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Climatic Zonality of Periglacial Landforms in Mountain Areas

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ABSTRACT. The alpine periglacial areas of the world can be divided into three distinctive landscape types dominated by one of the following: active rock glaciers, active block streams, or gelifluction landforms. These also correspond to distinct climates, the active rock glaciers occurring under cold, humid conditions; the active block streams in cold, dry climates; and gelifluction-dominated landforms occurring in warmer areas. These have distinct ranges of mean annual temperature and precipitation, which can be used in interpreting climatic changes based on distribution of fossil landforms.

Key words: alpine permafrost, block streams, rock glaciers, gelifluction

RÉSUMÉ. On peut diviser les régions périglaciaires alpines du globe en trois types de paysages distincts, dominés par un des éléments suivants : glaciers rocheux actifs, coulées de pierres actives ou reliefs de gélifluxion. Ces éléments correspondent aussi à des climats distincts, les glaciers rocheux existant dans des conditions de froid et d'humidité; les coulées de pierres actives sous des climats froids et secs; et les reliefs de gélifluxion dans des régions plus tempérées. Ces paysages ont des gammes différentes de moyennes annuelles de températures et de précipitations, qui peuvent servir à interpréter les changements climatiques fondés sur la distribution des reliefs fossiles.

Mots clés : pergélisol alpin, coulées de pierre, glaciers rocheux, gélifluxion

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INTRODUCTION

The major objective of the expeditions of the late Carl Troll was to explore the high mountain areas of the world so as to determine the variations in geomorphology and plant cover in these regions. The result was a remarkable collection of descriptions (e.g., Troll, 1972), but these were never integrated into a worldwide system.

The writer first visited the Alps in 1947 and has subsequently been fortunate to visit many more mountain ranges in different parts of the world. After 45 years of field work, it has become apparent that there may be a general worldwide zonation of dominant landforms in mountainous permafrost regions, and it is the purpose of this paper to describe some of the evidence for this.

During field work in cold mountain areas in various parts of the world, certain patterns of landforms have become apparent. This conclusion has been strengthened by recent publications by specialists on different mountain ranges. The main problem with the literature has been the dominance of works on certain accessible mountain ranges, e.g., the Alps, and English-speaking workers' inaccessibility to many other critical areas of the world, namely, Russia, Siberia, Central Asia, the People's Republic of China, and the Cordillera of South America. With increased access to these regions for Europeans and North Americans, and with the increasing availability of literature on these areas in languages other than Russian, Chinese, etc., it is now timely to attempt a zonation of the dominant alpine permafrost landforms. In this paper, examples are given of some of the key permafrost landforms from these newly accessible regions as well as from those that are better known.

DEFINITIONS

Three main groups of landforms dominate the zonation. Unfortunately, the names of two of the three groups have been under debate for a long time, so it is necessary to start with the definitions of the terms as used in this paper.

The term "active block stream" is used to refer to lines of angular or subangular blocks (Fig. 1) descending downslope as a stream (Washburn, 1973, 1979). The blocks have the same lithology as the underlying material, whether that be bedrock or a superficial deposit containing blocks. The blocks are apparently moved upwards and ejected from the soil or broken from the bedrock by frost action (King and Hirst, 1964; Joyce, 1950). There is little sign of rounding or chemical weathering, and they usually exhibit a sharp boundary with the surrounding deposits. They move at a rate of several centimetres per year (Romanovskii and Tyurin, 1983) and the movement may be due to creep of thawed blocks over an icy base (Czudek and Demek, 1972; Romanovskii and Tyurin, 1983) when the ice content in winter exceeds 50% by volume. Ice contents of up to 90% by volume in winter have been reported by Romanovskii and Tyurin (1983:1097) from southern Yakutia and northern Transbaikalia.

FIG. 1. Active rock streams, Kunlun Shan, China.

