GLACIAL AND PERIGLACIAL LANDFORMS, PROCESSES AND ENVIRONMENTS

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Contents

Summary

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. For the understanding of glacial and periglacial processes on Earth's surface, this article describes glaciers and 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.

1. Introduction

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 (Figure 1) and a distinctive part of the environment that contributed to the evolution of life. 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. Our description of glacial and periglacial 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.

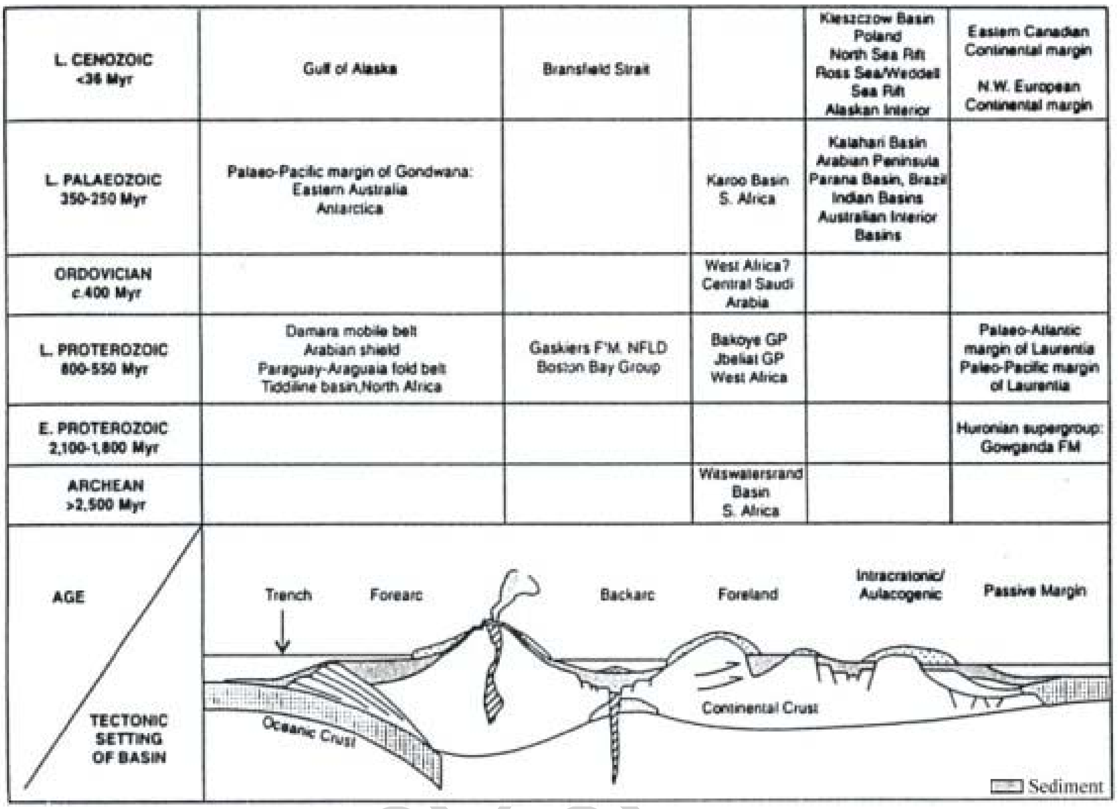

Figure 1. The tectonic setting of Earth's glacial record.Glacial successions are placed according to age and tectonic setting. (Note: in listings of geological ages, "Myr" indicates one million years.) (Redrawn and modified from Eyles N. (1993). Earth's glacial record and its tectonic setting. *Earth Science Reviews* **35**, 1–248.)

During the Quaternary, landform-shaping processes became strongly influenced by global cooling, oscillations of air temperature, and changes of humidity. Moreover, a 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. 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, mountain ranges, and their neighboring areas are acting as an inexhaustible laboratory, in which multiple and dynamic natural processes play out in the kind of extreme conditions beloved by researchers of the earth and life sciences.

2. Glaciers

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.

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 15.8×10^6 km^2, with a volume of ~33×10^6 km^3 (Table 1). 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 2000 m. In polar areas many glaciers terminate in the ocean, grounded on the shelf or even floating as tidewater glaciers with calving of icebergs (Figure 2). Mountain glaciers can be differentiated into many types, of which the valley glacier is the most distinctive relief-forming agent in high mountains. 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.

