THIN FLAKES, THICK ICE

When the temperature drops, rivers, lakes and seas become covered with ice, the water vapor in the atmosphere turns into snow crystals, and underground water turns into tiny ice lenses or veins. Glaciers and ice caps are formed in high mountains and in polar regions. All these large and small, visible and invisible forms of solid water on Earth together form what is known as the "cryosphere."

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Glaciers and ice sheets are, it seems, the most spectacular components of the cryosphere. Mountain glaciers form in favorable orographic and climatic conditions, in places where accumulated snow does not fully melt from one season to the next. This gives rise to so-called firn fields, where the snow transforms into firn – a collection of ice grains created from crystals and snowflakes that have melted under the sun and become consolidated. The snow in firn fields comes not only from snowfalls, but can also be brought in by wind or avalanches. Firn thickens due to repeated thawing and freezing, as well as under the growing weight of new snow. The density of snow, depending on its type, falls within the wide range of 0.004–0.4 g/cm^3, firn has a density of 0.4–0.8 g/cm^3. Further transformation of firn gives rise to milky firn ice, with numerous air bubbles (with a density of 0.8–0.91 g/cm^3), and finally to crystalline glacier ice. Pure glacial ice crystals absorb all the colors of sunlight, but allow the blue light to penetrate, hence its beautiful color. The process by which snow is transformed into blue glacial ice takes several hundred years. About 15 m of fresh snow is needed to create a 1 cm thick ice crystal.

Masses of packed ice flow out of firn fields located above the equilibrium line altitude (ELA) in the form of glacial "tongues." The tongue of the Fedchenko glacier in Pamir, for instance, is 70 km long. Glaciers are found in most mountains of the world, and the ELA depends on latitude and local topoclimatic conditions – it is 100–300 m above sea level in the Arctic, 2500–3000 m above sea level in the Alps, and the highest of all, at 5800–6000 m above sea level, in Tibet. In the Tatra Mountains the ELA is anywhere from 2200 m up to 2450–2550 m above sea level. So theoretically, glaciers would have a chance to form if there were adequate places for the firn fields at this level. There are no glaciers in the Tatras, but from the accumulation of fallen and avalanche-created snow in recesses and ravines sheltered from the sun, small ice-firn patches are created that may last until the following winter (including in the Wielki Mięguszowiecki Kocioł cauldron or near the Bula pod Rysami ridgelet).

However, the largest forms of ice accumulation on the Earth's surface are ice sheets. There are currently two huge ice sheets on the planet, located in Greenland and Antarctica. The Greenland ice sheet is made up of nearly 3 million km^3 of ice and if it melted, the Earth's ocean level would rise by 7 m. The Antarctic ice sheet, in turn, occupies over 12 million km^2 and accounts for 90% of the world's freshwater resources. The average thickness of the ice sheet is 2.4 km, but in some areas it can reach 4.7 km. Drilling done in recent years has shown that there are rivers and lakes under the ice sheet, and bacteria have been found in them!

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Fig. 1.
The front of the Krammer Glacier, Spitsbergen.

Fig. 2.
Sorted stone circles, Calypsostrandra, Spitsbergen.

Fig. 3.
The largest erratic boulder in Mazovia, near Mszczonów.

Underground strength

Underground ice is less spectacular, but involves no less enormous volumes. Although it is not generally visible, it covers the northern hemisphere from the Polar Regions to Siberia, central Asia, Tibet and high mountains at any latitude. In areas where the average annual air temperature is lower than -8°C, the land is frozen permanently (so-called *permafrost*). In regions where the average annual air temperature is not higher than -1°C, permafrost occurs locally (*sporadic* or *discontinuous* permafrost). Permafrost is nothing but water permanently frozen inside the soil. Such underground ice takes on various forms, depending on the amount of water and soil properties (grain thickness, porosity, sealing). They may be microcrystals, ice lenses, or also powerful macrostructures in the form of veins and wedges of pure ice, stretching to a depth of several dozen meters. In central Siberia, the ground is permanently frozen to a depth of over 1 km. In the Mackenzie Delta, the permafrost reaches a depth of 700 m, in Tibet 100 m, whereas in high mountains it often does not go more than 10 m deep.

