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Rock glacier and periglacial processes in the Mongolian Altai

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ABSTRACT: Fieldwork, air photos and satellite images in the Mongolian Altai showed the distribution of mountain permafrost and rock glaciers at elevations above 2200 m. Other periglacial features, e.g. solifluction lobes, can be observed in elevations above 2600 m asl only. Periglacial features and processes are mainly determined through existence of soil humidity during the freeze-thaw cycles. The accumulation of snow and/or the occurrence of frozen ground could mainly guarantee sufficient high soil humidity during the highest freeze-thaw cycles in spring and autumn seasons and determines cryogenic processes and periglacial forms (e.g. earth hummocks, patterned ground). The effects of radiation can reinforce this local influence. In *Larch* forests on northern slopes a cooler local climate with reduced evapotranspiration in the summer allows the preservation of frozen ground and/or permafrost. The distribution of rock glaciers is determined by the presence of rock fall or moraine debris composed of large boulders.

1 INTRODUCTION

This paper presents observations concerning the distribution of rock glaciers and periglacial features and processes in a previously unstudied area of the Mongolian Altai (Fig. 1). We focus firstly on the distribution of rock glaciers, and secondly on other periglacial processes in the investigation area. Detailed fieldwork, air photos, and satellite images provide the results for this study. The first foreign explorers to report on the mountain environment of Mongolia are Murzaev (1954), and on periglacial processes are Richter et al. (1963). The Quaternary evolution in western Mongolia is described by Russian scientists (Devjatkin 1981, Florenzov & Korzhnev 1982). More general information can be obtained from the National Atlas of Mongolia (Academy of Sciences of Mongolia & Academy of Sciences of USSR 1990). In western literature, few results have been published up to now. Some recent papers do focus on geomorphological processes, Quaternary geology, and climatic change of the region mentioned above (e.g. Grunert et al. 1999, 2000, Klinge 2001, Lehmkuhl 1998, 1999; Lehmkuhl & Haselein 2000, Naumann 1999, Walther 1999). Pekala & Repelewska-Pekalowa (1993), and Serebryanny & Gravis (1993). For literature on permafrost and periglacial processes in Mongolia see Choibalsan (1998), Lombroinchen (1998), Klimek & Starkel (1980), Owen et al. 1998.

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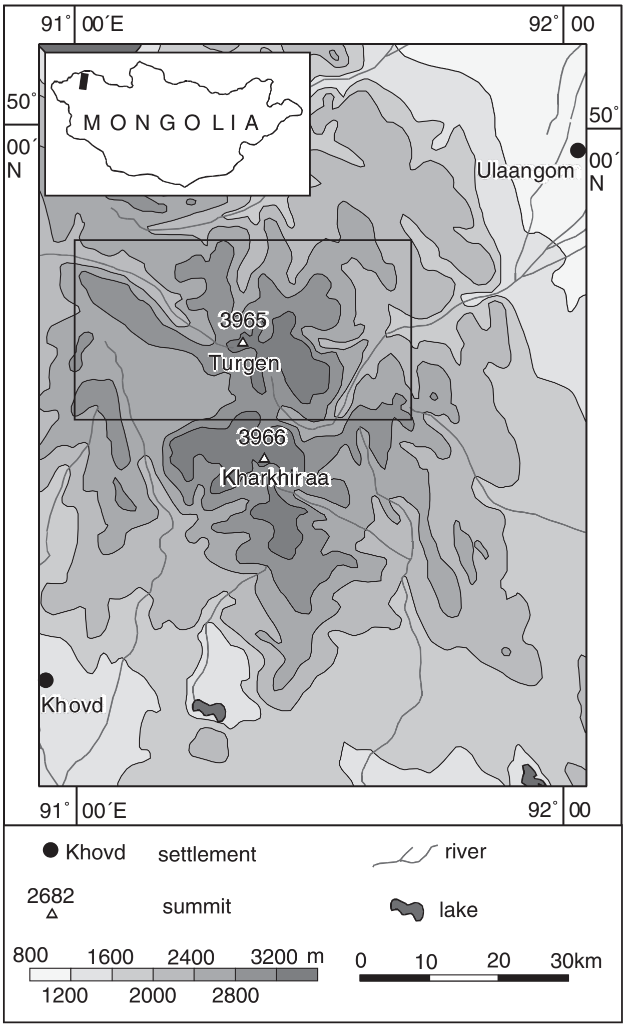

Figure 1. Study area. Box: Detailed investigation area.

