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PERIGLACIOLOGY: REVIEW AND DISCUSSION OF MODERN CONCEPTS AND ITS RELATION TO THE RESEARCH IN POLAND

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Abstract: This paper describes the foundations of the periglacial concept beginning from the introduction of this term by Łoziński in 1909 and 1912. Its etymology along with the meaning and definitions that change over time are analysed in the present paper. Originally derived from geology, periglacial now functions as a geomorphological term. It has been compared with other terms used in the characterisation of cold geographical environments; the role of freezing and ice has been especially emphasised for periglaciology, and the most important types of ice have been highlighted. The present paper aims to show that with the increasing specialisation of research and the evolution of the meaning of the term periglacial, it is still seen as playing an important integrating role. The relation of the periglacial environment and ice to the glacial environment is also presented, showing the places of mutual overlapping of both environments. Old and newly introduced terms related to this concept such as periglacial facies, periglacial landscape, paraglacial, and cryo-conditioning are critically assessed. Finally, a short description of the permafrost in Poland, occurring in two remote and specific places, is presented: the active mountain permafrost covering the alpine belt of the Tatra Mountains about 1900 m a.s.l. and the relict permafrost in the Suwałki area, located in the northern lowland of Poland at a depth of 357 m and below.

Key words: periglacial, permafrost, ice, Poland, Tatra Mts, paleopermafrost

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Introduction

Nowadays, the term periglacial has become ambivalent. On the one hand, it is still attractive and widely used owing to its simple name, which allows one to easily and clearly contrast the non-glaciated environment of the cold and frozen areas of the Earth with the surficial ice of the glaciated environment. On the other hand, with the progress of research, this term has lost its precision in relation to detailed research, where its generality is no longer sufficient, and it begins to be supported by more specific terms and is even negated. Today, we can say that this term has undergone a semantic drift (Washburn 1973, French 2000, French, Thorn 2006). What is its contemporary place in the Earth sciences? Should we finally break with it, or should we better define its position and scope of usefulness? How to use the past to serve the modern progress of science? Do we need the durability of scientific achievements or should we emphasise the variability of the studied environment? These are important and rarely asked questions. The main aim of the present

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paper is to show that despite the increasing specialisation of research and the evolution of the meaning of the term periglacial, it still plays an important integrating role. I would like to achieve this goal by first presenting the characteristics of the key terms and criticism of their contemporary use. First, scientific sub-disciplines related to the study of ice and cold will be discussed, and then cold, freezing, and ice – key terms for this work. I hope that this first part of the work will allow understanding of the considerations in the field of periglaciology. The issues presented here are largely based on old, perhaps often forgotten but still valuable, sources (i.e. *Biuletyn Peryglacjalny*). Their value and findings are critically analysed as to how they have stood the test of time. On the other hand, the latest original concepts and studies are analysed (Ryder 1971, Church, Ryder 1972, Berthling, Etzelmüller 2011, Slaymaker 2011, Dobiński 2012). The choice of these sources is largely subjective, intended to a large extent to confront older and newer achievements. The author desires that the result of this confrontation should be a new inspiration for further scientific research and for a better understanding of periglacial issues in the broadest possible context, having a transdisciplinary character.

The issues related to the periglacial environment are based on the particular specificity of difficulties in distinguishing: a) the surface – the geomorphology of the area, its topography, also functioning under the broader term landscape, and b) the sub-surface i.e. the geology of the area, which forms the basis for the former. In the periglacial environment, the demarcation of the geomorphology and geology of the land is particularly difficult and important because a) while geology covers the subsurface and periglaciology, geomorphology covers the Earth's surface, b) both environments overlap in a specific way: the geological layer of periglacial sediments is in direct contact with the surface, and creates it to form similar to any material structure. The periglacial facies is the shallowest layer of the lithosphere in a periglacial environment (Łoziński 1912). These basic components of the lithosphere are additionally overlapped by two specific phenomena: frost and ice, which in this environment have an essential impact both in geomorphological and geological relations (French 2007). In addition, ice in the lithosphere is a specific derivative of frost, a factor whose effect on the lithosphere comes from the atmosphere. In this way, all states of aggregation and all spheres of the Earth merge in the periglacial environment.

Terminology

Within the Cryological Sciences, several very popular expressions are used, names without which we would probably not be able to imagine a scientific agreement today. Since they are widely used, it is usually rare to think about critically evaluating the role they play in a scientific discipline. Are they helpful in every case, or are they sometimes, by the force of habit, even unconsciously making it difficult to understand the subject of research hidden under them? First, I want to focus on the names of the discipline and its sub-disciplines. The work will primarily use the method of critical analysis (Cisek 2010).

Cryology is the name of the main, overarching discipline, which includes others, such as Glaciology, Periglaciology or Permafrost science (Melnikov et al. 2018). Cryology involves the study of the entire cryosphere, and originates from Greek: κρὐο (cryo) – cold, σφαίρα (sfaira – sphere) – the globe. Part of it can include Hydrography, Hydrology, Geology, Climatology, Meteorology, and many others (Melnikov et al. 2013). It is usually defined by enumerating its components: different types of natural ice (e.g. Slaymaker, Kelly 2007), rather than pointing to the essence, which is the phase change of water over a fairly wide range of temperatures at and below 0°C, as occurs in seawater or the atmosphere (e.g. Allison et al. 2001, Barry 2009, Stocker et al. 2013, Hock et al. 2017, Yang et al. 2019). This term was introduced by Dobrowolski (1923) basing it on a logical combination of two Greek words*: κρὐο* (krio) – cold and *λόγος* – logos a word derived from the Greek *λέγω* – lego. This is the most logical combination of Greek words in terms of word formation of all the names listed below. In this way, the names of many scientific disciplines were created. In this case, however, Dobrowolski's proposal was met with severe criticism from Seligman (1947). His short text published in the first issue of the *Journal of Glaciology* ridiculed this term, which, among other things, was the reason why it was not widely adopted until our times. Seligman (1947) first wrote it down by rewriting the Greek term into English, which gave rise to the word 'cryo' instead of the Greek 'krio', and then stated that it was associated with screaming and crying, but not with the name of a scientific discipline. It was one of the arguments that decided that Selligman's preferred term Glaciology, already used then as a term encompassing the study of all kinds of ice, became symous with the unwanted Cryology. In this way, he also extended the thematic scope of the *Journal of Glaciology* as its founder. Ultimately from around the end of the 20th century, the term Cryology was revived in its English form. Probably, there would not have been a great problem with its adoption earlier, if it had been correctly implemented in Greek, using Latin letters as in the word Kriology instead of Cryology. It would certainly be more correct, as is the case with the term Karst which, after all, functions in the description of the periglacial environment as Cryokarst (e.g. Bodin et al. 2015). Today, the word Cryology and related terms are written using the letter *k* in languages based on the Greek alphabet – in Bulgarian, Greek, Polish and Russian, while elsewhere the letter *c* is used in the beginning. The Polish spelling remained specific, where the letter *k* is used in this name, in the alphabet based on Latin. Therefore, in my opinion, Kriology (instead: Cryology) should be defined as a scientific discipline encompassing the atmosphere, lithosphere and hydrosphere in relation to the temperature of 0°C, the phase change of water and various forms of natural ice (Melnikov et al. 2018). This understanding of Kriology was also previously presented by Zwoliński and Dobiński (2008).

The popular term Glaciology is formed by combining the Latin words glacis and the Greek logos, i.e. not following the principles of term formation. Names should be created from words of the same language (here: Greek or Latin). It concerns a glacier, more broadly – ice in general, but still its meaning is narrower than Cryology, which includes 'cold' in general. It should be added that today there are still doubts about whether glaciology studies all types of ice, or rather only glaciers (Jania 1993), because many more types of ice are the subject of research in permafrost science (Periglaciology) (Sjöberg et al. 2020; see below). Glaciology is the scientific discipline attributed to the study of all forms of ice, especially glaciers (Benn, Evans 2010), which means that sea ice could also be included. If we take into account the number of publications, they would have to be associated with glacial research, because this type of ice dominates the

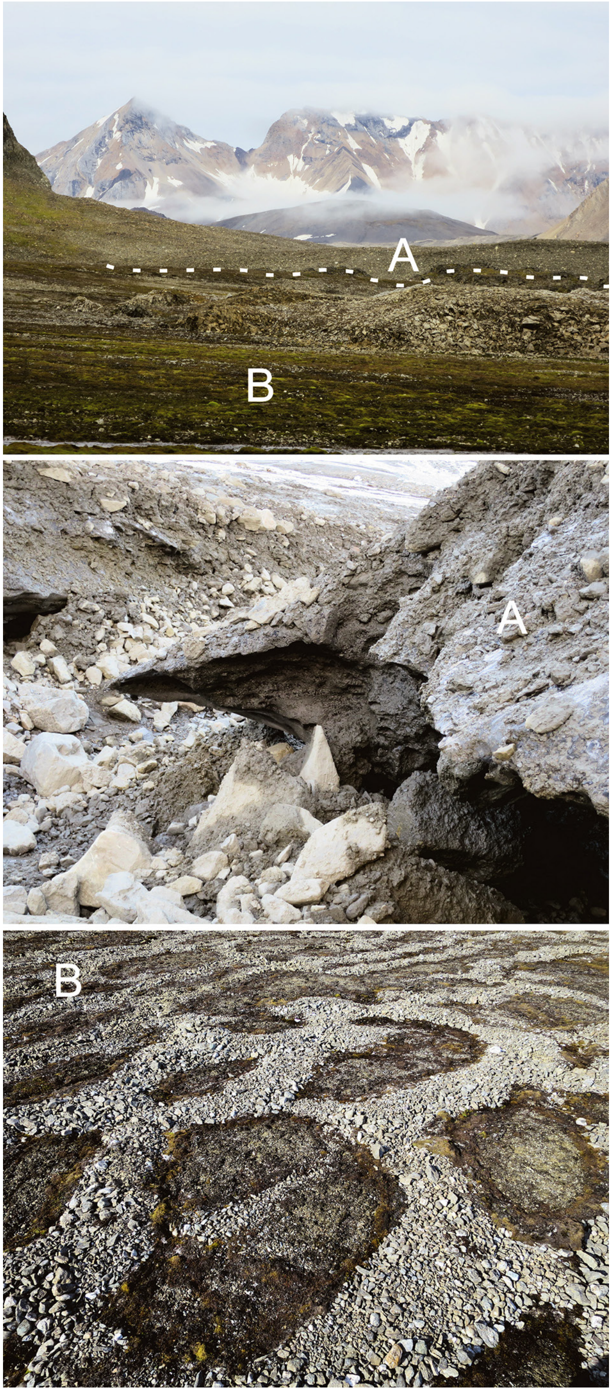

Fig. 1. An example of a relatively flat area where the proglacial zone A – contacts the periglacial zone B. In zone A, the presence of the dead glacial ice of Hansbreen is shown. In zone B, the flat terrain allows the development of periglacial relief forms created by the processes of frost sorting (Hornsund, Spitsbergen).

surface of the Earth, covering over 90% of all Earth's ice. The remaining ca. 9% are various other types of ice which, although can also be found in the glacial environment, are rather characteristic of the periglacial environment. There are at least 23 types of such ice (van Everdingen 2005). Glaciology is not as broad as Cryology, focusing not on cold in general, but on ice, predominantly of glacial origin.

