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PERMAFROST. THE CONTEMPORARY MEANING OF THE TERM AND ITS CONSEQUENCES

Abstract: Nowadays the term 'permafrost' means the thermal state of the ground, for which the temperature limit value is 0°C remaining for at least two years. It is the effect of the climate where the average annual temperature of the air is –1°C or lower. As a result of air temperature, it does not need to contain ice, so it can no longer be called underground glaciation, and the only processes which are subject to permafrost are aggradation and degradation. Also the occurrence of permafrost in the geographical environment is conditioned neither by the presence of water nor its phase change – freezing, as the cryotic state is its synonym. Although it is known that the majority of permafrost dates back to the Pleistocene, still the determination of its age is difficult because it consists in determining 'the age of the temperature', as it were. The maximum thickness of permafrost occurs in the Antarctic, and it is estimated to reach 2600 m. Permafrost covers more than 25% of the Earth surface together with ice-sheets and ice-caps.

Key words: permafrost, definition, processes, extend, origin and age

Introduction

Permafrost is a term that in recent publications is defined as the thermal state of the ground (cf. Haeberli et al. 2006; French 2007). Perceiving permafrost in such a way triggers the necessity to revise some of the views on its characteristics and the processes associated with it. The consequences of such a revision in some cases may be far-reaching, which creates the need for clarification of the views. Some of them are presented below in order to both emphasize the existing inconsistencies and explain them.

Definition

The perennially frozen or cryotic ground (permafrost) is a phenomenon which is difficult to classify in Earth sciences. It is defined as rock or soil that remains at a temperature equal to or lower than 0°C for at least two consecutive years (Muller 1943; Everdingen 1998). This definition therefore defines perennially cryotic ground/permafrost as the thermal state of the ground. Such a stand occurs consistently in several publications (Black 1954, 1976; Brown and Kupsch 1974; Haeberli et al. 2006; French 2007). Being a condition, not a thing, it has proved to be difficult to be captured by several classifications adopted in Earth sciences. It cannot be classified, *sensu stricto*, to geomorphology because it is not a form of the land surface. It may affect the development of the geomorphologic relief of the land surface but mainly when its presence is accompanied by H_2O. I use the term H_2O because, according to the definition, water may occur in permafrost both in the solid and liquid phase. Nonetheless, the presence of water in any form is not a prerequisite for the occurrence of permafrost, because it is determined by the temperature. This strictly artificial temperature limit of 0°C applied in the definition is very often associated with a phase transformation which occurs in nature. Freezing and melting water at this temperature, however, is not common on Earth. Let us consider the ubiquity of salt-water worldwide, or the pressure occurring under the ice sheets of Antarctica and Greenland to see that the majority of water on Earth freezes at a temperature significantly below 0°C. Also fresh water occurring on the surface of the Earth in the form of groundwater, rivers or lakes often does not freeze at the temperature of 0°C for different reasons (mineralization, movement etc).

Bearing in mind these obvious facts, the definition of permafrost has been supplemented with the concept of cryotic state which is synonymous with permafrost; however, it also covers the part of it which, despite remaining at a temperature of ≤ 0°C for a certain time, remains not frozen. The features of permafrost described here make it a 'hidden' phenomenon, as it were, because being the thermal state of the ground it remains invisible. What is visible is only the numerous effects of its presence in the ground which are sometimes identified with permafrost, as for example the existence of some form of underground ice. Therefore, in the light of present knowledge permafrost cannot be called ‘eternally frozen’ or ‘underground glaciation’ (Danilov 1990). Glaciation is a process of accumulation of snow on the Earth surface, and in consequence the development of glaciers, whereas permafrost is a process of accumulation of ‘cold’ (equal or less than 0°C) temperature under the ground. Contemporary clarification of the definition of permafrost and its full understanding results in consequent determining of its thickness, origin and age, the content and the genesis of the ice as well as its presence on the Earth. These issues are explained below.

