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THE PERIGLACIAL BELT OF MID-LATITUDE MOUNTAINS FROM A GEOECOLOGICAL POINT OF VIEW

With 4 figures and 2 tables

Peter Höllermann

Zusammenfassung: Die periglaziale Höhenstufe der Mittelbreiten-Gebirge in geoökologischer Sicht

Für die Lage und Höhengliederung der heutigen Periglazialstufe in Mittelbreiten-Gebirgen bildet das periglaziale Kaltklima zwar eine notwendige Voraussetzung, aber keine hinreichende Erklärung. Entgegen naheliegender Erwartungen fällt die größte Höhenlage der Periglazialstufe mit der höchsten Intensität des Kaltklimas zusammen (Abb. 1 u. 3, Tab. 1). Die geoökologische Diskontinuität zwischen dem Waldgürtel und der exponierten Hochgebirgsstufe (Waldgrenz-Ökoton) erweist sich als die beste Annäherung an den Verlauf der Untergrenze der Periglazialstufe. Entlang eines erdumspannenden Latitudinalprofils bei 42–43 °N lassen sich unterschiedliche klimatisch-geoökologische Typen der Periglazialstufe und ihrer Höhengliederung unterscheiden (Abb. 3 u. 4, Tab. 2). Die Höhengliederung steht jeweils in enger Beziehung zu den Vegetationshöhenstufen und wird in trocken-kontinentalen Gebirgen mit geringem Deckungsgrad der Vegetation undeutlich. Bei kleinräumiger Betrachtung sind Morphodynamik und Verbreitungsmuster der periglazialen Kleinformen vornehmlich von lokalen geoökologischen Faktoren abhängig (Abb. 2). Die heutige Periglazialstufe

der Mittelbreiten-Gebirge muß in komplexer geoökologisch-synergetischer Betrachtung und nicht nur unter klimatisch-morphologischen Aspekten i. e. S. gesehen und untersucht werden.

Introduction

Periglacial studies appear to be a field for specialists in climatic geomorphology rather than an appropriate subject for broad geoecological research. Studies in periglacial environments of the arctic or of the high mountain type have generally concentrated on the obvious and fundamental influence of climatic factors on processes and landforms. This paper, which is focused on the present-day periglacial belt of mid-latitude mountains in the northern hemisphere, will point out, however, that the periglacial belt and its morphodynamics must be studied from a complex geoecological rather than merely from a climatic point of view.

A "standard model" of the periglacial belt in European mountains

Field studies in the Central Alps and in other European mountain groups (e. g. Central Pyrenees, Southern Scandinavia, Tatra Mountains) show a distinct altitudinal zonation of the periglacial belt, which is most obvious in the vertical arrangement of small-scale periglacial or cryogenic landforms. The diagnostic importance of meso-scale landforms for the delimitation and subdivision of the periglacial belt was discussed on a systematic base only recently (POSER a. SCHUNKE 1983), and needs further investigation.

A "standard model" of the altitudinal zonation can be derived from the regional field studies by generalization (e. g. POSER 1954, HÖLLERMANN 1964, 1967, FURRER 1965, STINGL 1969, FITZE 1969, RUDBERG 1972, 1977, GARLEFF 1970, HÖLLERMANN a. POSER 1977, KARRASCH 1977, KARTE 1979, KOTARBA 1979). The general problem how the altitudinal limits of the periglacial belt or sub-belts are defined (on the basis of landforms) was discussed in great detail in this literature and needs no further comments here.

Active periglacial landforms are absent or very rare in the timberline ecotone, while inactive or relict features may be common. The present-day periglacial belt is divided into two sub-belts. *The lower sub-belt of bound solifluction* begins with the lower limit of active solifluction (LLAS) some 50–200 m above the actual timberline, and has a vertical expanse of about 400–500 m. In this lower sub-belt forms of active and inactive solifluction (steps, benches, terraces, lobes) are covered by alpine meadow vegetation, while there is a general absence of active sorting processes. The fact that even in present-day periglacial environments relict and fossil cryogenic forms are abundant complicates the delimitation of the LLAS. A contemporary and measurable slow mass movement should be the strict criterion of activity. In this sense even old forms with an original formation up to a few thousand years ago can still be active.