Rock glaciers are typical landforms of high mountain environments. Two types are distinguished; ice-cemented rock glaciers built up by unconsolidated rock of talus or morainic deposits. They are generated by the creep of mountain permafrost saturated or supersaturated with ice. Ice-cored rock glaciers consist of glacier ice mantled with a debris cover and originate from dead ice (Ishikawa et al. 2001). Rock glaciers develop from unconsolidated but frozen rock fragments. They creating characteristic landforms, with a tongue or lobate shape and a surficial pattern of furrows and ridges that indicate the internal flow process (Barsch 1996, Fort 2002, Haeberli 2000). In addition, protalus ramparts, and talus slope or talus cone rock glaciers are described in the literature (e.g. Barsch 1996). Such features could be observed in the study area (Figs 2, 3).

It is generally accepted that the distribution of rock glaciers is a good marker of (discontinuous) mountain permafrost (e.g. Barsch 1996). However, Fort (2002) mentioned that the identification of rock glaciers in the Himalayas is similar to other features such as rock-slides and/or debris covered glaciers.

Figure 2. South-facing rock glaciers in the northern part of the Turgen Mountains in about 2760 m asl (see arrow in Figure 4).

Figure 3. North-facing lobate talus rock glacier in the northern part of the Turgen Mountains in about 2780 m asl (see arrow in Figure 4).

Rock glaciers are described in detail especially in the European Alps and in mountain regions of North America (see reference in Barsch 1996). However, only a few recent papers focus on rock glaciers in the mountains of Central Asia and the Himalayas (e.g. Fort 2002, Owen & England 2000, Schröder et al. 1996). The knowledge of the distribution of rock glaciers in the different mountain systems on Earth is still very incomplete (Barsch 1996). Nevertheless, mountains with a continental climate, and thus the greatest differences between timberline and snowline (up to 1500 m) are more favourable for rock glaciers than those with a difference of less than 500 m (Höllermann 1983, Barsch 1996).

Concerning other periglacial phenomena in mountain environments, small-scale periglacial or cryogenic landforms are extensively described in the literature (Washburn 1979). In general, the periglacial zone can be divided into two sub-belts: firstly, the lower periglacial sub-belt, characterised mainly by bound solifluction (steps, benches, terraces, lobes). Secondly, the upper sub-belt, characterised by unbound solifluction, blockfields, debris, stone pavements, and patterned ground (Höllermann 1985). This periglacial zonation is obvious in most mid-latitude mountains above the timberline and provides information on the geoecology of high mountain environments as the distribution of these landforms depends on several different factors (e.g. topography, geology and substrate, climate, vegetation, soil water).

2 STUDY AREA

The detailed investigation focuses mainly on the Turgen-Kharkhiraa Mountains, which lie in the northernmost part of the Mongolian Altai and are situated southwest of the Uvs Nuur Basin (Fig. 1). These mountain systems cover an area of approximately 5700 km^2 and comprise mainly Palaeozoic rocks, whereas at the margins of the mountains pelites, sandstones, conglomerates and schists are dominant. Palaeozoic granites and gneiss build up the central part of the mountains. In addition, a small area of Devonian basalt is located in the northwestern part of the Turgen Mountains. Planation surfaces (probably of Cretaceous and Tertiary age) were formed by Cenozoic tectonism. The area is still tectonically active (e.g. Cunningham et al. 1996, Tapponnier & Molnar 1979). The Turgen-Kharkhiraa Mountain system can be roughly divided into seven main morphotectonic regions, comprising three mountain areas separated by tectonic basins of different altitude (Lehmkuhl 1998). At the margins of the mountains and in the basins, younger Quaternary sediments – mainly fanglomerates, sands, gravels and lacustrine sediments – overlie the basement rocks.