The structure and the processes

Permafrost occurs in the lithosphere and has the nature of a thermophysical layer, inside which the temperature is generally negative (Fig. 1). This layer is limited from the top and bottom by a thermophysical surface of 0°C. Above the layer of permafrost there is a so-called active layer which freezes seasonally, that is in winter. When we are dealing with active permafrost, which is related to the contemporary climate, then the active layer freezes to the permafrost and the temperature of the permafrost may drop even deeper, slightly modifying its thermal characteristics year by year. When the seasonal freezing is shallower then we are dealing with inactive permafrost, which in a shorter or longer time is not subject to modification by seasonal freezing. This does not mean, however, the absence of any thermal influence (upon it) of the seasonally changing stream of heat reaching it from above. The surface of 0°C restricts the layer of permafrost also from the bottom. It constitutes the boundary of the balance between climatic cooling coming down from the top and geothermal heat rising from the bottom.

The both surfaces are uneven, depending on a number of factors, such as land use, vegetation, snow cover, aspect, thermal properties of the medium of permafrost occurrence and others that affect the depth of freezing and thawing and thus the thickness of the active layer and the thickness of permafrost. These conditions mean that along with it disappearance and a decrease in the permafrost thickness goes from the continuous to the sporadic form of existence through the discontinuous one (Fig. 2). Sub-polar permafrost vanishes along with the decline in latitude, while mountain ermafrost disappears along with the decrease in altitude.

