An interdisciplinary programme on changes of the natural environment of Poland in the late Pleistocene and Holocene was launched and developed by Professor Leszek Starkel in the 1970s. It was affiliated to the INQUA framework. He brought together geomorphologists, palaeobotanists, Quaternary geologists, archaeologists, and others. The programme stimulated a number of interdisciplinary studies reported in a series of volumes on *Evolution of the Vistula River Valley During the Last 15,000 Years*, edited by the Professor.

One of the most spectacular and useful achievements of Leszek Starkel has been developing the concept, coordinating the preparation, and publishing an important monograph on *Geography of Poland. The Natural Environment* (in Polish), was published in 1991 (second edition in 1999). He also contributed several chapters to it. The book is still the most comprehensive presentation of knowledge on the natural environment of Poland.

In this short text it is impossible to list all or even the most important projects and publications written, initiated, created and edited by Professor Starkel. His major scientific interests and achievements have taken several directions. Besides those mentioned above, his research activity could be grouped in the following fields: Relief evolution of the Polish Carpathians. Palaeogeography of the Polish Carpathians, Poland, and Europe as a whole in the Holocene. Palaeohydrology of the late Quaternary, including the evolution of the river valleys during the last 15,000 years at different scales: Poland, the temperate zone, and the globe. Present-day geomorphic processes (especially the role of extreme events in the evolution of landscape in temperate and monsoonal zones, in the Darjeeling Himalayan and the Cherrapunji regions as examples). Latitudinal and vertical zonality of the geographical environment in the continental climate of Asia (with the Khangai Mts in Mongolia as an example).

Over more than the last four decades Professor Starkel has served on several geomorphological commissions of the International Geographical Union: the ones on Geomorphological Mapping, Periglacial Processes, Slope Evolution, Present-day Geomorphic Processes, and GERTEC. However, outside Poland he has chiefly been engaged in the work of the International Union for Quaternary Research (INQUA). In the years 1973–1981 he chaired the Euro-Siberian Subcommission of its Holocene Commission, after which he headed the Working Group on Human Impact on Soil Erosion from 1981 to 1988. In 1991 he founded the INQUA Commission on Global Continental Palaeohydrology, which he also chaired until 1995. He has also been engaged in the work of the Commissions on Palaeoclimate and Carbon Cycle.

To sum up the half-century of Professor Starkel's scholarly activities, he has attended more than a hundred international events in 37 countries, including seven IGU, nine INQUA and two geological congresses, and all five congresses of the International Association of Geomorphologists. At two of them he gave a plenary lecture. His field studies have brought him not only to such European countries as Romania, Bulgaria, Georgia and the Ukraine, but also to India, Mongolia and China in Asia.

Back at home, Professor Leszek Starkel has participated in developing the concept of the Integrated Monitoring of the Natural Environment; he has worked out the conception of monitoring catastrophic processes. A founding member of the Association of Polish Geomorphologists, he has always taken active part in its work.

His stimulating role in the formulation of new, original research topics at the national and international scales is well known and appreciated. As a co-ordinator of studies carried out under national geomorphological programmes, Professor Starkel has contributed to the development of the methodology of geomorphological research.

Professor Starkel still engages in the scientific life of Polish geographers and geomorphologists. On their behalf we would like to wish him further achievements enriching Polish geomorphology, and all the best in his private life.

*Andrzej Kostrzewski*
*Jacek Jania*

*Landform Analysis, Vol. 4: 7–15 (2003)*

# The problem of the identification of relict rock glaciers on sedimentological evidence

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***Abstract:*** In order to establish sedimentological criteria for the identification of relict rock glaciers, a study of published information about the internal structure of both active and relict rock glaciers has been carried out. The literature survey revealed that there is no single lithological feature which could independently serve as a proof of the decisive role of ground ice for the transport of rock debris. However, a sequence of a bouldery mantle and a core composed of diamict, together with a layering which dips steeply up-slope are the strongest premises for the elimination of any process other than that associated with a cold environment. Certainly, in attempting to distinguish between a moraine and relict rock glacier, the geomorphological setting must be taken into account and, notwithstanding this, an effective differentiation is often virtually impossible. Sedimentological parameters such as grain size distribution, sorting and grain morphology are largely controlled by the properties of the source rock and, as such, they are of no value in attempts to identify relict rock glaciers.

***Key words:*** sediments, ground ice, relict rock glaciers

## Introduction

The imprint of the Pleistocene periglacial environment in the Central Europe has been recognised since the beginning of the previous century. Usually, sedimentary structures were supposedly evidence of permafrost, whereas landforms typical of the periglacial environment are very scarce. Indeed, only two types of such landforms are known, i.e. remnants of pingo mounds and relict rock glaciers. There are very few examples of both and, in any case, inferences often have to be preceded by various restrictions.