The upper sub-belt of unbound solifluction and patterned ground is dominated by blockfields, débris, stone pavements, and bare bedrock. Sorting processes have produced stone-banked solifluction features as well as active patterned ground of various scales. The lower limit of active patterned ground (LLPG) divides the two sub-belts. Active rock glaciers or other indicators of discontinuous permafrost are generally confined to the upper periglacial sub-belt of the Alps and of similar mountains (see e. g. BARSCH 1978, HÖLLERMANN 1982). An *upper limit of the periglacial belt* results from the steep and rugged high mountain topography or from the extent of perennial ice and snow in the higher altitudes. The periglacial belt and the glacial belt overlap considerably, with the highest solifluction features well above the equilibrium line of the glaciers (up to 3400 m in the Central Alps).

In order to explain the altitudinal arrangement and zonation of the present-day periglacial belt, the assumption was widely accepted that the lower limit of active solifluction (LLAS) as well as the lower limit of active patterned ground (LLPG) are controlled directly by cold climatic factors. The altitudinal separation between timberline and contemporary frost features seems to signify that active solifluction is not limited by forest growth but directly by climatic controls (BÜDEL 1937, CAINE 1978). The sorting processes at a higher elevation evidently need stronger frost action than solifluction processes at a lower level (POSER 1954). If these assumptions of a direct climatic control of the LLAS and LLPG are correct, it should be possible to specify the controlling cold climatic factors and thresholds of the periglacial belt and its limits on a general base.

The climate at the level of the lower limit of the periglacial belt

In order to test the assumption of a direct climatic control, as many macroclimatic data as possible were calculated for the level of the LLAS in mid-latitude mountains. These data include the number of frost alternation days, the mean annual air temperature MAAT, the freezing index FI (= the annual total of the mean daily temperatures below freezing), the ratio freezing index/thawing index FI/TI, the mean annual range of air temperature MART, the mean air temperature of the warmest month (July) MJAT, the depth and duration of snow cover, and the mean annual precipitation sum MAP. Since the availability of the climatic figures differed for the various mountain systems, studies had to be concentrated on some of the best investigated mountain regions (Alps, Southern Scandinavia) and/or on some selected data as cold climate indicators. Nevertheless the basis for a statistical approach was heterogeneous and too small in some cases. Extrapolations from lower elevations bring uncertain data, but are unavoidable, wich explains some weak points of the statistical analysis. As expected the significance level is highest for the Eastern Alps, where the climatic materials and records are most complete compared to the other areas.

