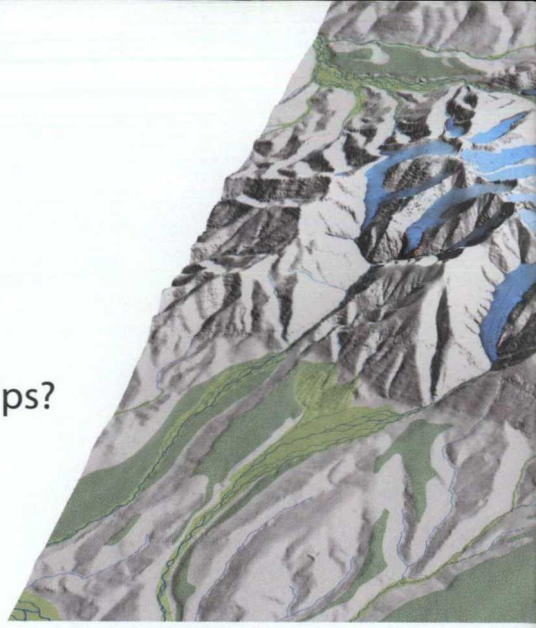

Were there glaciers in the Tatras? If so, what did the mountains look like back in the Ice Age? Perhaps similar to the Alps? To journey more than 20,000 years back in time and find answers to these questions, we have created the first 3D paleogeographic map of the Tatras.

Ancient Rivers of Ice

Dr. Jerzy Zasadni

AGH University of Science and Technology
jerzyzasadni@geol.agh.edu.pl

The author is a geologist working in the Department of Environmental Analyses, Cartography and Economic Geology at the AGH University of Science and Technology. He is engaged in the reconstruction and dating of the ranges of glaciers in the Alps and the Tatra Mountains.

In recent decades, climate change has become a major concern for humanity. However, in the longer term, on the scale of tens or hundreds of thousands of years, such climate shifts are not uncommon. Over the last 2.5 million years, during the Quaternary period, the world has seen repeated and cyclical growth and disappearance of large ice sheets covering the continents and smaller glaciers in mountains around the world. Various forms and sediments left behind by glaciers bear geological testimony to these processes. Most of Poland bears traces of a great ice sheet which pushed south from Scandinavia several times. In the highest parts of the Sudeten and Carpathian Mountains, which were outside the largest extent of this continental ice sheet, small local mountain glaciers developed. The most impressive set of mountain glaciation landforms and sediments is preserved in the Tatra Mountains.

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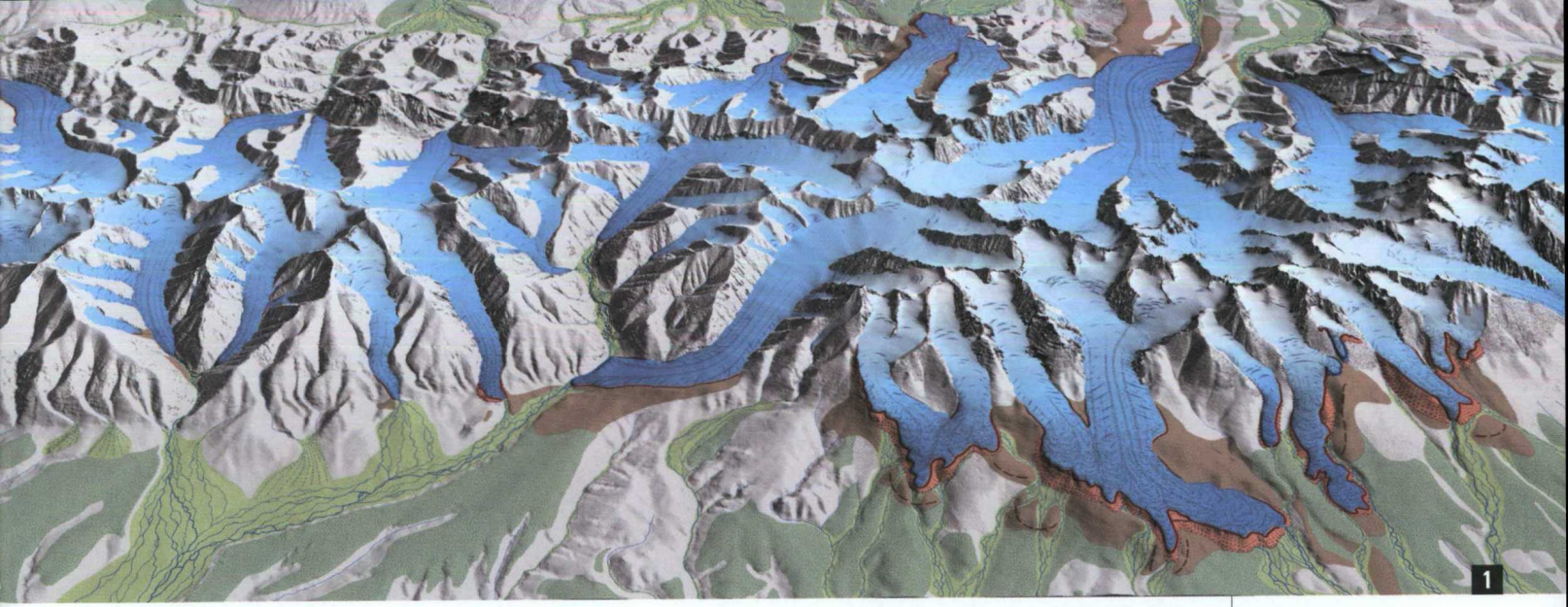
A glacier erodes its substratum ten times faster than a river. This is in part why the glacially sculpted forms that can be found in the Tatras are so extraordinary. There are sharp mountain crests, oversteepened rock walls, deep U-shaped valleys, and glacial cirques with overdeepening now filled with water as tarns. Terrain of this sort, called glacial alpine landform, does not appear in other Polish mountains. In terms of geology and landscape, the Tatras are said to be like miniature Alps, with one small exception – there are no modern glaciers. They disappeared from the Tatras at the beginning of the current interglacial, the Holocene, more than 10,000 years ago. Interestingly, we can suppose that the present-day "glacier free" conditions in the Tatra Mountains are more the exception rather than the rule over the last few hundred thousand years, which have largely been dominated by cold glacial climate.