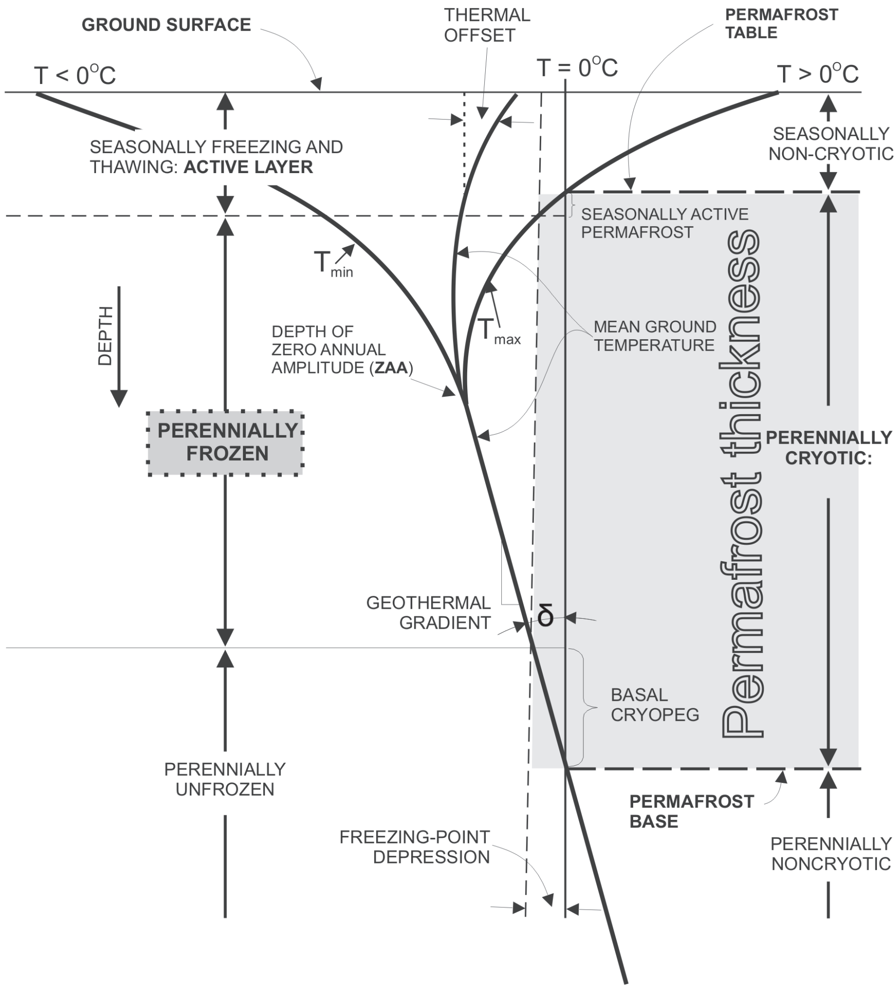

Fig. 1. Geophysical model of permafrost (after Everdingen 1998 with changes from Dobiński 2011a) with slight modifications. Permafrost is the marked area on the right side of the model both in the form of frozen and in the cryotic state, above and below the frozen layer

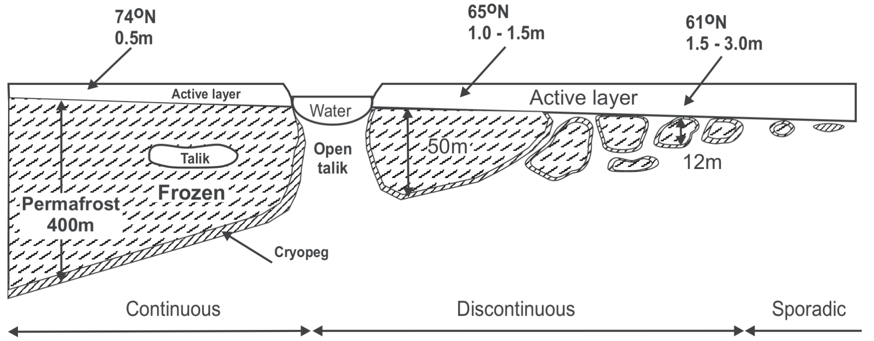

Fig. 2. Terrain model of permafrost. Local diversity in physical properties of the ground means it occurs in a continuous, discontinuous and sporadic form (Washburn 1973 and Dobiński 2011b)

Processes

Processes related to permafrost give rise to major misconceptions. Because of the fact that its very occurrence is often associated with the presence of different types of underground ice, it is often attributed the role which should be *de facto* assigned to ice or ice-rock mixture. The processes associated with the presence of ice in the areas connected with the occurrence of permafrost encompass processes such as frost heave, frost cracking, thaw settlement, frost sorting, frost jackling, frost shattering, frost wedging, etc. (Jahn 1970; Washburn 1973; Everdingen 1998; French 2007). They are connected rather with the so-called frost action, i.e. the recurring cycle of freezing and melting of water, which is the major process-inducing factor, and this action usually spreads over the active layer of permafrost and in areas of seasonal freezing. One of the major and long lasting misconceptions is the so-called ‘permafrost creep’ (Haeberli 1985). This term has been adopted to describe the process of creeping of weathered material, usually cemented with ice, in the high-mountain environment, where permafrost also occurs. This process is attributed to rock glaciers, i.e. the forms which are of lobe or tongue shape and indicate the signs of creep in a specific undulation of the surface. Also in this very case, ice with its plastic properties is responsible for the process and the created form. As permafrost is defined in physical terms – as a state, not a thing – it cannot creep, just as it is impossible for the temperature to creep. In view of this, the only processes that occur in permafrost are aggradation and its opposite, degradation.

Aggradation of permafrost is the process of the ground temperature reaching or falling below 0°C, which often, but not necessarily, induces freezing of water, if it is present there, and makes permafrost thicker. Degradation, by contrast, is the inverse process, which initially makes the temperature rise within sub-zero temperatures, and then, when the temperature is higher than 0°C, causes melting of ground ice which may exist there. As result it makes permafrost thinner. Climate changes depending on their intensity and durability may be recorded in the frozen ground in the form of changes in the course of its temperature (Fig. 3). The longer and more intense the change, the deeper it affects the lithosphere.

