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# Dynamics of glacial and periglacial processes as evidence of global change

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## Abstract

Glacial and periglacial processes, their landforms, influences of cryogenic destruction, and repeated freezing and thawing effects in rocks and their weathered mantle are described. Main features and dynamics of present-day and former glacial and periglacial environments are presented as an evidence of significant global change of various landscapes in the Quaternary epoch. Dramatic changes in morphotectonic activity of lithospheric plates, sea level, properties of water and air masses, volume of cryosphere, and the types of landscapes in glacial–periglacial cycles during the Quaternary are emphasized. Knowledge of glacial and periglacial processes and landforms provides a background for understanding the present-day global change processes of the Earth.

**Key words:** global change, glacial processes, periglacial processes, Quaternary

## 1. Introduction

Glaciated landscapes together with the periglacial environment reflect one of the most extraordinary and sensitive features of our planet. The coexistence of liquid and frozen water on Earth's surface is evidence of the long-term equilibrium state of the biosphere on the timescale of hundreds of millions of years. Global change of glaciers and water masses in the history of Earth can also be understood as a testimony to the fragility of paleogeographical conditions for the evolution of life in the tiny space between extremely cold cosmic space and overheated stars without any traces of water vapor. This article describes glacial and periglacial processes, their landforms, influences of cryogenic destruction, and repeated freezing and thawing effects in rocks and their weathered mantle. Knowledge of the main features and dynamics of present-day and former glacial and periglacial environments is presented as evidence of significant global change of various landscapes in the Quaternary epoch (Kalvoda, 2004).

Glaciation of the Earth, and landforms that originated by the activities of frost, snow, ice, and glaciers, has been an outstanding feature of palaeogeographical history and a distinctive part of the environment that contributed to the evolution of life (Dawson, 1992; Williams et al., 1993). These qualities of glacial phenomena also apply to features and landforms that are produced by the intense freeze-thaw activity of water in rocks, their weathered near-surface mantle, and soils. The dynamics of glacial and periglacial processes are expressed on Earth's surface mainly in the distinctive features and diverse landscapes that originated recently or at various times during the Quaternary epoch. Description of glacial and periglacial processes and landforms thus provides a background to the endeavor to determine the course of Quaternary glaciations as one of the keys for understanding the present-day global change processes of the Earth.

## 2. Glaciations of the Earth in the Quaternary

Regions with large extension of glaciers were somewhat distant from the cultural centres where the fundaments of scientific thinking were created in the Middle Ages. Therefore, a description and quite correct climatic explanation of the origin of Iceland's glaciers by the Scandinavians in the second half of the thirteenth century fell into oblivion. Only in the eighteenth century – when European researchers began to investigate the Alps and some pioneer expeditions explored the polar regions – was the first systematic knowledge about glaciers and related phenomena collected (Anderson, Borns, 1994). The term "glacier" (Gletscher) was used by Petterman Etterlin of Luzern in 1507 and in the map of Raetische Alps by Aegidus Tschuldi in 1538. The first descriptions of mountain glaciers are in the papers of Sebastian Munster, Johan Stumpf, and Josias Simler. In 1780 Henri Benson measured the speed of glacier movement around Chamonix and again, in 1789, in the Pyrenees. Horace Bénédict de Saussure's long journeys and investigations in the Alps were the foundation of his extensive research into glaciers. Correlation of these studies with the experience of highlanders led, at the end of eighteenth century, to the opinion that glaciers in the Alps had in the past covered much more space than in the present. Attempts at reconstruction of the paleoenvironment of the Northern Hemisphere in the Quaternary began in the mid-nineteenth century (Embleton, King, 1975; Dreury, 1986), when J. L. R. Agassiz (1807–1873) interpreted crystalline tills and boulders (erratics) of a rock type different from the bedrock on which they are deposited as relics of an earlier huge continental glaciation of the northern part of Europe. He also traced these erratics to their source in Scandinavia and its neighboring polar regions.

Frequent changes in global climate in approximately the last two million years of Earth's history led to a succession of cold glacial and relatively warmer interglacial ages. Interdisciplinary studies of the pattern and timing of these variations in the past climates improve our understanding of the causes of significant and rapid paleoenvironmental changes on the Earth (Dawson, 1992; Williams et al., 1993). Weathering, mass vasting, and erosion have not had time to alter the landscape since the latest glaciations in the Quaternary. Evidence of former glacial erosion and deposition as well as periglacial processes on continents are still present as documents of Pleistocene glaciations. But evidence from studies of fossils found in deep-sea sediment cores suggest that there were more than 20 glacial stages that occurred during this epoch (Ehlers, 1996).

Periods of glaciations much earlier than the Quaternary are known from the geological record, mainly from preserved consolidated glacial deposits (tillites) and glacial striations. The earliest recognized glaciation was approximately 2.5 billion years ago and at least tens of other glaciations are recognized as having occurred during geological history (Deynoux et al., 1993). Significant evidence of the Precambrian ice shield is constituted by deposits of the Huronian Glaciation in Canada, consolidated to form glacial sediments more than 11 000 m thick, partly subaqueous in origin. Other distinctive evidence for Palaeozoic glaciations exists in Africa (centred on the South Pole circa 400 million years ago), Australia, Antarctica, southern India, North America, and Scotland. In the Mesozoic and early Tertiary periods, the global climate was warm and mostly dry, but at least 50 million years ago temperature decreases in deep oceanic waters and wetter climatic conditions on the continents are documented in the geological record. The Antarctic ice shield originated between 40 and 20 million years ago, gradually growing (with some periods of volume reduction) to its maximum size in the Pleistocene (Dowdeswell, 1987). The best example of the late Miocene to Quaternary glaciation in the polar regions of the Northern Hemisphere is the 5 km thick formation of glacimarine sediments of the Gulf of Alaska.

Variations in climate on the timescale of tens of millions of years on a continent were caused partly by the drifting of continental plates towards the poles or the equator. Moreover, orogenetic processes changed the relief of lithospheric plates via the uplift of mountainous regions to cooler air masses of the atmosphere (Eyles, 1993). However, it is thought that the causes of glacial ages on the Earth as a whole are controlled by astronomical and atmospheric factors related to the amount of solar radiation reaching the planet, and, therefore, to short-term variations in climate (Drewry, 1986; Oerlemans, 1989). We should recognize the combined effects of three astronomical factors: (a) variation in the eccentricity of Earth's orbit around the Sun with periods of ~100 000 y and 400 000 y, (b) variation in the tilt of Earth's axis with a period of ~41 000 y, and (c) variation in Earth's wobbles on its axis (precession) with a changing period ranging 19 000–23 000 y. Calculations of solar radiation curves at any latitudes for the past half million of years have shown that those in lower latitudes are driven by the 41 000 y tilt cycle and those in the higher latitudes by the precession cycle.