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These landforms must be clearly differentiated from "stone runs" (Geike, 1894; Andersson, 1906), which are streams of subrounded or rounded boulders lying on slopes. In these cases, water has removed the finer material from between the boulders and has aided in chemical and physical weathering of the blocks, increasing their roundness. These can be observed forming today — for example, at the Upper Glaciological Station, Tien Shan, near Urumqi — from sorted patterned ground and till. They differ from the deposits of blocky "debris flows" in the bottoms of gullies by the absence of finer material in the deposit, the absence of lateral levees, the lack of a hollow up-valley where the blocks came from, and the slow movement that mainly occurs in winter. They probably grade into certain kinds of "block slopes", which are slopes greater than 10° (Washburn, 1979) mantled in blocks of rock. Some of these slopes at maximum angle of rest of material are called "talus slopes" and also show slow downslope movements (e.g., Luckman, 1988), but the nature of the movement is quite different (Loughran and Loughran, 1979; Gardner, 1979; Kotarba, 1984; Kotarba and Strömquist, 1984; Luckman, 1988; Pérez, 1989, 1993). However, ongoing studies by the author and his students on edaphically dry block slopes at Plateau Mountain, southwestern Alberta, show similar processes occurring to those on active block streams. Active block streams differ from the other landforms in always occurring in cold climates in the active layer overlying permafrost.

The term "active rock glacier" is used in this paper to refer to masses of rock debris containing substantial quantities of interstitial ice and moving slowly downslope as a sheet. The rocks are matrix supported in the ice, which may reach 60% by volvme (Barsch, 1978). The movement is normally most rapid in the centre, decreasing towards the sides and terminus (Jackson and MacDonald, 1980; Gorbunov *et al.*, 1992). This differential movement causes an oversteepening of the front slope (Fig. 2). Movement is now believed to be due to deformation and flow of the ice in the interior of the mass (Haeberli, 1985), sometimes aided by zones of high hydrostatic pressure (Giardino, 1983). Good examples of factors affecting the movement of rock glaciers will be found in Gorbunov *et al.* (1992).

FIG. 2. Rock glacier above Bow Summit, Banff National Park, Alberta, Canada.

The third major group of landform comprises the "gelifluction" deposits. The original term used for flowage of saturated soil downslope over a relatively impermeable substrate was "solifluction" (Andersson, 1906). However, this could include flowage over an unfrozen clay layer, which can occur in any climate, although it is relatively uncommon. Gelifluction was defined by Baulig (1956:50-51) as flowage of wet, unfrozen soil downslope over a frozen substrate. The latter may be either seasonal or perennial frost (permafrost). It is therefore movement of the upper layer of the superficial deposits that takes place, and the most extensive examples appear to be the deposits described as the "Kunlun Shan-type rock glacier" (Fig. 3) of Cui (1983). The front of these features has a low slope (Fig. 4) and the deposits exhibit small lobes on the surface due to soil flowage when snow melts (Fig. 5). Larger blocks act as braking blocks (Fig. 6), since the active layer in the main mass at this site is rarely over 50 cm thick. Thus blocks of rock more than 1 m in diameter are permanently frozen into the ground, and the moving superficial material piles up behind them. The movement is also indicated by elongation upslope of the roots and/or stems of the few plants growing on the landform (Fig. 7) in these areas of relatively rapid movement, where most plant species cannot survive. Braking blocks are a good indicator of gelifluction on a slope in cold climates.

FIG. 3. Active gelifluction deposit moving down a valley floor, Kunlun Shan. Note the contrast between the vegetated ridges and the bare active material.

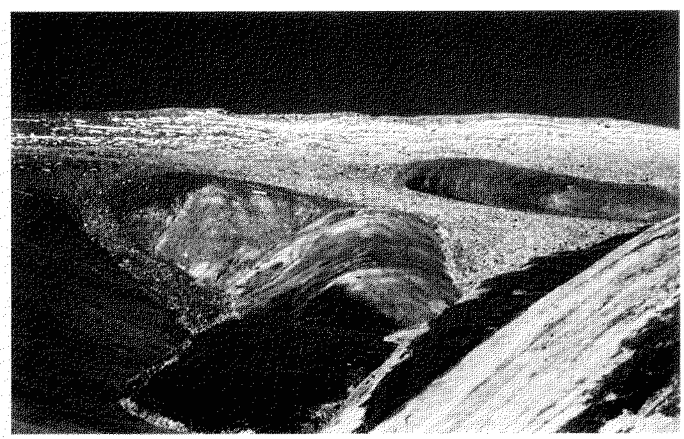

FIG. 4. Front of an active gelifluction deposit (the Kunlun Shan-type rock glacier) on the north slope of the Kunlun Shan.

