, intermediate (=discontinuous), island, sparsely island, and sporadic. In 1971, permafrost covered 63% of the country's territory. South of the southern boundary of the permafrost region (red arrows), the two zones of the permafrost-free area are overflows and potential permafrost as well as seasonally frozen ground.

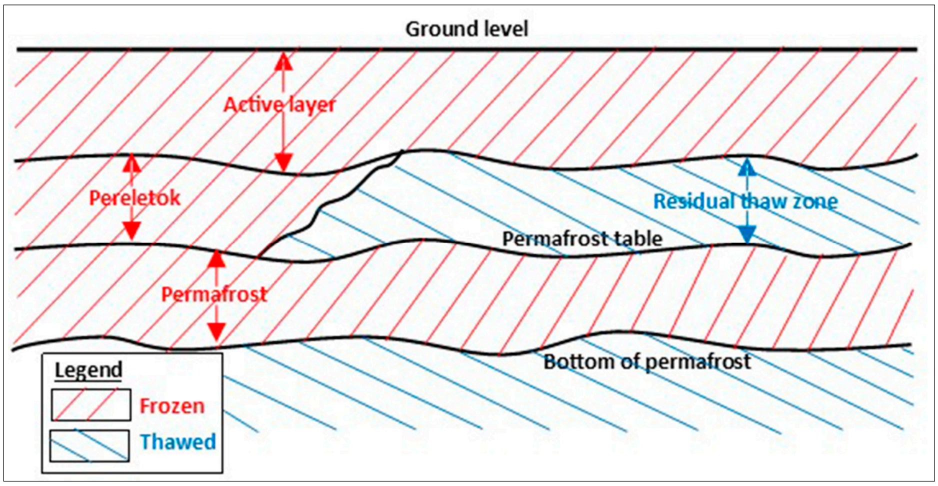

Figure 3. Schematic permafrost profile: the pereletok layer is a zone at the base of the active layer and part of the supra-permafrost rather than the actual permafrost [39].

It is important to underscore that the 'Gravis Map,' published in Russian, used the term island permafrost with an occurrence of 40–80% (massive island and island combined) (Table 1). Unfortunately, in several subsequent studies, e.g., [36,40], island permafrost has been translated as isolated permafrost, a term that does not exist in the Russian terminology and has a permafrost occurrence of only up to 10% in the English terminology. In other words, the Russian island permafrost and English isolated permafrost represent two very different classes.

The permafrost coverage within Mongolia's territory was put at 63% in 1971 [22,30,41], 51% in 2009 [37], 29% in 2013 [20], 26% in 2013 [38]), and 29% in 2015 [29]. Based on the 'Gravis Map,' the share per permafrost zone of the country's total territory in 1971 was as follows: 11.2% continuous and discontinuous, 22.4% island and sparsely island, and 29.4% sporadic [22,33,42] (Table 4). For 2013, the numbers by Jambaljav et al. (2022) [20] were as follows: 7.5% continuous, 8.1% discontinuous, and 7.1% sporadic. Zorigt et al. (2020) [38] calculated that of the total permafrost region in 2013, 33% were of continuous and 67% of discontinuous type; no other permafrost (sub-)zone was presented.

Table 4. Geocryological zones and their altitudinal occurrence, area, and coverage of the total territory of Mongolia in 1971 after Gravis et al. (1990, modified) [42].

Geocryological Zone	Altitude (m)	Area (km^2)	Coverage (%)
Permafrost		985,950	63.0
- Continuous and discontinuous	1200–2800	175,280	11.2
- Insular and sparsely insular	700–2600	350,560	22.4
- Sporadic	600–1900	460,110	29.4
Seasonally frozen ground	600–1800	579,050	37.0

When calculating the change in the permafrost area across Mongolia, results from more recent studies are commonly compared with the 'Gravis Map' from 1971 being the baseline. Such studies concluded a reduction in the permafrost area from 63% of Mongolia's territory in 1971 to 26–29% in the 2010s and named degradation under climate change conditions as its main cause [43] (Figure 4). Based on these and the numbers from Gravis et al. (1990) [42] (Table 3), only 453,850 km^2 of permafrost remained in 2015, after the loss of 532,100 km^2 (53%) since 1971.