Basically, there are two approaches to the definition of a rock glacier. The first, best represented perhaps by Martin and Whalley (1987) or Hamilton and Whalley (1995), assumes the morphology as the sufficient premise. Such an opinion, shared also by Humlum (1996), results from a conviction that there is a genetic continuum between a true glacier and a rock glacier and hence, no unambiguous limit between these two phenomena can be established.

The second approach is the genetic definition advocated by Haeberli (1985) and Barsch (1996), who both assume that a rock glacier is a landform which has resulted exclusively from creep in a permafrost environment.

The accepting of either the former or the later causes far-reaching divergences in interpretations. Complications arise from the fact that creeping permafrost does not always produce a landform which shows the relief typical of a rock glacier, whereas, by contrast, processes not necessarily connected with permafrost can be expressed as forms morphologically similar to rock glaciers (Fig. 1). The so-called "kurumogletchers", described from Siberia by Romanovskii *et al.* (1989), serve as an example of the former and the earthflows or "Bergsturzes" (Barsch, 1983, 1996; Whalley and Martin, 1992) may be regarded as a good example of the latter.

Having adopted such a morphological option, one is thereby released from the task trying to explain origin of a landform. However, in such a case, rock glaciers then lose any importance in

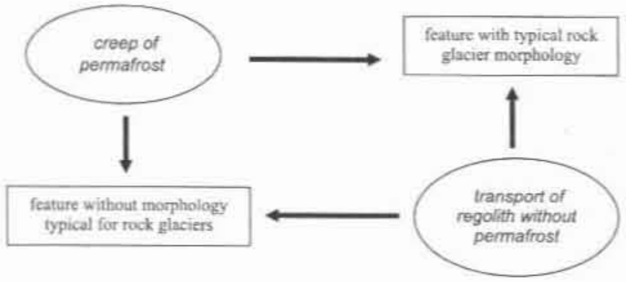


**Fig. 1.** A sketch showing why the identification of a rock glacier is difficult

environmental considerations (Johnson, 1983) and any palaeoclimatic interpretation of relict rock glaciers becomes impossible.

By contrast, such interpretations are valid in terms of the genetic Barsch-Haeberli's model. In such a case, the definition of "rock glacier" is uncomplicated and the landform *ex definitione* becomes strictly related to the climate (Haeberli, 1983; Barsch, 1996). In their terms, an active rock glacier is a "visible expression of steady-state creep of ice-supersaturated mountain permafrost bodies in unconsolidated materials" (Barsch, 1996, p. 4).

Nevertheless, the application of the genetic option leads, in turn, to an extremely complicated problem, both methodologically and methodically. As morphology itself cannot serve as unambiguous evidence of the decisive role of the interstitial ice in the development of a landform, the establishment of sedimentological features which are diagnostic of rock glaciers becomes necessary. Beyond dispute, investigations on active rock glaciers should serve as the base for such considerations, before they can realistically be applied to the sediments of relict landforms.

Unhappily, a review of literature shows that our knowledge about the internal structure of active rock glaciers, as derived from direct observations, is far incomplete. Valuable exceptions are papers by Fisch, Fisch and Haeberli (1977), Haeberli and Vonder Mühll (1996) and Elconin and LaChapelle (1997) who provide results of observations on large excavations.

Further, the situation is even worse with regard to relict rock glaciers, because almost no information based on direct observations is available. To a considerable extent, this is a reflection of the technical problems of exploration of deposits of relict rock glaciers and their almost complete lack of commercial value.

The main methodological difficulty is, that not only the presence of interstitial ice, but also the movement of a landform in the past, and – what is most difficult – the causal link between the ice content and the movement, requires to be proved. It is hardly surprising that a concise sedimentological model has yet to be proposed, one which permits the establishment of a set of features diagnostic of creeping permafrost.

An attempt to elaborate such a model should be preceded by a critical revision of the present-day knowledge about the sediments of active rock glaciers and, additionally, of the accessible information about the deposits of landforms which have previously been considered to be relict rock glaciers on geomorphological premises. Such a review is the aim of this paper. The deposits review has been arranged in order of the most important sedimentological features associated with these deposits.