The variations in Earth's orbit are considered the timekeeper of the ice age rhythms. Moreover, the energy output from the Sun also may fluctuate, along with density, circulation, and composition of Earth's atmosphere and oceanic waters. Studying air bubbles in drill core samples of glacial ice in Greenland and Antarctica with an age of up to 300 000 y reveals (Benn, Evans, 1998) that during past glaciations the amount of dust in the atmosphere was higher (e.g., due to large volcanic eruptions or rapid wind erosion activity after extensive continental shelves emerging and recession of vegetation cover), and the concentration of global warming greenhouse gases (such as carbon dioxide ($CO_2$) and methane ($CO_4$)) was lower than during interglacial periods. During glacial periods much seawater was tied up in glaciers, and the sea level was therefore lower with the glaciated parts of continents depressed by the weight of ice. In contrast, during interglacial periods sea level was higher as a consequence of the ice melting and formerly glaciated land was uplifted due to removal of the ice. These glacio-isostatic movements resulted in subsidence and/or uplift of the Canadian and Scandinavian plates, including continental shelves, at a maximum rate of ~1 cm $y^{-1}$ (Menzies, 1996).

The dynamics of large continental and mountainous glaciers reflected a remarkable spectrum of rapid fluctuations in climate in the Quaternary. In the period of maximum extension, glaciers covered ~30% of Earth's land (more than $45 \times 10^6$ $km^2$) along with large parts of the northern oceans (Anderson, Borns, 1994; Gillespie, Molnar, 1995). During times of extensive Pleistocene glaciation, the Antarctic Ice Sheet in the Southern Hemisphere dominated, being fortified by the Patagonia Ice Cap and large mountain glaciers or ice caps in the Andes, New Zealand, Tasmania, and southern Africa, as well as in high mountains located near the equator. The largest continental glaciers in the Northern Hemisphere were the Cordilleran, Laurentide, Greenland, Scandinavian, and Siberian Ice Sheets, accompanied by a huge belt of glaciated high mountains and highlands of Asia, Europe, northern Africa, and Middle America (Hambrey, 1994; Ehlers, 1996). The area and volume of ice masses in the periods of maximum glaciations in the Pleistocene, which were essentially larger in comparison with their present-day geographical distribution, and the position of permanent snow line suggest that major reorganizations of the ocean–atmosphere–landscape system must be called upon to explain the nature of climatic and landform records, and other types of data.

The stratigraphical scheme of the Quaternary Era particularly emphasizes four main glacials and interglacials that were globally synchronized and satisfactorily confirmed by sedimentological, geomorphological, pedological, paleomagnetical, and radiometrical sets of data (Gale, Hoare, 1991; Warren, Croot, 1996). These glacial or interglacial stages are often indicated by different regional names. For example, the largest glaciation in the Pleistocene, which occurred during 300 000–140 000 BP, is marked as the Saalian in North European region and as Riss in the Alps. Similarly, Cromer and Elsterian continental stages (780 000–420 000 BP) in northern parts of Europe are supposed to be equivalent to the alpine Mindel glaciation. Among interglacials, the Eemian stage was very significant (140 000–115 000 BP, Riss/Würm interglacial in the Alps): during this stage the Greenland ice sheet may have completely disappeared (Lowe, Walker, 1997). The most distinctive of the earlier glaciated landscapes are the relics of the last Pleistocene glaciation (alpine Würm, north European Weichselian, and North American Wisconsinan glaciation), which began after the Eemian interglacial, culminated 20 000–18 000 BP, and terminated by the Younger Dryas stage at approximately 10 000 BP.

The correlation of many geological data bears witness to the time asymmetry of paleoclimatic changes during Pleistocene glaciations (Deynoux et al., 1993). Ice ages appear to have taken a long time to build up to maximum glaciation, but, after this very cold period, to have terminated abruptly in interglacial conditions in a few thousand years. Some of the changes to interglacial conditions in the last 200 000 y have occurred only on time scales of only $10^2$–$10^3$ y, during which temperatures increased ~5–7 °C (Oerlemans, 1989; Menzies, 1996). Large-scale reconstructions of oceanic and land environments in the Quaternary, due to the glacial–interglacial cycle of climatic changes, caused dramatic migrations or drastic adaptations of plants and animals and in some cases their extinction. For example, the extinction of genera of large mammals (mammoths, mastodons, giant beavers, etc.) at the end of the last Pleistocene glaciation was the result of the abrupt climatic and vegetation changes and, in some regions of Northern America, Europe, and Asia, also of predation by human hunters (Williams et al., 1993).

The Holocene, as the present interglacial, started by sudden climate shifts (Dansgaard–Oeschger events) during 12 000–11 500 BP, which were simultaneously recorded in the archives of ice core samples, loess deposits, or marine sediments across the northern hemisphere (Clark, 1988; Anderson, Borns, 1994). Warming at the end of the last glacial maximum in the Antarctic precedes evidence of significant warming from the Greenland ice cores. Recessions and termination of the main centers of ice sheets and mountain glaciers occurred in the Lower Holocene. Later there began a mild growth of ice masses (Neoglacial period) with very asynchronous advances of glaciers during 8000–3000 BP. One of reasons for these regional differences is that during the cold phase glaciers may advance in humid areas and may retreat in arid areas owing to low precipitation (Gillespie, Molnar, 1995). The most recent of the glacial stages in the Holocene, with distinctive geomorphological and biogeographical features and consequences, was the Little Ice Age between the late sixteenth century and the first decades of twentieth century.

The evidence of climatic fluctuations suggests a significant process of warming in the past century, which resulted in reduction of ice masses in polar latitudes and high mountain ranges. For example, Antarctica saw the origination of a new "oases," i.e., ice-free land in the frontal parts of the continental glacier. Areas of isolated nunatacs (individual mountains or large rock outcrops surrounded by glaciers) also significantly increased. Sea level is rising at ~1–2 mm $y^{-1}$, caused mainly by melting of glaciers and thermal expansion of ocean waters (Dowdeswell, 1987, Hambrey, 1994). A published analysis of climatic records indicates that the second half of twentieth century was the warmest period of the millennium in the Northern Hemisphere. During recent decades, there are indications of an increasingly strong correlation between the temperature trend and the influence of atmospheric $CO_2$. This trend can be understood to represent a higher impact of human actions compared with solar or volcanic influences (Smellie, Skilling, 1994). It might also constitute support for attempts to predict future global environmental change in the light of recent human-induced modifications of the climatic system. The present-day reduction of glaciers and the melting of permafrost are warning signals for humankind of the possible overheating of Earth's surface and biosphere.