Periglaciology (Łoziński 1909, 1912; Washburn 1973) is a term that, despite attempts to introduce it, has not yet found wide application, similar to Permafrostology, which in principle can be used as a synonym for the former when it covers an active modern periglacial environment (cf. French 2007). It will be the subject of further analysis below, but here it is worth saying that it was composed of two Greek words *περὶ* (peri – around) and *λόγος*, separated by the Latin *glacis*. It can therefore be said that in terms of word formation, it is probably the worst of all the listed ones. Periglaciology can be defined as a science of cold, frosty, non-glacial environments (French 2007).

Periglacial science (Periglaciology) covers not only the above-mentioned types of ice present in the ground but also the remaining cold covering the Earth's surface. Permafrost science (Permafrostology) can be attributed here. It includes, first of all, the specific condition of all rocks other than ice, which, regardless of the content of H_2O, may remain at negative temperature for a shorter (seasonal) time, or longer – as the so-called permafrost (van Everdingen 2005). Although the permanently frozen ground is most often associated with some form of ground ice, it does not necessarily contain it, because it is the negative temperature in the ground for at least two consecutive years that determines what is permafrost (van Everdingen 2005) (Fig. 1). Moreover, there are many places in the world, and this applies in particular to the Arctic coasts, where due to mineralisation – salinity – water does not freeze at 0°C. Such areas are also included in permafrost and therefore in the cryosphere. A similar situation applies to sub-glacial areas. Many of them are covered with glaciers or ice sheets remaining at the pressure melting point, which means that despite the negative temperature, they are not frozen and despite containing liquid water, they are included in permafrost and also in the cryosphere (Dobiński et al. 2022).

Cryology, Glaciology, and Periglaciology are disciplines dealing with cold and ice. These are different concepts, but so far the differences between them are not quite clearly defined therefore it is worth proposing a solution here that would help in better understanding both the content to which they are assigned and the relationships that exist between them.

Thus, we can see that the material and conceptual scope of various scientific disciplines related to the study of ice, freezing, or cold so far is not at all precise. The research scope overlaps to a large extent. Ice is the subject of research in a variety of sub-disciplines. The freezing process, very important in the cryosphere, usually associated with temperatures of 0°C, is not perceived as a separate subject of research apart from Periglaciology. Even more, a temperature of 0°C or lower, which occurs in a significant part of the Earth, seasonally or permanently, is not subject to separate analysis when it is as such not responsible for visible processes. The above characterisation of sub-disciplines related to the study of cold and ice shows the specific scientific scope that remains for periglaciology, presented below.

Cold, freezing, and ice

Cold as such does not appear to be a scientific term, and probably the term is not widely used in science outside the Earth Sciences, where it appears rather in a relative, undefined form as opposed to heat, such as it is in characteristics of climates. As mentioned above, it is commonly believed that the term cold is associated with freezing, which in turn means a temperature of 0°C or lower. Cold is a thermal state that affects all spheres either seasonally or permanently, depending on latitude or altitude. In a very general sense, it can be said that cold and cold areas (latitudinal zones and altitudinal belts) occur where the mean annual air temperature (MAAT) is equal to or below 0°C. This rule applies to the entire globe but to a different spatial extent.

The temperature of 0°C and negative temperatures on this measuring scale are commonly associated with the freezing process – the formation of ice. This process is common on land. The small amount of freshwater found on land freezes most often at this temperature, and it is a common experience wherein it is wrongly equated sometimes more generally to the belief that water on the Earth's surface freezes at this temperature. We know that 97.5% of the water on the Earth's surface is salt water, freezing at a temperature of about −1.8°C (Thomas et al. 2019). Therefore, if we are talking about cold, it includes not only ice or ground with no moisture under 0°C, but also liquid water at a negative temperature.

Freezing is a specific spectacular manifestation of the occurrence of cold on Earth concerning water. Freezing is a phase transition where a liquid turn into a solid when its temperature is lowered below its freezing point, and in the natural environment on Earth, it generally begins at a temperature between 0°C and −2°C depending on the degree of mineralisation and the prevailing pressure. Supercooled water without a condensation nucleus that usually initiates the process can act as a liquid down to −72°C (Dorsey 1948, Rabel 1948). The pressure melting point below the ice sheet may reach a value close to −3°C in Antarctica (Benn, Evans 2010).

Ice at a temperature of −20°C and atmospheric pressure absorbs heat linearly at a constant rate of 2090 J kg^{-1} until it reaches 0°C. At this temperature, the melting process begins, in which the ice absorbs a huge amount of heat: 333,000 J kg^{-1}. However, the temperature during the phase change is constantly 0°C, and only when all the ice has melted does it rise. This is caused by latent heat. In periglacial science, this is commonly seen as the so-called *zero curtain*. This term means the persistence of a nearly constant temperature, very close to the freezing point, during annual freezing of the permafrost active layer. It results from the dissipation of the latent heat of fusion of water during freezing or thawing of the ground and can persist for several hours or even weeks depending on the water content of the ground, snow cover, and air temperatures (van Everdingen 2005; definition 597). The main result of the freezing process is the transition of the liquid to a solid, which is associated automatically and absolutely with depriving it of its basic property, which is wet. In fact, ice must be and always is dry (Dobiński 2020a). It is for this reason that Antarctica is known as the driest continent in the world. As a result of the occurrence of cold and the accompanying freezing process, ice appears on the surface of the Earth in very different forms, both on the surface and below the surface of the Earth, as the lightest rock of the lithosphere (Dobrowolski 1923, Shumskii 1955, 1964).

Despite its obviousness and widespread occurrence on Earth, as evidenced by the distinction of the Earth's cryosphere, ice is the cause of a complicated scientific problem. Despite increasingly interdisciplinary research, it is easy to see completely different treatments of ice depending on the scientific discipline. The belief taken from everyday life that ice is water, but only frozen, prevails. The most fundamental difference becomes apparent when we realise that it is not known whether ice is classified into the hydrosphere or the lithosphere (Dobiński 2006). After all, the two differ in the most basic criterion relating to matter: the state of aggregation. This criterion is of key importance especially when the subject of discussion is the process that differentiates water the most – freezing and ice – the result determining the essence and subject of research of the most important sub-disciplines of cryology – permafrost sciences and glaciology.

Currently, there is no major issue in cryology that requires a final settlement between some disciplines, such as the place of ice in Earth Sciences. Despite making such attempts and reaching a consensus on this matter in the 1960s–1970s of the last century (Shumskii 1955 and its English translation 1964) with the deepening specialisation in Earth Sciences, the previously established position seems to blur and the ice is again becoming some kind of additional or supplementary material of the lithosphere (Dobrowolski 1931, Solomatin, Belova 2008) in Earth Sciences or even the fourth state of the matter (Hauck et al. 2008, Li et al. 2008).

Although ice seems to us the most unstable among all natural solids in inanimate nature, it is worth remembering that its role in the formation of geology and crystallography was crucial. The ancient Greek word κρύσταλλος – kristallos was initially translated to English as water in frozen form (cf. Glosbe[1]), which means that the ancient Greeks used it in this sense. Indeed, Aristotle, the first scientist in history, uses κρύσταλλος in Metaphysics to denote ice. Similarly, Herodotus in The Histories, Homer in Iliad and Odysei,

[1] Tłumaczenie hasła "ice" na starogrecki (translation of "ice" in Ancient Greek) Online: https://glosbe.com/en/grc/ice, (accessed 18 December 2023).

Pausanias Description of Greece, Plato in Symposium and Timaeus (cf. Perseus[2]). So, the term crystal, crystallisation, commonly used in geology, petrography, and crystallography, derives from ice, freezing, and cold. Even the rock crystal – quartz was treated as fossilised pieces of ice in ancient Greece (Edmeier, Jung-Hüttl 1996). It is worthwhile to follow this way of reasoning if we want to classify it correctly in spheres that are the most general categories in Earth Sciences.

One of the types of ice that does not genetically belong to the glacier is icing. van Everdingen (2005) writes about it that it is *A sheetlike mass of layered ice formed on the ground surface, or on river or lake ice, by freezing of successive flows of water that may seep from the ground, flow from a spring, or emerge from below river or lake ice through fractures,* adding that one of its older names was chrystocrene (or crystocrene). Tyrrel (1904), who tried to introduce this name into scientific life, characterised it in his work:

… In addition to masses of ice formed on the surface every winter, and which regularly melt away during the following summer, other masses are formed beneath the surface in such positions that they are protected from the action of the sun and atmospheric agencies; and thus it is possible to them to increase from year to year to very considerable dimensions. These underground masses of clear ice are also locally known in the Klondyke county as <*glaciers*> *but the name* <*crystosphene*> (κρὐσταλλος – *ice;* σφήν, – *wedge) is here suggested for them, as indicating a mass or sheet of ice developed by a wedging growth between beds of other material.*

So, we can see that at the beginning of the 20th century, the word crystal was equated with ice. Such an understanding of ice consistently prevailed in Dobrowolski (1923), Shumskii (1955), and many others who treated it as a mineral and monomineral rock as I have already mentioned in other places (Dobiński 2006, 2012). This finding was once known and widely accepted, but today it cannot breakthrough in Earth Sciences, although it is the key to the proper understanding of ice in all sub-disciplines, also in permafrost and periglacial sciences.