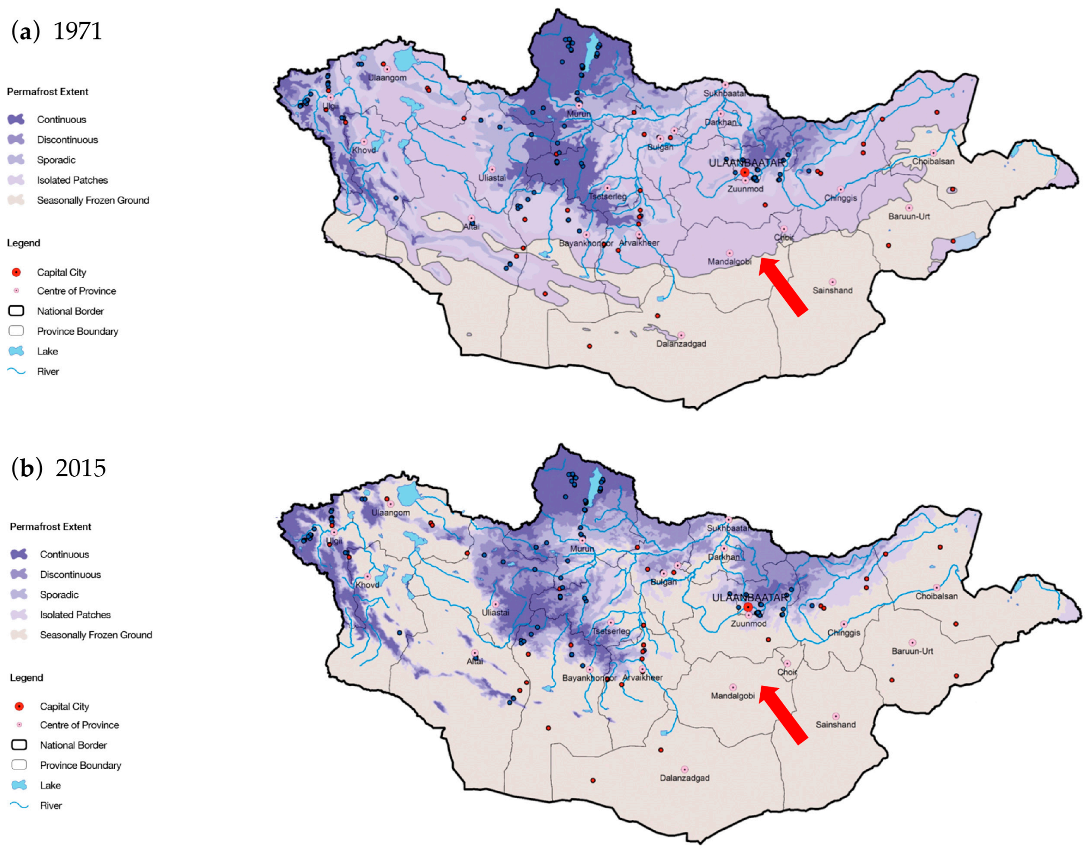

Figure 4. The recession of the southern permafrost boundary in Mongolia between 1971 and the 2010s has been interpreted as an impact of climate change. Digitized versions of the maps by (**a**) Gravis et al. (1971) [22] and (**b**) Jambaljav et al. (2016) [29] in Evans et al. (2018) [40]. The isolated patches class in (**a**) is, in fact, the island class in the original 'Gravis Map'. The red arrow points at the southern boundary of the permafrost region in 1971. The dots are the permafrost borehole monitoring sites form Jambaljav et al. (2016): blue = permafrost, red = no permafrost.