### 3. Glacial processes and landforms

The transformation of snow into glacier ice is realized in areas where the rate of the snow's melting is lower than the rate of its accumulation. Fresh snow crystals are tiny hexagonal plates, stars, or needles, while glacier ice crystals range from millimeters to several tens of centimeters in size and are, in contrast, very irregularly shaped aggregates. Many years of snow packing and recrystallization in varied conditions of stress, temperature, and humidity result first in firn (with density 300–500 kg $m^{-3}$) and later in very compact and plastic glacier ice. The typical density of glacier ice is ~800 kg $m^{-3}$, rising to more than 900 kg $m^{-3}$ at greater depths in ice sheets (Paterson, 1994; Benn, Evans, 1998).

There are two broad categories of glacier masses primarily related to geographical extent and to the underlying topography: (a) ice sheets (continental glaciers, ice caps), and (b) mountain glaciers. Present-day glaciers occupy a total area of more than $15.8 \times 10^6$ $km^2$, with a volume of $\sim 33 \times 10^6$ $km^3$. The Antarctic ice sheets and those of Greenland contain about 98% of the world's glacier ice. The bedrock of Antarctica and Greenland is almost completely buried under ice sheets which have a mean thickness of over 2 000 m (Smellie, Skilling, 1994). In polar areas many glaciers terminate in the ocean, grounded on the shelf or even floating as tidewater glaciers with calving of icebergs (Dowdeswell, 1987). Mountain glaciers can be differentiated into many types, of which the valley glacier is the most distinctive relief-forming agent in high mountains (Photo 1). However, many other glacier shapes in the mountainous regions are described, mainly related to their relief and climate-morphogenetic positions. For example, summit, hanging, slope or cirque glaciers develop in the ridge parts while piedmont and outlet glaciers spread out in the large basins or at the foot of mountain ranges.

Mountain glaciers have very changeable mass balances and flows of ice, depending particularly on altitude, latitude, relief configuration, local climatic situation, and distance from oceans. Therefore, measurements of glacier flows range from 10 cm $d^{-1}$ to 25 m $d^{-1}$ (Paterson, 1994). Hanging and slope glaciers, in contrast to the major, slowly flowing main-valley and composite glaciers are very mobile. This situation can lead to sudden and even frequent advances of main glacier fronts, due to occasional excessive amounts of avalanche ice in catchment areas, or an abrupt decoupling of the glacier from its bed as the result of changes in the subglacial water flow system (Owen, Derbyshire, 1993; Goudie, Kalvoda, 2004, and others). A rapid advance of the glacier front may laterally dam the main river valley and, when a temporary ice or ice–stone dam is broken through, catastrophic floods may occur. These surging glaciers, which after a period of many years of quiescence develop a very rapid flow (up to several meters per hour), have been de-

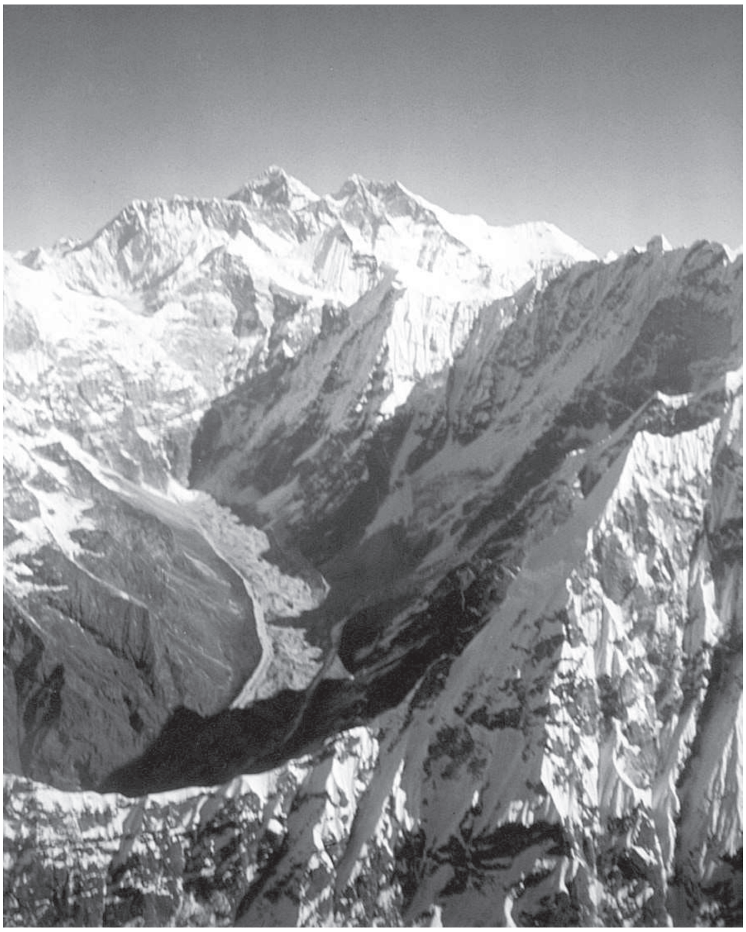

*Photo 1* Deeply denuded relief thrusts of crystalline rocks in the Nepal Himalaya evolved during the collision orogeny in the Late Cainozoic. Extremely dissected high-mountain landforms developed with distinctive prevalence of physical (e.g. cryogenic) weathering and glacial, nival and periglacial factors. They are consequence of a long-term integration of very dynamic morphotectonic as well as climate-morphogenetic processes. In the background, behind the Hunku ridges, is the Chomolongma Massif with Mount Everest (8848 m) and Lhotse (8501 m).

*Photo 2* The uppermost part of the broad accumulation basin of the Barun glacier northwest of the Chomo Lönzo (7790 m) is situated in the semi-arid and very cold region of the East Nepal Himalaya.