## Sediments of rock glaciers

### Content of ice and water in active rock glaciers

Certainly, the amount of ice within the sediments of active rock glaciers must influence the form of possible sedimentary structures and their preservation within relict rock glaciers. According to the observations from many regions this varies considerably. The core drilling which has been carried out by Barsch (1977a) in the active rock glacier Murtel I in the Swiss Alps revealed layers of almost clear ice alternating with layers of ice which have a large content of sand and gravel. As estimated by Barsch (1977a), 50–60% of the volume of the rock glacier was ice. 25–30% of this was pore ice and further 30–35% were ice lenses, which were up to 30 cm thick. Similar values have been obtained by Barsch, Fierz and Haeberli (1979) from drilling in the Gruben rock glacier. The maximum thickness of an ice lens observed there was 30 cm and the estimated theoretical maximum was 60 cm. Moreover, a decrease of the ice content from 90% at the permafrost table to c. 60% several meters deeper has been demonstrated (Barsch, Fierz and Haeberli, 1979). By contrast, observations by Wayne (1981) from the Andes indicate that, in the periglacial rock glaciers, ice lenses up to 1 m thick may occur. Similar values of ground ice content are reported in many synthetic works about rock glaciers. For instance, Höllermann (1983) considered that a 40–70% ice content is typical for tongue-shaped rock glaciers. Gorbunov (1983) observed 50–70% of ice within the rock glaciers of Central Asia. On the basis of many observations, Barsch (1983, 1996) estimated the ice content within active rock glaciers to

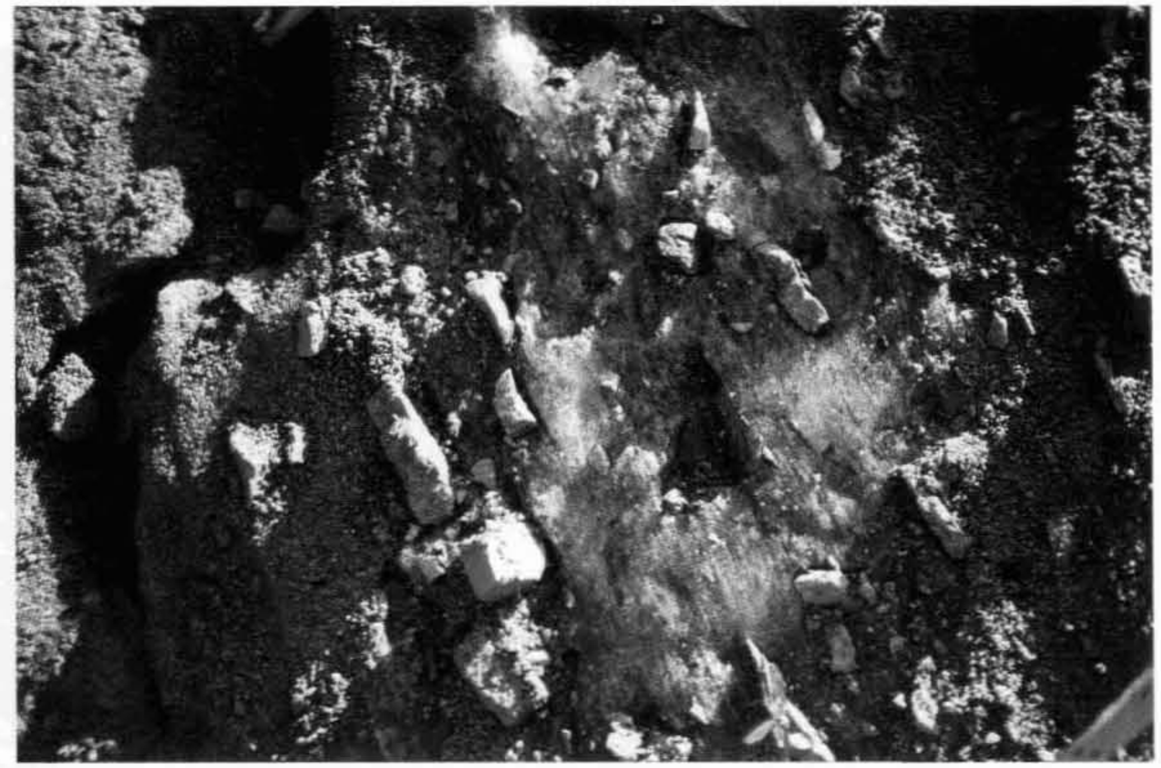

**Fig. 3.** Close-up of sediments of the active Fireweed Rock Glacier, Alaska. The sediments are exposed transverse to the flow direction and the profile is approx. 1 m in height. Distinct lamination and orientation of pebbles can be seen. Pocket knife for scale (Photo courtesy Roger Elconin, Anchorage)