The cryosphere reacts strongly to any climate changes during the daily, seasonal, or long-term cycle, but also in geological time. The state of dynamic equilibrium between melting and freezing translates into significant changes in the environment not only in the immediate vicinity of individual elements of the cryosphere. Changes in the cryosphere are an important element of global environmental changes. Permafrost can persist deep beneath the surface for hundreds of thousands of years, whereas the top ground layer melts every summer to a depth of up to several meters. This is called the active layer of permafrost.

When water trapped in the pores and crevices of sediments and rocks freezes it breaks them further apart, as during the freezing process water increases its volume by about 9%. On a home laboratory scale, this breaking power of ice is easiest to test by leaving a glass of water out in the freezing cold. Most of us who drive cars are also familiar with the appearance of numerous holes in the asphalt at the end of win-

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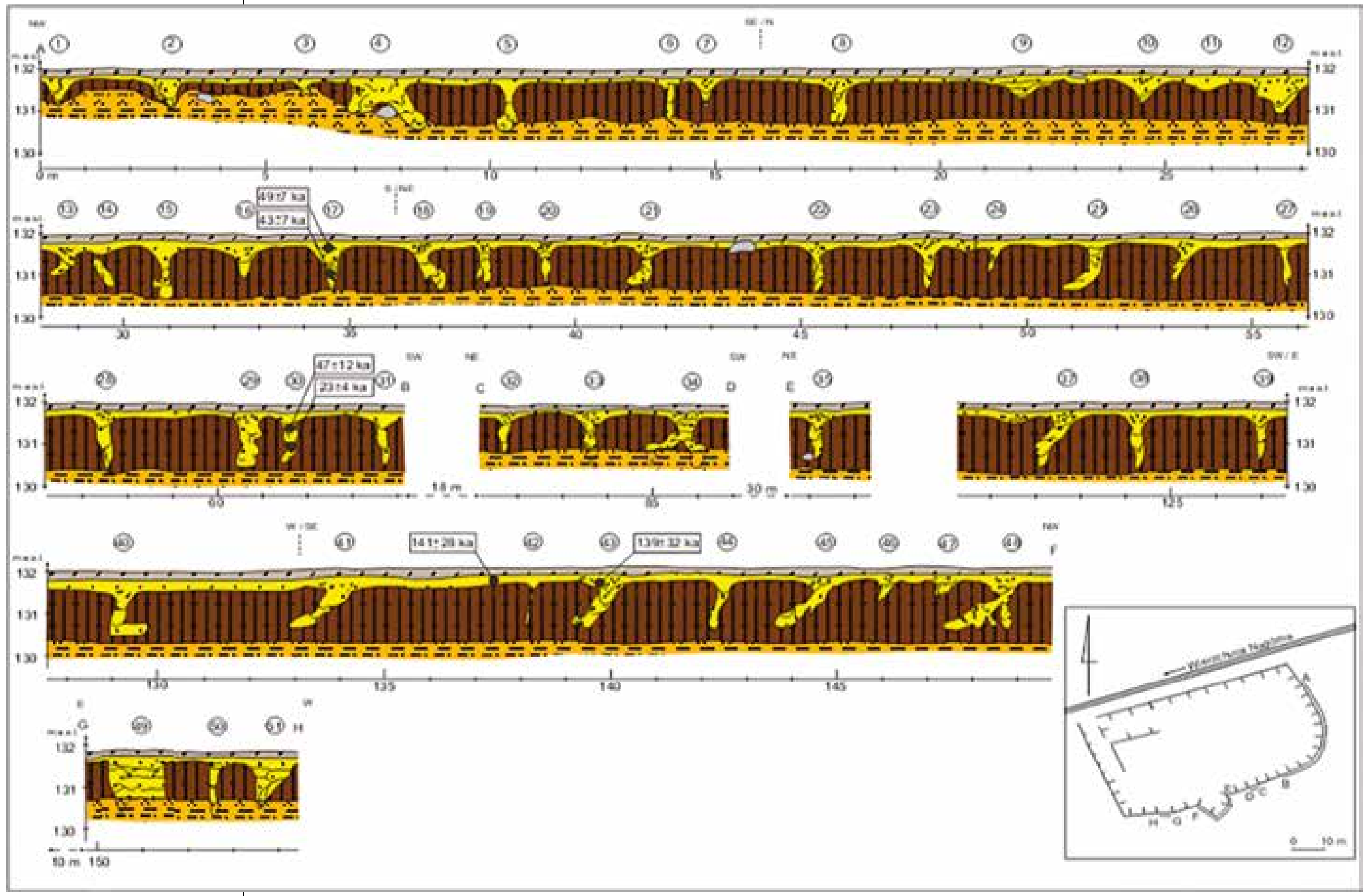