Therefore, if the definition of permafrost states that it is soil or rock remaining at a temperature equal to or lower than 0°C for at least 2 consecutive years, then the glacier meets all three criteria: time – at least 2 years, thermal – remains at 0°C or lower and the one which is probably the most difficult to accept actually – it is a crystalline rock with moraine inclusions.

Theory: conclusion

The theoretical considerations contained in the above chapter characterise first the scientific sub-disciplines related to periglacial and then the key terminology, which also has its reference in the periglacial environment and the discipline that studies it. Together, they create a broader context helpful for understanding the research subject of the periglacial zone with all its wealth of forms and processes. I hope that against this background, the strengths and weaknesses of periglacial science presented below are better visible.

Periglacial: Definition and characteristics

The term periglacial in its original meaning is a geological term referring to the shallowest geological layer, that is, the one that is in contact with the atmosphere, which additionally affects the mechanical block weathering caused by frost action (French 2007). It was introduced at a geological congress, not a geomorphological one, and is worth recalling that geomorphology is a scientific discipline that originated later than geology, in some way superimposed on a theoretical geological foundation. This was due to the scientific need to locate in the geological space, forms, and processes related to erosion, transport, and deposition occurring in various ways on the Earth's surface. This process approach was initiated by Davis (1899) and Penck (1953), albeit in slightly different ways. It is worth noting that Davis's publication contains no measurable observations and only cites one reference. According to modern criteria, this article would not be considered a scientific study at all. However, it is one of the most important works in geomorphology. The situation is similar to the map of the middle mountains in Europe included in the post-conference publication by Łoziński (1912), illustrating

2 Perseus digital library Crane G.R. (ed.) Tufts University Online: http://www.perseus.tufts.edu/hopper/searchresults?q=ice (accessed 18 December 2023).

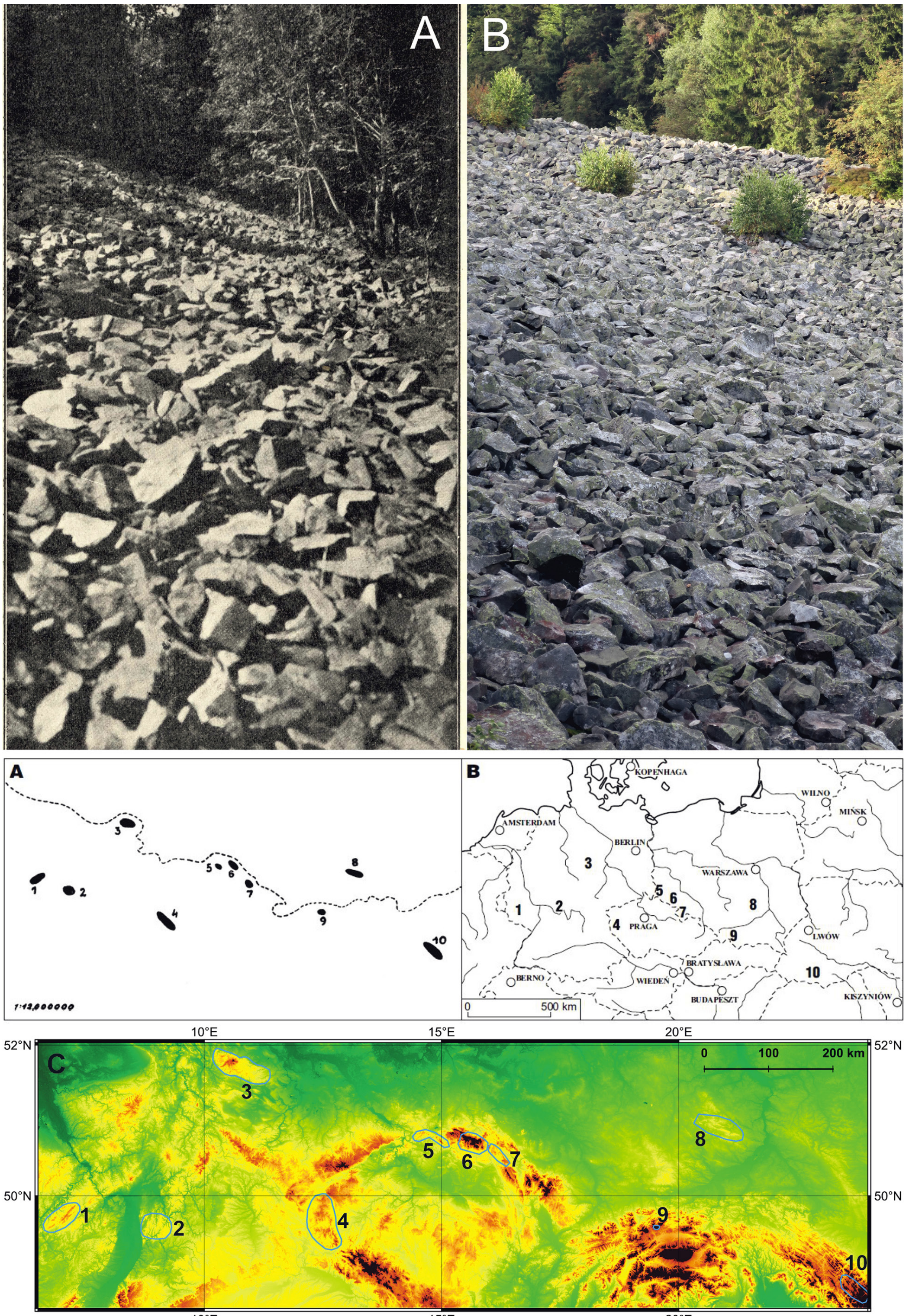

Fig. 2. The periglacial facies and the location of research areas in the work of Łoziński (1912). Left photograph A – blockfield of the Holy Cross Mountains (Rückens in original) from the original work of Łoziński; right photo B – the current look (2021) of the Holy Cross (in Polish: Świętokrzyskie) Mountains blockfield (in Polish: gołoborze). A – Original map of Łoziński (1912) (adapted by Mroczek (2010) with location of research areas and the border of Pleistocene glaciation. B – Contemporary identification of Łoziński's research areas according to Mroczek (2010). C – Terrain model of the middle mountains of Europe mentioned in the work of Łoziński (1912): 1 – Hunsrück, 2 – Odenwald, 3 – Harz, 4 – Böhmerwald/Šumava, 5 – Jeschken/Ještěd, 6 – Karkonosze, 7 – Stolowe Mountains, 8 – Świętokrzyskie Mountains, 9 – Babia Góra, and 10 – Gorgany.

the area of research – the periglacial zone. Today, such a sketch would have no chance of being published (Fig. 2). Nevertheless, as we know, his publication creates a new scientific discipline.

However, in both cases, the works of these authors had an inspiring influence on their contemporaries, and the ideas presented have stood the test of time. Whatever we say about these modest publications, it must be said that despite very poor empirical documentation and not embedded in the literature on the subject, they played an extremely important role in Earth Sciences. It is worth asking whether today there is such an open mind that would allow for a similar success for such modest and at the same time so creative scientific works.

However, because geomorphology began to develop dynamically at this time, the term periglacial was almost immediately transferred to the scientific discipline, where it was then well developed in the initial period of research (French 2003). No longer was it written about the geological periglacial facies, but about geomorphological sculpture and periglacial geomorphology, noting the enormous role of two decisive factors: ice and frost. Each of them has a separate value in this environment, although very often even today their impact is identified with each other. A not-new problem arises here, which is the boundary between geology and geomorphology and the subject of their research. In addition, there are new original views on this issue, which try to understand and describe in a broader context the issues once called periglacial zone issues (Jahn 1975).

Periglacial zone

Despite the geological nature of the periglacial facies, even in this approach, it can be seen that it has a zonal character. First, this zoning is related to the glaciation dependence. After all, the Pleistocene glaciation also has a zonal character to some extent, as it develops depending on the cooling climate of high and middle latitudes. The periglacial facies zone is located south of it, as shown in Łoziński's (1912) map (Fig. 2). The transfer of periglacial to the field of geomorphology greatly facilitates a zonal view of the periglacial science.

In the first period of periglacial research, this term turned out to be very convenient, because it could cover both the geomorphological situation of the studied areas and the mechanism of changes in the environment in which the role of frost is in the foreground. However, with the progress of research and the development of knowledge about the contemporary and Pleistocene periglacial environment in the Arctic and high mountain areas, the term periglacial zone has become ambiguous. Two versions of the term appear among the authors who use it. Some, according to etymology, interpret the term periglacial spatially as an area located to the glacier (Łoziński 1909, 1912), while others use it to primarily denote a separate morphogenetic domain with a specific cold climate and a set of morphogenetic factors depending on it (Jahn 1975, French 2007). Under such conditions, the pressure demanding a decision appears relatively early: either the concept of a periglacial area must be broader than that resulting from the etymological message, or the concept and scope of phenomena called periglacial must be substantially limited (Dylik, Dylikowa 1964). So, we can see that the problem with the definition of periglacial appears relatively early.

The discussion on the term periglacial that took place in the 60s–70s of the last century was classified into three groups after Dylik and Dylikowa (1964):

1. azonal definitions, defining the periglacial area as a zone adjacent to the glacier, where climatic changes in its forefield are generally caused by the vicinity of the glacier;
2. zonal definitions, recognising the distinctiveness of the periglacial environment as the area between the forest boundary and the line of permanent snow; and
3. other definitions, based on criteria related to the presence of zonal or azonal periglacial phenomena (Boesch 1960, Dylik, Dylikowa 1964).

