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# The Occurrence of Permafrost within the Glacial Domain

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**Abstract:** The occurrence of permafrost within glacial environments has never been comprehensively defined based on scientific evidence, despite its importance in determining how all the components of the cryosphere associate and interact. Here, the relation between glaciers and permafrost is discussed based on what scientific field they have been traditionally associated with. As the most accepted definition of permafrost is not exclusively linked to the presence of a geological medium, this can also be ice of any origin, including snow and glacial ice. Thus, active glaciers can act as permafrost medium. Indeed, all thermal types of glaciers meet the definition of permafrost as they remain at or below 0 °C for certainly more than two consecutive years. Active rock glaciers, regardless of the origin of the ice within, also meet the definition of permafrost. The presence of an active layer is not a prerequisite for the existence of permafrost either. Therefore, a comprehensive definition of permafrost occurrence across the cryosphere is essential to appropriately understand the phenomenon as a whole, not only as seen from our planet but also as it occurs for example on the icy moons of the Solar System and other frozen rocky bodies.

**Keywords:** permafrost; glaciers; glacier–permafrost interaction

## 1. Introduction

Understanding the patterns of occurrence of permafrost within the glacial domain is key for cryosphere sciences as an essential component of the cryosphere. Both periglacial environment and glaciers include it in their composition as a thermal state and hence their research overlaps to some extent. Yet, both elements tend to be considered as defined separate entities to this day. This is largely an artificial division resulting from the separation of glaciology and permafrost science as individual subjects. Here, a common ground for the combined research of glaciers and permafrost is defined within ongoing discussion on how these environments link and interact. The opinions on this discussion are also divided; whilst some consider it an important issue to clarify, other researchers consider it a purely theoretical problem [1,2]. The latter tend to rather focus on quantitative research and predictive models based on empirical data. Nevertheless, to ensure scientific discoveries are consistent and comparable, it is important to pay extraordinary attention to its specific order, for example, how scientific achievements are classified. In other subjects, such as biology, this type of classification is widely considered essential to properly understand the structure and dynamics of the living world. In a similar way, this is also essential to understand issues affecting cryosphere components such as ice and freezing.

The term cryosphere refers to the combination of physical environments under cold conditions, defined as temperatures equal to or below 0 °C. This encompasses both ice as a material medium and freezing as a process. Ice is indeed the material expression of the cold, while freezing is the process whereby the cold leads to the presence of frozen materials. Glacier ice and perennially frozen ground are the two largest and most important components of the cryosphere. Glacier ice and ice sheets are in fact the most spectacular manifestation of the presence of ice on the Earth's surface, apart from sea ice [3]. They represent a form of ice occurrence resulting from the accumulation of snow via diagenesis and its metamorphism over land, resulting in a mass in permanent motion. Permafrost, on the other hand, is an invisible phenomenon hidden underground, where the layer of the lithosphere remains at or below 0 °C during at least two consecutive years [3–6]. Thus, the accurate classification of these processes and materials is key to understand their relationship. This study presents an attempt to define this classification to this end.

This study is significantly built around the article by M. Dąbski [7], providing a creative criticism to the issue of glacial permafrost. Dąbski refers in his text to the work led by Dobinski et al. over a 10 year period (2006–2017) [4,8–12], evolving and crystallizing not without the influence of criticism. Here, I present the foundation of my work over this period as the background support to the response to M. Dąbski's criticism. These include the historical context and a clarification regarding the glacier–permafrost relationship, to be applied by analogy to both the glacial and periglacial environment.