The recent continental climatic conditions are characterised by a wide annual range of temperature, with winter values of below −20 to −30°C and summer values up to and exceeding 20°C (for example, the mean temperature at Ulaangom is −32.9°C in January and 19.2°C in July with an annual average of −3.7°C). Annual rainfall, about 60% in the summer months, averages about 200 mm at the altitude of 2000 m and is estimated to exceed 300 mm in the high mountain areas, whereas precipitation in the basins is less than 100 mm per year.

The modern altitudinal belts of the vegetation (Hilbig 1995), the soils (Haase 1983), and the geomorphological processes (Lehmkuhl 1999, Richter et al. 1961) are controlled by these general climatic conditions, but also by the different radiation on the northern and southern slopes. In particular, east-west trending valleys are asymmetric in shape with more gently dipping northern slopes and steeper southern slopes as a result of stronger Pleistocene solifluction on the northern slopes. In the highest parts of the mountains, cirques and nivation funnels produce steeper northern slopes (Lehmkuhl 1999).

Five modern geomorphic altitudinal belts can be distinguished in the Turgen-Kharkhiraa Mountains according to typical morphologic forms and processes (Lehmkuhl 1999). A glacier and nivation zone is found at elevations above 3000 m in the highest mountain ranges. The present snowline (equilibrium line attitude = ELA) occurs at about 3500 m asl and the timberline is in an elevation of about 2700 m (*Larix sibirica* limited on northern slopes). The morphological slope processes below 2600 m are weak and largely restricted to frost shattering of the bedrock. Below 2400 m at the southern flank and 2200 m at the northern flank of the Turgen-Kharkhiraa Mountains, small Holocene gullies cut into the bedrock and slope debris. In addition, in the lowermost, semiarid and arid areas below 1200 m, fluvial incision is stronger, especially in Pleistocene deposits (Lehmkuhl 1999).

Pleistocene valley and cirque glaciers covered an area of 1300 km^2 in the Turgen-Kharkhiraa. Different types of terminal moraines and ice margins can be mapped in the various valleys of the Turgen-Kharkhiraa Mountains. The accumulation of ice marginal ground and terminal moraines are controlled by the topography. Six main ice margins terminated at elevations of between 1950 and 2250 m asl. They provide evidence for the extent of Pleistocene valley glaciers during the Last Glaciation. The ELA of the last glaciation was about 600 m lower than at present reaching an elevation of about 2900 to 3000 m asl (see Lehmkuhl 1998, for further details).

In the highest parts of the mountains, and in front of the present valley glaciers, modern end moraines can be recognised. As they have only little or no vegetation cover and soil formation they can be correlated with the global glacier advances of the "Little Ice Age" in the 16th to 19th century (Lehmkuhl 1998, Grunert et al. 2000).

3 METHODS

Fieldwork was undertaken in the Turgen-Kharkhiraa Mountains (Fig. 1) and in other selected mountains of western Mongolia and parts of the Russian Altai. This included geomorphological mapping and the analysis of structures and landforms, aided by the use of global positioning systems, barometric altimetry and leveling, maps, Landsat-TM images, and aerial photographs. Selected exposures were studied in the field to examine the sediment and landform associations. Detailed sedimentological and geomorphological analysis of the alluvial fans and terraces, together with the glacial, periglacial mass movement, aeolian, and lacustrine deposits were undertaken in order to provide a framework of the late Quaternary evolution of landforms and sediments in this area. This includes the sampling of suitable material for radiocarbon and luminescence dating from key locations and horizons. In addition, measuring of soil temperatures and the water temperatures of sources in the study area were undertaken to get more detailed information on the freeze-thaw cycles and the distribution of frozen ground and permafrost (Lehmkuhl & Klinge 2000).