The distinctiveness of the present and the past Pleistocene periglacial areas is defined by the sets of features of the geographical environment specific to these areas. The content of these climatically conditioned groups consists of specific sedimentary soil and plant covers and, above all, specific morphogenetic processes. The most important of them are the formation of ground ice and permafrost; specific disturbances of the original rock material system caused by thermal contraction; intense frost-weathering; intensive slope processes in the form of congelifluction, as well as the specific creep of frozen masses; intense and morphogenetically efficient aeolian activity; and seasonal, thermally conditioned water outflow poorly organised and characterised by relatively high flow values. In areas that were periglacial only in different periods of the Pleistocene, where the periglacial processes were extinct for a long time, we can only infer periglacial morphogenetic features based on the symptoms of their former activity. The evidence of periglacial processes and forms related to the influence of the cold Pleistocene climate discovered in Pleistocene sediments are called paleoperiglacial, while analogous ones occurring today and constantly active are called actuoperiglacial. These are the characteristic forms of relief and sediments of the subsurface geological structure (Dylik, Dylikowa 1964, French 2007).

The most important, due to the certainty and completeness of their remains, are sediments with structural and textural features and epigenetic structures formed in prior, non-periglacial and not necessarily Pleistocene forms. These are the results of intensive frost weathering, congeliflucent sediments, rinsing sediments in a frosty climate, sediments of Aeolian sands and loess, and characteristic valley sediments of non-drainage basins. The characteristics of these sediments are determined by the granulometry and the graining system with properties distinct from their primary structure. The structures formed as a result of the deformation of the original arrangement, formed as a result of the development of ground ice and thermal contraction, are very important here. These structures, called periglacial structures, could arise synchronously with the sediments or epigenetically. Epigenetic structures developed both in periglacial sediments and in other Pleistocene or earlier deposits. Therefore, the distinctiveness of periglacial areas is not determined by single forms and morphogenetic processes, but by their complexes (Dylik, Dylikowa 1964, French 2007).

These assemblies are not just composed of zonal processes but also extrazonal, polyzonal, and azonal processes (Popov 1961, Tricart, Cailleux 1961). Some of them, azonal qualitatively, acquire the zonal characteristics of the periglacial areas, for quantitative reasons, i.e. because of their intensity. This zonal intensity is called geomorphological efficiency (Dylik, Dylikowa 1964) of a non-zonal process, which often depends on the zonally defined geographical background in which the given processes operate (Fig. 3). Undoubtedly, the zonal periglacial processes include the formation of permafrost, the formation of injection ice, thermal karst processes and the formation of thermal contraction crack ice. This also applies to the effects of these processes. The polyzonal periglacial processes include segregation ice formation, seasonal freezing, needle ice, frost weathering, and congelifluction. The affiliation of these processes to periglacial areas does not depend on their qualitative features but on their intensity or geomorphological efficiency. The action of the wind, flushing, and linear runoff of surface water are azonal processes. They are commonly active on the surface of all continents, but the characteristics of the course of these processes, their intensity, and geomorphological efficiency differ zonally, depending on the other features of the geographical environment. Surface flushing, on the other hand, is a common process, but the peculiarities of periglacial flushing are that it is caused not only by rainfall but also by water from ground ice thawing in the permafrost areas. Hence, frequent associations of flushing and congelifluction arise. Extrazonal forms and processes can be called those that arise in a similar way to zonal ones, but their occurrence is related to the cold, climate that occurs

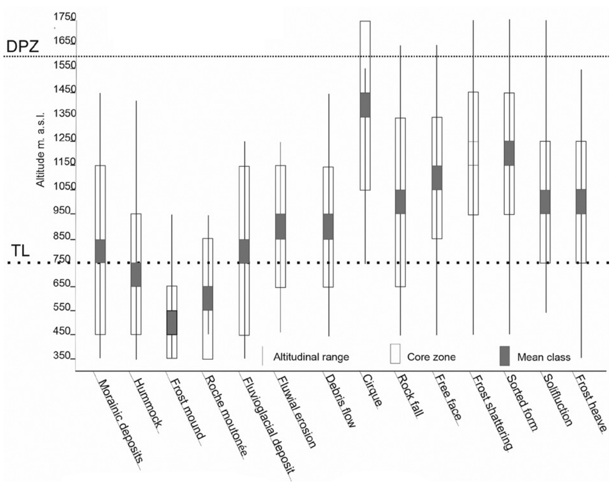

Fig. 3. Altitudinal zonation of selected geomorphological phenomena in the Alpine periglacial area of Northern Scandinavia according to Niessen et al. (1992) (with changes). DPZ – lower border of the DPZ. TL, tree line.

azonally – for example, in the high-mountain environment of various latitudes (French 2007).

The sentence stating that all areas covered by contemporary permafrost are periglacial areas is true and does not require justification (Dylik, Dylikowa 1964). The situation is different in the case of the relict permafrost, which lies at a considerable depth and does not cause any changes on the Earth's surface (e.g. Suwałki region in Poland or some area in western Siberia). Also, beyond the border of the modern permafrost, there are several features, even in terms of the morphogenetic features we see as inherent in periglacial areas. However, strictly zonal phenomena are undoubtedly limited outside the permafrost areas. However, they are not eliminated, as exemplified by the formation of polygons of frost cracks resulting from strong thermal contraction. Permafrost areas are also remarkably diversified for many reasons, including, *inter alia*, the dominant tendencies in morphogenetic development, which mark areas with a dominant feature of denudation, accumulation, and stagnation. Permafrost areas have the richest and the most complete set of the most typical zonal phenomena. As a result, they can be treated as standard areas, classic periglacial areas. However, the concept of periglacial areas has a broader substantive and spatial scope, which means that there are also periglacial areas beyond the range of permafrost. Rather, the antinomy of the climatic conditions of glacier formation and permafrost must be assumed. This found expression in the interesting concept of Shumskii (1955), which distinguishes two forms of glaciation: surface and underground (see also Jahn 1975). Each of these forms is created in different climatic conditions. If we agree with the opinion that permafrost areas can be treated as classic periglacial areas, then it must be concluded that their climatic conditions are direct, independent of the influence of ice masses (Dylik, Dylikowa 1964).

The fact of the climatic condition of the distinctiveness of periglacial areas prompts us to define their specific climatic features. It is primarily about considering the climatic differences between two cold climates – glacial and periglacial. In almost all characteristics of the periglacial environment, frequent temperature oscillations around 0°C are emphasised as typical (Jahn 1975, French 2007). The correctness of this view is beyond doubt, as the significance of these fluctuations is fundamental to one of the most typical periglacial phenomena, which is frost weathering. According to Tricart and Cailleux (1961), glacial areas are an environment of permanent frost, while in periglacial areas, frost is intermittent. Fluctuations in low temperatures well below 0°C are also important. Temperature fluctuations in the range of low and very low temperatures are a characteristic feature of periglacial areas and may determine their boundaries. Temperature changes passing through 0°C occur also in glacial areas, but they generally do not penetrate deeply the rock surface (e.g. under polythermal glaciers), except for nunataks, which are the site of extrazonal periglacial phenomena. The same is true of fluctuations in very low temperatures, which cause thermal contraction and, consequently, the formation of frost fissures in the glacial mass. Snow and ice cover play an important role in differentiating cold regions into glacial and periglacial ones. The formation of ground ice, which we see one of the most characteristic features of periglacial areas, takes place in the conditions of the penetration of low temperatures with frequent gradients more or less deep into the ground. It is possible only when the snow or glacial cover is thin. The same applies to the formation of frost cracks. On the other hand, the contact of snow and ice cover with the ground is always associated with the temperature of 0°C or lower. It depends on the thickness of the ice mass, which has a pressure melting point temperature in the substrate, and therefore temperature is always lower than 0°C. This is a common phenomenon, demonstrating the widespread presence of permafrost under glaciers. Seasonal thermal fluctuations are a symptom of climate contrast that is a predominant feature of continental areas, which disappears as oceanic influence increases. Thus, cold oceanic climates define directly glacial domains, while the disappearance of them in space and time leads to a periglacial dominance.

Periglacial – critics

The definition of periglacial proposed by Łoziński (1912) as a space remaining in the immediate spatial vicinity of the glaciated area differs from that proposed today (French 2003, 2007, French, Thorn 2006, Thorn et al. 2011, Vandenberghe 2011). Currently, the periglacial environment is not defined in terms of any spatial dependence on the glacier, but solely on the impact of the cold climate. Certainly, this is the result of extensive research today on the so-called periglacial environment, which has led to the recognition and isolation of more detailed forms and processes and their complexes. Such fragmentation (specialisation), which is always the result of scientific progress, led in this case to the division of the main discipline into smaller scientific sub-disciplines, assigned to separate issues. As a result, in the case of the term periglacial, a situation has arisen where it no longer means what was originally attributed to it, because its entire subject was divided into sub-disciplines (e.g. cryology, permafrost science, pedology, glaciology). Hence, the question of whether there are still grounds for continuing to use this term arises (Linton 1969). Periglacial issue manifests itself in different ways.

Criticism of Łoziński's periglacial concept was presented in the best form by French (2000). It can be presented as follows. First of all, in the contemporary geographic environment, apart from Greenland and Antarctica, there is no such environment that would correspond to the concept of the periglacial zone proposed by Łoziński. In his conception, this zone extends as a marginal area to the Pleistocene glaciation of Europe. It is characterised in particular by the presence of catabatic winds, which made the periglacial zone not only very cold but also very dry. This questions whether the sandstones and quartzites described by Łoziński's blockfields were formed by the traditional freeze–thaw process requiring the presence of water. It should also be borne in mind that Łoziński's periglacial concept concerned the mid-latitude environment, where there are different lighting conditions, and there is no polar night. As a result, the Arctic does not experience such diurnal temperature variability as in mid-latitudes. This, in turn, affects the intensity of frost processes.