What was mentioned already earlier for the general literature is also true for the literature on the Mongolian permafrost: in the light of different classification systems, any comparative studies must be carried out with caution. For example, when comparing the southern boundary of permafrost in Mongolia in several maps, the most extensive class that covered vast areas in 1971 but significantly receded by the 2010s was named either sporadic permafrost [22,23,31,36,42] or isolated permafrost [18,28] (Figure 5). Further-more, a comparison of results from Gravis et al. (1971) [18] and Jambaljav et al. (2022) [20] would reveal a change in the coverage of the continuous and discontinuous permafrost from 11.2% in 1971 to 15.6% in 2013, and a change of the sporadic permafrost coverage from 29.4% in 1971 to 7.1% in 2013. However, are these authors referring to the same zones? Jambaljav et al. (2022) [20] stated that "*the isolated zone described in the Gravis map has disappeared*". Yet, the 'Gravis Map' does not include any isolated permafrost zone. In fact, it is Gravis's sporadic permafrost that had widely disappeared.

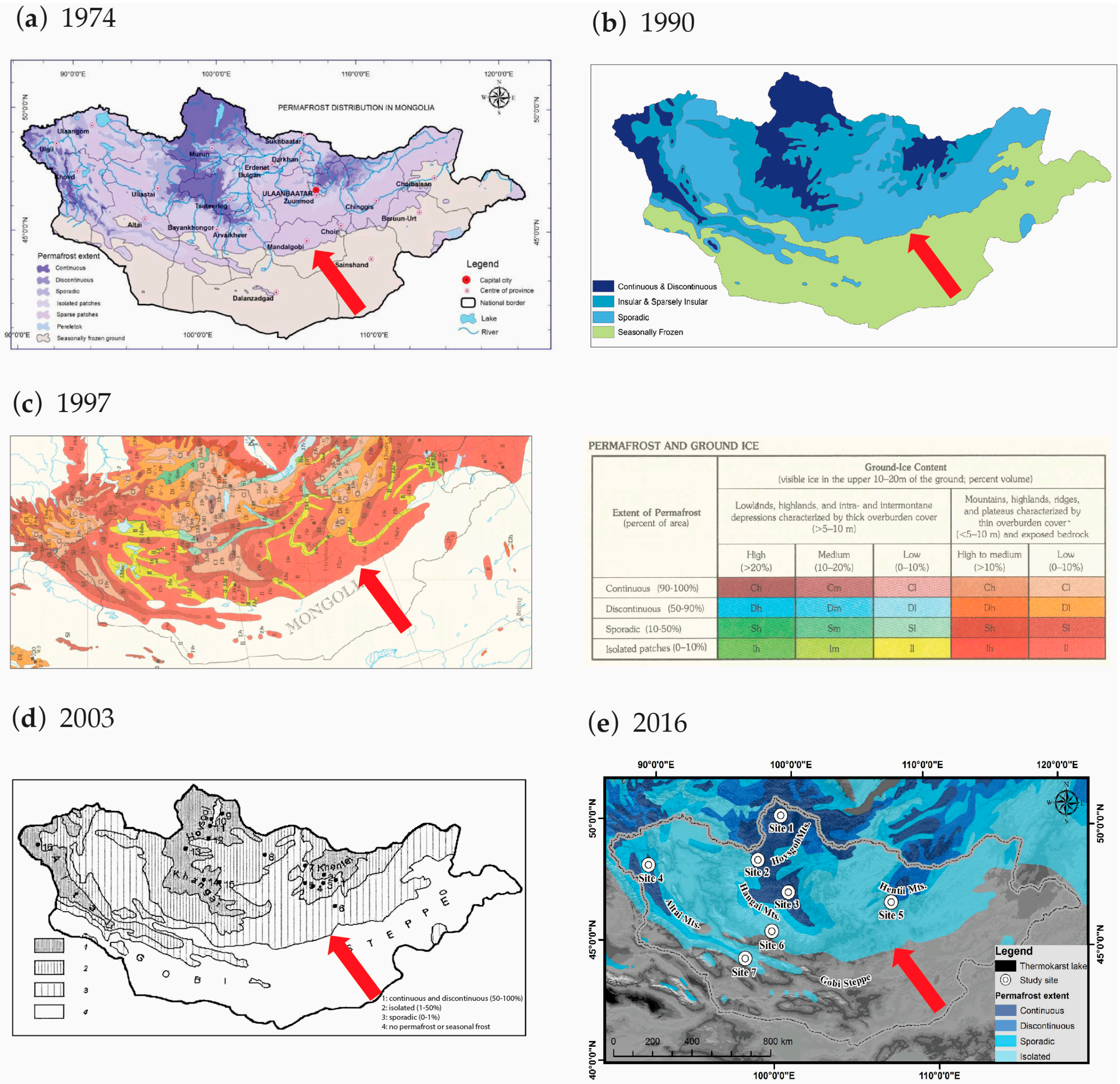

Figure 5. Permafrost maps for Mongolia from different authors, Part 1: 'Gravis Map' and maps that are based on it and, hence, display a permafrost region that covers 63% of Mongolia's territory (see

largest permafrost extent highlighted by red arrows). (**a**) Reconstructed map of the original map by Gravis (1974) [30] in Minayeva et al. (2018) [43]; (**b**) digitized 'Geocryological Regions' map by Gravis et al. (1990) [42] in Sodnom and Yanshin (2005) [33]; (**c**) clip from Brown et al. (1997) [18] with legend; (**d**) Sharkhuu (2003) (modified) [36]; (**e**) Saruulzaya et al. (2016) [28]. While map (**a**) has five permafrost zones, (**c**,**d**,**e**) have four zones, and (**b**) has three.