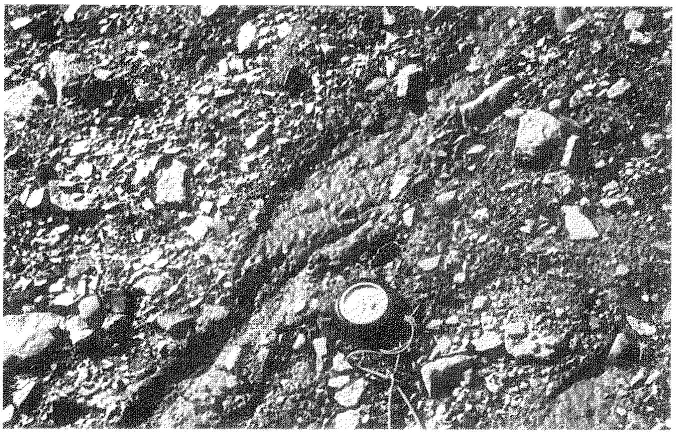

FIG. 5. Gelifluction on the surface of Kunlun Shan rock glacier number 6.

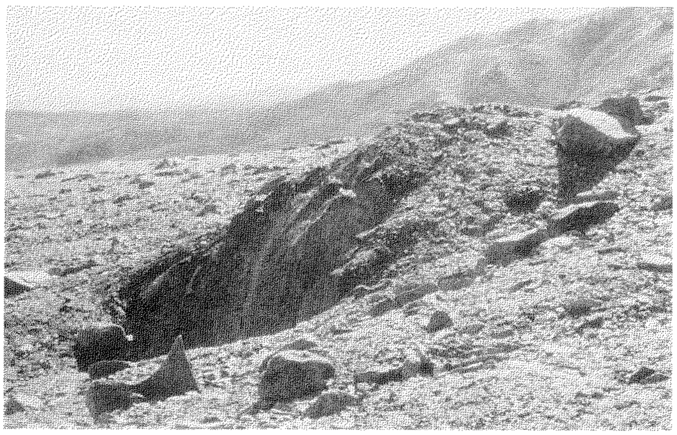

FIG. 6. Braking block being overridden by finer material on Kunlun Shan rock glacier number 6.

FIG. 7. Elongation of the stems of *Aster himalaicus* on an active block stream, 4800 m elevation, Kunlun Shan.

Other landforms produced by gelifluction include gelifluction lobes, sheets, benches, and streams (Washburn, 1979:206). The gelifluction features of the Kunlun Shan are examples of gelifluction sheets and streams. Turf-banked terraces and stone-banked terraces and lobes (Benedict, 1970, 1976; Smith, 1987, 1988) are examples of the lobes and benches of Washburn. In extreme cases, gelifluction can smooth out large surfaces, producing altiplanation terraces (Eakin, 1916:77-82), equiplanation terraces (Cairnes, 1912:344-348), and goletz terraces (Jorré, 1933), all of which are now usually called cryoplanation terraces (Bryan, 1946:639-640). These gently sloping surfaces cut across the bedrock structure and it is argued that they are developed by gelifluction, since gelifluction deposits form a veneer over bedrock (Fig. 8), often with patterned ground or ice wedges developed on them (Fig. 9). Gelifluction lobes may occur on their surfaces, as on the west side of the Mackenzie Mountains, Yukon Territory (Fig. 10). French and Harry (1992) argue that it remains to be proven that cryoplanation terraces in unglaciated terrain are formed under the present climate (e.g., those in Fig. 8), but some cases can be found where they are present on Late Wisconsinan till (Fig. 11) in central Alaska. These must have been formed during the Holocene.

Where the frost is deep but seasonal, gelifluction produces ploughing blocks, and these can also occur where there is a deep active layer over permafrost, for example, at Marmot Basin, Jasper, Alberta. The moisture is supplied by melting snow and the heavy rocks tend to move downslope faster than the surrounding sediments (see Gorbunov, 1991).

Gelifluction occurs on most slopes with medium- to fine-grained material present in areas of freezing ground. It can

FIG. 8. Cryoplanation surface cutting across the rock structure east of Boundary, Top of the World Highway, Yukon, Canada.

