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PERIGLACIAL GEOMORPHOLOGY. CONTINUED FASCINATION AND NEW PERSPECTIVES

Research on the geomorphology of circumpolar and high-mountain areas has a century-long tradition but presently also experiences a number of remarkable changes. Generations of scientists have been attracted by the beauty of remote periglacial ecosystems widely undisturbed by man. The fascination of scientific analogues with respect to Ice Age conditions in now warmer, densely populated areas constituted another excellent reason to explore the cold regions of the earth. Classical textbooks such as those by Ballantyne & Harris (1994), French (1996) and Washburn (1979) or the reviews by Clark, ed. (1988) and Dixon & Abrahams, eds. (1992) clearly illustrate the close relation between paleoclimatic reconstructions and research on present-day processes in arctic and alpine areas. World War II and subsequent years brought along a marked increase in the previously limited technological developments. The construction of entire settlements, military structures, pipelines, traffic connections, power generation schemes or tourist installations soon revealed the high vulnerability of cold environments, especially with respect to perennially frozen ground (Brown, 1997; cf. the circum-arctic permafrost map by Brown & *alii*, 1997). The proceedings of the International Permafrost Conferences (ICOP, 1966; 1973; 1978a; 1978b; 1984; 1988; 1993) contain a vast amount of literature on corresponding technological and environmental aspects (cf. also the bibliographies).

At the Fourth International Conference on Geomorphology thirty contributions covered a wide variety of topics on permafrost and periglacial environment, with considerable emphasis on alpine conditions. Thirteen of these were focussed on permafrost and related slope processes in temperate mountain areas (J.-M. Gardaz, R.Lugon & R. Delaloye; M. Guglielmin, G. Rossetti & C. Tellini; M. Guglielmin, C. Smiraglia & N. Cannone; A. Pancza; A. Ribolini; E. Reynard & L. Wenker; L. Schrott; C. Vannuzzo & M. Guglielmin) and in the Arctic (O. Humlum; A.G. Lewkowicz & J. Hartshorn; C. Harris & A.G. Lewkowicz; J.L. Sollid, I. Berthling, B. Etzelmuller & S. Saetre); ten contributions concerned present-day periglacial processes (I. Berthling, T. Eiken, B. Etzelmuller & J.L. Sollid; H. Christiansen Hvidtfeldt; S.W. Grab; K.J. Hall; S.A. Harris, C. Zhijiu & Cheng Guodong; N. Matsuoka; M.B. Potschin & H. Leser; A. Prick; N.N. Romanowski; E. Stocker); and seven regarded past periglacial landforms and deposits (J. Vandenberghe; K. Turkowska; J.C. Boelhouwers; S. Ginesu; M. Pappalardo; T. Oguchi; Y.K. Vasil'chuk & A.C. Vasil'chuk). Moreover, eighteen papers were presented at the Meeting on «Mountain Permafrost Monitoring and Mapping», held in Bormio on August 27, during the M-4 pre-Conference field trip (Dramis & Guglielmin, eds., in press).

During recent years, it has become clear that cold environments would be among the most heavily affected ecosystems with respect to ongoing and potentially accelerating atmospheric temperature rise. This fact creates a new situation in that questions about processes, signals and impacts relating to climate change in cold regions are being raised within the framework of international programmes and policy making. As examples of corresponding developments and requirements in the domain of periglacial geomorphology, global change aspects within the framework of world-wide monitoring programmes and of high-mountain research are briefly sketched in the following.

In high mountain areas, displacements of slope materials under periglacial conditions (rock falls, permafrost creep, solifluction and debris flows) have been observed and studied for decades. Renewed attention and remarka-

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ble progress can now be observed, however, for three main reasons:

1) advanced technologies including core drilling, borehole measurements, geophysical soundings, continuous datalogging under harsh field conditions, detailed laboratory experiments and sophisticated numerical modelling help building up a much more precise process understanding than hitherto possible;

2) full treatment of all involved scales in time and space, including impacts on and effects from thick, ice-bearing permafrost layers help recognizing processes and phenomena of rock destruction and slope stability not investigated before and relating to important environmental and hazard aspects in cold-climate mountain topography;

3) observed glacier shrinkage and permafrost warming/degradation at secular to decadal time scales leads to the recognition by a wide public of the growth tendency, recent activation and sensitivity of periglacial mountain belts as related to effects of atmospheric warming.