Nevertheless, despite the described map correlation issues, it can be concluded from the research by Jambaljav et al. (2016) [29] and by many others that Mongolia's permafrost is in a stage of significant degradation with its southern boundary considerably receding for the last five decades. Probably, more than half of Mongolia's permafrost area disappeared. Furthermore, all permafrost zones from 1971 still existed in Mongolia in 2015, but the sporadic one (up to 30% permafrost coverage) that existed in almost 30% of the country's territory had widely disappeared. Today, permafrost in Mongolia is only found in mountains and their immediate forelands. Based on HadCM3 climate scenario modeling, Mongolia's permafrost is projected to disappear by 2070–2099 [44].

In contrast to these numerous studies on permafrost, the term periglacial is almost absent in the Mongolian literature. What is often mentioned is the existence of seasonal frozen ground that is a phenomenon of the periglacial environment, like many other periglacial landforms (Table 5). Seasonal frozen ground covers all parts of Mongolia that do not have permafrost; in 1971, it was 579,050 km^2 or 37% of Mongolia's territory (Table 4). Today, after the widespread disappearance of permafrost, seasonal frozen ground makes up a much larger area.

Table 5. Periglacial landforms and processes, their scale compared with global examples, and exemplarily locations in Mongolia.

Landform/Process	Scale (Mongolia vs. Global)	Locations in Mongolia
Pingo	Small	Chuluut, Darkhad Depression, Nalej, Uvs Nuur
Pals	Medium	Tsagaan Nuur
Ice wedge	Small	Altai (inactive fossil)
Thermokarst lake	Large, widespread	Chuluutiin Gol, Uvs Nuur
Solifluction lobe	Widespread	Altai, Khangai, Khentii, Sayan
Rock glacier	Medium, widespread	Altai, Khangai
Patterned ground	Medium, widespread	Altai, Khangai, Khentii, Sayan
Cryoturbation	Small to medium	Altai (inactive fossil)