	Area (km^2)	**Volume (km^3)**
Antarctic	13 500 000	29 500 000
Arctic	2 100 000	3 200 000
Asia	114 000	220 000
North America	78 000	150 000
South America	25 000	48 000
Europe	9000	16 000
New Zealand	1000	1800
Africa	25	35
New Guinea	15	25
Total	15 827 040	33 135 860

Table 1. Area and approximate volume of the present-day glaciation of Earth

Mountain glaciers have very changeable mass balances and flows of ice (Figure 3), 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}. 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 (Figure 4), or an abrupt decoupling of the glacier from its bed as the result of changes in the subglacial water flow system. 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 described 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 (Figure 5). They are known by the Icelandic term jökulhaupts.

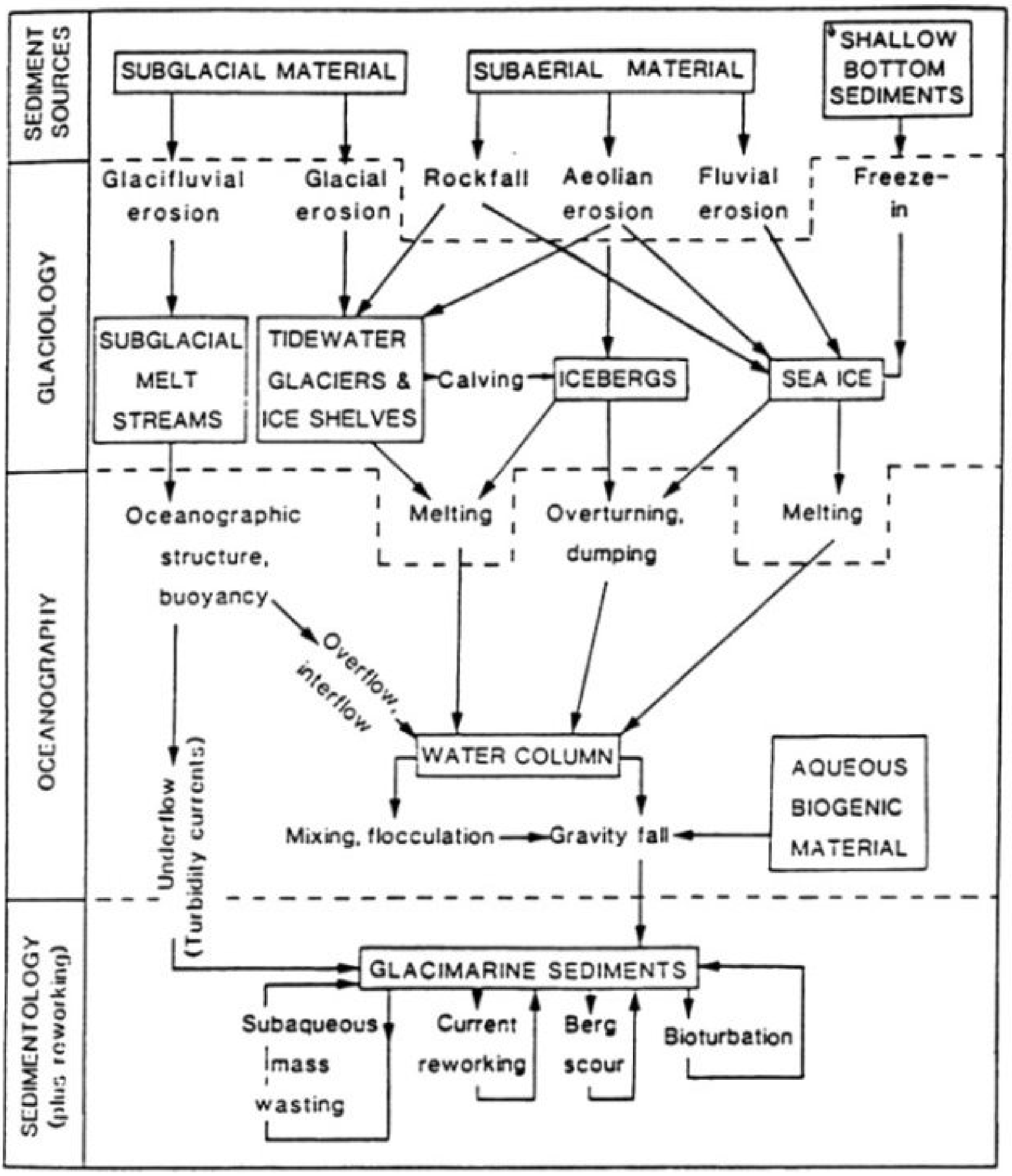

Figure 2: Model of the glacimarine sedimentary system illustrating the sediment sources, glaciological and oceanographic constraints, and subaqueous processes. Boxes represent sediment stores, and unboxed terms represent processes. (From Dowdeswell J.A. (1987). Process of glacimarine sedimentation. *Progress in Physical Geography* **11** (1), 52–90.)

Figure 3: Avalanche from the western wall of Distaghil Shar Massif (7885 m) in the Karakoram, which had a detachment area in the frontal part of a hanging glacier with a huge accumulation of fresh snow. (Photo Jan Kalvoda.)

Figure 4: The middle part of the Gharesa Valley, south of the Trivor Massif (7750 m) in the Karakoram, is completely covered with ice masses at 5000–5800 m asl (above sea level), which are also accumulated from slope and hanging glaciers of alpine-type relief. (Photo Jan Kalvoda.)