Łoziński based his proposal on the mechanical fragmentation of resistant bedrock terrain, which means that the periglacial environment was dominantly bedrock-controlled; it had a geological character. This is confirmed by the introduction of the geological term periglacial facies by him. Today, the periglacial concept is identified with geomorphology rather than geology (French 2000, 2003, 2007, French, Thorn 2006). It should also be noted that the periglacial zone in the shape proposed by Łoziński consisted in fact of isolated mountain massifs outside the continental ice sheet. So it was rather a discontinuous zone. Today we have more evidence that it can be considered continuous in at least some cases. The evidence relates it today to the geomorphological, not geological structure (French 2000). French and Thorn (2006) argue that contemporary periglacial geomorphology must be firmly process-based. It must reject its climatic geomorphology underpinnings, because there is no core, typical, or definitive periglacial region, and Łoziński's periglacial realm is a largely academic concept that does not exist today. While most of these areas contain permafrost as a central element, there are no clear-cut boundaries. The core of contemporary periglacial geomorphology should concern the study of both long-term and seasonal ground ice and the related landscape development. This perspective makes permafrost a central, but not defining element of periglacial geomorphology. The geomorphology of non-glacial cold regions must include the study of not only periglacial geocryology and geomorphology but also azonal processes (French, Thorn 2006).

Periglacial and ice

When characterising the issue of the occurrence of the periglacial zone, it is necessary to refer to the issue of ice occurrence within it. Of course, it is something other than frost, which is defined rather in thermal, non-material terms, although this value relates to the phase change of water. Ice has a material expression. Frost/freeze indicates the process rather than the thing.

So, when we talk about permafrost, which – in the most general way – is associated with permanent freezing of the lithosphere, we are talking about its thermal state (Fig. 4). Material definition of permafrost automatically eliminates this popular and important figure from use. The geological structure in terms of its mineral composition, petrography, tectonics, and other properties is of secondary importance here, because permafrost is somehow superimposed on this material structure, adding two characteristic

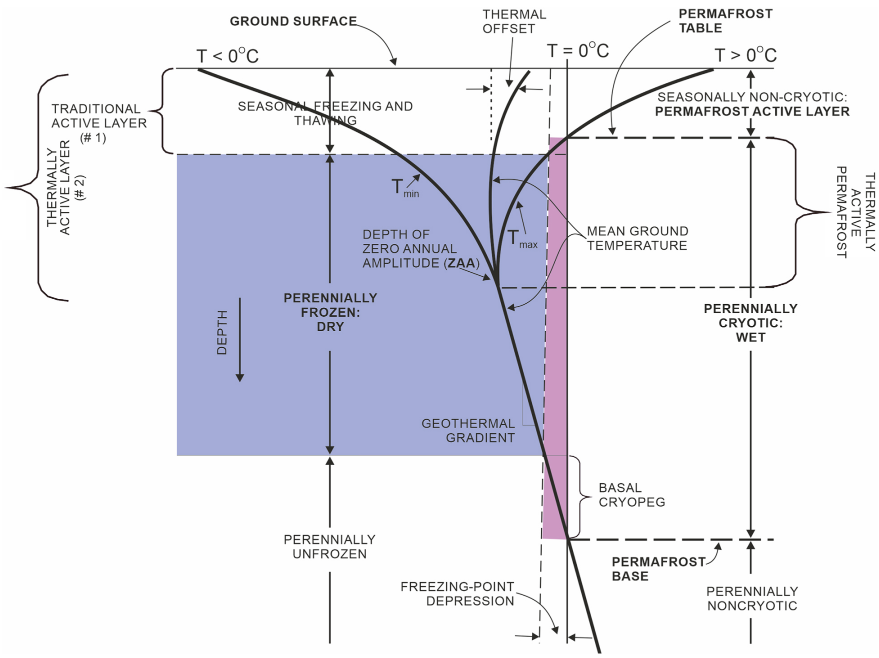

Fig. 4. Thermal profile of the ground affected by permafrost. Blue – frozen ground; Pink – cryotic ground, i.e. unfrozen but permanently at negative temperature – the vertical extent of permafrost. White – seasonally (up) or permanently (bottom) unfrozen ground. Note two types of active layers: #1 traditional, based on freezing and thawing, and #2 based on thermal activity/changes, consistent with the permafrost definition (after Dobiński 2020b). This model cannot be applied to latent fossil permafrost.

boundaries – surfaces 0°C: permafrost top and permafrost base, between which there is a temperature of 0°C or lower for at least 2 consecutive years. Permafrost can therefore include a geological structure that has any amount of ice in its volume: it may be ice-free, or it may contain 100% ice, such as a glacier or ice sheet.

The presence of ice in the natural environment is most closely associated with the glacial and periglacial environments. The glacial environment is identified with the icy environment consisting exclusively of the ice that builds the glacier or ice sheet. However, the decisive issue in the classification of glacial and periglacial ice is its origin. Glacial ice is therefore, in particular, that type of ice that not only forms but most of all creates a glacier in its genetic sense. This ice is not formed by freezing directly but uses the frozen sediment: snow accumulating in the upper part of glaciers. Without sedimentation, metamorphism/diagenesis, and movement, a glacier will never form. It follows that any other type of ice present in a glacier, resulting from the freezing of water, has a non-glacial origin – it will never create a glacier. Thus, there is only one ice of glacial origin, because the remaining types of ice must be assigned in the genetic sense to the non-glacial environment. It is most natural to assign them to the frosty periglacial environment, but it also means that the glaciers contain the ice of periglacial genesis, i.e. freezing water of the so-called internal accumulation, which can constitute even the majority of glaciers (Trabant, Mayo 1985). There is also the possibility of glacial ice in the periglacial environment. This happens quite commonly when blocks of dead glacial ice are buried in its forefield, e.g. in the process of a glacial recession. This also applies to the ice included in some types of rock glaciers.

The strictly glacial processes should be considered as only those that are related to the ice of glacial genesis in the glacial area; they cover only the interior of Antarctica. Wherever there is any melting, although short, freezing water no longer forms the ice of the glacial genesis, and therefore such ice should be classified differently, perhaps as periglacial. This would mean that both environments overlap to a significant extent.

Periglacial landscape

The issue of the periglacial landscape is difficult to apply, but it has appeared in the literature for quite a long time (Karte 1981, Rouet et al. 2019, Holloway et al. 2020, Fedorov 2022). Its meaning is variable, in the same way as the term periglacial and it refers either to the geological conditions of the area in question or to its relief (French 2007). This dichotomy is probably the basic difficulty in the unequivocal characterisation of the periglacial landscape. An additional difficulty here is the question of the definition of landscape, which is extremely blurred (Simensen et al. 2018). The definition of landscape in geomorphology is ambiguous. In its simplest sense, the landscape is synonymous with topography and can be considered as a continuous surface in visible space characterised by morphometric properties or a specific assemblage of landforms (Berthling, Etzelmüller 2011). In a synthetic work on landscape in general, Simensen et al. (2018) provide 54 different landscape characteristics used in the World for its description, which means that there is no uniform definition of it. Murton (2021) uses the term subjectively: *periglacial landscape is defined as an association of periglacial landforms at micro- to mesospatial scales*. However, the basic feature of any landscape is that it must be observable, which means it must have a material expression (Simensen et al. 2018). If permafrost is one of the basic criteria for the delineation of the periglacial landscape, this condition is not met. Permafrost cannot be observed materially, as is the case with other components of the geographical environment. It has an immaterial character, appearing as a state (temperature) of the ground, not a thing. Therefore, it is impossible to distinguish something like a permafrost landscape (Vincent et al. 2017). Often, however, still permafrost and its definition are identified