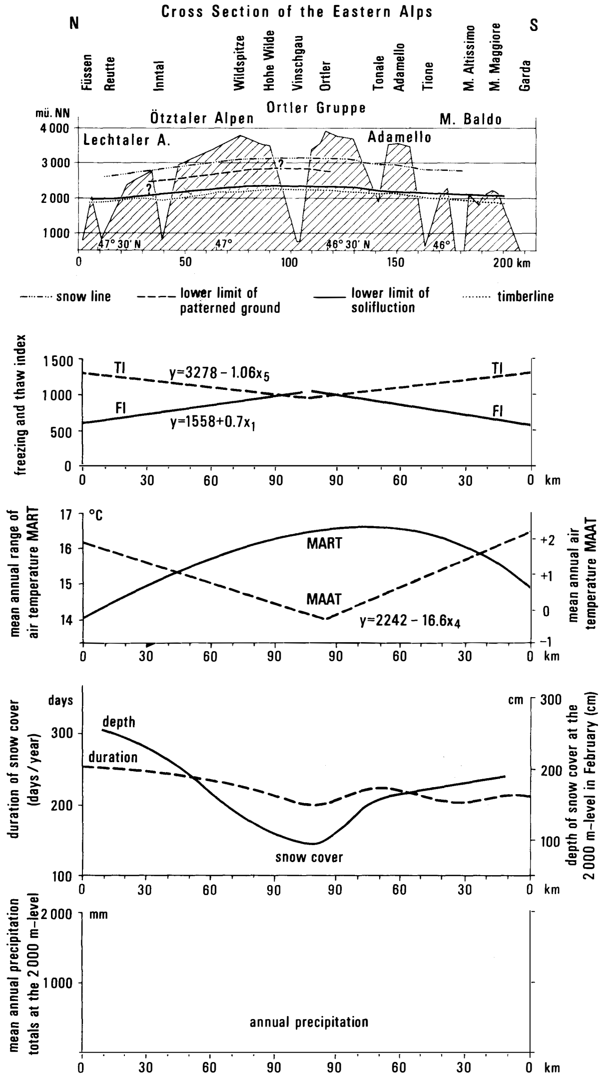

Fig. 1: Eastern Alps: Climate at the lower limit of the periglacial belt

Ostalpen: Das Klima an der Untergrenze der Periglazialstufe

The freezing index FI and the mean annual air temperature MAAT were used as macroclimatic indicators for the intensity of the cold climate. We should expect a low altitudinal position of the solifluction limit (LLAS), where the cold climate is the most intense, and where the ground is poorly protected by a snow cover. Fig. 1 gives a meridional cross section of the Eastern Alps and shows the culmination of the altitudinal limits in the Central Alps in relation to climatic parameters. Contrary to the evident expectation, the LLAS culminates where the freezing index FI is high and where the mean annual air temperature MAAT is low. The highest intensity of the cold climate and the lowest protection by the snow cover coincide with the highest altitudinal position of the periglacial belt.

These findings for the Alps were substantiated by further climatic calculations and comparisons for other mid-latitude mountains in Europe, Asia, and North America (see Table 1 and Fig. 3). As a general rule the lower limit of active solifluction finds its highest elevation at a given latitude, where the freezing index FI is high and where the mean annual air temperature MAAT as well as the depth and duration of the snow cover are low. The statistic correlations (Table 1) show a different significance level (not too impressive in some cases), but there are evident and consistent basic trends. The specific cold climatic conditions at the altitudinal level of the LLAS prove to be very different from region to region (Fig. 3). The results of the climatic analysis can hardly support the concept of a direct causal relationship between the altitude of the LLAS and cold climatic control factors.

It is a remarkable fact, however, that the mean temperature of the warmest month of July MJAT, at the level of the LLAS, comes close to 10 °C nearly everywhere in the cross-

Table 1: Elevation of the lower limit of active solifluction (LLAS) in relation to the temperature factor

Die Höhenlage der Untergrenze aktiver Solifluktion (LLAS) in Beziehung zum Temperaturfaktor

Regression	Correlation R	R Squared	Significance
x_1=freezing index (FI)			
EA[1] $y=1558+0.7\ x_1$	0.6138	0.3767	0.00004
SS[2] $y=\ 818+0.16\ x_1$	0.4949	0.2450	0.01324
LP[3] $y=2150+0.278x_1$	0.3477	0.1209	0.02988
x_2=mean annual range of air temperature (MART)			
EA $y=\ 338+11\ x_2$	0.4200	0.1781	0.00722
SS $y=\ 589+\ 2.18x_2$	0.4589	0.2107	0.02090
LP $y=2028+\ 2.13x_2$	0.1931	0.0373	0.15329
x_3=quotient freezing index/thaw index (Q)			
EA $y=1717+0.52\ x_3$	0.6789	0.4609	0.00000
SS $y=\ 872+0.106x_3$	0.4158	0.1729	0.03414
LP $y=2078+0.38\ x_3$	0.4596	0.2113	0.00531
x_4=mean annual air temperature (MAAT)			
EA $y=2242-16.6\ x_4$	-0.7057	0.4980	0.00000
SS $y=\ 987-\ 4.17x_4$	-0.4991	0.2491	0.01250
LP $y=2494-\ 9.3\ x_4$	-0.4291	0.1841	0.00899
x_5=thaw index (TI)			
EA $y=3278-1.06x_5$	-0.7465	0.5572	0.00000
SS $y=1419-0.41x_5$	-0.4717	0.2225	0.01787
LP $y=3888-1.1\ x_5$	-0.5967	0.3560	0.00025

Mean July air temperature (MJAT) at the level of LLAS

EA	9.2 °C	(n=33)
SS	10.0 °C	(n=20)
LP	10.4 °C	(n=28)
av.	9.8 °C	(n=81), standard dev. 0.89

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[1] EA=Eastern Alps

[2] SS=Southern Scandinavia

[3] LP=latitudinal profile at 40–44 °N

sections and test areas (see Table 1 and Fig. 3). Only a few significant exceptions exist, particularly in Mediterranean and arid mountains with a scanty vegetation cover. In conclusion, the lower limit of the contemporary periglacial belt shows better relations to summer temperatures than to cold climatic figures. That brings the further discussion to the role of the vegetation cover.