## 2. The History of the Research and Its Classification

Here, we are basically addressing the question of whether glaciers and permafrost should be considered and studied together or as separate entities; its pros and cons. Today, they tend to be treated separately largely without extensive support for this approach. Indeed, this division has been long seen as arbitrary [1,13]. Current tendency to treat and study them separately is the result of habituation; a tradition that developed in the first decades of the 20th century and which led to the emergence of glaciology as a separate scientific discipline. Glaciology was thus created as an independent discipline related to the study of ice; however, what is exactly covered by this subject is still not clearly defined. Some authors narrow this range to glaciers and glacial ice [14], while others [15] see it as a discipline dealing with all types of ice found on Earth and even beyond. Periglacial research with its associated permafrost science is rather dedicated to freezing itself instead of only just ice, naturally including different types of ground ice. Glaciology, like ice itself, is in a very ambiguous position among other scientific disciplines such as geology and hydrology, and to a large extent intertwined with both. This type of separation can in fact lead to confusion, as hydrology studies the hydrosphere, where water is most often seen as a liquid, while geology is associated with the lithosphere mainly reserved for solids. Ice encompasses both: it is created from liquid water, but it is solid. However, glaciology as a self-contained discipline has been led to consider ice as an "additional body". In fact, the term itself was introduced as early as 1931 by A.B. Dobrowolski [16].

Here, the historical context is extremely important, as, in my opinion, it decisively influenced the perception of ice within the physical environment. For example, Shumskii [17] clearly showed that since mid-19th century, ice has been traditionally considered as part of the lithosphere. On this achievement and traditional basis, the Commission International des Glaciers was established in 1894 as an initiative from the Sixth International Congress of Geology. Founded at the end of World War I, the Union of Geodesy and Geophysics decided in 1924 to transfer the study of glaciers to a commission associated with the Association of Hydrology, which was part of the union. However, this decision was adopted mainly with the disapproval of the glaciologists, as P. Baird [18] emphasized in his Note on the Commission on Snow and Ice of the International Association of Scientific Hydrology. At the Lisbon Congress in 1933, the Association of Hydrology established the Commission of Snow. At that point, it was obvious that the snow committee and the ice committee should merge and they finally did at the 1936 Edinburgh Congress. At that point, the Vice President of the Snow Commission A.B. Dobrowolski advocated for the separation of the resulting organization from the Hydrological Association for obvious reasons. Like his predecessors, he clearly classified ice as a rock [16], although the home organization did not agree [18]. Contrary to the obvious classification of ice as part of the lithosphere and continuing with the existing tradition, the study of ice was then entrusted to an organization not related to the study of ice but water (liquid). Already at that stage and against the existing tradition, ice began to be combined and identified with liquid water and, as a consequence, even included in the hydrological cycle [19], whereas freezing inhibits this cycle [20]. Surface and underground ice was no longer associated with rock but rather with surface and underground waters [21]. Unfortunately, this misperception of ice remains common to this day when ice is treated as a water reservoir [22]. Subsequent attempts by Russian (Soviet) scholars also failed to separate snow and ice committees from hydrology ones [23]. Their position was similar to that of A. B. Dobrowolski, probably because of the influence of the book by A.P Shumski *Principles of structural glaciology* published in Russian in 1955 and translated to English in 1964. Today, hydrologists and hydrographers emphasize the alleged instability of ice and classify it as part of the hydrosphere (e.g., [24,25]). On the other hand, geologists, mineralogists, and petrographers have worked to prove that ice is a mineral, recognizing its stability in the Earth's crust, and treating it as part of the lithosphere ([8,16,17], and many others). One can get the impression that glaciologists do not play a role in this dispute and regard its importance as marginal to conducting glaciological research, as they do not get involved in this discussion anymore. To some extent, this is justified by the fact that this discipline has grown to the point of becoming entirely independent and self-sustained, no longer subordinated to other subjects (hydrology/geology). However, this discussion came back to the glaciology community for a brief period of time following the translation to English of the A.P. Shumski book in 1964. This publication became a significant influence to glaciologists and others in the second half of the 20th century, although its importance faded to nearly disappear thereafter. To this day, ice is under a double classification, as part of both the hydrosphere and the lithosphere. This ambiguity was seemingly unimportant, but reappeared with the increasing number of studies working on the glacial/permafrost interface. From this point, it has become increasingly obvious that the long-standing classification of ice and glaciers is contradictory to a medium and can indeed be considered as covered by permafrost. Set against this background, the issue of ice classification in science is still waiting for a solution.