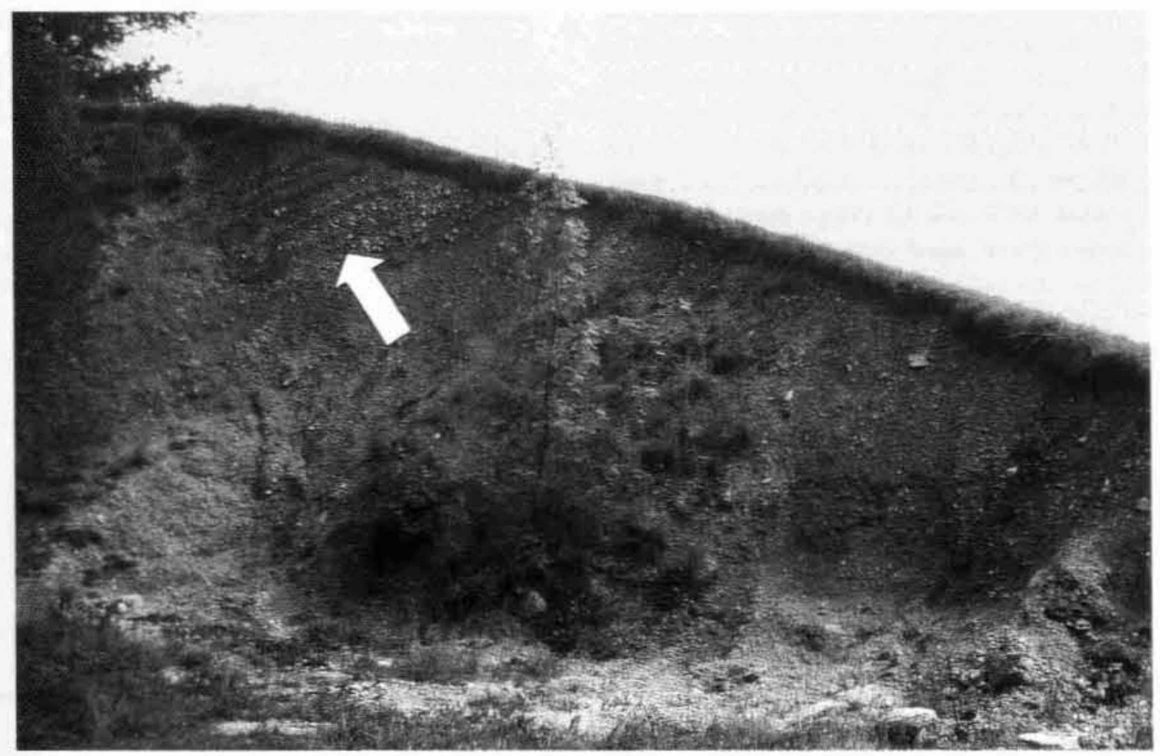

**Fig. 4.** Layering (arrow) within sediments of a relict rock

be 40–60%. Gorbunov and Titov (1986) concluded that the minimal ice content necessary for the mobilisation of permafrost to be 35–50%. As it is based on observation of a large (3000 $m^2$) natural excavation, which revealed at least 50% of ice within the front of an active Fireweed Rock Glacier in Alaska, that of Elconin and LaChapelle (1997) is probably the best work dealing with the structure of rock glaciers. They reported that the clasts were supported by ice, even by ice layers as thin as a few millimetres.

There are several descriptions of massive ice bodies within rock glacier cores (*cf.* Brown, 1925; Benedict, 1973; Whalley & Martin, 1994; Gordon, 1994). However, as the landforms described are not necessarily rock glaciers in terms of the genetic definition (Barsch, 1996; Haeberli, 1985) or, at least, have not been recognised as such by the cited authors, their usefulness for the present discussion is limited.

Nevertheless, as Wayne (1981) assumed, the difference between active and relict rock glaciers in Nevada and in the Andes in volumetric terms is 30–60%, a figure that is independent on their origin, i.e. whether they are regarded as "glacier-derived rock glaciers" or "permafrost rock glaciers".

In summary, the ice content of an active rock glacier may vary in space and time, but the usual range is 30–70%. Moreover, even in landforms which surely have nothing to do with the glacial realm, ice is present not only interstitially, but also as lenses or layers.