The influence of the vegetation cover in the altitudinal zonation of the periglacial belt

Since the isotherm of 10 °C in the warmest month (July) is well known as a rough approximation of the upper timberline, the assumption of a causal connection between the natural timberline and the LLAS seems reasonable, even though statistical correlation does not necessarily imply a proof of causation. Under natural and undisturbed conditions, which still prevail in many mountain regions of Western North America, the geoecological transition (ecotone) between the forest belt and the alpine belt brings a change in the morphodynamic system. Active solifluction features may appear above the timberline or in the timberline ecotone, where the stabilization and protection of the ground by forest growth and the balanced forest climate end, where the microclimate near the ground becomes more extreme, and where the geoecological pattern of the high mountain belt is highly diverse over short distances. In many mid-latitude mountains of North America, where the human impact on timberline is slight or nonexistent, field evidence shows a direct contact of active solifluction features with the timberline ecotone (Höllermann 1980; for different interpretation see Caine 1978). In the Alps and in other European mountains the general depression of the natural timberline by human activities has severed the original contact between the timberline and the LLAS here. If this were true, the "model" taken from the example of the European mountains would not be the original one as to the relation of LLAS and timberline.

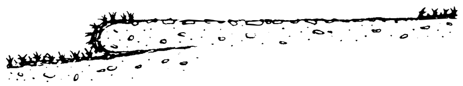
The conclusion from the field evidence as well as from the climatic studies is that the lower limit of the present-day periglacial belt in mid-latitude mountains is not caused directly by cold-climatic thresholds, but in the widest sense by the geoecological discontinuity between the exposed high mountain belt and the more protected forest belt. Experience reveals that the natural timberline ecotone gives a much better approximation of the lower limit of the contemporary periglacial belt than any cold climatic factor. The morphodynamic transition in the timberline ecotone takes place gradually rather than abruptly, however. The rates of denudation by active solifluction and frost creep are low, according to all recent field experiences (see Benedict 1970, 1976, Brundsden 1979, Washburn 1979, Harris 1981), and give no support to the thesis of some American geomorphologists, that the greater morphodynamic activity above the timberline brings about gentle alp slopes with timberline accordance (Daly 1905, Russel 1933, Raup 1951, Thompson 1962b, 1968). The time scale for vegetation changes and for the development of mesoscale landforms is different. In European mountains, where the depression of the timberline took place several hundred years ago, only small-scale periglacial features developed in the deforested and disturbed areas. For critical discussion of the problem of "timberline accordance" see Hewitt (1972), Caine (1978), Höllermann (1980), and Price (1981).

In the Central Alps and in similar European mountains the lower limit of active patterned ground (LLPG) coincides with the upper limit of the alpine meadow vegetation some hundred meters above the timberline. A dense turf cover and rhizosphere impede the sorting processes. A closed vegetation cover appears to limit the development of active patterned ground more than any cold climatic threshold. Where natural or man-made openings exist in the alpine or subalpine vegetation cover, small-scale patterned ground can be formed down as far as the timberline ecotone or even into the upper forest belt. Openings in the vegetation cover as potential sites for the development of minutely patterned ground may result from recent deglaciation in the glacier forelands, edaphic aridity of a permeable substrate, long-lasting snow patches, deflation, overgrazing and trampling, mining activities, and mountain tourism, particularly in winter ski areas. In some places the actual frost activity reaches down as far as 400 m below the upper timberline, when the vegetation cover is disturbed.

In some semi-arid mountains with sparse vegetation minutely patterned ground appears throughout the periglacial belt, as well as in the open upper forest belt, provided that substrate and soil moisture favour the sorting processes. On the eastern slope of the Cascades-Sierra System from Washington to California active small-scale patterned ground may appear as low as in the arid basebelt below the forest belt and far away from the high mountain belt.

In Western North America the high mountain vegetation above the timberline is more discontinuous and open than in European mountains of the central-alpine type. Some extensive mountain systems of Pacific North America give a rather bare impression with some scattered patches of plants in the alpine belt only. In consequence the altitudinal zonation of the periglacial belt is less distinct than in European mountains, and the differentiation of a lower limit of solifluction (LLAS) and a lower limit of patterned ground (LLPG) is hardly possible. Some of these mountain systems are relatively poor in active periglacial landforms, however (Höllermann 1980).

Sorting processes in the formation of patterned ground generally need no stronger frost action than solifluction or frost creep, but remain confined to more specifically geoecological conditions with bare, fine-grained, and moist substrate. The distribution of active patterned ground therefore is largely dependent on local geoecological factors. Active large-sized patterns up to several meters across are restricted to the higher altitudes, however, and probably need permafrost for typical development (Goldthwait 1976, Washburn 1981). Because of the different environments of formation it may be advisable to distinguish



Morphodynamic processes

- frost action, weathering
- thawing of frozen ground, thermoerosion
- mass-wasting (rockfall, creep, gelifluction etc.)
- nivation
- action of running water
- wind action

etc.