## 3. The Definition of Permafrost

To clearly define permafrost is a first important step to define how it relates to glaciers and to ultimately classify ice. Reaching a definition however, involves considering all knowledge and understanding of the issue. Ultimately, there should be only one definition, for accuracy reasons. If more than one definition is currently in use, further scientific discussion should solve whether the definition must be expanded to include different features. Any two separate definitions differing not only semantically but also in their essence shows that we have still not reached a comprehensive understanding of the examined object and its interaction with other geographical components, but rather we are still expressing opinions about it. The definitions of International Permafrost Association (IPA) and National Snow and Ice Data Center (NSIDC) [5,7,26] differ in terms of meaning. While the first defines permafrost as a ground whose temperature is equal to or below 0 °C for two consecutive years, the second specifies that the ground temperature must remain below 0 °C for the following few years. The latter indirectly implies freezing and the presence of ground ice while the first does not, and consequently, these two definitions are contradictory.

Permafrost is not a material element but a physical condition (temperature) of the ground. Indeed, neither ice nor ground as such are permafrost. Permafrost is a condition, an attribute that may or may not accompany the lithosphere. Without permafrost, the characteristics of the soil/ground/rock remain the same, the only thing that changes is its thermal state. Physical changes in the ground also relate to the amount of water experiencing the phase change, from water to ice or vice-versa, with smaller changes occurring on ground with little water content. Ground covered by permafrost are at or below 0 °C, while the same ground at a positive temperature is not regarded as permafrost, even if the only difference between both of them relates to temperature. This change is most often seen in areas of marginal permafrost, where very small and short-term climate changes can cause its thin imperceptible layer to arise and last only for one summer.

Therefore, the presence of water does not alter whether a ground is considered permafrost or not or its phase. Temperature is the only defining factor. This definition then follows the widely accepted and used definition of IPA while the definition of NSIDC contradicts it, even if the difference is apparently not that big.

The term cryotic state (or cryotic ground) was introduced to clarify the concept of permafrost. Thus, a cryotic ground or soil at cryotic state is soil or rock at or below 0 °C. The terms "cryotic" and "noncryotic" were introduced to solve a major semantic problem identified by Brown and Kupsch [27], namely the lack of specific separate terms to designate "above 0 °C" and "below 0 °C" as opposed to "unfrozen" (i.e., not containing ice) and "frozen" (i.e., containing ice). Cryotic and noncryotic refer solely to the temperature of the material described, independent of its water or ice content. Therefore, perennially cryotic ground refers to that ground continuously at or below 0 °C for two or more consecutive years, coinciding with the definition of permafrost [5].

As per this definition, a cryotic ground includes ground where water (if present) could either be at 0 °C, or in a supercooled state at a temperature below 0 °C. Thus, the cryotic state regarding water refers rather to its potential to freeze, not its state as frozen. Defining a cryotic state helps clarifying and narrowing the definition of permafrost. To this end, the term permafrost describes a thermal state, not a state resulting from a phase change, while the term cryotic ground clearly delimits its definition in relation to concepts such as ice, water, freezing, and temperature, all aspects also used to describe permafrost. In simpler terms, a cryotic ground is an unfrozen permafrost.

There is a big difference however, between unfrozen ground (with or without water) and frozen ground cemented by ice, even for ground at or below 0 °C for a sufficiently long time (cryotic permafrost) [13,28]. Frozen ground cemented by ice is commonly identified as permafrost as a material reality rather than a state. This simplification can be accepted as to some extent necessary (e.g., for lower-level education) but not as its comprehensive scientific definition.