(Photos 1–8 by Jan Kalvoda)

scribed in Alaskan mountains and the Karakoram. Catastrophic glacier floods with outbursts up to 50 000 $m^3$ $s^{-1}$ occur after subglacial water drainage has been blocked by the internal plastic flow of ice, or after the rapid melting of glacier caused by volcanic activity. They are known by the Icelandic term jökulhaupts.

Glaciers very efficiently polish and abrade the bedrock floor, which is also usually disintegrated by frost weathering, meltwater activity and related geomorphic processes. Abraded rock material is slowly transported by glacier ice and accumulated into current frontal, basal, or side parts of the glaciated area. These phenomena and processes are the substance of the origin of the very diverse scale of glacial landforms (e.g. Embleton, King, 1975; Summerfield, 1991). Erosion of Earth's surface by glaciers combined with frost action is the most effective process of rock massif destruction. There are many variants of erosional landforms of glaciers, such as striations, rock polish, "roches moutonnées," rock drumlins, glacial grooves, cirques, U-shaped valleys, or fjords. The removed rocky material is transported by ice masses and deposited as moraines and related accumulation landforms of glacial origin. The exact erosion processes responsible for the evolution of such landforms in glacial environments depend on the type of ice masses movement (Gale, Hoare, 1991; Owen, Derbyshire, 1993, and others). Glaciers frozen to the ground at their base move by internal strain of the ice with relatively small erosional effects at the bottom (Photo 2). On the contrary, temperate glaciers are warm-based, near to the pressure melting point of ice, and therefore move along their base by sliding. Meltwater in fissures of the rock bottoms can freeze, which is the next step towards frost disintegration of near-surface rocks. The material is then transported as an active agent in the process of glacial abrasion.

The combination of the effects produced by layers of isothermal ice responsible for high sliding velocities, abundant subglacial meltwater and step bedrock slopes, produces strong erosion and gives rise to deeply denuded incised troughs and extensive rocky surfaces with "roches moutonnées" (Paterson, 1994; Warren, Croot, 1994). Rock polish and striations in size from millimeters to a few centimeters deep and wide indicate the local direction of ice movements by their long axis, which can be meters long. These small landforms are present in the landscape of former continental glaciation as well as mountain glaciation. The freshest of them are currently evolving at the bottom of present-day glaciers. Rock drumlins are stream-like hills selectively eroded by glacial action, from a hundred meters to several kilometers in length and from meters to hundred of meters high, which can be found in regions of continental glaciation.

The positions as well as shapes of the morainic material related to the glacier body are very diverse, and these depositional landforms are therefore variously described as ground, internal, lateral, middle, push, or terminal moraines. In general, the morainic landforms of continental glaciers are much larger than those of mountain glaciers, and from relics of these accumulations ground moraines in particular (e.g. in the form of streamlined ridges of drumlins) cover large regions of parts of continents that were glaciated in the Pleistocene.

*Photo 3* Slope and hanging glaciers on the alpine relief of the gneiss and granodiorite crests (6200–6800 m a. s. l.) significantly contribute to the amount of ice masses in the accumulation basin of a large valley glacier in the Hispar Karakoram.

In high mountain ranges, typical landforms produced by glacial erosion are cirques in the shape of large hollows, found in the head parts of glacial valleys as the most distinctive areas of snow and ice accumulation (Photo 3). Alpine-type relief represented by sharp peaks, horns, ridges, and U-shaped and hanging valleys is the result of effective complex activity of cryogenic and glacial modellation processes (e.g. Embleton, King, 1975; Kalvoda, 1992; Benn, Evans, 1998). Even on ridge parts of mountain ranges or stratovolcanoes in tropical regions, a set of glacial or periglacial landforms can be found. A historical-genetic analysis of a set of landforms, individual relief entities, and Quaternary mountain sediments testifies to an interaction of orogenic and climatic processes in the formation of the alpine-type relief of the mountain ranges, as well as to the distinctive vertical morphoclimatic zoning that gradually took place on the slopes of the rising mountain ranges

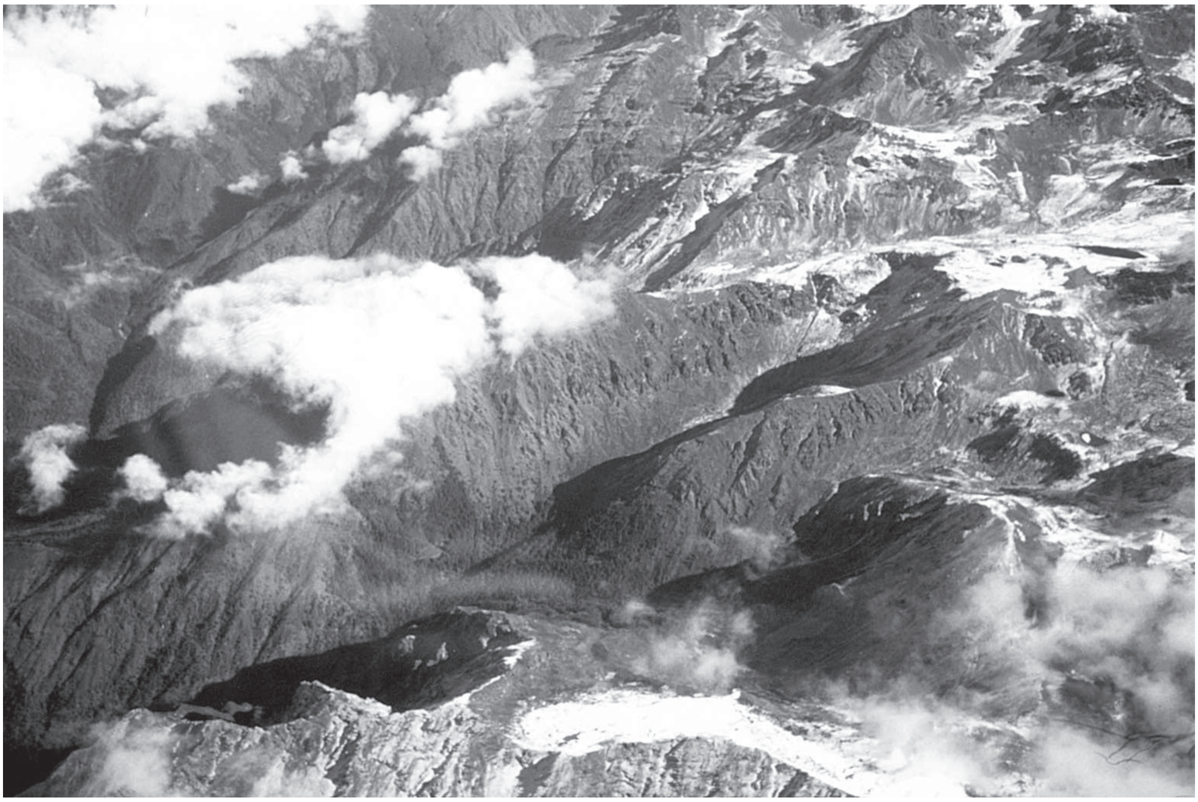

*Photo 4* The most effective geomorphological processes and related landforms changes are manifested in large regions of southern part of the Main Central Thrust. This very specific relief type of the Himalaya between 3800 and 5900 m a.s.l. resulted by combined and/or integrated activity of glacigenous and periglacial processes in the seasonally humid (monsoonal) and cold mountainous environment.