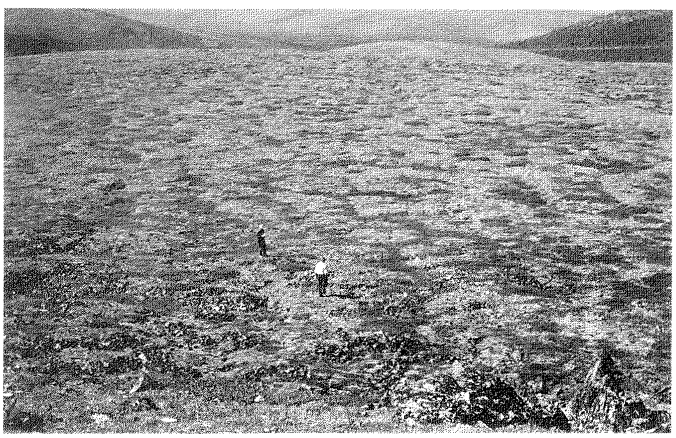

FIG. 9. Patterned ground on the cryoplanation surface, east of Boundary, Top of the World Highway, Yukon.

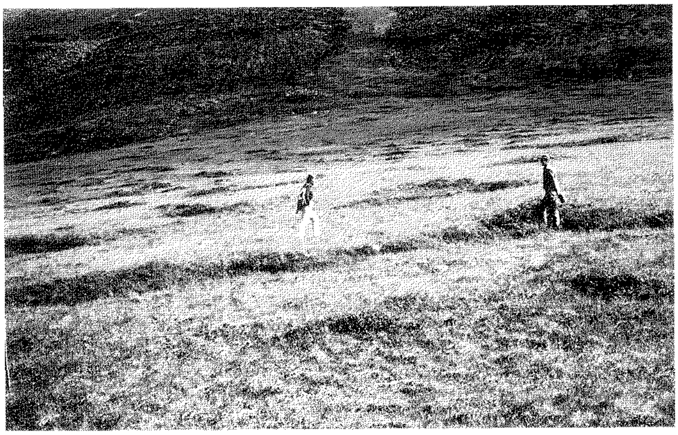

FIG. 10. Gelifluction lobes, developed on a cryoplanation surface on west side of the Rat Pass, Dempster Highway, Yukon Territory.

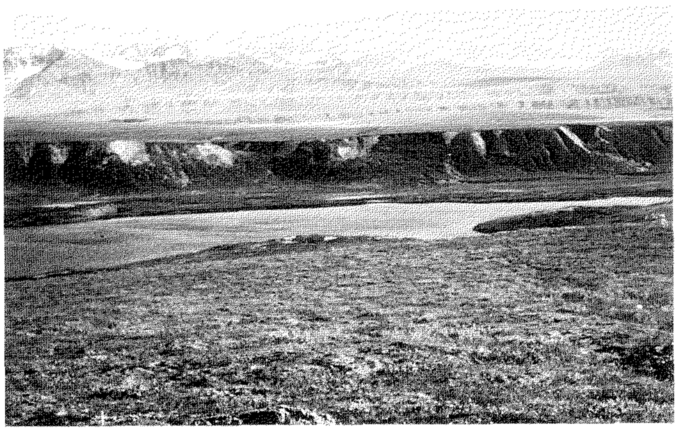

FIG. 11. View of the Alaska Range from the south, Denali Highway, Alaska, showing cryoplanation terraces developed on Late Wisconsin till.

occur on rock glaciers if there is fine-grained material present in the matrix on the surface of the landform, such as in the rock glaciers in the PreCordillera of Argentina near Mendoza (Fig. 2), and in these cases results in the presence of braking blocks as the finer unfrozen material flows downslope, overriding the large blocks still frozen in the underlying permafrost.

Gelifluction is a slow surface phenomenon, in contrast to rapid, catastrophic flows such as debris flows and detachment failures or active layer detachment flows and skin flows (see Hughes, 1972; McRoberts and Morgenstern, 1974; Harris *et al.*, 1988). All these other processes result in a hollow where the material came from and a cone-shaped undulating accumulation area. These are local phenomena and rarely dominate the landscape, but are often found in association with gelifluction. Similarly, the retrogressive thaw-flow slides and retrogressive thaw slumps consist of various combinations of catastrophic slides and debris flows, together with gelifluction, but the slides and debris flows dominate the resulting landforms (Mackay, 1966; Rampton and Mackay, 1971; Hughes, 1972; McRoberts and Morgenstern, 1974; Washburn, 1979; Harris and Gustafson, 1988, 1993). Since these are caused primarily by highly ice-rich permafrost, they are more important as local phenomena than as major worldwide processes.