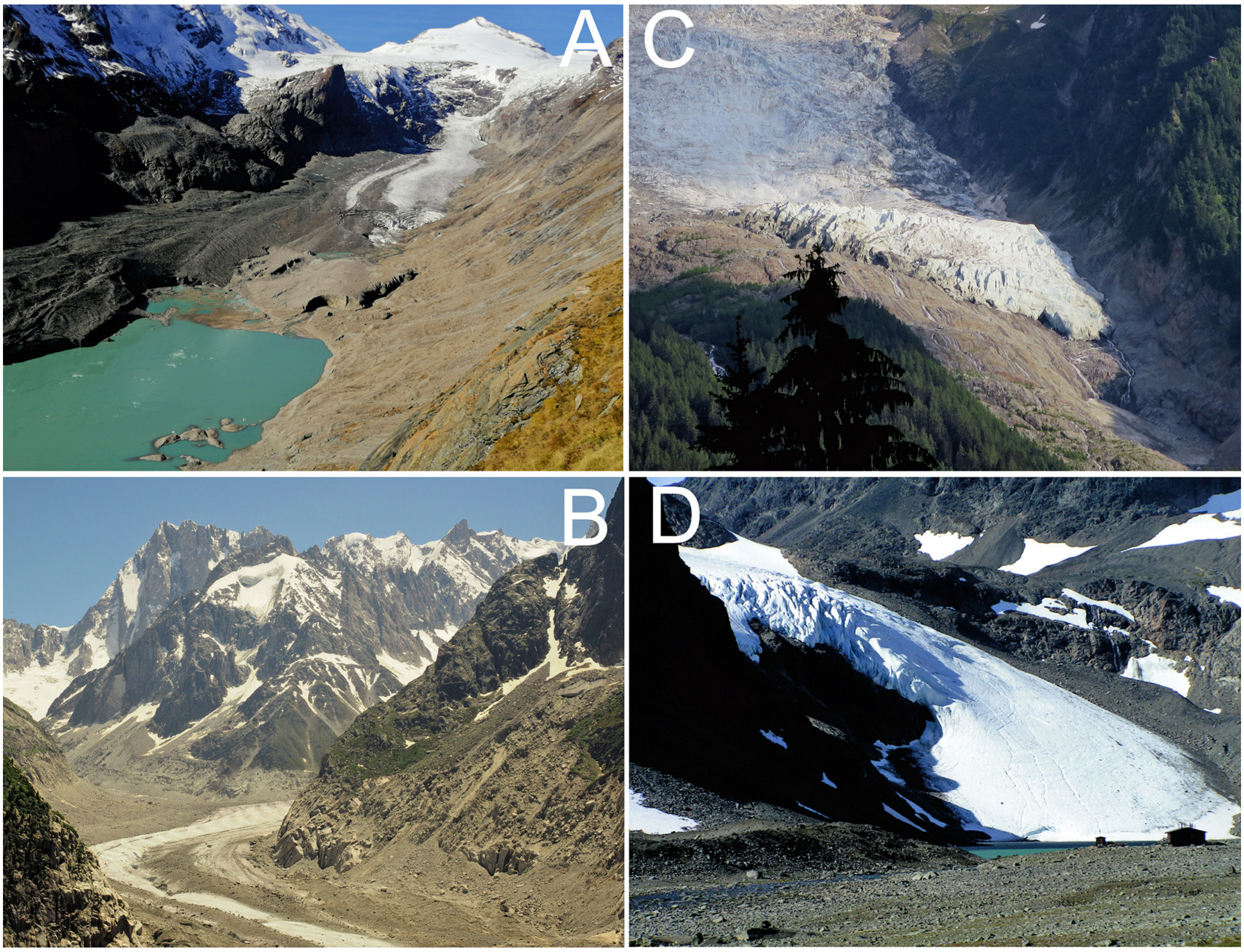

Fig. 5. On the left–hand side photos: A, B – glaciers with high sedimentary yield rate (Pasterze glacier, Eastern Alps, Austria (above)), and Mer de Glace, Mt Blanc Massif, France (below). On the right-hand side photos: C, D – glaciers devoid of morainic material. Glacier des Bossons, Mt Blanc Massif, France (above), and Kebnepakteglaciaren Kebnekaise Massif, Northern Sweden (below). An example of contrasting conditions for the formation of a periglacial/proglacial zone.

with the presence of some kind of underground ice. Such an opinion is visible in the description of Murton (2021) reinforced by the opinion that permafrost can undergo a glaciogenic deformation. Also, French (2007) takes up the issue of periglacial landscape by writing that it is commonly assumed that active (containing permafrost) periglacial landscapes are distinct. This is because most periglacial landforms are associated with permafrost, and the most widespread are tundra polygons. Figure 5 shows that it is not so obvious and in the Suwałki region, permafrost has a particularly hidden character. Less widespread but equally classic periglacial landforms are ice-cored hills and Pingos. Ground-ice slumps, thaw lakes, and irregular depressions are also permafrost-related as thermokarst features. Other geomorphological features result from frost wedging and cryogenic weathering of exposed bedrock. Superimposed upon these typical landscape features is the occurrence of patterned ground. A final result is related to the overall smoothing of slopes attributed to mass wasting and cryoplanation (French 2007).

Thus, we can see that the periglacial landscape can be distinguished when we talk about the forms of the relief of the Earth's surface, i.e. geomorphology. The landscape does not concern the geological structure, although it is directly related to it, because it occurs under the visible surface and is hidden beneath it, just like any type of ground ice or permafrost in general. Here, we can see the difference between the geomorphological and geological meanings of the term periglacial.

Periglacial facies

The term periglacial facies proposed by Łoziński (1912), as mentioned above, quickly gained recognition and was widely used as a geological term (Brodzikowski, van Loon 1987). This means that the idea met the specific needs of geologists who were unable to correctly understand and describe this least subsurface geological layer consisting of rock–rubble accumulations. Whittow (1984) defined facies in general *as the character or appearance of part of a rock by comparison with other parts, or as a rock unit that exhibits lithological or sedimentological characteristics which enable them to be classified as distinct from another rock unit, and finally as a lateral change of character within a stratigraphic unit, especially in its lithology*. The disintegration or mechanical breakdown of bedrock in periglacial regions creates such periglacial facies at the surface. The most spectacular features of such weathering are extensive surfaces of angular rock fragments, commonly referred to as block fields in English-language literature. These are the present-day equivalents of periglacial facies (French 2007). As such periglacial facies can be observable at the Earth's surface as a part of the periglacial landscape and can be attributed equally to the geological and geomorphological domain.

Paraglacial

In recent years, the term paraglacial has been gaining in importance and to some extent tries to replace the term periglacial by encompassing that part of its conceptual scope which is related to the glacier (French 2000). The term thus refers to the original Łoziński (1912) concept, spatially connecting the ice sheet and its foreland, not in a geological/climatological context, but in geomorphological terms. Its creator is considered to be Ryder (1971). However, the term appears much earlier (c.f. Nangeroni 1959). It was then discussed already in the 1960s as a potential replacement for the term periglacial, which (as mentioned above) was also losing its sharpness in those times. Nevertheless, many scientists (Dylik, Dylikowa 1964, Black 1966, Bout 1966, Cotet 1966) argued for keeping the term periglacial as traditional and widely used.

More precisely, paraglacial is defined in later years as *non-glacial processes that are directly conditioned by glaciation, and refers to proglacial processes, and to those occurring around and within the margins of a former glacier* (Church, Ryder 1972). Ultimately, the concept of paraglacial landscape adjustment was included in the so-called paraglacial geomorphology. Ballantyne (2002) elaborated far beyond the alluvial context in which it was first conceived. The term describes landscape relaxation from a glacial to a non-glacial state and is applied also to the evolution and chronology of many postglacial landforms and deposits (Ballantyne 2002). It refers to the specific disequilibrium that occurs as one geomorphic environment moves from one equilibrium condition to another (Church, Ryder 1972, French 2007, Zwoliński 2007). Slaymaker (2011) summarises these differences by saying that *the term periglacial is a function of process, proglacial is a function of location and paraglacial is a function of degree and mode of recovery from the disturbance of continental glaciation*.

It can therefore be seen that the paraglacial concept, which has primarily geomorphological significance and is more closely related to the landscape visible on the surface, does not refer to the subsurface periglacial environment conditions. In particular, it does not address the question of the presence of permafrost, and the geological meaning of the term, i.e. periglacial facies. Paraglacial is a concept that also does not consider any type of ice other than glacial ice. Therefore, considering the entire specifics and functionality of this concept, especially in the sense of processes, it can be said that in a very general sense, the paraglacial can be subordinated as a part to the whole, to the broader term which is the glaciogenic environment. Brodzikowski and Van Loon (1991), the authors of an extensive synthesis entitled Glacigenic sediments, were familiar with works introducing the term paraglacial, such as Church and Ryder (1972) and Ryder (1971). However, they did not decide to follow it and used the category of glaciogenic morphology, or as part of the proglacial sub-environment (Brodzikowski, van Loon 1991, p. 363). In the authors' opinion, changing this classification would require a more extensive discussion of the existing findings. The spatial relationship between the following environments: glacial, periglacial, proglacial, and paraglacial is shown in Figure 6. Paraglacial and proglacial processes are mainly related to shaping the Earth's surface and are unanimously assigned to geomorphology (for example Zwoliński 2007). The glacial environment includes the shallowest geological formations, which are ice of various origins and durability, located on the Earth's surface, whereas the periglacial environment contains traditionally periglacial facies. Naturally, all these environments contact each other or interpenetrate to some extent, because in the natural environment, boundaries almost do not exist.

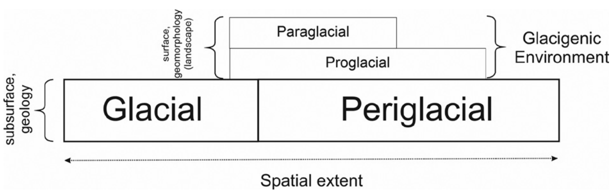

Fig. 6. The diagram shows in general the basic spatial relationship between the glacial, periglacial, proglacial, and paraglacial environments.

Cryo-conditioning

One of the newer concepts that also touch the periglacial environment is the cryo-conditioning. Its authors write that *cryo-conditioning is a concept to appreciate the interconnected nature of cold climate environments and processes. This concept underscores the interconnected role of periglacial, glacial, and azonal processes in the development of cold region landscapes, by emphasizing that they have a crucial common control here*. The concept of cryo-conditioning is broader than the definition of periglacial, recognising that cold climate influences azonal, glacial, and periglacial processes. Cryo-conditioning is the admission of cold as the basic control of geomorphological processes occurring in a cold climate. Cryo-geomorphology would therefore be a discipline encompassing the forms of sculpture and landscapes subjected to cryo-conditioning. This is the interaction of thermal regimes of the cryotic surface and subsurface with geomorphic processes, linking landform and landscape evolution in cold regions (Berthling, Etzelmüller 2011). The term cryo-conditioning has its specific application to rock glaciers. In this context, Berthling (2011) defines active rock glaciers as *the visible expression of cumulative deformation by long-term creep of ice/debris mixtures under permafrost conditions*. This definition very well describes the essence of a rock glacier. He also adds that this definition is genetic in the sense that it puts weight on the process responsible for deformation (and thus morphology), but it is not genetic in terms of the origin of the ice and debris (Berthling 2011).

In this interesting and broad look at the issue of cold present on the Earth's surface, however, there is no precise distinction between cryo-conditioning and freeze–thaw processes, i.e. between the role of cold/freezing as a process, and the presence of water/ice, i.e. a material factor existing or non-existent in this process (Dobiński 2006, 2011). Of course, also in this case, it should be noted that it is a geomorphological concept, not a geological one, as it refers to the land surface expressed in the term landscape and does not refer to the periglacial as a geological category, which is crucial for the concept of periglacial facies. Cryo-conditioning is therefore not a concept that could effectively replace the term periglacial.

Periglacial conclusions

The term periglacial, although its meaning has become blurred due to progressive specialisation in research, can nevertheless be used similarly to the term geography, which is no longer a description of the Earth, or geology, which is not the exclusive science of explaining the Earth fabric, and its scope has even passed to other celestial bodies in cosmic space. This does not mean that their value is over. Another argument in favour of keeping the term periglacial is the fact that none of the competing terms is free from the objections raised against the former.