Slope stability aspects involve time and depth scales ranging from daily cycles to rnillennia and from centimeters to hundreds of meters (Dramis & *alii*, 1997). At daily and centimeter scales, surficial frost weathering by volume expansion and frost creep from pipkrake formation predominate. At the decimeter to meter scale, rock destruction, frost creep and gelifluction through ice segregation and subsequent thawing within seasonally frozen ground and permafrost active layers take place. At the scales of tens to hundreds of meters and decades to millennia, permafrost creep (rock glacier flow) and destabilization of large rock masses result. Mapping, monitoring and modelling are fundamentally important elements of scientific research on such processes (Haeberli, 1994), indicating sensitive areas and situations in complex topography, enabling improved understanding of the multiple interactions and feedback mechanisms related to freezing and thawing of ground materials on slopes, and establishing the data base for estimating impacts from potential future climate change scenarios on living conditions in cold mountain areas.

The challenge of new methods becoming available, technological aspects arising in delicate environments and global climate-related programmes starting now for the coming century call for modern concepts of periglacial geomorphology, *i.e* precise field experiments and numerical modelling of processes, materials, time and space rather than morphogenetic speculations and cumbersome terminologies. The replacement of the term «glacial ice» or «glacier ice» in rock glaciers and in arctic permafrost by more appropriate terms characterizing the material properties in question illustrates corresponding possibilities.

The «porridge-like» surface morphology generally attributed to the «rock glacier» phenomenon indicates viscous flow in materials which would have no cohesion in an unfrozen state. The obvious cause of this striking flow pattern is the ice which interconnects and to a certain degree even separates individual rock particles at depth. The characteristics and origin of such ground ice, however, are difficult to investigate. The idea that remains of «glacier ice» embedded within mountain permafrost can be easily recognized and defined from simple visual field inspection is a basic misconception. Various ice-forming processes can be involved. The variability over several orders of magnitude of the electrical DC resistivity measured in numerous cases all over the world indeed indicates that the origins of ground-ice occurrences in rock glaciers are complex; remains from real glaciers are rare exceptions and even in the few known cases exist within frozen ground (Haeberli & Vonder Muhll, 1996) - a necessary precondition for their long-term preservation. The term «glacier ice» or «glacial ice» should be used with caution for several reasons. The term «glacier», indeed, describes a morphological rather than genetic/petrographic phenomenon of perennial surface ice. Moreover, the definition of the term «glacier» is commonly based on (a) a minimum areal extent of about 0.1 to 0.2 km^2, and (b) the existence of crevasses as visible expressions of relatively rapid movement from a well-developed accumulation area to a zone of predominant surface ablation (ICSI(IAHS)/UNEP/UNESCO, 1989). As most rock glaciers have surface areas far below the km^2-range, the perennial surface ice-bodies sometimes connected to them are mainly perennial snowbanks or glacierets. The thickness of such quasi-static ice bodies is limited to a few meters and ice formation occurs through refreezing of soaked snow rather than through slow compaction of a thick firn body. The simple fact that the ground underneath such thin ice bodies cannot warm above 0°C in summer but cool far below 0°C in winter leaves no doubt that permafrost conditions are related to such ice patches. The correct discrimination between «glaciers» and «perennial snowbanks» or «glacierets» could easily terminate the seemingly endless discussion in the geomorphological literature about «glacial origins» of rock glaciers. It would open the field for much more promising studies on ground thermal conditions and material properties. Similarly, the recognition that basal parts of large ice sheets consist of debris-rich regelation ice from ground freezing (!) underneath the former ice sheet base could explain why the physico-chemical composition of massive ground ice in arctic permafrost areas formerly covered by Pleistocene ice sheets does not necessarily differ from the one observed in massive ground ice outside former ice sheet margins (Burn & Smith, 1993). Moreover, the existence of a till cover on top of such massive ground ice occurrences would be seen as a logical consequence brought along by the meltout of debris from the basal regelation layer after disappearance of the (clean) sedimentary ice of higher ice sheet parts, which formed at the surface of the accumulation area. These examples demonstrate that better integration of knowledge and experience from neighbouring disciplines, especially correct consideration of involved cryosphere components, is a necessity in view to deeper process understanding and climate change assessments.

There is now high confidence that many components of the cryosphere react sensitively to changes in atmospheric temperature because of their thermal proximity to melting conditions. The varying extent of glaciers has often been used as an indicator of past global temperatures and significantly influences sea level. In fact, obvious thinning, mass loss and retreat of mountain glaciers has taken place during the 20th century. Areal extent of Northern Hemisphere continental snow cover has decreased since 1987 even though there is much variability from year to year and no definitive long-term trends can be defined. Climate projections into the coming century indicate that there could be pronounced reductions in seasonal snow, permafrost and glaciers with a corresponding shift in landscape processes. Such a reduction would have significant impacts on related ecosystems, associated people and their livelihoods. The thickness of the active layer of permafrost could increase and extensive areas of discontinuous permafrost could disappear in both, continental and mountain areas. More water would be released from regions with extensive glaciers. Both engineering and agricultural practices would need to adjust to changes in snow, ice and permafrost distributions (Fitzharris & *alii*, 1995). International programmes for monitoring key variables of global change, therefore, contain a number of cryosphere components.