## 4. Medium

The medium is certainly a rock or soil, i.e., the lithosphere. Therefore, establishing whether ice is covered by permafrost depends on whether ice is a rock, or in other words, whether it belongs to the lithosphere. A uniform perception of ice will follow the ever so important principle of noncontradiction. The resolution of this issue should be easy and simple; however, it is complicated by the fact that ice is included both in the lithosphere and the hydrosphere. The classification of ice as a mineral rock justifies its inclusion in the lithosphere [8]. A much broader justification can be found elsewhere [16,17], findings that remain valid to this day even if not apparently obvious to many modern cryosphere researchers. It is interesting to notice how the scientific achievements of Eastern European countries, especially Russia, seem much more consistent.

### *4.1. Types of Ice in Permafrost*

Glacial and periglacial environments contain ice from different origins [29]. It is commonly accepted that the glacial domain, defined narrowly as glaciers and ice sheets, consists of one type of ice, glacial ice, formed through sedimentation and metamorphism/diagenesis of snow, resulting in its recrystallization into glacial ice, able to slowly move. This is a purely geological process analogous to the formation of other sedimentary or metamorphic rocks, with two differences: the time scale for ice formation is shorter than that for the formation of sedimentary or metamorphic rocks, and ice transformation occurs at low temperature and lower pressures compared to other metamorphic rocks. There are also no other processes that lead to the formation of glacier ice, and when these conditions are met, other types of ice are also formed within the glacial domain. Glacial ice is metamorphic ice; however, other types of ice can form within and outside a glacier, particularly as a result of climate impact. For example, ice from internal accumulation [30] or congelation ice (ordinary freezing of water without metamorphism). These ice types are not genetically related to the glacier ice, indeed, this type of ice will never develop into a glacier independently. Thus, this different type of ice is characteristic of the nonglacial environment and is found in glaciers as a consequence of conditions arising in the glacier environment a posteriori. It is therefore epigenetic and heterogeneous in relation to the syngenetic and homogenetic glacial ice. Furthermore, epigenetic ice found within glaciers is also directly related to the periglacial environment, while still belonging to the overall mass of ice composing the glacier. Yet, no one would claim that a glacier built in this way does not belong to the glacial environment. This example illustrates how ice of different origins interact to build a glacial mass. A similar process also occurs within the periglacial environment, where a mix of ice from glacial and periglacial origin coexist.

From the petrography or mineralogy point of view, glaciers consist of one crystalline material with foreign inclusions in the form of moraines and non-ice deposits, regardless of the type of ice they contain. Therefore, glaciers are a monomineral rock. Indeed, this concept is thus defined beyond controversy at least within the geologist community, particularly for petrographs and mineralogists.

### *4.2. Snow*

Snow is the only material able to initiate glacial formation, as long as the annual balance of snow accumulation is positive. However, glacial formation is rarely exclusively through dry snow diagenesis (excluding Antarctica) [31]. A common process accompanying the formation of a glacial mass is ice and snow melt even in the accumulation zone [30]. Melting accelerates the recrystallization of ice while leading to the loss of the glaciers "purely glacial" origin and properties.

In terms of the importance of the different types of ice, ice formed from snow through dry diagenesis. In addition, other types of ice could be formed through regelation (or the freezing of mixtures of ice, snow, and liquid water), which tend to occur on places where some level of melting occurs. The freezing process itself, as in this case, does not lead to the formation of glacial ice. If we were to consider this as a glacial formation process, for example, any river freezing entirely from the bottom during winter (common e.g., in Siberia) could be considered a glacier.