The degree of activity of both block streams and rock glaciers may be gauged by the absence of lichens and vascular vegetation (Figs. 3, 5, 6). Measurements of the rates of movement on the surface of the main bodies of either landform are essential to **prove** this activity, however, since the lower parts of some active rock glaciers may be covered in forest (Blumstengel and Harris, 1988). The margins of active rock glaciers may show negligible movement (Jackson and MacDonald, 1980), and the front of the rock glacier may continue to reduce its oversteepened slope long after movement in the main mass has ceased.

ZONATION OF THE DOMINANT ALPINE PERMAFROST LANDFORMS

Geographical Distribution

Figure 12 shows the distribution of the mountain areas dominated by each of these three basic groups of landforms. Active block streams are best developed in Siberia (Romanovskii and Tyurin, 1974, 1983) and in the Urals (Romanovskii and Tyurin, 1986). They have also been seen by the writer in the Kunlun Shan in China and in the Richardson Range in northwest Canada.

Rock glaciers are widespread in the Alps (Capello, 1947; Evin, 1983; Haeberli, 1991), in the Cordillera of western Canada and Alaska (Capps, 1910; Wahrhaftig and Cox, 1959; Luckman and Crockett, 1978; Kershaw, 1978; Ellis and Calkin, 1980), in Argentina (Catalano, 1926; Marangunic, 1976; Corte, 1976, 1985; Igarzabal, 1983), and in isolated localities through Eastern Europe and the Middle East (Grötzbach, 1965; Schweizer, 1972; Gobadzhishvili, 1978). They also occur in the high mountains of the Tien Shan (Palgov, 1948; Gorbunov, 1983; Titkov, 1985; Gorbunov *et al.*, 1992) and on the north slope of the Hindu Kush in Afghanistan and India (Rathjens, 1978; Mayewski *et al.*, 1981).

Gelifluction landforms dominate elsewhere. They are found in the Cordillera of North America wherever permafrost is present, from Kananaskis, Alberta, southwards to about 20 °S in the Andes of South America (Troll, 1947; Schubert, 1969;

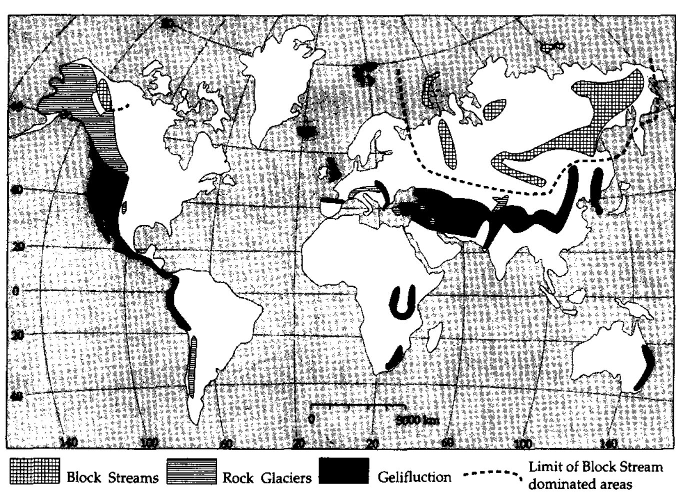

FIG. 12. Worldwide distribution of mountain areas dominated by active block streams, active rock glaciers, and active gelifluction deposits.

Graf, 1984; Pérez, 1985, 1988; Francou, 1988; Smith, 1988). The gelifluction zone is also found in East Africa (Sparrow, 1967; Hastenrath and Wilkinson, 1973) and through most of the belt between the Pyrenees and southeast Siberia, including Iran, Tibet, central China, Korea, and Japan (e.g., Zhigarev, 1967).

DISCUSSION

Relationship of These Features to Climate

Figure 13 shows the results of plotting the data for mean annual air temperature and mean annual precipitation for typical weather stations in the landscapes dominated by each of the three landscape types. Each occupies a discrete zone on the graph and there is remarkably little overlap. Note that the zones of distribution are merely picked out by drawing lines around the data points for all the weather stations where a particular landform dominates the landscape. No statistical manipulation has been performed. Part of the source data is listed in Table 1.

The overlap that does occur is probably due to a combination of five factors. First, the measurements of precipitation are not particularly accurate. There is little problem in measuring rainfall, but over half the precipitation is in the form of snowfalls. Snowfall is notoriously difficult to measure (Harris, 1972, 1973) and there is the additional problem that it can be redistributed by wind. Second, there is a considerable difference in the effect of a given amount of precipitation on coarse-grained soils, such as sands, and fine-grained soils, such as silts and clays. Third, many of the weather stations are located on valley floor sites as opposed to the mountain peaks. Fourth, the decision as to which of the three landforms is dominant in the landscape is not truly quantitative. Last, to form block streams or rock glaciers, suitable rock materials must be present. With more data, the degree of overlap should become apparent, and an overlap may occur between gelifluction and block stream-dominated landscapes.