The long tradition of glaciation research in the Tatras began with Ludwik Zejszner's discovery of the Pleistocene moraine of the Kuźnice glacier in 1856. However, despite a century and a half of research, accurately determining the number, extent and age of the Tatra glaciations is still a major research challenge.

Turning questions into a map

The problems largely stem from the nature of glacial processes, as the development of glaciers during each successive glaciation blurred or completely destroyed most of the evidence left by the previous one. Thus most of the landforms and glacial deposits that occur in the Tatras were formed during the



last ice age, which began approx. 115,000 and ended approx. 10,000 years ago. During this glaciation glaciers reached their largest extent more than 20,000 years ago, which we know thanks to cosmogenic-isotope dating of moraine boulders and glacially molded rock surfaces in the High Tatras. This was the peak of the last glaciation (known as the Last Glacial Maximum), 30,000-19,000 years ago, i.e. the period when large ice sheets and mountain glaciers reached their greatest extent globally.

What area was then occupied by the glaciers in the Tatras? How many glaciers were there? These are the questions the present author and Piotr Kłapyta from the Department of Geomorphology at the Institute of Geography and Spatial Management of the Jagiellonian University have been trying to answer for the past few years. Our work has culminated in a map showing the topography of the Tatra Mountains at that time, recognized as the best map published in 2014 by the *Journal of Maps*. It represents not only the range, but also a three-dimensional image of the glaciers along with the likely arrangement of structures on their surface, such as crevasses and medial moraines.

Our work was inspired by maps showing the vast ice cover in the Alps during the last glaciation. In the Alps, developing this kind of paleogeographic maps has a long tradition stretching back over 100 years. No such research had ever been undertaken for the Tatras.

Piecing together the past

A mountain glacier – in contrast to ice sheets, which reach much larger size – is constrained by the shape of the surrounding terrain. At the valley head, the glacier actively erodes the slopes to form oversteepening and rock walls called glacial trimlines. In the lower valley section, at the front and edges of the glacier, rock material is deposited in walls of latero-frontal moraines. We created our three-dimensional reconstruction of the Tatra glaciers based on observed glacial landforms and sediments collected during fieldwork. We also critically reviewed old geological and geomorphological maps using the latest remote sensing data. The next step was to interpolate the topographic surface of the glaciers, in line with known glaciological principles. The outcome is a three-dimensional digital model of the Tatras with glaciers. This means that, as well as producing the traditional "flat" map, we published the results of the study on YouTube in the form of a 3D-animated flight over the glaciated Tatras.

The map shows the layout of 55 glacial systems, stretching across an area of 280 km², which existed in the Tatras more than 20,000 years ago. The largest – the Białka Glacier – was 13.3 km long, over 400 meters thick, and covered an area of 43 km². This size cannot compare with modern largest glaciers in the Alps, such as Aletsch (25 km long and cover area of 87 km²), nor even less with the ancient Alps – during the Last Glacial Maximum a transection-type glacier there covered approx. 500 times more land than the total area of the Tatra glaciers. Indeed, the whole massif of the Tatra mountains with glaciers could be immersed in the ancient ice stream in the Inn valley, one of the largest in the Alps, which was 12 km wide and up to 2 km thick. This is due, of course, to the large difference in size and height of these mountain ranges, and therefore their topography, but it is also due to the climate. Today, the existence of glaciers in the Tatras is not possible, because the climactic snowline, or the height above which it is possible for them to form through the year-on-year accumulation of ice and snow, currently occurs at 2500-2700 m above sea level, which is above the highest peaks. Over 20,000 years ago, it was at an altitude of approx. 1500 m above sea level. However, this was not across the whole of the Tatra range, as there was a clear trend towards higher snowlines in the east. This indicates the significant influence of western atmospheric circulation and orographic induced precipitation during the glaciation – the glaciers located in the west received more precipitation than those in the east. The obtained paleoclimatic data are used for comparisons with contemporary conditions to identify the environmental changes that have occurred in this area over the past 20,000 years. ■

Photo 1:
The High Tatras during the last glaciation

Photo 2:
A virtual depiction of what the Białka glacier looked like