Certainly, the internal structure of a relict rock glacier may be regarded as a record of the terminal stage of its former activity. Thus, when considering the part played by the ground ice in the development of the landforms, which are today relict, the minimal ice content necessary for movement must be taken into account. Of course, a definition of such a content would probably not be possible, as this must, in turn, be controlled by parameters as variable as the thickness of the deposits, the ice temperature, the morphology of grains, etc. Nevertheless, if one presumes uniformity of grain size, a sufficiently large sediment thickness and a homogenous distribution of ice, a content slightly higher than 52% is, in physical terms, sufficient for mobilisation of the ice-debris mixture. Of course, when the shape of clasts departs from the spherical and they are oriented in parallel, smaller values guarantee the existence of excess ice which, in turn, causes a drastic decrease of the internal friction and so, of the shear strength (*cf.* Nickling and Bennett, 1984).

The presence of liquid water within active rock glaciers has also been suggested (Giardino, 1983). Unfortunately, the direct observations, detailed description by Barsch yet in 1977 (Barsch, 1977a) being as the best example, do not confirm any presence of liquid water.

## Thickness

A minimum thickness of loose sediments supersaturated with ice is necessary for the initiation of the movement of permafrost. As both minimum ice content and slope inclination are independent variables controlling movement, no universal minimum thickness can precisely be defined. Nevertheless, having taken into consideration the descriptions of rock glaciers from all over the world, it is reasonable to conclude that this thickness must be considerable, i.e. at least several metres. For instance: Johnson (1992) reports a rock glacier that was 10–12 m thick both at its margin and at the terminus. According to Humlum (1998) the values in respect of rock glaciers in the Faeroe Islands are 5–10 and 10–25 m at fronts of the landforms. By contrast, Barsch (1977b) estimated the thickness of two well-developed active rock glaciers in the Alps to be 80–100 and 60 m, respectively. Also, Barsch (1996) assumed that a thickness of 5–10 m at the front of a relict rock glacier is one of the diagnostic features of such landforms. This condition is certainly fulfilled in respect of relict rock glaciers described by the same author from Kendrick Peak in Arizona (Barsch, 1971). Their thickness has been estimated to be 10–20 m. Similar values apply to the relict rock glaciers reported from central Vorarlberg, Austria (De Jong and Kwadijk, 1988).

## Substrate rock

The type of rock providing debris does generally not limit the development of a rock glacier. However, in terms of development, Barsch (1996) assumed that rocks producing big clasts promote growth in case, when climatic conditions differ from the optimum. Similarly, Wahrhaftig and Cox (1959) considered that, for their formation, rock glaciers require rock which disintegrates into blocks with large interconnected voids; conversely that such landforms are rare on platy or schistose rocks. Glazovskii (1978) opined that granites and gneisses, and, among the sedimentary rocks, limestones and dolomites, are the most favourable types of rocks, respectively. Gorbunov and Titov (1986) shared the opinion that rock glaciers prefer rock weathering to big blocks and do not occur in areas where occur rocks like phyllites or schists, which produce platy clasts.

However, there is strong empirical evidence that petrography does not inhibit rock glacier development, indeed. For instance, relict rock glaciers on Dartmoor in Great Britain consist wholly of platy clasts (Harrison, Anderson & Winchester, 1996). Also Johnson (1992) reported rock glaciers in the Dalton Range, Yukon, which developed from rocks as variable as argillites, greywackes, conglomerates, shales, sandstones, basalts, andesites and pyroclastics. Furthermore, both crystalline and sedimentary rocks provide debris for Domaradzki's (1951) "Blockströme" in the Alps. Similarly, landforms described by Evin (1987) developed from these two rock types. Finally, the rock glaciers developed in western Canada from loess (Price, 1981, in Höllermann, 1983) are the ultimate evidence that the development of a bouldery regolith is not necessary for rock glacier formation.

### Grain size distribution, sorting and grain morphology

All direct observations of the internal structure of active rock glaciers indicate that with regard to grain size distribution of their sediments, there is a wide variation. The majority opinion holds that, beneath a bouldery "rock glacier mantle", a diamict of "rock glacier core" is present. Corte (1976) and Barsch (1996) assumed such a two-layered stratigraphy as one of the features diagnostic for relict rock glaciers. Nicholas (1994, p. 54) stated: "(...) most of a rock glacier is type of diamicton, and it shares this aspect common with many other types of mass-wasting deposits". Romanovskii (1993, p. 118) notices the similarity of sediments (and morphology) between rock glaciers and moraines. Similarly, Washburn (1979, p. 227) assumed that "The surface appearance is misleading, however, in that the interior of rock glaciers, where known, usually consists of a diamicton in which fines may be plentiful". The structure of the "rock glacier core" is sometimes characterised as blocks "swimming" within a fine matrix (cf. Barsch, 1983; Schröder, 1992). Humlum (1982) described rock glaciers composed of fine-grained sediments with some large blocks. Johnson (1992) reported coarse sandy gravel beneath a bouldery top composed of clasts up to 60 cm in diameter. Drilling carried out in the active Murtel I rock glacier showed decrease of average diameter from blocks to gravel size towards the core (Barsch, 1977a), and, within sediments of the Gruben rock glacier, a predominance of silty sand with some gravels below the permafrost table was revealed (Barsch, Fierz and Haeberli, 1979).