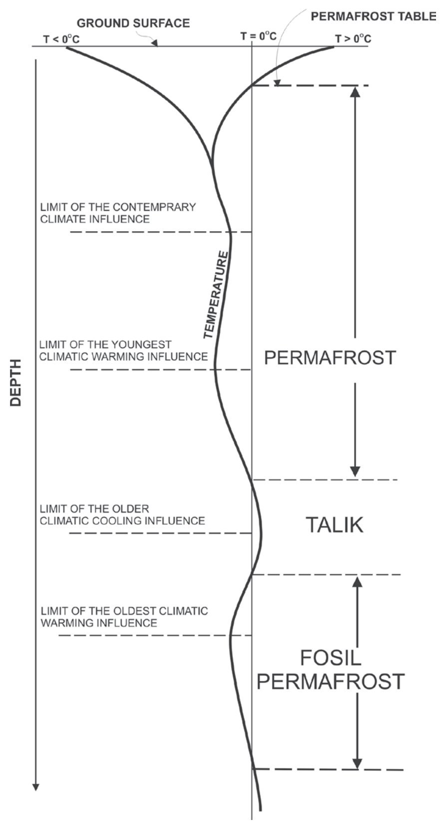

Fig. 3. Variability of the ground temperature within permafrost resembles alternating 'heat and cold waves' which are induced on the surface of the ground and come out of the atmosphere; they result from climate change (after Dobiński 2011b)

Origins and age

The majority of permafrost existing on the surface of the Earth is the result of the Pleistocene climate cooling, which caused both glaciation and deep freezing of the lithosphere, where glaciation did not take place and the adequately cold climate facilitated this process (Black 1954; French 2007). To a lesser extent the presence of permafrost is related to the present climate. Its development and maintenance is possible wherever thermal balance for the surface of the Earth is negative, i.e. where more 'cold' from the winter season remains in the lithosphere than the 'warmth' from the summer. In the initial form it may be a tiny layer of negligible thickness (of a few centimetres), which remained through one summer season. Permafrost of a few hundred metres thickness is much older. It is possible, however, that permafrost layer can be preserved at a significant depth as it is in western Siberia (Ananajeva-Malkova et al. 2003) or in the Suwałki area, Poland (Szewczyk and Nawrocki 2011).

Determining the age of permafrost of great thickness is very difficult as in fact it involves determining 'the age of the temperature' reaching and persisting at freezing point, as it were (Lunardini 1995). Therefore, what can be stated for sure is only that its age cannot be smaller than the time necessary to create permafrost of a given thickness (Lunardini 1995). The speed of permafrost aggradation depends on the air temperature which comes into contact with the surface of the lithosphere, and the physical properties of the ground, which can transmit heat deep inside faster or slower (sub-zero temperature). Also, the presence of water is of great importance. Latent heat which is utilised in the process of the phase transformation of water/ice or ice/water has a significant impact on the speed of freezing of the ground (the process involves heat release or taking heat respectively).

An important factor is climatic variability occurring on the surface of the Earth – it influences temperature at the surface. It can change the rate of freezing, and in the case of a temperature rise above 0°C, degradation of permafrost. Short-term climatic variability may cause a change in the thickness of the active layer, which may comprise the upper part of permafrost. This variability may induce periodic appearing and disappearing of this part of permafrost which comes into contact with the active layer, proportionally to the change in its thickness. During the long period of warming, a significant part of permafrost layer may undergo a total degradation. However, during the following cooling a new layer of permafrost may reach the roof of the older layer, or even deeper, as takes place, for example, in western Siberia (Fig. 4). Overlapping waves of cooling and warming modify the thermal structure of permafrost. Repetitiveness of this process in principle complicates the determination of permafrost age. Other modern methods, such as radiometric dating, also fail us here since neither water nor any other matter can be equated explicitly with perennial freezing. Nevertheless in the Dry Valleys of Antarctica, where the residues of the Taylor glacier are believed to have been discovered, the frozen sludge found there was dated. The minimum age estimated for these sediments is 2.3 million years (Schafer et al. 2000). This makes it probably the oldest dated permafrost on the Earth.