(Kalvoda, 1992). During the Quaternary, the width, position, and thickness of the glacier and the abrasive action of its ice masses were influenced – in addition to the effect of climatic agents – by tectonic activity, which affected the relief and the developing extreme dissection of individual mountain massifs. Therefore, the glaciers in the high mountains developed in a Pleistocene landscape (Photo 4) where tectonically stimulated erosion and denudation produced very deep, often canyon-shaped valleys. The deep entrenchment resulting from glacial action was further responsible for the steep rocky slopes susceptible to sliding and rockfalls in response to glacial unloading, frost riving, and earthquakes.

Valley glacier tongues are covered with a surface moraine, and the lateral detrital ridges of the recent glacier oscillations contain interlayers and lenses of dead ice. Ablation underneath a surface moraine at the glacier terminus is reduced to such a degree that ice completely fills the Subrecent morainic bed. The strong ablation resulting from the intense solar radiation and low relative humidity give rise to bizarre variants of “nieves penitents” on the surface of glacier tongues, leaflike and honeycomb structures, bolus-like ice forms and intermittent lakelets (e.g. Oerlemans, 1989; Kalvoda, 1992; Hambrey, 1994). Temperatures above 0 °C lead to rapid surface melting, and selective ice forms undergo deformation and disappear. Amongst surface-ablation phenomena, crevasses, labyrinths of corridors, galleries, and caves in the ice are found in places where ice movement is slow.

The variety and dissection of the landforms on the glaciers and permanent firn fields reflect the dynamics of the ice under the given relief and microclimatic conditions (Paterson, 1994). The most pronounced landforms of this type include ogives, the system of glacier crevasses, and individual glacier fissures, which all represent sculptural features of the glaciers. Mobile ice towers (called séracs) are striking in terms of their height (5–40 m) and volume. They occur at the position of faults where the dip of the eroded bedrock suddenly steepens. In the ablation part of glacier tongues, they become emphasized by the selective melting off and sublimation of ice (e.g. Kalvoda, 2004). On hanging glaciers and steep areas of snowfields, there develop large vertical and oblique firn and ice ribs carved out by the wind as well as obliquely wind-smoothed firn ice layers. The variants of small impermanent forms on the surfaces of the ice and snow masses (whose appearance and positions are controlled by their layering, plasticity, contamination by sand and dust, exposure to insolation, and prevailing wind currents) are very multiform. The maximum height range of surface features on high-mountain glaciers is 30–50 m, with an average of ~10–15 m, and the depth of vertical fissures in icefalls, often gaping down to the bedrock, can be as great as 50 m.

The former or recent destruction and accumulation landforms produced by continental glaciers are, in general, more widespread than glacial landforms in the mountains. This is mainly a consequence of the global cooling of Earth’s climate in the Pleistocene. Many of present-day large lake basins of North America and the northeastern part of Europe, along with the deep troughs of fjords in Norway, Alaska, Greenland, New Zealand, and Antarctica, originated by large-scale glacial erosion (Dawson, 1992; Deynoux et al., 1993). The depth of erosion in heavily glaciated regions in the Pleistocene is thought to range meters to tens of meters, with these very diverse depths depending on many features of glacial environment. The efficiency of subaerial weathering, combined with the effect of basal ice being maintained at its pressure-melting point in the lower reaches of the glacier, produces a load of predominantly supraglacial and englacial debris containing a large amount of talus.

## 4. Periglacial processes and landforms

Intense freeze–thaw activity of water is the basis of periglacial processes and landforms. The geographical space of the periglacial zone is represented by a broad foreland of glaciated subpolar or high-mountains regions (Embleton, King, 1975; Clark, 1988; Kalvoda, 2004). How much of Earth’s surface is covered by long-term accumulations of snow, firn, and ice depends above all on the course of the perpetual snow line. The estimation of this snow line and of its changes of course in the Quaternary has a number of very noticeable physical–geographical aspects.

*Photo 5* Continuous surface and huge lateral moraines (composed mainly by strongly weathered claystones, limestones and marbles) of the retreating Bualtar glacier tongue (4000–2800 m a.s.l.) in the periglacial zone north of the Malubiting Massif (7458 m) in the Karakoram.

The course of the perpetual snow line depends mainly on the amount of rainfall, on the temperature, and on the relative air humidity. The highest position of the perpetual snow line has been found within 6300–6600 m a.s.l. in semiarid area at the Monte Pissis (Llullailaco, Andes) and its lowest position in Arctic regions above lat. 76° N and in the Antarctic continent, where it is situated at the sea level (Oerlemans, 1989; Gillespie, Molnar, 1995). In regions with suitable conditions for forest habitation, landscapes between the present-day positions of the perpetual snow line and tree line can be understood as the principal area of the periglacial zone. The difference in height between these lines is the lowest in Patagonia (200–400 m) and largest in Tibet (above 2000 m).

The vertical hierarchy of variable high-mountain reliefs of the Earth is striking, e.g. from the extremely cold extraglacial ridges through the heavily glaciated and periglacial areas (Photo 5) to the seasonally cold/warm humid and/or semiarid valleys (comp. Kalvoda, 1992; Benn, Evans, 1998, and others). Distinctive vertical climatic zoning also influences variable features of morphostructural and lithologi-

*Photo 6* Late Quaternary glacifluvial and slope deposits reaching thicknesses of over 200 m near Nagar village (2500 m a.s.l.) in the Karakoram are situated above junction of the Hunza and Hispar valleys. In the background is eastern part of the Batura Massif (7980 m).

cal control of characteristic weathering phenomena (Photo 6). The extraglacial high-mountain and polar zones with a rock-cut landscape of alpine-type ridges and/or Antarctic and Arctic platforms or mountains displays a dynamic integration of deep weathering with major glacial and nival morphogenetic processes. Gentle lithological and fracture control of georelief on the crystalline rocks is suppressed in these areas and, on the contrary, its presence is conspicuous at lower lying large slopes and in the periglacial zone. The intensity and duration of temperatures below freezing point led to deep rock disintegration and macrogelivation. By contrast, shallow freeze-thaw cycles are effective for microgelivation.