Impact of man and/or animals

- economic activities
- degradation of vegetation
- effects of skiing
- soil erosion
- trampling
- bioturbation

etc.

Topography

- slope gradient
- slope aspect
- slope profile
- slope position
- microtopography
- surface roughness
- topographic control of cold air drainage and water drainage

etc.

Climate

- zonal, local, microclimate
- frequency and intensity of frost action
- depth and duration of snow cover
- distribution pattern of snow
- effective precipitation
- atmospheric humidity
- solar radiation
- wind
- evaporation

etc.

Substrate

- bedrock, detritus, soil
- chemical and mineral composition
- structure (joints, fissures, etc.)
- texture (grain size, porosity, etc.)
- water holding capacity
- permeability
- frost susceptibility
- thermal conductivity
- organic matter
- colour

etc.

Time

- age of active landforms
- stage of development
- morphoclimatic period
- change in environmental factors
- change in processes

etc.

Vegetation

- density of vegetation cover
- external friction by vegetation cover and rhizosphere (binding effect)
- density and thickness of rhizosphere
- thermal insulation by vegetation and soil cover
- production of organic matter
- water consumption by transpiration
- microclimate of vegetation cover

etc.

Soil water

- effective water content
- surplus water
- waterlogging of bedrock, impermeable layers, or frozen ground
- thawing of ground ice
- edaphic aridity

etc.

Frozen ground

- permafrost (continuous, discontinuous, sporadic)
- seasonally frozen ground
- short-period frozen ground
- depth of freezing and thawing
- needle ice

etc.

Fig. 2: Factors in the development and distribution of periglacial phenomena
Faktoren der Ausbildung und Verbreitung von Periglazialerscheinungen

between a lower limit of small-scale patterned ground and the lower limit of large-scale patterned ground (Heine 1977, Hagedorn 1980).

The altitudinal zonation of the present-day periglacial belt in humid mid-latitude mountains is determined to a high degree by the type and density of the vegetation cover, which outranks the direct climatic control. In semiarid and continental mountains with open vegetation the altitudinal zonation of the periglacial belt becomes less distinct. Type and density of the vegetation cover are partly dependent on climatic factors, but many more geoecological factors are involved.

For detailed studies on vegetation as a factor in the dynamics of frozen ground see Tyrtikov (1964a, 1964b).

Examples for non-climatic geoecological control factors in the distribution of periglacial features

Substrate represents one of the most important factors of geoecological variations in the periglacial belt. One instructive example is set by the Limestone Alps, where the alpine vegetation tends to be open and discontinuous mainly because of the edaphic aridity of the permeable ground. Turf-banked steps and garlands (features of the "semi-bound" solifluction tpye) dominate, while on the bare surface between the turf-banked risers small-scale patterned ground is already a rather common feature in the lower periglacial sub-belt (e.g. Stingl 1969, 1971, Fritz 1969, 1976, Gračanin 1969). That means a lower limit of patterned ground as well as a less distinct altitudinal zonation in comparison with the Central Alps, the prototype of our "standard model". Substrate and not climate is the distinctive factor. Similar differences in the periglacial landform inventory and zonation between carbonate and siliceous substrates were reported from the Pyrenees, the Apennines, and from the Tatra Mountains (Höllermann 1967, Kelletat 1969, Midriak 1971). The substrate factor becomes effective in the periglacial morphodynamics particularly by grain size distribution, water holding capacity, shear strength, and frost susceptibility. Changes in substrate, which are common in most mountain environments, bring about changes in the type and distribution pattern of periglacial landforms, or may even cause an abrupt break in the altitudinal limits up to a few hundred meters.