Pleistocene ice wedge pseudomorphosis in Wierzchuca Nagórna, eastern Poland, according to Dzierżek, Stańczuk 2006.

ter – this is mainly due to water freezing. In natural conditions, this process causes the destruction of rock masses, gradually turning massive rocks into rubble. Parts of these rocks reach the surface of the glaciers and travel along with them further.

A careful observer knows that when water freezes in a puddle, it leaves an empty space at the bottom of the puddle. This is because the surface of the puddle freezes first (the air temperature being lower than the ground temperature), and the ice freely expands upwards where the pressure is lowest. The same thing happens to water that is trapped inside the ground. When it freezes it pushes the surface up. In heterogeneous soils, individual elements react differently. In the following ablation season the ground does not return to its original form, because the empty space created during the rising of the ground sucks in the water from the lower parts of the ground, bringing in small particles that fill up the empty space. The process is repeated every year. As a result of significant temperature drops (−20°C), the ground ice shrinks, causing the soil to crack. Contraction cracks form, often taking the shape of characteristic polygons and grids. Snow, or the water formed when it melts, falls in these cracks and freezes there, creating the beginning of a ground ice megastructure, which grows over the following seasons.

The repetitive freezing and thawing process of the active permafrost layer results in effective segregation of inhomogeneous soils in the form of debris rings and polygons (*patterned ground*), often resembling a network of frost cracks. Often, the water flowing in from deeper layers causes such a large increase of ice under the surface that it creates large (even as high as 100 m) hills with an ice nucleus, cutely dubbed "pingos." The slow movement of the surface layer of sediments due to the thawing of the ground (solifluction) is a basic slope-forming process in permafrost areas. This causes the formation of striped soils, terraces and tongues, types of debris flow, etc. As a result of the impact of the thermal surface water on the frozen ground (thermokarst), picturesque "alas lakes" are created on the tundra. The phenomena described above are characteristic of the periglacial zone – in the immediate and near proximity of glaciated areas.

Ice in the Earth's history

Throughout its history, the Earth has witnessed repeated expansion of mountain and continental glaciers. Ice first revealed its strength during the Proterozoic era, about 2.2–2.7 billion years ago. During the Cryogen era (635–720 million years ago) the entire Earth was most likely covered by a continental glacier, turning the Earth into a giant snowball. Traces of this glacial activity include metamorphosed glacial sediments (tillites), ice scratches on rock surfaces, and the so-called *dropstones* (rocks dropped down from melted icebergs into the muddy seabed). From our European point of view, the last ice age, the Pleistocene (from 11,700 back to 2.6 million years ago) is much more important. As a result of deteriorating climatic conditions at that time, major shifts of continental glaciers occurred from Scandinavia to areas of the Northern Hemisphere. The currently known periods of seven Pleistocene glaciations were separated by shorter interglacial periods with a climate similar to today's. The oldest transgression took place around 900,000–930,000 years ago during the Nida glaciation, correlating with the Marine Isotope Stage 22. The continental glacier covered the entire northern and central part of Poland, reaching the Moravian Gate and the western frontier of the Carpathian Mountains. During the next transgression (glaciation of San 1), the Scandinavian continental glacier covered most of Poland. It reached the Sudetes and the Carpathian Mountains, forcing its way with its powerful tongues into the river valleys open to the north. Its marginal part reached the main ranges of the Świętokrzyskie Mountains and the Polish Jura Chain, which formed extensive nunataks. During the last glaciation era (Vistulian), the continental glacier covered a large area of northern Poland, and in the central Vistula valley it formed a reservoir lake, called the Warsaw Ice-Dammed Lake.