Ice of only glacial origin can be found within the Greenland and the Antarctic ice sheets, in areas where the temperature never rises above 0 °C and the snow remains dry. In these cases, glacial ice diagenesis is long-lasting and thick perennial layers of hard snow may not experience a significant metamorphosis [32,33]. Under these conditions, the transition between low-density snow layers and the much denser glacial ice spreads through long sections of the profile. The medium is also completely frozen throughout. In other regions of the world where the weather conditions do not allow for snow to remain permanently frozen, the period for metamorphosis shortens and glaciers are smaller. In these locations, the entire glacial system also occurs transiently like many other geomorphological systems on the Earth’s surface. Thus, we can identify two complementary systems, that of large ice sheets and that of long-lasting snow patches including even seasonal snow cover. Yet, both are the same in geological and mineralogical terms and therefore both glaciers and ephemeral snow cover belong to the lithosphere in the same terms even if they differ in petrography. The time of their occurrence does not matter either for this classification, indeed they can be as ephemeral as the traditional rocks are around an active volcano. As a consequence, this classification is logical and consistent; therefore, snow cover also meets the temporal condition of the definition of permafrost, i.e., a period below 0 °C of at least two consecutive years. It then follows that with scientific certainty, we can affirm that glaciers are covered by permafrost with no contradictions [10].

## 5. Temperate and Cold Glacier Ice and the Cryofront

Glaciers can become “unfrozen” in a similar way that permafrost does. For example, polythermal glaciers partly consist of temperate ice under pressure melting point (PMP) conditions. In these glaciers, liquid water remains between the ice crystals, even at temperatures <0 °C. Only thin glaciers in cold climates are completely frozen and contain only “cold” ice (Figure 1).

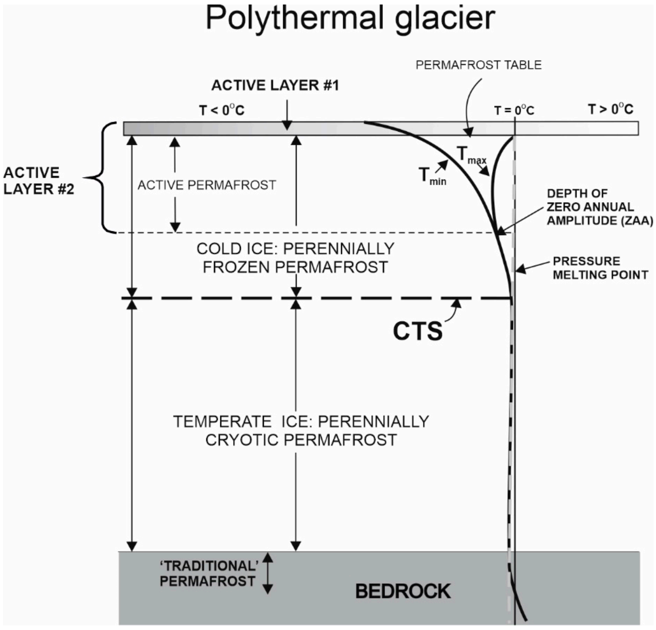


**Figure 1.** Geophysical model of glacial permafrost in polythermal glacier. Active layer #1 is the ice layer melting during the ablation period, reaching a seasonally positive temperature when it rests on the glacier surface in liquid form. Steep glaciers are deprived of it through the outflow. Active layer #2 is an ice layer subject to seasonal temperature variability to the depth of zero annual amplitude (ZAA). CTS—cold-temperate transition surface, Permafrost table—surface of glacier with or without water-layer.

The ice in the cryosphere can be defined through two main features: its state (frozen—solid; which does not necessarily mean cold as seen in polythermal glaciers) and its climatic influence, which leads to partial or full freezing. For the ice to remain completely frozen, the temperature must be below its PMP. The analogy between permafrost and glaciers at temperatures below the PMP is directly obvious. However, only the top surface layer is frozen in polythermal glaciers. In these glaciers, the temperature increases with depth until reaching the PMP value. This depth is known as the cold-temperate transition surface (CTS) [34,35]. This means that unfrozen water can be found and migrate between ice crystals. A glacier of these characteristics is to a large extent not frozen to the ground and will move at least in part by a bottom slide.