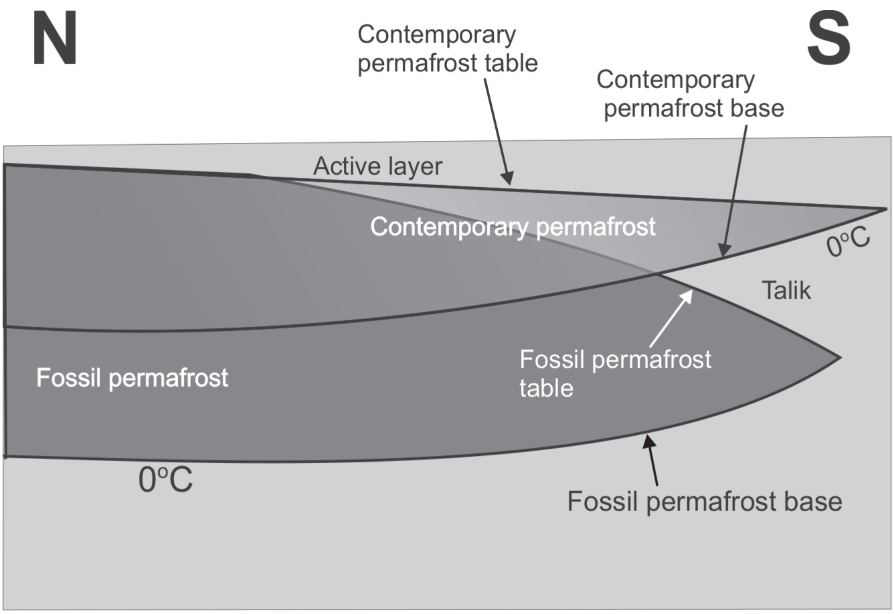

Fig. 4. Model of two-layer permafrost in western Siberia (after Jahn 1970). The older one being located deeper, and the younger located above the first one. Younger permafrost is an effect of contemporary cooling, which may overlap deeper located permafrost from the Pleistocene.

The effect of climate

Permafrost is an effect of climate. It may occur anywhere where the energy balance for the earth's surface within a year facilitates a constant temperature of ≤ 0°C in the ground (Jahn 1970; French 2007). Because of the fact that permafrost covers the greatest area of Siberia, Alaska and northern Canada, it is associated with a continental climate. It is justified to the extent that this climate is characterised by much less precipitation in comparison with a maritime climate. It means that snow cover in winter is too thin to protect it against freezing, while in summer rainfall is not sufficient to support the transmission of heat into the ground, except for river banks, where the influence of thermoerosion is clearly visible. However, neither large nor small annual temperature amplitudes are decisive factors. In this context, the most often given mean annual air temperature is the value of –1°C, which constitutes the boundary of sporadic permafrost occurrence on a regional scale, i.e. regardless of the geomorphology of the land, which obviously affects the presence of permafrost. The occurrence of permafrost on a regional, topographic scale may be substantially modified by topoclimate connected with specific geological conditions of the land. On a topographic scale noteworthy is a specific type of air circulation, also called Balch circulation or chimney effect (Balch 1900; Sawada et al. 2003). It occurs in particular landforms such as debris cones, specific depressions or ice caves. This phenomenon lies in the fact that cold and heavier winter air flowing into the low-lying depressions in the terrain is not removed by warmer air in the summer because the latter, being lighter, is not able to push out the low-lying cold air. This situation additionally facilitates accumulation of ice in the ground which may be in a significant part of atmospheric origin. Due to the extrazonality of this type of atmospheric circulation, the conditions facilitating the occurrence of permafrost may also exist in an area located in a much warmer climate zone where the mean annual air temperature may even exceed 7°C (Harris and Pedersen 1998).