Haeberli and Vonder Mühll (1996) suggested that the sediments of rock glaciers are controlled by features of the accessible substrate such as moraine or talus and therefore, often of sand size and coarser material prevails, whereas the silt fraction occurs only secondarily and clay is practically absent. When describing the high permeability of rock glacier deposits, Romanovskii (1993, p. 118) suggested that the clay content was minuscule. However, the direct observations on Fireweed Rock Glacier by Elconin and LaChapelle (1997) contradicted such an opinion. These authors stated that: "Ice laden with silt and clay is abundant" (p. 240). Also, observations by Evin (1987) suggested that a high content of fine grade fraction was typical. She distinguished three categories of rock glaciers, including "earthy or silty rock glaciers" and assumed that washing out of fines resulting from melting of interstitial ice, is not an effective process.

There are very few published quantitative analyses of grain size distribution within sediments of rock glaciers. Existing data indicates that these sediments can be composed of very variable material, and that the clay fraction is always a significant component (Fig. 2).

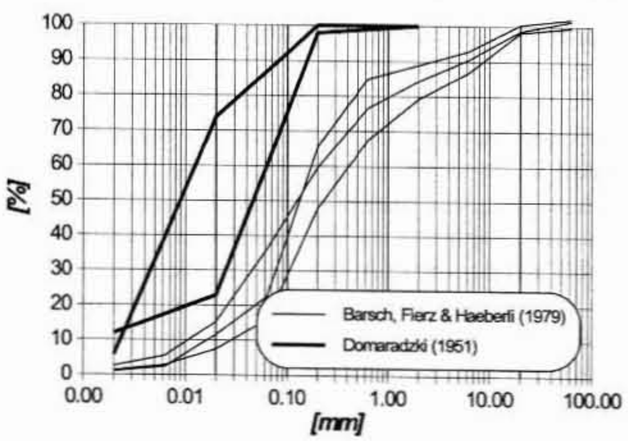


**Fig. 2.** Grain size distribution curves of deposits of active rock glaciers in the Alps, computed according to the quantitative data published by Domaradzki (1951) and Barsch, Fierz and Haeberli (1979)

Summarising: although information about the abundance of coarse clasts is reported by many authors, the content of fines seems to depend simply on such a content in the source material. Such were the observations of Trombotto, Buk and Hernández (1999), who emphasised that "the occurrence and proportion of fine cryogenic sediments depend very much on local petrological characteristics which participate in the genesis of a rock glacier". It may be that coarse material prevails in the rock glaciers known in high mountains, simply because mechanical weathering is the major agent providing debris in the high mountain environment. By contrast, fine fractions may be accessible at lower altitudes, where aeolian accumulation can provide silt and both warmer climate and the lack of high-energy processes favours the generation and preservation of clay minerals. Apart from the empirical data, the suggestions of a dependence between grain size of debris and the rock glacier development seem not to be valid from the physical point of view. The total volume of free space between grains, where interstitial ice can accumulate, does not depend on dimensions, but on shape and orientation of clasts, even if the presence of capillary and sub-capillary pore spaces complicates the relationship.

Not very much is known about the orientation of coarse material within the sediments of a rock glacier. Most information refers only to the rock glacier mantle, but as the mantle is merely transported passively upon the active rock glacier core (*cf.* Barsch, 1996), this is meaningless in any theological consideration.

The absence of preferred orientation of clasts composing rock glacier mantle has been demonstrated by Nicholas (1994). Quite different results were reported by Harrison, Anderson and Winchester (1996), who assumed the orientation of blocks on the surface of a relict rock glacier (high dip angles on ridges and low dip angles in hollows) was one of arguments against a solifluctional origin for the landform. With regard to the surface of a rock glacier, Johnson (1992) reported "preferred orientations down the maximum slope of the proximal and distal ridge flanks". He also stated that the orientation of the coarse material in a rock glacier core, was one where pebbles dip by 25–45° toward interior of the rock glacier. In contrast, an up-slope dip of clasts, varying to certain extent in a vertical 15-m-long profile has been documented by Giardino and Vitek (1988). Elconin and LaChapelle (1997) provide information concerning internal structure including its geometry; they demonstrated a distinct orientation of clasts. According to them "The plane defined by the long and intermediate axes dips steeply and strikes longitudinally, parallel to flow (p. 241)". The orientation of clasts within the Fireweed Rock Glacier (Fig. 3) imitates distinct foliation of ice, or more precisely: an ice-debris mixture and has been interpreted as a result of shearing resulting from transverse compression.