Despite this temperature structure, polythermal glaciers can also follow the analogy of permafrost. Thus, the upper part of the glacier consisting of cold ice is analogous to a completely frozen, cold glacier. Consequently, it is covered by permafrost. The bottom layer is at PMP but at a temperature still below 0 °C, also meeting the commonly accepted definition of permafrost (IPA) [5]. Some difficulty may however arise from the need to reconcile the glacial and periglacial terminology. To this end, two thermally different layers of glacial ice are separated by the CTS surface, a glaciological term. The term "cryofront" as defined by Dąbski [7] could be also applied here. This is a term I did not used in the 2006 publication, which he cites. I did not use at that point the term CTS either, as it subsequently appears in my later work [11,12]. Cryofront is defined ([5] definition 87) as the boundary between the cryotic and noncryotic ground as indicated by the position of the 0 °C isotherm in the ground. Therefore, the permafrost base and the boundaries between noncryotic and cryotic portions of the active layer constitute cryofronts. As a result of a freezing-point depression, the freezing front usually lags the cryofront as it moves downwards during the annual freezing of the active layer of the permafrost. Consequently, the use of the term cryofront as described by Dąbski [7] in relation to CTS is not correct. Rather, the glacial term CTS corresponds to the periglacial term "freezing front".

The bottom layer of glacial ice also meets the definition of permafrost (IPA) even if entirely at PMP, as this layer is still below 0 °C for over two consecutive years, and according to IPA the permafrost does not need to be frozen. It is also worth recalling that the unfrozen water content of temperate ice in reality only contains a small part of unfrozen water. Therefore, M. Dąbski [7] was right when marking the permafrost boundary covering the entire glacier together with the ground underneath, which also remains at or below 0 °C (Dąbski [7] Figure 2). Finally, the presence of glacial permafrost in the traditional sense is also not excluded, because the subglacial ground in contact with the glacier will always be below 0 °C. Thus, regardless of whether the glacier is frozen to the ground underneath or not, permafrost is found in and under any glacier. The thermal criterion is decisive here.

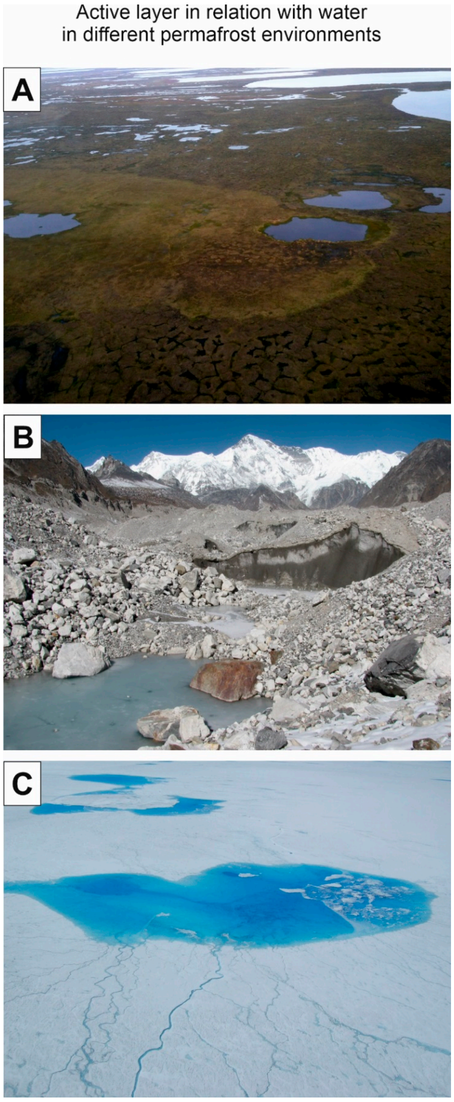


**Figure 2.** Differentiation of the active layer depending on the environment. **A**—traditional periglacial environment of patterned ground near Ivotuk, Alaska, covered by numerous melt ponds (July 2013); photo credit: Jennifer Watts, (https://www.uspermafrost.org/); **B**—Debris covered glacier/active rock glacier in mountainous periglacial areas: Ngozumpa Glacier, Everest region, Nepal. The rough topography of the Ngozumpa Glacier is shown covered by melt ponds, illustrating the thermokarst processes. (November 2009) photo credit: Kimberly Casey, courtesy: Andreas Kääb, (http://folk.uio.no/kaeaeb). **C**—in glacial environment: supraglacial lakes and melt water rivers on the Greenland Ice Sheet, June 2006, photo credit: Ian Joughin / University of Washington Polar Science Center, Courtesy: National Science Foundation (https://www.nasa.gov/).