Polar (Arctic) and mountain permafrost

Permafrost, being the result of climatic influence, is linked to the decrease in temperature caused by the decrease in the amount of solar radiation reaching the Earth's surface at high latitudes, or the decrease in temperature associated with the increase in altitude. The first is called arctic or polar, whereas the other one is Alpine or mountain permafrost. Its genesis is very well rendered by its English names, respectively: latitudinal and altitudinal permafrost. However, the occurrence of Arctic permafrost is not directly linked to a particular latitude which would constitute its boundary. Everdingen (1998) indicates that mountain permafrost may show some degree of altitudinal zonation. It is, however, associated with the high-altitude boundary above which permafrost is treated as mountain permafrost. A more detailed description is given by Gorbunow (1988). He proposed the contourline 500 m a.s.l. as an altitudinal criterion for distinguishing the difference between mountain and Arctic permafrost for several reasons. The most universal from the authors' point of view is probably the definition of the boundary between the Arctic and mountain permafrost (500 m a.s.l.):

"The height range 0–500 m is sufficient in order to give a clear distinction for the zones of seasonal and perennial freezing of soils because it corresponds to the 3°C difference of yearly mean temperatures. As far as the geomorphology is concerned, the level indicated coincides with the lower boundary of mountain valleys.… For a vertical temperature gradient of 0.6°/100 m, along this line at 500 m above sea level one should expect the occurrence of mountain masses cooled to 0°C. And this does satisfy the proposed criterion for identifying the region of the Alpine permafrost zone."

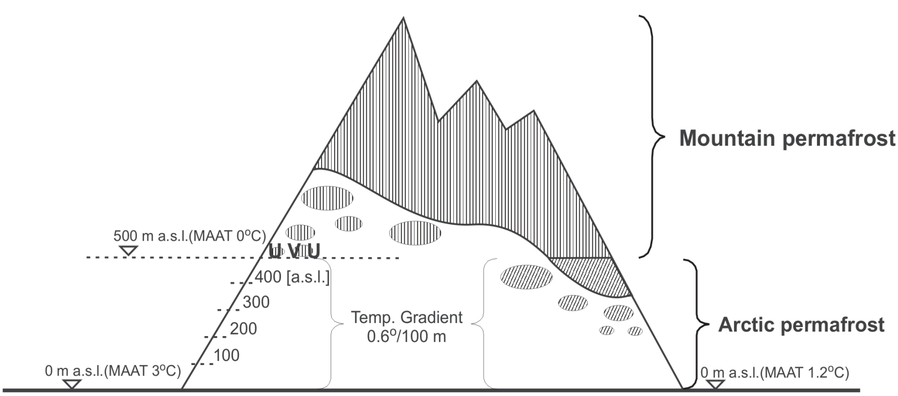

Fig. 5. Mountain and Arctic permafrost after Gorbunov's (1988) definition. MAAT – mean annual air temperatures, UVU – symbols for the main mountain valleys' bottom at altitude 500 m a.s.l. Mountain permafrost located above 500 m a.s.l. Arctic permafrost located in this case between 200 and 500 m a.s.l. Both located above altitude of 0°C MAAT, which is favourable for initial permafrost development

The presence of ice

As already mentioned, the occurrence of permafrost is associated or sometimes simply identified with the presence of underground ice. Earlier it has even been called incorrectly 'underground glaciation' (Jahn 1970). Therefore determining the relationship between permafrost and ice is essential for its proper understanding.

To find a solution to the above issues, you need to determine the position of ice in Earth Sciences. Universally it is qualified as an element of the hydrosphere, thus identifying ice with water. However, water is most often defined as liquid, hence ice as a solid does not correspond to the definition of water. Yet, it is commonly identified in Earth Sciences as one of the so-called primary minerals, and this – in relation to a larger accumulation of ice – justifies naming it as rock. Therefore it seems logical to qualify it as a component of the lithosphere, which has been substantiated by the author more extensively in other works (Dobiński 2006, 2011).