Most data about the shape of the clasts that compose rock glaciers concerns the coarse material of the rock glacier mantle. The majority view is that such material is usually only slightly rounded (Domaradzki, 1951; Schröder, 1992; Humlum, 1996), and that the shape is generally controlled by the features of the source material.

### Layering and its geometry

Most descriptions of the sediments of active rock glaciers provide information about its two-layered stratigraphy (*cf.* Humlum, 1982; Barsch, 1983, 1996; Evin, 1987; Gorbunov and Titov, 1986). Benedict (1973) described a two layered structure within the rock glacier mantle itself; a poorly sorted basal sand layer containing gravel and a few cobbles (1) and a surface layer of large open-work boulders (2). The opinions about the origin of the rock glacier mantle are diverse: for instance Barsch (1996) assumed that separation of coarsely clastic material on the surface results from a downwashing of fines, frost heave of boulders and changes in the active layer thickness. The latter was discussed by Haeberli and Vonder Mühll (1996) in more detail. In contrast, Elconin and LaChapelle (1997) considered that a melting of ice matrix was the process responsible for the development of the rock glacier mantle.

In spite of the fact that Barsch (1996) assumed the two-layered stratigraphy as one of the useful features for the identification of relict rock glaciers, the landforms in the Bernese Jura, which were studied by Barsch (1993) himself, are not of this nature. No bouldery mantle is developed here. This may result from the fact that they developed from limestone debris and limestone does usually not produce large blocks in course of weathering. However, a distinct layering dipping upslope is present here and this may have genetic implications (Fig. 4).

Stratification has also been observed within the sediments of active rock glacier cores. Drilling described by Barsch (1977a) and Barsch, Fierz and Haeberli (1979) showed layering in an ice-debris mixture, while a distinct orientation of the stratified ice-debris mixture was observed in some exposures. Outcalt and Benedict (1965) and Benedict (1973) reported layers which dipped steeply up-valley and interpreted them as an effect of accumulation in the accumulation zone of a true glacier. Gordon (1994) observed "banded ice dipping up-glacier between 22° and 26° containing debris bands up to 150 cm thick".

Further, Johnson (1992) reported poorly defined soil strata, which dipped at 25–45° into the rock glacier and Humlum (1996) described sediments of rock glaciers on Disko Island, Greenland (p. 370): "In the lower part of the rock glacier the foliation dips steeply upstream by 35–40° and is truncated at the ice-debris interface beneath the surface debris layer." A distinct foliation of the debris-laden ice, which dips steeply and is parallel to flow was observed in the sediments of Fireweed Rock Glacier in Alaska (Elconin and LaChapelle, 1997).

The above examples show that a rock glacier core does not always have massive texture and that layering of sediments may be regarded as a typical feature.

## Discussion

This review of the main sedimentological features of both active rock glaciers and the relict landforms allows us to discuss those sedimentological criteria which could conceivably serve as a tool for identification of relict rock glaciers. First of all, it must be emphasised that there is no single sedimentological indicator for an unequivocal and independent interpretation that a landform developed in the course of permafrost creep.

The two-layered stratigraphy, i.e. the sequence of "rock glacier core" and "rock glacier mantle" seems to be the most reliable criterion. However, even this cannot be considered without a geomorphological context and other sedimentological evidence. The two-layered stratigraphy is not only insufficient, but it is not a prerequisite condition, as the presence or absence of bouldery "rock glacier mantle" is simply controlled by the availability of blocky debris.

Since the type and parameters of debris are not a decisive factor in the development of rock glaciers, this also cannot serve as a tool for definition of relict landforms. It can control rock glacier development to some extent, but, certainly, it does not allow us to exclude the possibility that the creep of permafrost or, alternatively, processes such as solifluction, landslides, debris flows or true glaciers are involved. With regard to its size and shapes all these processes may affect all types of material. Descriptions of "ploughing blocks" in southern Norway (Reid & Nesje, 1988) demonstrates that even solifluction (understood to be any slow movement of slope material without the involvement of ice) may mobilise blocks as heavy as 36 t.

The shear stress of an ice-debris mixture needs a certain thickness to be exceeded and this thickness cannot be less than several meters. Hence, if such a thickness did not result from the superimposition of many lobes, a distinction between solifluction and other slope processes including creep of permafrost, becomes possible.