The activity and mobility of small-scale periglacial features are highly dependent upon *soil moisture.* The availability of soil water in high mountain environments

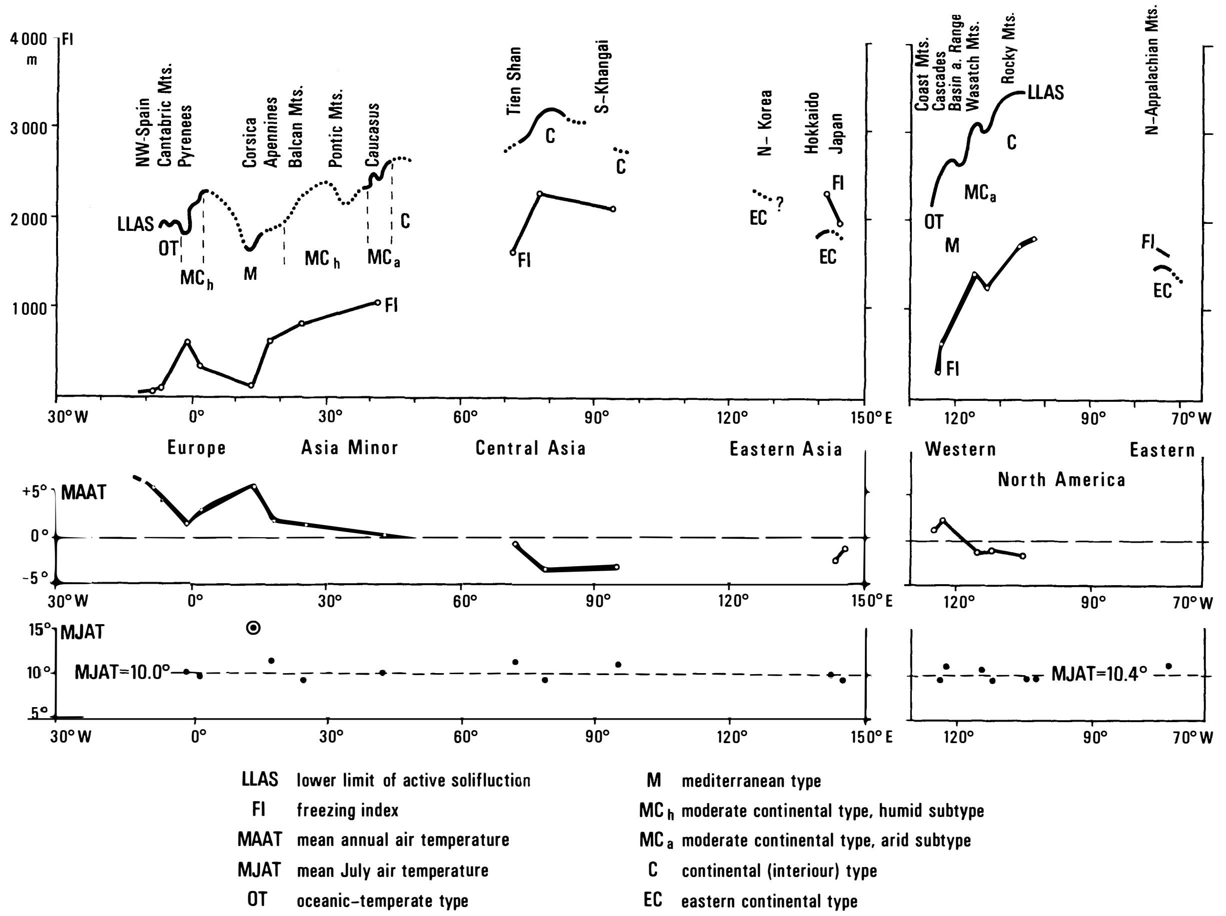


Fig. 3: The lower limit of active solifluction and some climatic parameters in a latitudinal profile at 42–43 °N

Die Untergrenze aktiver Solifluktion und einige klimatische Parameter entlang eines Latitudinalprofils bei 42–43 °N

depends not only on macroclimate, but also or even first of all on local conditions (as micro-topography, aspect, texture of the substrate, content of organic matter, snow distribution, permeability of the bedrock, and frozen ground).

The geomorphic role of small burrowing *animals* in the periglacial mountain environments becomes evident from several case studies (e. g. Price 1971, Thorn 1978, 1982). Evidence of modern *human impact* is obvious in winter ski areas of Europe or North America, where the local destruction of the natural vegetation cover presents the opportunity for small-scale patterned ground to develop even within the upper forest belt. The overgrazing of mountain pastures may result in a fragmentation of the alpine turf cover with gradual transitions between grazing steps and turf-banked solifluction forms on slopes.

All the examples illustrate that the development and distribution of active periglacial phenomena are dependent on a complex of climatic and non-climatic, of regional and site-specific environmental factors. Fig. 2 exhibits a rather incomplete inventory of the major groups of control factors and their subdivisions. Within the given macroclimatic framework – i.e. a periglacial climate as a minimum requirement – a wide variety of geoecological factors controls the formation and the threedimensional distribution pattern of periglacial landforms.