In the foreland of the present-day glaciers, a system of glacifluvial, fluvial, and lacustrine accumulation landforms develops (Clark, 1988; Gale, Hoare, 1991). The moraines in the vicinity of the present-day glacier tongues are shaped by melting-out and slumping processes resulting in the characteristic appearance of large ridges along the flanks and cones in the center of the valley (comp. Photos 1 and 5), often with radially incised meltwater channels floored by torrential coarse gravels.

*Photo 7* Alpine-type relief with distinctive glacial and periglacial landforms originated on Palaeozoic crystalline rocks of the Gissar Range in the western Thyan Shan. Present-day relics of glaciers are protected only above 4500 m a.s.l. Strongly weathered crests or ridges and various slope sediments as a result of intensive periglacial processes are conspicuous.

The most complicated depositional sequences of glacigenous origin have occurred in the places where the fronts of glacier tongues or ice shields oscillated during advances and retreats in the Quaternary over a distance of only a few kilometers. Outwashed sediments of meltwater streams are well sorted according to grain size, laminated, and bedded. The type of internal structure of outwashed sediments and their landforms can generally be divided into glacilacustrine and glacifluvial deposits (Menzies, 1996; Benn, Evans, 1998). The glacial tills are coarse-grained and very poorly sorted. They constitute a continuous series from subglacial lodgement tills to supraglacial tongues.

The outwashed sediments also modify the glacial deposits by eluvation of clays and silts. Modification of the particle-size distribution of the glacigenous and glacifluvial sediment surfaces due to deflation is widespread, as is their desert varnish and weathering (Gale, Hoare, 1991; Owen, Derbyshire, 1993). Near moraines, glacifluvial sediments occur at several stratigraphic levels usually interlayered with tills. In the foreland of the glaciers where their advance and retreat alternated (comp. Photos 4 and 7), it is common to find a gradation from fluted tills and push moraines dissected by meltwater gravel trains to the present dead-ice area of the moraine. The dead ice is conserved both in the form of loaves and also as layers between supraglacial meltwater gravels. Redeposition of supraglacial debris by sliding is also common.

The outwash deposits of sub- and pro-glacial streams of continental or shield glaciers form wide plains known as sandur. Distinctive glacifluvial landforms in outwash plains after the recession of a glacier are kames, kettles, and eskers (Williams et al., 1993; Warren, Croot, 1994). Kames and kame terraces have been produced as relics of stratified drift in the channels of streams over the terminus of a glacier. Kettles or ice pits are depressions in till or outwash after the thawing of separated ice blocks. In subglacial tunnels, streams deposit eskers, which are long ridges of stratified sand and gravel. These eskers can be tens of meters high and kilometers long, forming very distinctive glacifluvial features, especially in landscapes that exhibited continental glaciation in the Pleistocene. In glacial lakes, gravel, sand, silts, and clays are deposited in horizontal layers with accumulation of finer grain size farther from the beach. Rhythmical seasonal changes of this glacilacustrine sedimentation (e.g. silts in summer and clays in winter periods) form varves series typical of periglacial environment.

The most distinctive of periglacial landforms are solifluction accumulations on slopes with a thawing layer of permafrost (perennially frozen ground), patterned ground in the shape of stone rings, polygonal soils, thufurs, stone debris and taluses, rock glaciers and pingos (comp. Clark, 1988; Lowe, Walker, 1997). Typical for permafrost are polygonal (subvertical) cracks initiated in the soil by contraction in the very cold periods. In thawing periods water flows into these cracks and it freezes again in winter increasing the size of the ice-filled cracks, which can be up to several meters deep in the shape of ice wedges. The arctic soils on seasonally thawing layers of permafrost are also closely related to grassland or other tundra vegetation. Solifluction is the downslope movement of moisture-saturated surficial material over substratum material during seasonal periods of surface thaw. Exposed rock surfaces that have been broken up by frost action are often shaped like hard rocky ridges and towers (Photos 7 and 8), or large block fields like a "sea of rocks" with a thickness of some meters in the form of angular shattered boulders.

In periglacial areas, mass-wasting processes are intensified and slopes are deeply denuded (e.g. Dawson, 1992; Kalvoda, Rosenfeld, 1998). Because permafrost inhibits underground drainage, thousands of shallow lakes can be seen on flat surfaces in warmer periods when the surface active layer of permafrost is thawing. New freezing of water to ice is displayed by the pushing up of circular mounds. Pingos are large ice-covered mounds that may be hundreds of meters in diameter and several tens of meters high. Very marked periglacial landforms are rock gla-

*Photo 8* Granodiorite ridges and deglaciated valleys of the alpine-type relief in central part of the High Tatras (2663 m, Slovakia) originated by a long-term intensive glacial and periglacial processes in the Pleistocene.

ciers that have been continuing in glacier basins, in glacier valley ends in high mountains, and in zones from which glaciers have retired but a cold climate still persists (Thorp, 1986, Clark, 1988). These rock glaciers are often tongue-like bodies with a distinctive flowage of rock debris cemented by interstitial ice indicated by wavelike ridges on its surface. This slow movement (meters per year) can be due to flowage of the interstitial ice or creeping by frost action.

### 5. Discussion

The geographical distribution of former and/or recent glacial and periglacial landforms or paleoclimatic records in the Quaternary sediments, soils, and glacier ice are, above all, remarkable evidence to help us better evaluate the meaning of the observed present-day geodynamic processes and phenomena on the geological time scale (Drewry, 1986; Dawson, 1992; Summerfield, 1991). The most conspicuous feature of former and present-day glacial and periglacial processes and landforms as a whole is their varied palaeogeographical distribution and vertical zonality (comp. Photos 2, 6 and 8). These natural processes and events influenced, in a fundamental way, the history of life in the last million years.