Perennial freezing is not a selective process, so it may cover each component of the lithosphere, both natural and anthropogenic. The smallest amount of water is present in igneous rocks, while the largest in loose sedimentary rocks since they occur on the surface of the Earth or at a small depth. Ice existing on the surface of the Earth in the form of ice sheets and glaciers is also built mainly from H_2O, with an admixture of moraine material. It is obvious that it may become frozen, although with reference to glacier thermics other terms are also applied: cold glacier and temperate glacier. The first term refers to a completely frozen glacier, while the second one concerns glacier-ice which is at the pressure melting point, which in reality always means the temperature lower than 0°C at the base. Both cases meet the definition of permafrost. With this in mind, we can say that water content (ice) in permafrost can range from the value of almost 0 to 100%.

As already stated, water is not necessary for the occurrence of permafrost. However, when it is present in permafrost, it generates a number of morphogenetic processes, which will not be described here as they concern water and its phase transition (solid – liquid), and not the variability of the temperature, which is referred to in the description of permafrost. Morphogenetic processes and a phase transition engender different forms of ice within permafrost. The multi-language glossary of permafrost and related ground-ice terms (Everdingen 1998) lists 23 types of ice, which may result from the operation of diverse processes (NB the dictionary is available on the International Permafrost Association website). It is worthy of note that within permafrost there may occur not only ice of the periglacial environment, which it is associated with, but also ice of glacial genesis. This is possible in a situation of areal deglaciation of glaciers, where in front of the margin of a retreating glacier a relatively wide zone containing blocks of dead ice sometimes occurs. Although the ice is of glacial genesis, it passes through to the periglacial environment and meets the requirements of the definition of permafrost.

The geographical range on Earth

Describing permafrost, i.e. comprehending what it is, actually allows the determination of the extent of its occurrence on Earth. As already mentioned, its existence may be associated with horizontal cooling – polar permafrost – or vertical cooling – mountain permafrost. Due to the fact that the greater part of the land is located in the Northern Hemisphere, the most favourable conditions for the development of permafrost prevail just there. Arctic permafrost spreads over Alaska, northern Canada, the northern part of Sweden, Norway, Finland and Iceland, together with a portion of the Kola Peninsula, i.e. Lapland and a great part of Siberia. The second relatively large place of its occurrence is Tibet, located at a much lower latitude. Apart from that, it is widespread in a number of mountain chains around the world. In some places, where the mountain chains are of longitudinal course, i.e. in the Scandinavian Mountains, the Cordillera and the Urals arctic permafrost gradually transforms into mountain permafrost, and sometimes due to the specific characteristics of the ground, both of the types may overlap (Dobiński 2011b). Because of the specificity of the occurrence of huge mountain chains in the world – the American Cordillera, the Himalayas, the Andes – as well as single massifs such as Kenya, and Kilimanjaro, there is, however, no such latitude where permafrost does not occur. The only continent where it has not been found yet is Australia. Antarctica is entirely included in the permafrost zone in its frozen or cryotic form. Discovering the presence of permafrost in the Suwałki region (Poland) at a depth of more than 360 m (Szewczyk and Nawrocki 2011) is an event which makes it imperative to revise the views concerning the occurrence of the Pleistocene permafrost also in such places where hitherto no one had expected the possibility of its survival. This applies to the whole world.

Conclusions

Permafrost is a phenomenon which, as the state of the ground, is hidden, as it were, and therefore even today it still remains undetected in many places in the world. Its presence can be identified in both the traditional periglacial and the glacial environment, which has rather not been taken into account until recently. Acknowledging the presence of permafrost in glaciers and ice sheets in cryotic and frozen states makes it necessary to redefine the global range of its occurrence. In view of the generally applied definition of permafrost, it cannot be assigned processes other than aggradation and degradation, and especially creeping, which should be commonly attributed to the movement of glacier or ice-containing ground.

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