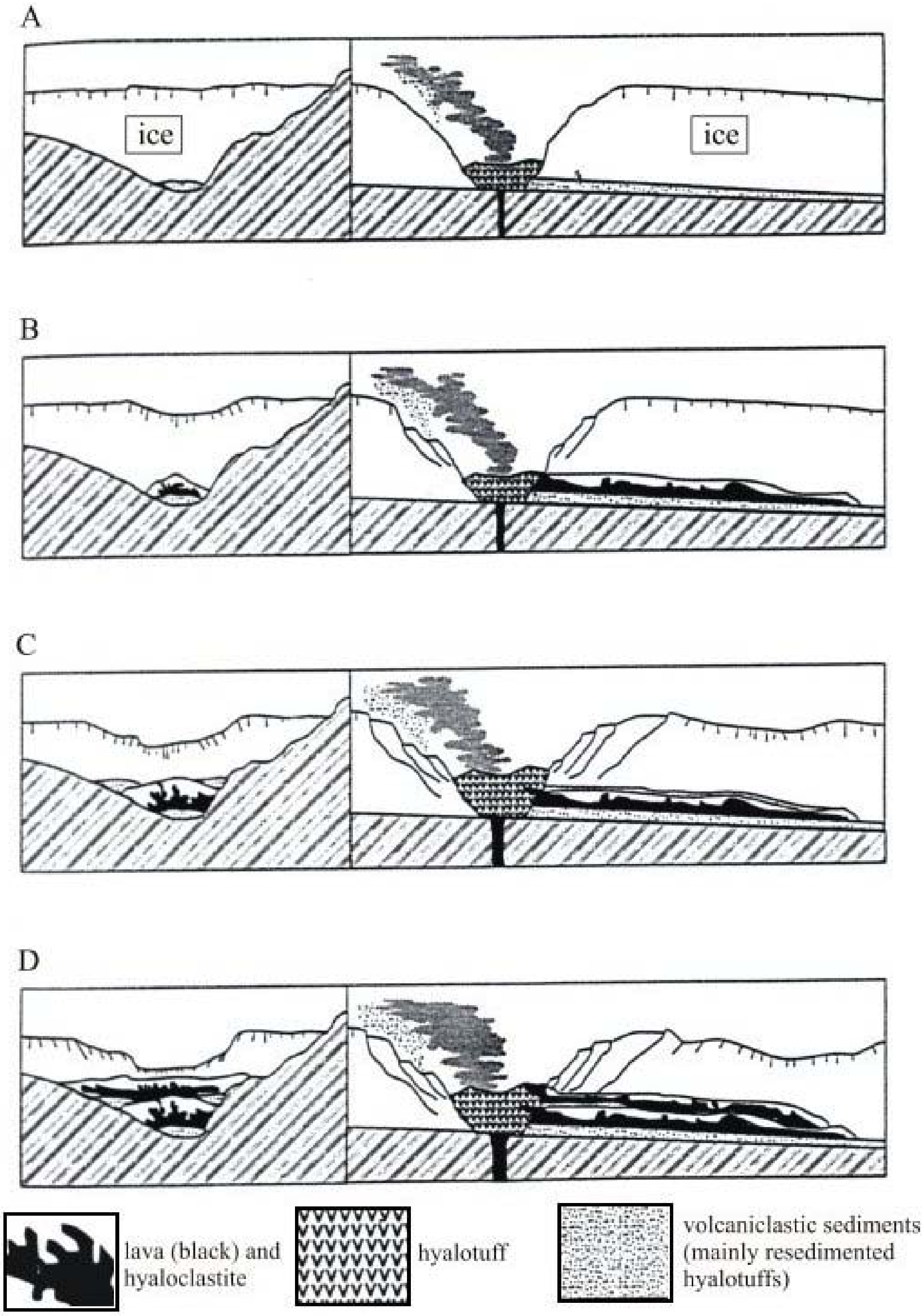

Figure 5: Example of interpretation of subglacial volcanic landform (toya) production. (A) and (C): flushing of volcanically heated meltwater; and (B) and (D) vitric tephra in a down-valley direction beneath the capping glacier is followed by lava effusion. The left and right sides of the figure are cross- and down-valley sections respectively.(From Smellie J.L. and Skilling I.P. (1994). Products of subglacial volcanic eruptions under different ice thicknesses: two examples from Antarctica. *Sedimentary Geology* **91**, 115–129.)

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. The most pronounced landforms of this type include ogives, "nieves penitentes," the main 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. 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 and often bizarre. The maximum height range of surface features on 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.

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.

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Biographical Sketch

Professor Jan Kalvoda, RNDr., Dr.Sc., Department of Physical Geography and Geoecology, Faculty of Science, Charles University in Prague.

Jan Kalvoda published a series of papers aimed especially at (a) relief evolution and recent geodynamics in the Bohemian Massif and the Carpathian System, and (b) geomorphological record of the Late Cainozoic orogeny in the Himalayas, Karakoram, and Pamirs. His current research activities are concentrated on: (a) glacial geomorphology and related phenomena in the Quaternary, (b) dynamic geomorphology of tectonic active zones, (c) geographical evidence of catastrophic natural hazards and present-day geodynamic processes with regard to their global change impacts on the environment, and (d) cosmology related to earth sciences.