Nonetheless, some broad relationships can be recognized. The landscapes of the warmer periglacial climates are dominated by gelifluction and debris flows. Rock glaciers are the characteristic landforms of landscapes in colder, wetter climates, whereas active block streams are the outstanding landscape features in cold, dry climates. At the same time there are zones of overlap around the field dominated by rock glaciers in Figure 13.

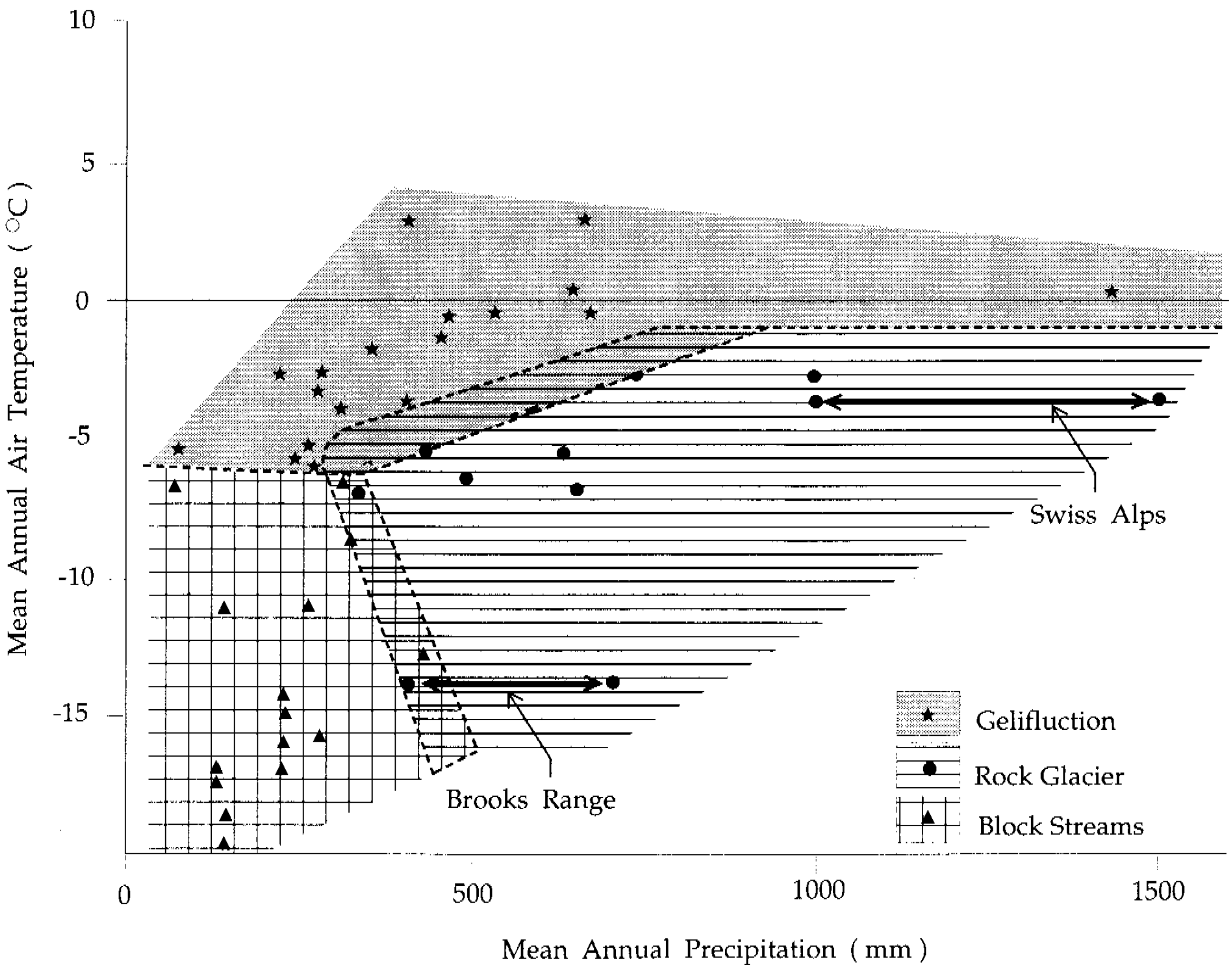

FIG. 13. Distribution of climatic parameters (mean annual air temperature and mean annual precipitation) for mountain landscapes dominated by active block streams, active rock glaciers, and active gelifluction deposits. Examples of typical data are found in Table 1.