According to Humlum (1998), the thickness of solifluction lobes in the present-day permafrost zone does not exceed 2–3 m. The same value was proposed by French (1996, p. 156). Also, Gorbunov and Severski (1999) describe relief features induced by solifluction as 1–1,5 m in height. Even solifluction tongues consisting of coarse debris, as reported by Tarakanov (1980) are not higher than several decimetres. Nevertheless, the deposit thickness must also be regarded with some caution as a criterion for distinguishing between creep of permafrost and solifluction. The possibility that during the degradation of permafrost, the movement of the active layer can lead to development of landforms comparably large as rock glaciers cannot be excluded (Chaus, 1995). On the other hand, the creep of permafrost can produce relief less spectacular than typical rock glaciers (see Romanovskii *et al.*, 1989).

The presence of layering dipping upslope and the sympathetic reorientation of coarsely clastic material with this stratification are very significant sedimentological features. Such a reorientation may result from any process causing "collective" particle movement (solifluction, debris flows and grain flows), but, in such a case, imbrication normally develops (Bertan *et. al*, 1997). Within a rock glacier, pebbles or blocks are not necessarily in contact with each other, however distinctly they are arranged, as a rule (Fig. 3). Reorientation not caused by imbrication, allows us to exclude practically all the processes which operate without ground ice as causative agents (*cf.* Mills, 1983).

On the contrary, the layers dipping up-slope, as observed in many rock glaciers, are typical for those sections of true glacier where compression prevails. This has been demonstrated both theoretically (Nye, 1951), as well as observed in nature (*cf.* Boulton, 1970; Knight, 1988). The fact that structural planes within rock glacier sediments dip upslope suggests that they may have developed in the course of shearing and are not accumulation surfaces, as Carrara (1973) suggested. Certainly, the accumulation surfaces can be preserved in ice as well. However, they are subtler and they often are deformed by failure surfaces (*cf.* Hambrey, 1975; Knight, 1988). Thus, one can expect that thrust planes are recorded within deposits much better than any accumulation or ablation ones.

The similarity of the sediments of true glaciers and those of rock glaciers means that even layering (and its characteristic orientation) cannot be regarded as an ultimate criterion of delimitation between structures of glacial and periglacial origin. However, scale of deformation of synkinematic structures may be of use as an auxiliary criterion. The layering and orientation of pebbles ought to be preserved within rock glacier sediments better than in moraines. Quantitative investigation by Lawson (1979) showed, for instance, that pebbles within glacigenic deposits maintained the orientation of their long axes parallel to the flow direction, but their dips differed considerably from the orientation of clasts within a moving glacier.

Certainly, geomorphological analysis is necessary for reliable distinction between glacial and periglacial environments. First of all, the altitude differences between surfaces limited by the lateral ridges of a rock glacier (or lateral moraines) and the lateral ridges themselves should be concerned (Żurawek, 1999). In doubtful cases and when traces of glacial erosion, such as glacial cirques occur above the hypothetical relict rock glaciers, the question of their glacial or periglacial origin may prove to be an intractable problem. This may also be true of fossil, i.e. buried rock glaciers.

## Conclusions

1. Virtually no single lithological feature can be defined which could independently serve as a criterion for the unambiguous identification of the sediments of a relict rock glacier. This is also true in respects of attempts to define a landform as a product of permafrost creep.

2. The presence of two characteristics might serve valuable evidence in respect of genetic considerations, i.e. the two-layered stratigraphy (the bouldery "rock glacier mantle" covering "rock glacier core") (1) together with the steep dip of strata up-slope and accompanying reorientation of the coarse fraction (2). In tandem, these allow one to exclude all the slope processes operating without ice. The thickness of a rock glacier which is more than several meters, is an additional premise against solifluction as a genetic possibility.

3. A distinction between glacigenic sediments and those of relict rock glaciers seems to be especially difficult. The main premises here should be the possible presence of the two-layered stratigraphy typical for a rock glacier (1) and/or well developed sedimentary structures, including layering (2). The geomorphological setting of a landform must also be taken into consideration. However, in certain cases, no ultimate definition of origin of sediments and, therefore, landform, is possible.

4. Lithological features such as grain size distribution, sorting or grain morphology do not have any importance in genetic considerations. These features are basically controlled by the properties of the source material and the distribution of rock glaciers is generally not controlled by them.

## Acknowledgements

The author wishes to thank Dr. Peter Walsh for the linguistic assistance. The agreement to reprint a photograph that shows sediments of the Fireweed Rock Glacier is greatly appreciated by Dr. Roger Elconin (Anchorage).

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