Hidden permafrost in Poland

The terminological characteristics presented above, as well as their criticism and discussion, form an important basis for understanding the occurrence of permafrost in Poland. It occurs to a very limited extent in two contrasting locations: the lowland of Suwałki region (north) and the Tatra Mountains (south). Each of these locations

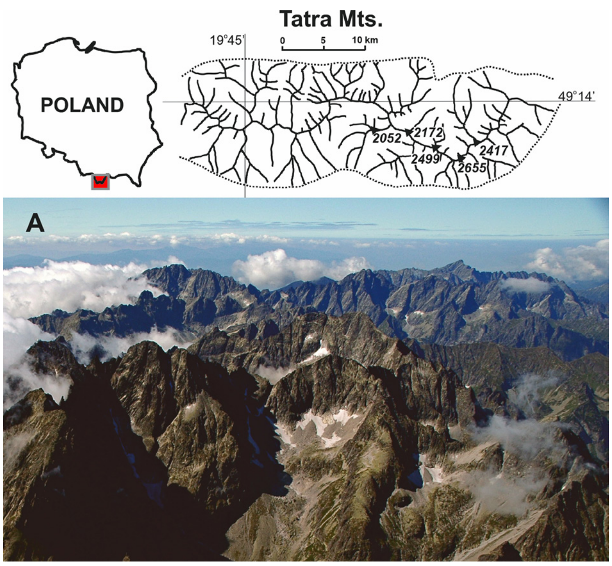

Fig. 7. Tatra Mts. A – view from the East to the highest part of the massif, with a.s.l. altitudes marked on the sketch map above. Photo courtesy B. Gądek.

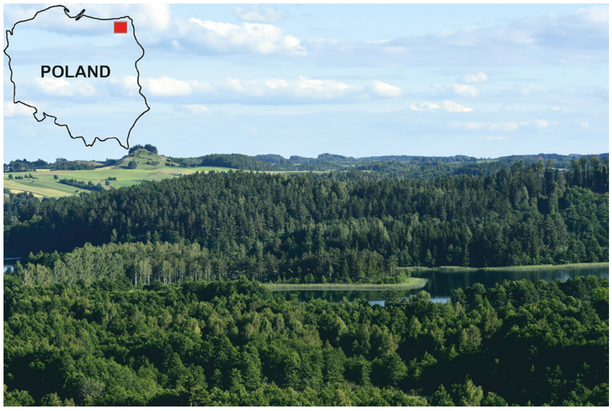

Fig. 8. Suwałki region, General location of the relict permafrost drill hole Udryń PIG1. View on the postglacial landscape. Photos courtesy J. Nawrocki.

is affected differently by issues of ice, frost, periglacial environment, proglacial and/or paraglacial processes, and cryo-conditioning. The Tatra Mts is a relatively small but sufficiently high, predominantly rocky massif. Suwałki Region is a hilly land in northeastern Poland, covered with a thick cover of glacial sediments from the last ice age, along with a large number of lakes (Figs 7 and 8). A different, although analogous, situation occurs in north-eastern Poland. While in the Tatras, the global climate cooling also manifested itself in mountainous climatic variability, in northern Poland, as in the whole of Europe, it had a zonal character. Hence, the effect of the climatic cooling in the Pleistocene was the formation of both altitudinal permafrost and latitudinal permafrost.

The areas of Polish lowlands and mid-mountains are places where world periglacial research begins (French 2003). Until recently, they included only the paleoenvironment associated with the impact of the Pleistocene glaciations (Mojski 1993). Both the glaciations and the harsh cold climate that accompanied them in this area ended several thousand years ago. For this reason, it was previously unthinkable that permafrost could be found in the Polish mountains and lowlands. Such discoveries, however, have been made, which radically affect the perception and understanding of the occurrence and degradation of permafrost on a global scale. It turns out that it occurs in places that do not show any external, i.e. surface signs indicating its presence. So, it has a kind of hidden character. It is worth briefly characterising them here because it can be very inspiring information concerning other areas where similar conditions exist. It also contributes to the determination of the permafrost's global range.

Tatra Mountains

Studies on azonal permafrost, outside the Arctic of Siberia and N. Canada, began in the mid-twentieth century in the Alpine countries and Scandinavia. In Poland, they started relatively recently. The knowledge and experience gathered by the author in the Alpine periglacial environment in 1992, allowed for a hypothesis that permafrost is also present in a small but spectacular massif of the Tatra Mts. on the Polish–Slovak border. The Tatra Mts. range lies between 49°05′ and 49°15′ N and is the highest mountain range of the Western Carpathians. It covers an area of 750 km^2. The highest peaks of the Tatra Mts. reach approx. 2500–2600 m a.s.l. The isolated nature of this massif causes, however, that the variability of climatic and plant belts is lower than in the great mountain massifs. Due to the large slope and vigorous slope processes, in the Tatra Mts., apart from some exceptions, there are practically no characteristic forms of periglacial relief that could indirectly indicate the presence of permafrost. The lack of these indicative landforms was the reason that in 1992 the height of 2200 m in the Tatra Mts. was considered the lower limit of permafrost based on general climatic conditions (Kotarba 1992). In the 70s of the 20th century, the MAAT at the Łomnicki Peak in the Tatra Mts. (49°N, 2632 m a.s.l.) is −3.7°C (Lukniś 1973), almost the same as that in the vicinity of the research station in Tarfala (Northern Sweden, 68°N; 1151 m. a.s.l. −3.9°C) and close to MAAT in the vicinity of the Polish Polar Station on Spitsbergen (77°N, 12 m. a.s.l. −4°C). All these places lie at a similar longitude. One of the most famous tourist peaks in Tatras is the Kasprowy Wierch (1987 m. a.s.l.) that became known especially because of the construction of a popular cable car at the top, already some 100 years ago. Due to its availability, a second weather station was established there, where the MAAT is approx. −1°C. This is almost the same as the Abisko research station (68°N ca. 400 m) in N. Sweden. In both of these Swedish locations, the presence of permafrost is no surprise. The simple climatic index was also the first indication of the possibility of contemporary permafrost in the Tatras. As a result of the analyses (Dobiński 2004), the 1900 m a.s.l. with a temperature limit of −1°C was recognized as the climatic limit of its occurrence (Haeberli 1985). Due to the latitudinal course of the main ridge of the Tatra Mts., the position of this border on the southern and northern slopes may differ by approx. 150 m in relative height. Everywhere in the Tatra Mts., the permafrost covers the bare rock walls (Fig. 7).

Permafrost studies undertaken in the 90s allowed to indirect identify permafrost at an altitude of about 1700 m using the climatic and geophysical methods in places particularly favourable for its occurrence: shaded places with a concave shape and in places of greater accumulation of sedimentary materials, such as inactive rock glaciers (Dobiński et al. 1996, Dobiński, 1997, 1998). However, nowhere are there any spectacular signs of permafrost in the form of Arctic relief or ground ice.

The analysis of permafrost evolution in the Holocene was based on relatively simple but certain assumptions of the climatic-palaeobotanical method and on the geomorphological criterion – topography (Dobiński 2004). The most important are a) the upper limit of the forest, which corresponds to the MAAT of +2°C (Hess 1965, 1968) and b) the lower limit of the active permafrost, i.e. MAAT of −1°C (Harris 1981, Haeberli 1985). With the beginning of the Holocene, in the Pre-Boreal period, the tree-line was at an altitude ca. 1000 m a.s.l. The significant warming of the climate that took place then caused this border to rise (Patzelt 1975, Mojski 1993, Burga 1995). Obidowicz (1993) proves that the upper tree-line in its maximum range did not run about 100–200 m higher than today's maximum. Studies based on pollen and macrofossil analyses indicate that in the Alps also the change in the range of the upper forest border did not exceed 100–150 m (Patzelt 1975, Wick, Tinner 1997). Based on these results, the lower boundary of the discontinuous permafrost in the Tatra Mountains during the Holocene was reconstructed. This means that the conditions for the presence of active permafrost in the Holocene always existed around 600 m above the upper forest limit. These considerations show that even in the warmest – according to Obidowicz (1993) – the Holocene period, permafrost could occur below 2000 m and embrace the highest Tatra valleys, as it is today (Dobiński 2004). It is worth adding that in the period of Würm, the depth of permafrost in the Tatras is estimated at even 420 m (Czudek 1986). During the entire Holocene, the temperature in the Tatras could have been higher than today by 2°C for only 4500–5900 years supporting permafrost preservation (Obidowicz 1993), which means that even with a relatively high permeability after the glaciation period, there were never any conditions for the complete degradation of Pleistocene permafrost here. It means that the highest peaks in this warmest Holocene period MAAT were not lower than about −2°C (Dobiński 2004). Currently, many scientists have already confirmed the presence of permafrost in the Tatra Mts (Gądek, Kotyrba 2003, Uxa, Mida 2017, Senderak et al. 2019), but there is still no direct evidence of its presence. It can only be obtained by monitoring the temperature in the ground for at least 2 years. It would only be possible by making a fairly deep bore at the height of about 2000 m a.s.l. Obtaining such data is extremely difficult in the Tatras due to the inaccessibility of such high-lying areas for empirical research. Therefore, Tatra permafrost remains a hidden and inaccessible phenomenon.

Suwałki region

The Suwałki Region is the coldest region of Poland, where the MAAT is about 6°C. It is characterised by a more continental climate than the western part of Poland. For millennia, it has been a region also covered with large forests, often still intact, of which the Białowieża National Park is an excellent example. Still, no one would have thought that permafrost might still be present in this area. The distance to the Scandinavian Arctic (66°33′N) is 1500 km and to the northern Urals – the border of Siberia – is over 2500 km. The ice sheet of the last glaciation left this area around 18 ka BP (Marks 2005, 2012). Since then, this area has been particularly exposed to the frosty climate for so long that the permafrost has reached a depth of about 600 m. However, until recently, it was considered that the last part of the Younger Dryas (12.9–11.7 ka BP) is characterised by the disappearance of local permafrost in the northwest European lowlands (Vandenberghe 1993). The discovery of relict permafrost in this region was the result of the analyses of the subsurface geothermal regime together with the hydrogeological, petrophysical, and geophysical data obtained from wells drilled here (Szewczyk, Nawrocki 2011, Szewczyk 2017).