A circumglobal latitudinal profile for mid-latitude mountains

Spatial variations in macroclimate as well as in the combination of the various geoecological factors bring about different types of the periglacial belt. In the existing literature these types were mainly studied under zonal aspects along meridional profiles, while comparative studies of the typical variations along latitudinal profiles are less common (see e. g. Graf 1973, Karrasch 1977, Höllermann 1977).

To test the climatic-geoecological variation of the periglacial zonation in mid-latitude mountains, a circumglobal latitudinal profile at 42–43° northern latitude (with some minor deviations) was studied (Fig. 3). In these latitudes the absolute and relative proportion of high mountains is maximal. The comparative study had to be based on regional field experiences of the author as well as on the available literature. The circumglobal profile under discussion represents a rather provisional outline because of the heterogeneous and fragmentary stand of knowledge. Even so some general rules and conclusions become obvious.

The *lower limit of the present-day periglacial belt* shows a wave-like rise from the western margins to the interior of the continents, with culminations above 3000 m in the Tien Shan and in the Rocky Mountains, and sinks down again towards the eastern periphery of the continents (Fig. 3). The absolute altitudinal variation of the lower level comes close to 2000 m even at the same latitude. Comparable to the example of the Alps – already mentioned before – high altitude of the LLAS coincides with a high frost intensity (= high FI, low MAAT) and a low winter snow cover. Neither the freezing index FI nor the degree of thermal continentality (MART as indicator) give a satisfactory causal explanation for the position of the LLAS, however. July temperatures (MJAT) near 10 °C at the level of the lower limit of the present-day periglacial belt suggest a causal relationship to the timberline ecotone and thus to the vegetation as the essential limiting factor.

Along the west-eastern profile through a continent distinct *climatic-geoecological types and sub-types of the periglacial belt and its altitudinal zonation* can be distinguished, namely the oceanic temperate, the Mediterranean, the moderate continental, the continental interior, and the eastern continental type. Since a detailed characterization and explanation for the different types or sub-types would exceed the scope of our contribution, an outline of the basic characteristics has been summarized in Table 2.

As a general rule the altitudinal zonation of the present-day periglacial belt appears to be best developed in moderate continental mountains of the humid sub-type, while the zonation becomes less distinct with increasing continentality and aridity as well as under highly oceanic conditions. The lower limit of the periglacial belt is not sharply defined in arid and highly continental mountains. The increasing frost intensity from the oceanic temperate to the continental interior type becomes effective by a successive overlapping of different types of frozen ground: the short-term periodic, shallow freezing (including needle ice action), the deep seasonal freezing, the discontinuous and the continuous permanently frozen ground (see Table 2, last section). In highly continental mountains all these types of frozen ground are acting together (and did so in the past), consequently the inventory of active and inactive periglacial landforms is particularly manifold. Most of the general differences and spatial variations in the periglacial zonation are easy to explain by the specific interaction of the vegetation cover and the frost regime.

The oceanic temperate type of the periglacial belt shows a rather limited vertical expanse between the timberline and the snowline. The alpine fell-field vegetation has an open and fragmentary character. Solifluction features of the bound, semi-bound, and unbound types as well as small-scale patterned ground and nivation features, are closely associated within the narrow periglacial belt. The distribution pattern is split into a minute mosaic of various sites, controlled by local factors such as microtopography, substrate, aspect, wind exposure, vegetation, snow cover, and soil moisture. With increasing altitude a gradual decrease in the variety of periglacial features takes place, but the altitudinal zonation appears rather indistinct.

In the high mountains of the *Mediterranean type* (= subtropical type with winter precipitation) a wide scale of local and regional variations exists, particularly in relation to substrate and human impact. In some Mediterranean mountains the deforestation and heavy grazing was followed by a general depression of the lower solifluction limit (LLAS). The volcanic cones of the southern Cascades Mountains (U.S.A.), which may be attributed to the subtropical-„Mediterranean" type, present a very small inventory of periglacial features, primarily because of the edaphic aridity of the permeable pyroclastic substrate and the nearly complete lack of an alpine vegetation cover. Here some similarities with the mountains of the arid zone become obvious and the gradient to the arid-continental type is rather steep.