A Landsat-7 scene (124–25; Path-Row) from September 10th 2000 and airphotos from August 28th 1991 were used for mountain-wide mapping of rock glaciers. Aerial photographs with a resolution of approximately 1:50 000 provided a stereoscopic coverage of the area. These air photos and the panchromatic channel (pixel size 15 × 15 m) of Landsat-7 were used for the recognition of rock glaciers while a false colour image of the reflected infrared channels (30 × 30 m) of Landsat-7 gave the possibility to distinguish between active and passive forms. Because of the low resolution of the false colour image compared to the aerial photographs, only large- and medium-scaled rock glaciers could be identified as being active. Furthermore, rock glaciers which became inactive in the recent times will still show the same spectral signature as an active form.

4 RESULTS

One hundred and seven rock glaciers have been mapped in the Turgen Mountains based on the methods

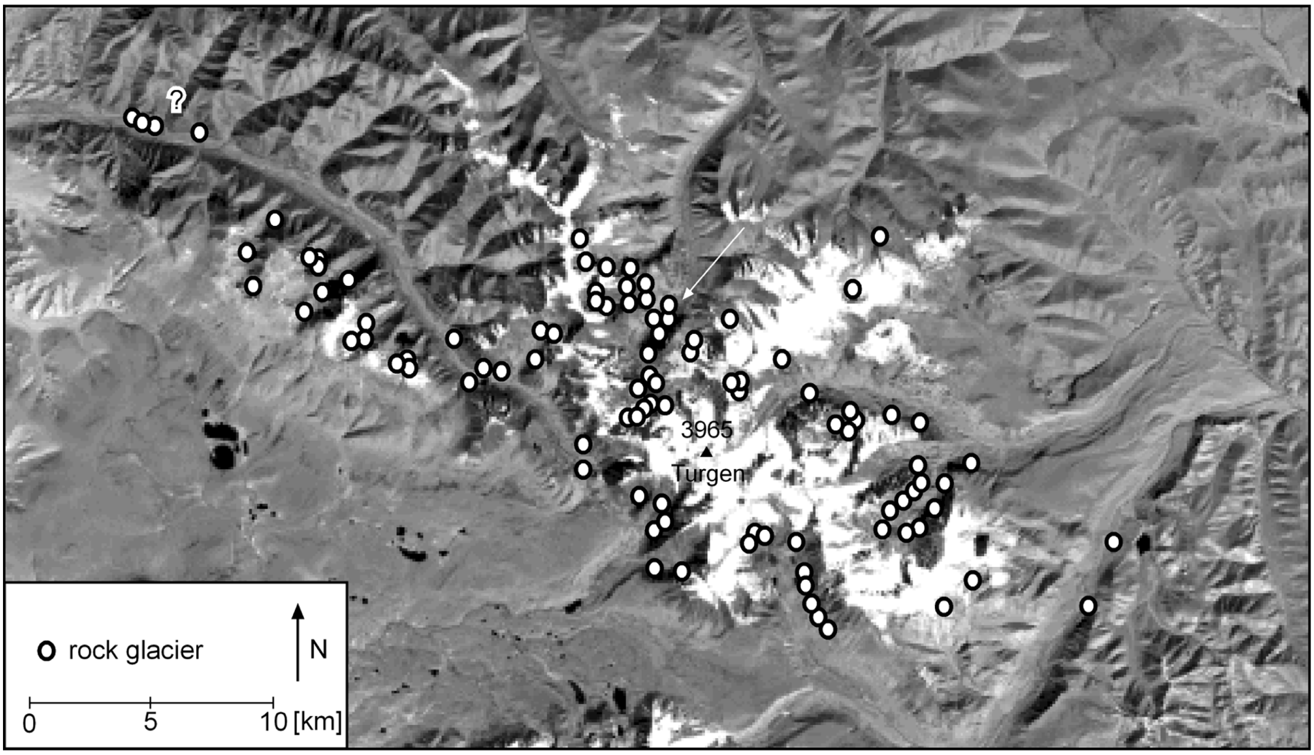

Figure 4. Distribution of Rock glaciers in the Turgen Mountains. The arrow indicates the position of figures 2 and 3.