In 1992, the Global Climate Observing System (GCOS) was established by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC of UNESCO), the United Nations Environrnent Programme (UNEP) and the International Council of Scientific Unions (ICSU). This programme should make systematic and comprehensive global observations of the key variables available to nations to enable them to (1) detect and quantify seasonal and interannual climate change at the earliest possible time; (2) document natural climate variability and extreme climate events; (3) model, understand and predict climate variability and change; (4) assess the potential impact on ecosystems and socioeconomics; (5) develop strategies to diminish potentially-harmful effects and amplify beneficial ones; (6) provide services and applications to climate-sensitive sectors; and (7) support sustainable development. GCOS will take a comprehensive, integrated view of the requirements for all the climate system components, including the global atmosphere, the oceans, the biosphere, the hydrosphere, the cryosphere and the linkages among them. Such an integrated view is required to adequately interpret climate variability, as well as to determine anthropogenic climate change. Complementary to observations relating to the atmosphere and the ocean, the initial operational system includes land surface and ecosystems. Characteristics of the land surface and cryospheric elements are important for the climate system. Many of these variables are especially important for monitoring the impact of change, and for input into models for applications and national policy-making. A special Terrestrial Observation Panel for Climate (TOPC) has published version 2.0 of a plan for the Global Terrestrial Observing System (GTOS) and defined the minimum set of required variables for the biosphere, the hydrosphere and the cryosphere (Cihlar & *alii*, 1997).

Implementation of the cryosphere part within the GTOS plan should involve (1) continuation of existing monitoring programmes for snow, sea ice, glaciers and permafrost active layer, (2) further development of monitoring programmes for ice sheets, permafrost thermal state, temperatures in cold firn areas and lake/river ice, and (3) coordination of an integrated cryosphere monitoring programme possibly under the guidance of the International Commission on Snow and Ice (ICSI/IAHS) and the International Permafrost Association (IPA). Priorities with respect to initial implementation of monitoring cryosphere variables are being attributed according to climate relevance and feasibility, *i.e* already existing techniques and structures. The following cryosphere variables have been selected (sea ice is part of the ocean component of GCOS):

Cold firn areas (borehole temperature)
Glaciers and ice caps (mass balance, geometry)
Ice sheet geometry and surface balance
Lake and river freeze-up and break-up (timing)
Permafrost (active layer, thermal state)
Snow cover area and snow water equivalent

Frozen ground activity and subsurface temperature regime are two out of 27 internationally selected geoindicators of rapid environmental change. Efforts of the International Permafrost Association (IPA) with respect to long-term monitoring presently concentrate on the rescue of borehole temperature data, on Circumpolar Active Layer Monitoring (CALM, cf. Nelson & *alii*, 1996) and on mountain permafrost monitoring. First interesting results are already available. Interannual comparisons of thaw from within a site and among different sites within a region show significant season-to-season variations. Within a region, such as northern Alaska, seasonal extremes between some sites are similar. Although all sites are not using the same grid size and configuration, late summer mean thaw values within sites yield remarkabiy similar values. Argentina, USA, Canada, Norway, France, Germany, Switzerland, Austria, Italy, Russia, Kazakhstan, China and Japan are participating in an effort to map, model and monitor mountain permafrost. Data input to the Global Geocryological Database of IPA (GGD, Barry & Brennan, 1993, Barry & *alii*, 1995) is now going on. Permafrost temperatures at about 15m depth in the few presently existing boreholes appear to have increased in the European Alps, the Kazakh and Kirghiz Tien Shan and in the Qinghai-Tibet area but not in the Canadian Rockies. The establishment of a systematic borehole temperature monitoring network in Europe is planned within the new EU-PACE-project. Priority attribution for initial implementation of internationally co-ordinated monitoring programmes is based on the importance of the feed-backs involved with changes in active layer depth (CH_4 emission, soil moisture, growth conditions), practical apolications (stabilities of foundations for roads, pipelines, buildings etc.) and the existence of monitoring structures (CALM, PACE).

Periglacial geomorphology is an interdisciplinary research field in full development. Best use must now be made of the techniques, knowledge and understanding developed by the various specialists and disciplines involved in order to make appropriate contributions to our understanding of complex environmental systems interconnected at various scales of time and space.

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