5. Mountain Permafrost

At the Third International Conference on Permafrost (ICOP) of the IPA in Edmonton, Canada, in 1978, multiple regional studies were presented on alpine permafrost: Northern Hemisphere [45], Central Asia [46], Alps [47,48], Mongolian Khangai [49], and Rocky Mountains [50]. At the same event, Lunardini (1978) [51] presented his so-called n-factors that define periglacial processes: climatic (e.g., wind, rain, snow), edaphic (e.g., soil type), orographic (e.g., exposition), biological (e.g., vegetation), and hygric (e.g., soil water, ground water table). Soon after, Washburn (1979) [4] mentioned, "*it is desirable to make a marked distinction between lowland zones (of periglacial environment) controlled by latitude and highland zones controlled by altitude as well as latitude*". In 1991, both themes were discussed at the International Workshop on Permafrost and Periglacial Environments in Mountain Areas in Interlaken, Switzerland, in 1991, e.g., [52–58]. Nevertheless, by 2010, mountain permafrost was still seen as a "*young research field*" [59].

Mountain permafrost is predominantly understood as of discontinuous type, and this even at the highest elevations, i.e., mountains are not landscapes of continuous permafrost. Rock glaciers have been found to be markers of the lower limit of discontinuous mountain permafrost [60,61]. For example, talus-derived rock glaciers (ice-cemented rock glaciers) demarked the lower limits of discontinuous permafrost in elevations of 4800 on north-facing and 5300 on south- to east-facing slopes in the Kanchanjunga Himal in Nepal [62]. Yet, caution is needed as mass movement deposits can be misinterpreted as rock glaciers [63], resulting in an erroneous mapping of the distribution of discontinuous mountain permafrost.

In their permafrost map for the northern hemisphere, Brown et al. (1997) [18] separated into 'lowlands, highlands, and intra- and intermontane depressions characterized by thick overburden cover (>5–10 m)' and 'mountains, highlands, ridges, and plateaus characterized by thin overburden cover (<5–10 m) and exposed bedrock' (Figure 5c). In Mongolia, the lowland type is only found along streams, while the rest of the country's permafrost region is of the highland type. Without a doubt, Brown et al. (1997) [18] paid tribute to the impact of topography and elevation in permafrost evolution and distribution.

Although rare, studies on mountain permafrost in Mongolia exist. Lehmkuhl et al. (2003) [64] used the term mountain permafrost in relation to the distribution of rock glaciers in the Turgen Range, and they mentioned both active and inactive periglacial mass movements. Kynicky et al. (2009) [37] mentioned a latitudinal permafrost in northeastern Mongolia and an altitudinal permafrost in the Mongolian Altai, Khangai, and Khentii mountains. Dashtseren et al. (2017) [65] acknowledged that "*the elevation gradient is important for locally existing permafrost*". Jambaljav et al. (2022) [20] analyzed borehole measurements from the Mongolian Altai and found the lower limit of discontinuous permafrost at 1900–2000 m on northern slopes and at 2400–2700 m on southern slopes.

When looking at the more recent maps of the permafrost distribution in Mongolia from the 2010s, it becomes clear that, in fact, it is Mongolia's mountain permafrost that is displayed as the permafrost area that almost perfectly matches the outlines of the country's mountains [11,24,29,35,38] (Figure 6). While most of these maps still used the traditional latitudinal-focused classification system, there is also an approach of using zones of temperature regimes, i.e., MAGT zones, instead [38].