Many branches of science have been involved in the construction of Quaternary chronology based primarily on glacial fluctuations influencing geological, climatological, and biological phenomena. We may also include anthropology and history of humankind, because glacial and periglacial environments and their temporal and spatial changes deeply affected the evolution of humans (Williams et al., 1993; Lowe, Walker, 1997). The development of the genus Homo was undoubtedly strongly influenced by these global changes of the paleoenvironments. The African species Homo habilis and the younger Homo erectus, which occurred also in Europe and Asia, lived in the late Pliocene and/or early Pleistocene in a temperate climate and favorable landscapes. But our probable predecessors, Homo sapiens, had to be adapted in the Pleistocene to very dynamic environments of the Northern Hemisphere, where temperate and humid periods with optimal vegetation conditions were transformed into rough periglacial landscapes, e.g. with tundra vegetation, in large regions around continental and mountain glaciers.

The main features of recent landform changes in the polar and high-mountain regions are (Kalvoda et al., 2004): 1) extraglacial zone: extensive weathering of rocks in a very cold and semiarid environment, frequent avalanches and rockfalls, rapid wind erosion, stagnation of volume of ice and snow masses, 2) glacial zone: recent regression of glaciers and rapid decrease in their volumes, spreading of the periglacial zone to the detriment of lower areas of the extremely cold extraglacial region, 3) periglacial zone: rapid erosion of rock massifs and Quaternary sediments and/or accumulation landforms, very frequent slope movements of various types and magnitude.

The geomorphological observations on a decade scale suggest that the frequency and magnitude of recent landform changes in the polar and high-mountain regions are increasing from a very cold and dry extraglacial zone across a large periglacial area up to subtropical landscape with humid climatic conditions (Oerlemans, 1989; Gillespie, Molnar, 1995; Menzies, 1996; Kalvoda et al., 2004). Dynamic changes of landscape pattern are controlled and/or accompanied by rapid endogenic and exogenic geomorphological processes and events, which are an important evidence of the present-day severe natural hazards. The dynamics of recent geomorphological processes in vertical climate-morphogenetic zones of dissected reliefs in the mountains also shows that glacial, nival and cryogenic processes are very effective at destroying the rock massif uplifted during orogeny (Eyles, 1993; Goudie, Kalvoda, 2004). Rapid unroofing and exhumation of deeper parts of the rock massifs needs also vigorous transport agencies (comp. Photos 3 and 5), e.g. transgression of glaciers and intensive activity of winds in extraglacial and glacial zones and/or rapid action of water in periglacial and seasonally cold/warm zones.

Observations suggest a significant feedback between the rate of tectonic exhumation of deep rocks and the high intensity of recent glacial and periglacial denudation and transport of weathered and eroded material (Dawson, 1992; Lowe, Walker, 1997; Kalvoda, 2004). Climate fluctuations in extraglacial, glacial and periglacial morphogenetic zones of polar and mountainous regions determine the short-term and rapid geomorphic response of the landscape. The effectiveness of weathering and transport of its products also increases with the frequency of alternations of glacial, periglacial and fluvial processes during the paleogeographical evolution of these sensitive natural regions.

The observed recent landform changes confirm the high intensity of climate-driven morphogenetic processes, especially with very effective erosion and transport of weathered material in humid periglacial and seasonally warm regions. This phenomenon is in a striking contrast to the relatively small range of denudation and transport of weathered material in the cold arid and semi-arid climatic zones (Ehlers, 1996; Goudie, Kalvoda, 2004). The paleogeographical consequence of these long-term differences is conspicuously deep penetration of erosion and denudation to rock massifs in regions with the influence of humid air masses. The distinctive activity of these climate-driven morphogenetic processes in large regions of mountains as well as platforms of all continents also stimulated an isostatic contribution to the uplift. The recent rapid retreat of the glaciers in polar and mountainous regions is accompanied by a distinctive increasing of the active periglacial zone which is a dominant phenomenon of the present-day changes of landform patterns (Gillespie, Molnar, 1995; Kalvoda, Rosenfeld, 1998). It raises not only the volume of transported products of denudation, but in this rugged landscape also the level of geomorphological hazards, including frequent rapid events of mass movements triggered by earthquakes, avalanches, flash floods and landslides.

## 6. Conclusions

Research into the dynamics of glacial and periglacial processes in the Quaternary and prediction of their trends in the near future is fundamental to ensuring humankind's survival on the Earth. Monitoring of the main features and changes of glacial and periglacial environments has many facets that are valuable for everyday life as well as for understanding the global change of our planet (Clark, 1988; Summerfield, 1991). Glaciers are freshwater resources, their ice masses subdue extreme climatic events, and cryogenic and periglacial processes affect slope movements, soil formation, and the degree of hazards at construction and operation of large engineering works.

During the Quaternary, landform-shaping processes became strongly influenced by global cooling, oscillations of air temperature, and changes of humidity. Basic necessity in global change research is the present-day monitoring of key variables, such as the snow line, glacier mass balance, or morphotectonic activity, each of which varies over distinct spatial and temporal scales (Drewry, 1986; Eyles, 1993). Another exciting endeavor is research into extraterrestrial glaciation on Mars, Europa, and the other planetary bodies of the Solar System. These aspects of the study of glacial and periglacial environments are also reasons why glaciated polar regions, high-mountain ranges, and their neighboring areas are acting as a laboratory, in which multiple and dynamic natural processes play out in the kind of extreme conditions.

By analogy with landforms on the Earth, it has recently been possible to detect not only the existence of permanent (mainly $CO_2$) ice caps in the extreme cold and arid environment of Martian polar regions, but also the probable occurrence of fluvial and glacial landforms that originated during the past history of this planet. The interpretation of photographic records from Viking spacecraft missions has led to possible detection of landforms similar to cirques, moraines, outflow channels, esker and kame topography, and other stream-like residuals known from the Earth. Improving technological capabilities will allow us in the near future to answer a set of questions connected with the possibility that relics of multiple past glaciations and also fluvial erosion exist on the surface of Mars.

Theoretical models of the history of the remodellation of Earth's surface by glaciers, snow and ice, and related agents are supplemented by the results of measurements and other data about the course of geodynamic processes. The models are tested and confronted with observations of nature, especially on the time scales from $10^2$ to $10^6$ years, which are indispensable for the prognosis of main features of the dynamics of geosystems in the near future. Dramatic changes in morphotectonic activity of lithospheric plates, sea level, properties of water and air masses, volume of cryosphere, and the types of landscapes in glacial–periglacial cycles during the Quaternary have been discovered. These confirm how diverse the global changes of Earth's environmental system have been and how fragile is the shell of the biosphere in the Solar system.