TABLE 1. Typical climatic data for the three types of mountain permafrost landscapes

Dominant landforms in the landscape	Location	Mean annual air temperature (°C)	Mean annual precipitation (mm)	References
Rock glaciers	Tungsten, N.W.T.*	-5.7	645	AES, 1982:53
	Columbia Icefields, Alberta	-2.1	930	AES, n.d., a:47
	Tsischu, N.W.T.*	-8.3	c.600	AES, 1982:51
	Macmillan Pass, Yukon	-7.0	650	Wahl *et al.*, 1987
	U. Glaciological Station, Tien Shan, Xinjiang	-5.3	430	Shi Yafeng and Zhang Xiangson, 1984:9
	Dawson City, Yukon	-5.1	306	AES, 1982:5
	Spitsbergen	-1.5 to -4.8	400	Liestøl, 1976:9; Salvigsen and Elgersma, 1985:148
	Brooks Range, Alaska	-14.0	400-700	Ellis and Calkin, 1980
	Swiss Alps	-4.0	1000-2600	Haeberli *et al.*, 1992
	French Alps	-2.0 to -4.0	800	Haeberli *et al.*, 1992
	Central Andes (35°S)	-2.0	400-800	Corte, 1985
	E. slope, Central Andes (33°S)	-2.0 to -10.0	>950	Corte, 1985
	Sunshine ski area, Alberta	-6.9	>1000	Harris, 1989
	Parkin, Yukon	-6.4	473	Wahl *et al.*, 1987
Gelifluction	Kunlun Shan, Qinghai	-5.5	320	Cui Zhijiu, 1983
	Kluane Lake, Yukon*	-2.7	224	AES, 1982:10
	Haines Junction, Yukon*	-3.2	292	AES, 1982:8
	Burwash Landing, Yukon*	-4.4	301	AES, 1982:3
	Niwot Ridge, Colorado	-3.3	c.700	Benedict, 1970
	Aishihik, Yukon*	-4.4	256	AES, 1982:1
	Pink Mountain, B.C.*	-0.5	534	AES, n.d., b:176
	Muncho Lake, B.C.*	-0.7	459	AES, n.d., b:147
	Kapp Linne, Spitsbergen	-4.6	400	Åkerman, 1980
	Central Andes (33°S)	-0.2 to -4.3	400-800	Corte, 1985
	Marmot Basin, Jasper, Alberta	-1.8	600	Harris, 1989
Block Streams	Fenghou Shan, Qinghai	-6.5	50	Guo Dongxin *et al.*, 1993
	Kunlun Shan summit, Qinghai	-6.0	320	Guo Dongxin *et al.*, 1993
	Verkhoyansk, Siberia*	-16.0	127	Critchfield, 1966:396
	Aklavik, N.W.T.*	-8.9	226	AES, 1982:18
	Yakutsk, Siberia*	-11.1	348	Koeppe and De Long, 1958:331
	Cape Chelyuskin, Siberia	-13.8	96	Koeppe and De Long, 1958:330
	Bulun, Siberia*	-13.8	226	Koeppe and De Long, 1958:330
	Shingle Point, Yukon*	-14.5	214	Wahl *et al.*, 1987
	Komakuk Beach, Yukon*	-11.4	136	AES, 1982:11

*Denotes a valley-floor weather station.

Relationships of the Features to Latitude, Altitude, and Aspect

The three periglacial landscape zones as defined by climate show a marked latitudinal, altitudinal, and aspect zonation. The gelifluction landscapes tend to dominate at the lower latitudes, whereas active rock glaciers and block streams are found in more polar situations. Within a given mountain range, there is often a substantial change in climatic conditions with altitude and aspect. This can often cause a change in the dominant major zonal landform from one part of the mountain chain to another. Good examples of this are found in the Kunlun Shan and Fenghou Shan, along the Qinghai-Xizang highway, where gelifluction landforms are dominant at altitudes below 5000 m. Above this elevation and beginning on southwest-facing slopes, block slopes appear and quickly replace the gelifluction landforms.