## 6. Debris Covered Glaciers and Rock Glaciers

Active rock glaciers and intermediate forms such as debris-covered glaciers or fossil rock glaciers are geomorphological forms that combine both glacial and periglacial environments [36]. To this end, active rock glaciers present physical activity associated to its periglacial character e.g., seasonal thermal variations leading to the presence of an active layer of the permafrost, a depth of zero annual amplitude (ZAA), and a glacial-type of activity (whereby the rock glacier presents a typical glacial creep). For rock glaciers, the origin and volume of their ice core determine how they are classified within the physical environment. Indeed, the volume of ice determines whether they are classified as of glacial or periglacial origin. Active (moving) rock glaciers are actually an indicator of the presence of permafrost, as they demonstrate the presence of ground ice therefore fulfilling the definition of permafrost [37]. This double activity implies the presence of a nonglacial environment covered by traditional permafrost. Therefore, these forms can be referred as glaciers of the periglacial environment or periglacial glaciers. Even if the name could appear to be an oxymoron, its definition is deeply justified.

Consequently, classic active glaciers can also contain ice of nonglacial origin and rock glaciers associated with the periglacial environment can contain ice of glacial origin. Even if the ice within a rock glacier is only of nonglacial origin, its deformation and visco-plastic properties responsible for its movement are similar to those seen in glaciers.

This argument shows how the glacial and periglacial environment overlap and their material composition relate in material, kinetic, and thermal terms. From the material point of view (the ice), the relation is more obvious in its thermal aspect (negative temperature). Ice and temperatures below 0 °C can be present in both glacial and periglacial environments [38–42], and it is this overlap that allows applying the term permafrost to both environments. In fact, the term permafrost is in this sense not in conflict with any of the characteristics of these environments.

## 7. The Active Layer in Periglacial and Glacial Environments

The active layer is the topsoil/rock layer of the ground (Figure 1), presenting seasonal positive temperatures as it is under the direct climatic influence ([5] definition 6). Strictly speaking, it is not part of the permafrost, although it represents an important part of the periglacial environment.

Here it remains to understand whether the traditional permafrost always includes an active layer. While M. Dąbski [7] is in favor of the presence of an active layer as a necessary condition for the existence of permafrost, this has a counterargument. First, under standard climatic conditions in ordinary permafrost environments, above 0 °C temperatures creating an active layer may not occur at all. High altitude environments, like the Andes, is an example of a permafrost environment where the annual thermal variability is never large enough to cause an active layer and only daily thermal variations are experienced. In this example, at altitudes above 5600 m a.s.l., the mean annual air temperature is around −15 °C or even lower. These are also very dry environments, where the active layer depends only on insolation. Thus, the active layer may not occur at all in shady areas, with the permafrost directly originating at the ground surface [43]. Recent empirical data seem to confirm this possibility [44].

Fossil permafrost is another example, such as that present in West Siberia. In this case, the top of the fossil permafrost is located at a depth of 100–150 m below the ground surface [45]. In northern Poland, this layer occurs at depths of ca 365 m below the surface [46]. This fossil permafrost is of Pleistocene origin and unrelated to the current climatic conditions above the surface. Therefore, any thermal variation in the ground surface is not an active layer in relation to the permafrost below, even if it includes seasonal negative temperatures.

The definition of the active layer of the permafrost must therefore be consistent and analogous to the definition of permafrost. Because the permafrost is defined based on its temperature, the active layer must also follow this feature in its definition. Therefore, in the surface, the active layer seasonally freezes and thaws based on a temperature variation. Once the temperature variation reaches the depth of zero annual amplitude (ZAA), the seasonal activity stops. This thermal variability is visible both in periglacial environments covered by permafrost and in glacial environments, although the temperature variation in the latter occurs within a negative gradient.