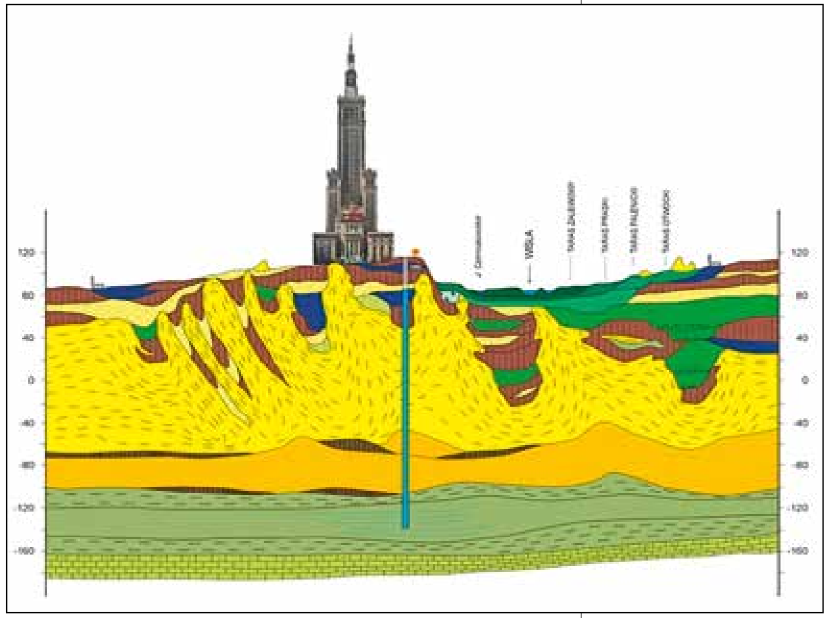
A cold future

Pleistocene glaciers left a lasting mark on the geological shape and structure of Poland and in the large part of the northern hemisphere. The power of the continental and mountain glaciers can be seen in both erosive and accumulation processes. Thanks to glaciers, the Earth's high mountains today have strongly indented, U-shaped valleys, often suspended, deep glacial cirques, partially occupied by picturesque lakes, terminal moraine shafts, sharp peaks, and scree fields. The evidence of the presence of continental ice sheets is extremely spectacular and widespread. Glacitectonic disturbances, such as shifting the original position of the layers as a result of the significant glacier load, are often observed in the sediments in the Pleistocene glaciation areas. Sometimes they are several hundred meters deep. Rarely do we realize that post-glacial settlements contributed to the formation of nearly 75% of Poland's surface, and their thickness in extreme cases (such as in the area of Dylewska Mountain) exceeds 450 m. A mixture of silt, clay, sand, gravel, with an admixture of giant boulders (erratics) formed as a result of having been collected from the ground, transferred, restructured and deposited by a glacier is called glacial till (diamicton). Bundles of clay could have been detached from the bottom of the glacier and deposited during its transgression, or remained after the ice had melted. The clay contains information on the direction of movement, the place of origin and the age of glacial transgression. The clay forms the surface of post-glacial upland areas and dominates on the map of surface sediments in Poland. Surfaces formed from the deposits of older glaciations are generally leveled (denuded). Areas covered by the youngest glacier have a very diverse surface shape with large denivelations, thousands of lakes, and a multitude of glacial sculpture forms (eskers, kames, drumlins). The waters from the melting glacier brought huge amounts of sands and gravel to the frontier, creating vast areas of outwash plains.

The best way to understand the power of ice is to stand near a large erratic boulder, a fragment of a bedrock detached and carried by a continental glacier from the region of Scandinavia, or at the bottom of the Baltic Sea and transported over a long distance. The Trygław boulder in Western Pomerania, considered to be the largest erratic boulder in Poland, measures over 3 m in height and 50 m in circumference, and weighs about 2,000 tons.

The last ice age ended about 11,700 years ago and today, in the era of global warming, we are mainly talking about the shrinking of the cryosphere and the resulting threats. However, although it is difficult to believe, when studying the rhythm of climatic changes in the Pleistocene, we can see that the current interglacial period is slowly coming to an end. Does this mean that in the next few thousand years we can expect another ice age?

TEXT AND PHOTOS BY **JAN DZIERŻEK**



Glacitectonic disturbances below Warsaw streets (diagram), according to Dzierżek 2006.

Further reading:

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