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## References

ANDERSON, B. G., BORNS, H. W. (1994): The Ice Age World: An Introduction to Quaternary History and Research with Emphasis on North America and Northern Europe during the Last 2.5 Million Years. Scandinavian University Press, Oslo.

BENN, I. D., EVANS, D. J. A. (1998): Glaciers and Glaciation. Arnold, London.

CLARK, M. J. (Ed., 1988): Advances in Periglacial Geomorphology. Wiley, Chichester.

DAWSON, A. G. (1992): Ice Age Earth: Late Quaternary Geology and Climate. Routledge, London.

DEYNOUX, M., MILLER, J. M. G., DOMACK, E. W., EYLES, N., FAIRCHILD, I. J., YOUNG, G. M. (Eds., 1993): Earth's Glacial Record. Cambridge University Press, Cambridge.

DOWDESWELL, J. A. (1987): Process of glacimarine sedimentation. Progress in Physical Geography 11 (1), 52–90.

DREWRY, D. J. (1986): Glacial Geologic Processes. Arnold, London and Baltimore.

EHLERS, J. (1996): Quaternary and Glacial Geology. Wiley, Chichester.

EMBLETON, C., KING, C. A. M. (1975): Glacial and Periglacial Geomorphology. Arnold, London.

EYLES, N. (1993): Earth's glacial record and its tectonic setting. Earth Science Reviews 35, 1–248.

GALE, S. J., HOARE, P. G. (1991): Quaternary Sediments: Petrographic Methods for the Study of Unlithified Rocks. Belhaven, London.

GILLESPIE, A., MOLNAR, P. (1995): Asynchronous maximum advances of mountain and continental glaciers. Reviews of Geophysics 33, 311–364.

GOUDIE, A. S., KALVODA, J. (2004): Recent geomorphological processes in the Nagar region, Hunza Karakoram. Acta Universitatis Carolinae, Geographica, XXXIX (1), 135–148.

HAMBREY, M. J. (1994): Glacial Environments, UCL Press, London.

KALVODA, J. (1992): Geomorphological Record of the Quaternary Orogeny in the Himalaya and the Karakoram. In: Development in Earth Surface Processes, 3, Elsevier, Amsterdam.

KALVODA, J. (2004): Glacial and periglacial landforms and processes. In: Earth System: History and Natural Variability (Ed. V. Cílek), in: Encyclopedia of Life Support Systems (EOLSS), UNESCO, Eolss Publishers Oxford. (http://www.eolss.net)

KALVODA, J., ROSENFELD, Ch. (Eds., 1998): Geomorphological Hazards in High Mountain Areas. The GeoJournal Library, Vol. 46, Kluwer Academic Publishers. Dordrecht, Boston, London.

KALVODA, J., KOŠLER, J., SVOJTKA, M. (2004): Morphotectonic evidence for chronodynamics of uplift in the East Nepal Himalaya. Acta Universitatis Carolinae, Geographica, XXXIX (1), 149–162.

LOWE, J. J., WALKER, M. J. C. (1997): Reconstructing Quaternary Environments. Longman, Harlow.

MENZIES, J. (Ed., 1996): Glacial Environments. Vol. 1: Modern Glacial Environments: Processes, Dynamics and Sediments, Vol. 2: Past Glacial Environments: Sediments, Forms and Techniques. Butterworth–Heinemann, Oxford.

OERLEMANS, J. (Ed., 1989): Glacier Fluctuations and Climatic Change. Kluwer Academic Publishers, Dordrecht, Boston, London.

OWEN, L. A., DERBYSHIRE, E. (1993): Quaternary and Holocene intermontane basin sedimentation in the Karakoram Mountains. In: J. F. Shroder (Ed.): Himalaya to the Sea. Routledge, London, 108–131.

PATERSON, W. S. B. (1994): The Physics of Glaciers. Pergamon, Oxford.

SMELLIE, J. L., SKILLING, I. P. (1994): Products of subglacial volcanic eruptions under different ice thickness: two examples from Antarctica. Sedimentary Geology 91, 115–129.

SUMMERFIELD, M. (1991): Global Geomorphology. Longman, Harlow.

THORP, P. W. (1986): A mountain ice field of Loch Lemond Stadial age, western Grampians, Scotland. Boreas: An International Journal of Quaternary Geology 15(1), 83–97.

WARREN, W. P., CROOT, D. G. (Eds., 1994): Formation and Deformation of Glacial Deposits. Balkema, Rotterdam.

WILLIAMS, M. A. J., DUNKERLEY, D. L., DE DECKER, P., KERSHAW, A. P., STOKES, T. J. (1993): Quaternary Environments. Arnold, London.

## Résumé

### Dynamika glaciálních a periglaciálních procesů jako důkaz globálních změn

Glaciální a periglaciální prostředí jsou výjimečné a velmi citlivé přírodní systémy naší planety. V práci jsou popsány ledovce, glaciální tvary, kryogenní zvětrávání a efekty opakovaného mrznutí a tání vody v horninách a zvětralinovém plášti. Hlavní rysy a dynamika glaciálních a periglaciálních procesů jsou charakterizovány zejména v kontextu globálních změn přírodního prostředí v kvartéru. Výzkum dynamiky těchto procesů v mladším kenozoiku a prognózy jejího trendu jsou součástí poznávání globálních a regionálních změn životního prostředí v blízké budoucnosti. Glaciální procesy a jevy v polárních a vysokohorských oblastech Země jsou v současné době již systematicky porovnávány s aktuálními výsledky extraterestrických výzkumů přírodního prostředí Marsu a dalších těles sluneční soustavy.

Reliéfotvorné procesy v kvartéru byly podstatným způsobem ovlivněny globálními a regionálními změnami morfotektonických a klimatických procesů a jevů. Měření a monitoring jednotlivých faktorů současných glaciálních a periglaciálních procesů svědčí o variabilním průběhu jejich změn ve velmi různorodých prostorových a časových měřítkách. Tyto výzkumy jsou součástí vytváření a testování koncepčních modelů globálních změn přírodního prostředí. Studium geografického rozšíření reliktních a současných glaciálních a periglaciálních tvarů umožňuje poznání dynamiky morfotektonických a paleoklimatických procesů v neogénu a kvartéru, které se významně podílely na vývoji reliéfu a přírodního prostředí Země.