The traditionally understood active layer usually contains water and undergoes a seasonal phase transformation. In this case, the permafrost table is at a cryotic state surface and the seasonally active permafrost (defined as the upper layer of the permafrost) thaws seasonally but remains below 0 °C. However, if we define the permafrost based on its thermal state, then the term "active" also refers to a thermal state, not the medium itself. Thus, the thermal activity would be based on temperature variation in general, a variation present until the ZAA depth.

The basal cryopeg is a layer of unfrozen ground in a perennial cryotic state (T < 0 °C), forming the basal portion of the permafrost where freezing is prevented by a freezing-point depression ([5] definition 37). At this level, there is no activity that can be attributed to permafrost.

Due to the specific features of ice as a rock, an active layer in the traditional sense usually cannot occur within glacial environments, i.e., as a layer reaching positive temperature seasonally. This layer is rare on glaciers, but it can also be distinguished here. On steep glaciers, for example, the active layer is the layer of seasonal ablation, which melts and flows down the glacier seasonally. On flat glaciers, an active layer may still exist in the form of surface lakes. These structures present a positive temperature and create forms analogous to the lakes formed as a result of thawing of the active layer in periglacial environments (Figure 2). Set against this background, glaciers can also present a traditionally defined active layer, analogous to that defined for periglacial environments.

As a result, glacial and periglacial environments are more similar than expected in relation to the definition and existence of an active layer of the permafrost.

## 8. Conclusions

Accurate definitions and classifications of permafrost phenomena are essential to determine whether glaciers and ice sheets are covered by permafrost. Following the principle of noncontradiction, a comprehensive and unifying classification across all Earth science disciplines is still necessary, particularly in relation to the classification of ice as a monomineral rock, placing ice as part of the lithosphere.

Classifying ice as a component of the lithosphere allows a full understanding of its role in the physical environment. The classification presented here also allows resolving standing issues such as whether ice can be covered by permafrost. Any subsequent arguments are therefore of secondary importance.

The traditional active layer of the permafrost may or may not exist analogously in both a glacial and periglacial environment; however, the freezing process is a sine qua non condition for the existence of ice. Thus, freezing is not the process behind the formation of permafrost, but rather a process responsible for the formation of a specific medium covered by the permafrost (a physical state).

A decrease in temperature below 0 °C therefore leads to the formation of permafrost, defined as such when its temperature is reached for at least two consecutive years. This condition may or may not be accompanied by freezing.

The occurrence of permafrost in periglacial environments is also often accompanied by the occurrence of different types of ice, including glacial and periglacial genesis. All these types of ice, just like the dead glacial ice found inside a moraine or the ice from an active glacier, belong to the lithosphere and they are equally a medium encompassed by permafrost.

For the occurrence of permafrost, whether the rock is loose or compact, dry or wet, frozen or not frozen, permanent or not permanent, homo- or heterogeneous is overall irrelevant, as it is its chemical or mineral composition or geological properties. It may even have an anthropogenic origin. The presence of permafrost is solely determined by time and temperature.

These key findings finally provide a definite basis for determining the global extent of permafrost, which was not possible to calculate so far. Indeed, the global extent of the permafrost has not been accurately estimated yet not due to a lack of data but due to a classification problem.

The use of the traditional understanding of permafrost is widespread; however, its diversity and distribution together with the development of permafrost science no longer allows restricting it only to the periglacial environment. A full understanding of the nature of the permafrost requires consistency in relation to all its possible presentations. This study presents a broad approach to our understanding of permafrost, in order to include all its possible expressions in nature. This approach is especially necessary to apply permafrost science to Icy Moons and frozen bodies of the Solar System and beyond; however, this extended discussion shall be considered separately.

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