Table 1. Distribution of rock glaciers in the Turgen Mountains for different aspects (average, maximum, and minimum elevation, standard deviation).

Aspect	N	NE	E	SE	S	SW	W	NW	Total
No.	20	14	16	8	7	9	10	23	107
Av. elv.	2850	2831	2919	2925	2886	2918	2816	2745	2861
Max. elv.	3120	3240	3420	3200	3200	3280	3000	3000	3420
Min. elv.	2480	2320	2600	2680	2640	2520	2560	2480	2320
St. dev.	190	290	172	178	191	291	145	169	203

mentioned above (Fig. 4). They are situated at elevations between 2320 and 3420 m asl (Table 1). The mean elevation is 2861 m asl, which is 650 m below the present glacier snowline (Lehmkuhl 1998, 1999). All of them are located in areas of Pleistocene glaciations and most are talus rock glaciers composed from morainic or rock fall material.

Forty percent of the rock glaciers can be found on north or northwest orientated slopes. The lowest average elevation on northwest facing slopes indicates the high influence of precipitation delivering winds in this arid area. The low number of rock glaciers on slopes facing southern directions is caused by high radiation in the cloud-poor area.

More than 90% of the rock glaciers are located in areas characterized by granites and metamorphic sand- and siltstones, while only 10 rock glaciers are situated in the area of Devonian basaltic vulcanite.

Limitations of remote sensing techniques for the mapping of small scale geomorphological features are demonstrated by four small forms in the northwestern area of the Turgen Mountains (see "?" in Fig. 4). In this case it was not possible to distinguish between rockslides and rock glaciers by the use of air photos. The combination of reflected infrared channels of the Landsat-7-scene shows signs of fresh movement. Because of the relatively low elevation (2160–2200 m asl.) and the position on south facing slopes they were not included in the calculations.

However, other periglacial features, e.g. solifluction, can be observed at elevations above 2600 m asl only. In addition, small palsa and earth hummocks occur at lower elevations (>1200 m asl) close to rivers and other ground water sources. These periglacial features and processes are mainly determined through existence of soil humidity during the freeze-thaw cycles (e.g. Matsuoka et al. 1997). The main difference in the intensity of periglacial processes in the basins and mountains areas, respectively, can be seen in the freeze-thaw cycles in springtime on the specific sites.

This was indicated by detailed investigations and hourly measurements of the soil temperatures at different depths at distinct geoecological sites between 940 and 2690 m asl in the Turgen Mountains (Lehmkuhl & Klinge 2000). Accumulation of snow (e.g. in nivation hollows) and/or the occurrence of frozen ground could guarantee sufficient soil humidity apart from the distribution of precipitation during the highest freeze-thaw cycles in the spring and autumn seasons and determines cryogenic processes and periglacial forms (e.g. earth hummocks, patterned grounds). The effects of radiation can reinforce this local influence. In *Larix* forests at northern slopes a cooler local climate with reduced transpiration in the summer allows the preservation of frozen ground and/or permafrost. The distribution of rock glaciers is determinates by the occurrence of rock fall or moraine debris composed by large boulders (e.g. granite).

5 CONCLUSION

Due to the low winter temperatures and the small amount of snow, frost weathering occurs down to the basins below 900 m asl. However, the distribution of rock glaciers in the continental climate conditions of western Mongolia is determined by the existence of low mean annual air temperatures, and granite and metamorphic rocks. They occur in elevations above 2300 m. Initial observations from other parts of the Mongolian Altai and the western Russian Altai show that they can be found in almost every mountain system composed of granite or other metamorphic rocks. Other periglacial phenomena, such as solifluction, palsas, and earth hummocks are related to soil moisture and, therefore, occur in higher elevations or exceptional geoecological site with a higher water supply.

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