Jan Kalvoda had been, before his arrival at the Faculty of Science, Charles University in Prague (1991) for about 20 years research worker of geological institutes of the Czechoslovak Academy of Sciences. He especially examined slope movements and other hazardeous geomorphological processes, morphotectonically active areas and Late Cainozoic landforms development in Central Europe, as well as in the Balkans, Asia Minor, Tian-Shan, Pamirs, Himalayas and Karakoram, very often in landscapes with an extreme dissected relief. In the period 1994–1997, Jan Kalvoda was Vice-dean of the Faculty of

Science at Charles University in Prague. He was member of the Scientific Boards of the University of Ostrava (1998–2001), the Charles University in Prague (2000–2003) and Department of Physical Geography and Geoecology (1997–2003). At present time, he is member of the Scientific Board of the Faculty of Science, Charles University in Prague, member of the Editorial Board of journal „Geomorphology“ (Elsevier) and member of the International Association of Geomorphologists.

Jan Kalvoda visited universities in Amsterdam (1991), Manchester (1993), Heidelberg (1995), and Jena (1996), and in France he was awarded by M.E.N.E.S.R. a Senior Scientific Fellowship (four months, in 1996) at the University Louis Pasteur, Strasbourg. In 1997 he spent four months at the University of Oxford as Visiting Research Fellow of the School of Geography, and in 1998 two months at the University of Cambridge as Visiting Research Fellow of the Department of Geography. Jan Kalvoda continued his research work at University Louis Pasteur in Strasbourg in September 2001 and the University of Oxford in summer 1999, 2001 and 2005, especially in theoretical physical geography and geomorphology.