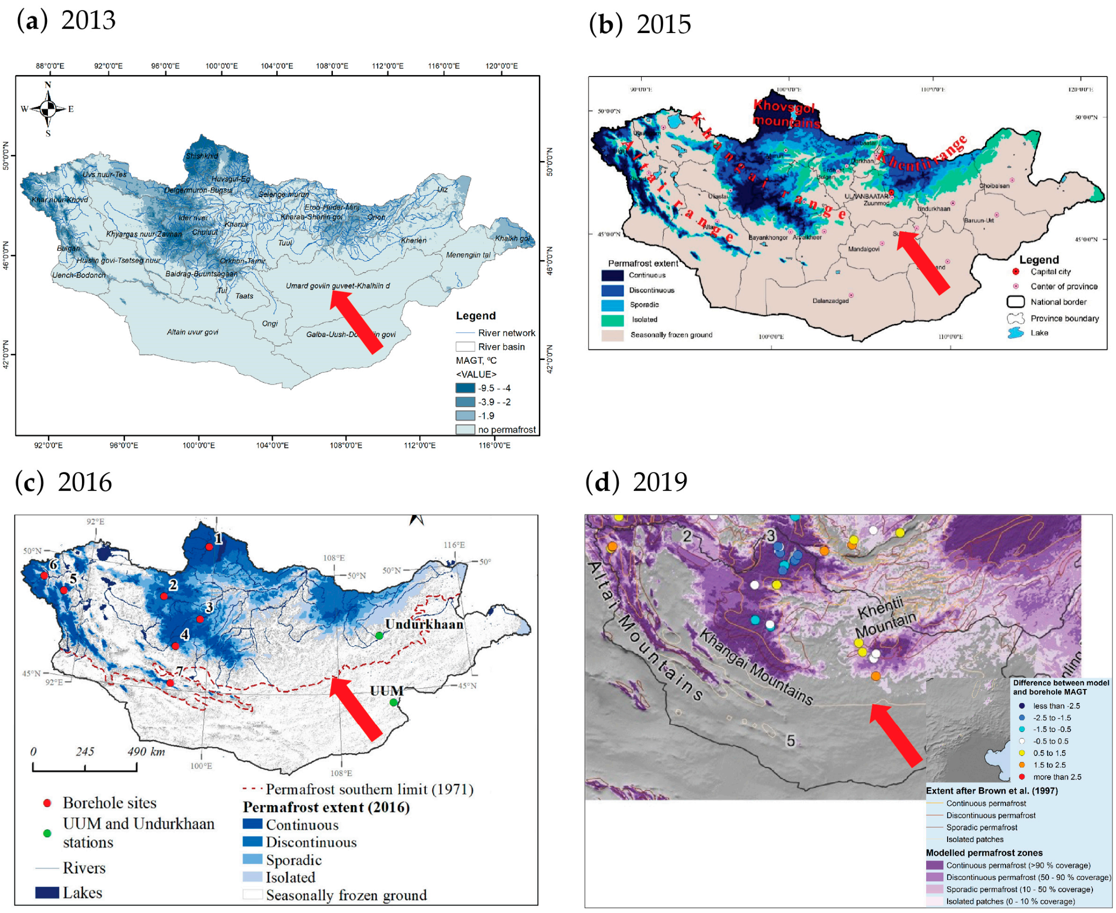

Figure 6. Permafrost maps for Mongolia from different authors. Part 2: maps that display the permafrost region for the 2010s, when less than 50% of the country's territory (see permafrost-free

area highlighted by red arrow and Figure 5 for comparison). (**a**) Zorigt et al. (2020) [38]; (**b**) Jambaljav et al. (2016) [29]; (**c**) Saruulzaya et al. (2021) [35]; (**d**) clip from the map by Obu et al. (2019) [11]. Map (**a**) includes three permafrost zones, while (**b**–**d**) include four. The red arrows points at the southern boundary of the permafrost region in 1971.

6. Conclusions

Discussions about the distribution of permafrost in Mongolia have been proven difficult because of the following reasons:

- The identification of permafrost landscapes when only periglacial conditions are given that do not permit permafrost development. Not all periglacial environments have permafrost.
- The interpolation of results from individual borehole observation sites across vast regions or even the entire Mongolia.
- The application of a permafrost classification system based on latitudinal changes to Mongolia's complex mountains, where altitudinal environmental changes play a major key for permafrost development.
- Different definitions of permafrost and related classification systems in the English, Mongolian, and Russian literature. Mistakes have been made in the translation of terms and the comparison of individual permafrost zones.