The same situation occurs in North America. In the south-central portion of the Cordillera of the United States, rock glaciers tend to occur at high altitudes where the moisture regime is sufficiently humid to form interstitial ice, whereas gelifluction forms are dominant elsewhere in this region. In southwestern Alberta, active rock glaciers occur from Jasper northwards, but south of Banff National Park these are replaced by gelifluction forms. On Sheep Mountain, Kluane Lake, Yukon Territory, active block streams appear on south-facing slopes, while gelifluction forms occur on west- and northwest-facing slopes. On the east-facing slope, a rock glacier is found (Johnson, 1973), and others occur at wetter sites with a southwest aspect at lower elevations on the east side of the Slims River (Blumstengel and Harris, 1988). This is because Sheep Mountain has a climate that approximates the intersection of the three boundaries on Figure 13. Thus substantial changes in microenvironment can cause changes in the major zonal permafrost landforms within a given mountain range.

The Edaphic Factor

One of the major modifiers of the effects of climate on landforms and plants is the nature of the soil. Harris (1989) showed that the different landforms in the Plateau Mountain area compared with those in the Banff–Jasper parks in southwest Alberta appear to be correlated with the edaphic effects of the soil, specifically its drainage and moisture-holding capacity. The climate change from Jasper to Plateau Mountain is small, but the soils are different. At Marmot Basin, Jasper, the soils have a higher clay and silt content and hold moisture better, whereas those at Plateau Mountain contain primarily rock, sand, and coarse silt over fissured, porous limestone bedrock. The change from the rock-glacier-dominated landscapes in the mountain parks to the block fields at Plateau Mountain appears to be the result of these edaphic factors, and similar examples can be found elsewhere, for example in the Ogilvie Mountains at Engineer Creek at km 217, Dempster Highway (Harris *et al.*, 1983:79).

CONCLUSIONS

This zonation is important because it may enable geomorphologists to determine the nature of the local climate on the basis of which landforms are present in alpine permafrost areas. Once such a zonation can be firmly established, it will become possible to look at the distribution of these landforms in the recent geological past and interpret their presence or absence in terms of past climates. Obviously this has tremendous application in identifying and understanding past climatic changes in the alpine areas. Thus, where inactive rock glaciers occur in an area dominated by active gelifluction forms today, e.g., in the higher mountains of Arizona and New Mexico (Barsch and Updike, 1971; Blagbrough and Farkas, 1968), the climate must have been colder but moist at some time in the past. If these landforms can be dated, this will provide the age of the climate under which they formed.

The alpine zone of the mountain areas of the world are dominated by three distinctive landscape types, namely, active rock glaciers, active block streams, and gelifluction landforms. Landscapes dominated by rock glaciers are best known to English-speaking geomorphologists, being found in western Canada, Alaska, the Alps, the central Andes, the Tien Shan, and the Hindu Kush. Active block streams are widespread in the Urals, Siberia, the northern slopes of the Tibetan Plateau, and northeast Yukon Territory. The active gelifluction landscapes occupy most of the rest of the mountains, especially at low latitudes and in maritime areas.

When the climatic data for typical weather stations at these sites are plotted on a graph of mean annual air temperature (MAAT) and mean annual precipitation, they fall in discrete zones separated by limited areas of overlap. Gelifluction and debris flows are dominant in dry climates where the MAAT exceeds −5°C, but give way to rock glaciers in moist climates at a MAAT below about −1°C. There is a limited overlap between active block streams and rock-glacier-dominated landscapes between a MAAT of −5°C at 350 mm precipitation and a MAAT of −16°C at 480 mm, the active block streams occurring under cold, dry climates.

Two recapitulations of the climatic sequence occur: latitudinally and with altitude. In both cases, the climatic changes produce conditions favouring different dominant landforms with latitudinal or altitudinal changes. Thus rock glaciers may occur at the summits of mountains in otherwise arid areas, such as in the Tien Shan. Locally, the edaphic factor of soil moisture-holding capacity and drainage may cause modifications to the pattern, as in southwestern Alberta.

Correct identification of the landforms is essential; for instance, the "Kunlun Shan-type rock glacier" is actually a massive gelifluction deposit, while block streams must be carefully differentiated from stone runs. Care must also be taken to prove whether landforms such as rock glaciers are truly active.

ACKNOWLEDGEMENTS

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