The borehole that directly documented the presence of the relict permafrost is located near the village of Udryń (54°14′49 ″N, 23°03′29″ E, 223 m a.s.l.). The lithological profile of this borehole consists of ca. 300 m of Cenozoic clastic rocks that cover Cretaceous limestones, marls, and mudstones (Szewczyk, Nawrocki 2011). The measurement of the temperature in it showed the value of 0.245°C, which gives almost direct proof that the relict permafrost is here in the form of ice–water transition phase at the present thermodynamic conditions of its occurrence, i.e. that it is almost certain that near the drill hole, the ground temperature is below zero. The permafrost layer there is at least from 357 m to more than 450 m. It covers an area of about 50 km^2 and is at least 150 m thick. A very important factor that allows it to survive to this day is the presence of an anorthosite massif of magmatic intrusion covering an area of approx. 250 km^2 at a depth of 800–1200 m below it which isolates the geothermal influence (Szewczyk 2017).

The occurrence of the relict permafrost in the Suwałki region, northeastern Poland is a result of two factors: a) cold climate during the last glacial period with a mean surface temperature of about −10°C, and subsequent periglacial conditions after and b) very low heat flow density in this area resulting from the low natural radioactivity of the anorthosites, norites and diorites that constitute this massif, which allow deep permafrost penetration. On the other hand, the calculated heat flow density value ranging from 37.9 mW m^{-2} to 47.3 mW m^{-2}, with a tendency for decreasing values towards the centre of the Suwałki anorthosite massif was the reason that allows the preservation of the permafrost for a much longer time than expected. In the centre of the anomaly, the heat flow density is probably even less than 30 mW m^{-2} (Szewczyk, Nawrocki 2011). The relict permafrost drilled in the Udryń is probably in the phase-transition state, i.e. at the melting point. Such a situation of permafrost decay consumes a large amount of energy and usually lasts longer. The occurrence of a very low heat flow value and the very porous, highly water-saturated sedimentary layers was of crucial importance.

Specificity of permafrost in Poland

In the post-glacial period, the periglacial area developed in Poland throughout its entire territory. Its most characteristic forms were first noticed by W. Łoziński, but later the full scope of periglacial research developed on the area left by the retreating ice sheet. It included only the palaeoperiglacial environment, devoid of the characteristic climatic influence and the active forms of ground ice that formed them at the end of the Pleistocene. The results of the work were so interesting that the journal *Biuletyn Peryglacjalny* was created, which was the first periodical to publish articles on this phenomenon from around the world in the years 1954–1999, later replaced by Permafrost and Periglacial Processes. Initially, therefore, despite the clear awareness that the periglacial environment is associated with freezing and ground ice, the presence of permafrost did not dominate the issues discussed, which were predominantly geological and geomorphological in material terms of the subsurface layer of the lithosphere.

Undertaking research on mountain permafrost in the Alps and Scandinavia in the middle of the last century gave a new impulse to periglacial research in Poland. Its discovery in the 90s of the last century in the Tatra Mountains was possible, by analogy with these mountain areas, but the discovery of permafrost in the lowlands of northern Poland is unprecedented and is a great surprise. There are no, even the smallest, premises that could in any way substantiate the thesis about the presence of permafrost in Poland based on external signs, occurring on the ground, so common in the Arctic, Siberia, Scandinavia, Alaska, or high-mountains cold environments.

In both cases, Polish permafrost can be seen as a specific case of hidden cold, either in the form of underground ice or in the form of a specific temperature, close to 0°C. When it occurs in a cryotic state, or where there is no water at all (Fig. 9). Its detection is extremely difficult because indirect geophysical methods also may fail and its discovery then becomes a matter of chance. It also turns out that its survival potential is much greater than previously thought.

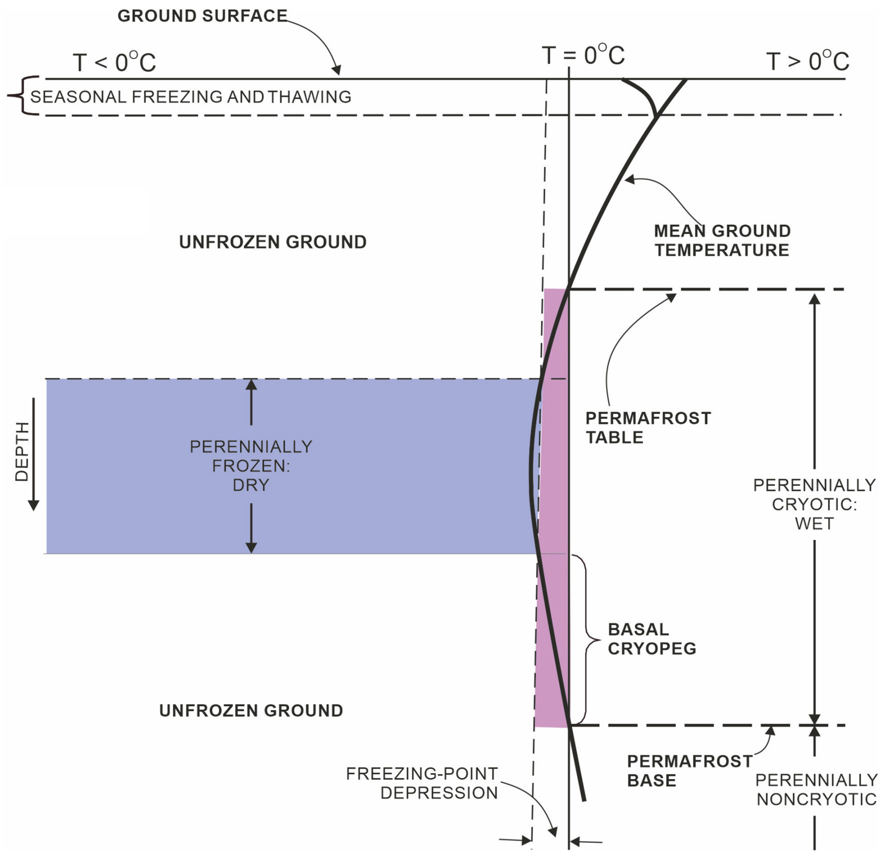

Fig. 9. Conceptual, simplified profile of relict permafrost located in northern Poland (Suwałki region) as an analogue of the general permafrost profile shown in Figure 4.

Moreover, the relic permafrost of the Tatra Mountains or the Suwałki Region shows that it must be extremely old. If it survived the Holocene climatic optimum, it means that its presence may be associated with the beginning of the last glaciation.

Conclusions

The term periglacial came into use and spread quickly, and was widely accepted, not by some sort of promotion, but by the obviousness of the object it means. Since the beginning of the 20th century, it has continued uninterruptedly until today, fulfilling its role.

Periglacial was created as a *geological* term describing the surface-and-subsurface part of the lithosphere subjected to frost weathering, the effect of which is characteristic block fields deposited *in situ*: *periglacial facies*. If it remained as a geological term, it would not be difficult to link it either with permafrost or with various types of ground ice that commonly accompany the occurrence of the periglacial environment, but only as part of its geological foundation.

The transfer of the periglacial concept from geology to geomorphology was because relatively shallow geological processes such as frost processes and the water phase change directly shape the characteristic relief under the influence of exogenic climatic factors. However, while the relief forms belong to geomorphology and shape the landscape as visible forms, permafrost is neither a component of the Earth's surface nor is it visible, because it is the condition of the ground, not a thing. Having no material expression, it cannot be either an element of a sculpture or a landscape.

In a particular case, underground ice of various origins, exposed naturally, may be an element of relief and a landscape component, as is the case with landslides, debris flow, or other mass movements on land, near rivers or sea, or lake shores. However, ice, lying on the surface of the Earth or below the surface, in any form and of any genesis, is a component of the lithosphere as its lightest rock. The periglacial concept is not a very precise term. Its vagueness results mainly from the unclear boundaries that can be used to define the periglacial environment occurring in environmental zones or belts. Periglacial as a general concept, however, still fulfils its function well, allowing for a clear definition of the most general long-lasting frost and ice processes and forms occurring outside the glacial environment. All other attempts at classification, although often accurate and necessary, are rather part of the whole.

Difficulty in the unambiguous understanding of ice and freezing and a certain natural human tendency to introduce novelty causes attempts to be made to question the meaning of this term in the system of geographical sciences. However, upon careful examination, it is easy to see that, in principle, all of today's proposals have either been previously considered or are simply part of the periglacial research field.

The history and meaning of the Greek term: *κρὐο* (cryo, krio) in various forms and combinations is still a value that allows a better understanding of the term cold in Earth sciences. However, replacing the spelling of cryology and cryosphere with the correct kriology and kriosphere would certainly help in the correct description of the research object, as would the term describing the chemical weathering of soluble rocks: karst.

The specificity of research on permafrost in Poland is that the permafrost present here has an exceptionally hidden nature, which made its discovery on the one hand very difficult, and on the other – it has a special scientific significance. The extrazonal occurrence of paleo-permafrost, both in the latitudinal (zonal) and altitudinal (mountain) terms, is still a difficult puzzle to solve. The relict permafrost of the Pleistocene genesis is likely to occur in a much wider range, both in Arctic and mountainous environments.

The discovery of permafrost in the Suwałki region, however, allows us to believe that there are other similar places in Europe and in the World where permafrost may occur, even though nowadays nothing indicates it. Such specific positions of the azonal occurrence of it have the potential to fundamentally influence the understanding of its occurrence now and in the past.

Unfortunately, the dating of permafrost is extremely difficult, as it is essentially the dating of temperature. This is where the biggest problem and the greatest scientific opportunity arise: the age and extent of relict permafrost in the World is the biggest puzzle in periglacial research today.

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