In mountains, orography and elevation easily result in a busy mosaic of changing local conditions from ridge to ridge, slope to slope, peak to valley, etc. (Figure 7). For example, one might find permafrost on a northern slope but not on a southern slope of an individual ridge. Thus, we like to propose that a combination of the terms 'periglacial' and 'mountain permafrost' is more appropriate for Mongolia, where permafrost is restricted to the mountains.

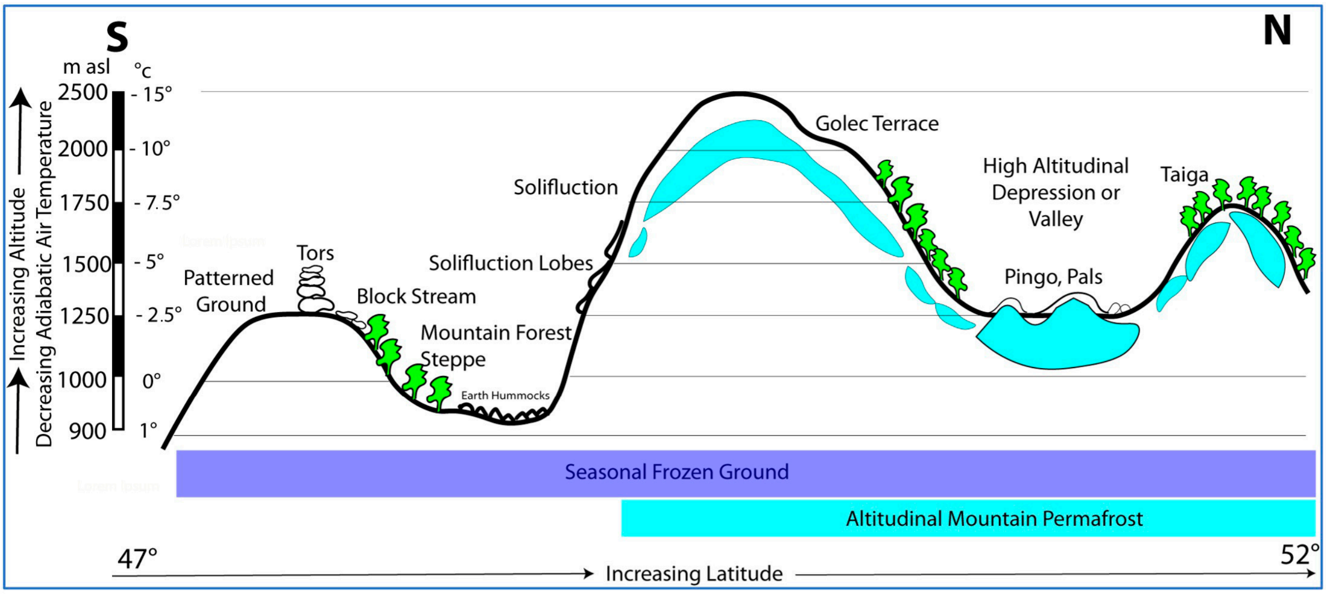

Figure 7. Model of the distribution of permafrost and seasonal frozen ground in Mongolia's mountains at the southern border of the Siberian permafrost region.

Long-term observations in Mongolia showed that air and soil temperatures as well as topography, i.e., elevation, are the most influential factors in the development of periglacial processes and the existence of permafrost. Useful measures to describe these conditions are the mean annual ground temperature (MAGT), mean annual ground surface temperature (MAGST), and temperature at the top of permafrost (TTOP). Other important characteristics are exposure, vegetation cover, and soil water, which control the appearance of periglacial forms and, thus, set limits for the distribution of periglacial and permafrost landscapes.

All these factors help to identify permafrost conditions and are better suited to describe the distribution of permafrost in mountains than a latitudinal classification system that separates into continuous, discontinuous, sporadic, isolated, and other permafrost zones.

Without a doubt, comparative studies on the periglacial and permafrost environments in Mongolia must be carried out with caution. One way to enhance our knowledge on mountain permafrost within the periglacial environment is extensive fieldwork including detailed mapping that produces detailed regional- and large-scale maps.

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