The humid sub-type of the *moderate continental type* with a well-developed altitudinal zonation of the periglacial belt in close relation to the vegetation distribution was already described as a „standard model" by the example of the Central Alps. The arid sub-type takes a transitional position and needs further investigations (Table 2).

The most extreme development of the *continental (interior) type* along the latitudinal profile is represented by the Tien Shan (see e.g. Gorbunov 1966, 1967, 1969, 1970, 1983, for the Sovietic section) and by the southern Khangai Mountains (Mongolia) a little north of the profile line (see e.g. Richter et al. 1961, Babiński a. Pękala 1975/76, Klimek a. Starkel 1980, Zietara 1981)[1]. The hypsometric change in the periglacial zonation takes place more gradually than in the mountains of the moderate continental type. Discontinuous permafrost extends down to the timberline ecotone, while sporadic permafrost occurs even in the forest-steppe belt. Consequently the lower limit of the present-day periglacial belt is difficult to define under highly continental conditions, particularly where the forest belt is replaced by an open forest-meadow – or forest-steppe belt. The lower periglacial sub-belt with alpine vegetation presents a large variety of active and inactive features of solifluction and patterned ground, including active rock glaciers and other permafrost indicators (Gorbunov 1983). The distribution pattern is largely controlled by local geoecological factors. Towards the upper sub-belt of bare blockfields and débris the variety and number of periglacial features decrease, though the processes of periglacial denudation, cryoplanation, and nivation appear to be particularly active here.

In the North American mountains of the continental (interior) type (e. g. in the Middle Rocky Mountains and

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[1] Some special literature references are given for mountain areas, which are not known to the author by personal field experience.

Table 2: Climatic-geoecological types of the periglacial belt in mid-latitude mountains
Klimatisch-geoökologische Typen der Periglazialstufe in Mittelbreiten-Gebirgen

TYPE OF THE PERIGLACIAL BELT (Regional examples in paranthesis)	CLIMATIC DATA for the lower limit of the periglacial belt	ALTITUDINAL ZONATION OF THE PERIGLACIAL BELT	CHARACTERISTIC PERIGLACIAL LANDFORMS	DISTRIBUTION OF PERMAFROST
OCEANIC-TEMPERATE TYPE (NW Iberia, Pacific Northwest of the United States) *OT*	MAAT +1/+4 °C MART <15 °C FI 0–600 Q(FI/TI) 0.0–0.4 MAP >2000 mm (winter maximum) Frost action restricted by deep snow cover	A.Z. rather indistinct. Limited vertical expanse of the periglacial belt between timberline and snowline. Local and site-specific factors are more important for the distribution of periglacial features than macroclimate and the altitudinal variation of climate.	Different types of small-scale solifluction features and of minutely patterned ground are found in close proximity to each other. The active periglacial landforms are not very frequent, however. Many nivation features.	No recent permafrost. Short-term periodic (shallow) freezing of the ground is most extensive, including needle-ice action.
MEDITERRANEAN TYPE or Subtropical Type with Winter Precipitation (Southern Pyrenees, Central Apennines, Southern Cascade Mountains) *M*	MAAT +2/+6 °C MART 12–18 °C FI 0–300 Q(FI/TI) 0.0–0.25 MAP variable from region to region, mostly lower than in mountains of the OT-type (winter maximum)	A.Z. is evident in the highest mountain groups. *Upper sub-belt:* bare solifluction features and patterned ground; few medium-sized forms resulting from seasonal freezing. *Lower sub-belt:* turf-banked solifluction features and small-scale patterned ground.	Small turf-banked solifluction garlands or terracettes and minutely patterned ground dominate.	No recent permafrost. Deep seasonal freezing of the ground may appear in the upper sub-belt. Short-term periodic (shallow) freezing of the ground is dominant.
MODERATE CONTINENTAL TYPE *humid sub-type* (Central Alps and similar mountain groups in Europe) *MCh*	MAAT −1/+1 °C MART 15–17 °C FI 600–1200 Q(FI/TI) 0.6–1.3 MAP 1000–1500 mm (mostly summer maximum)	Well-defined A.Z. in close relation to the vegetation belts. *Upper sub-belt:* bare solifluction features and patterned ground, active rock glaciers. *Lower sub-belt:* turf-covered (bound) solifluction features are dominant.	Small and medium-sized features of solifluction and patterned ground. Acitve rock glaciers in the upper sub-belt.	Permafrost in the upper sub-belt. Deep seasonal freezing and short-term periodic (shallow) freezing of the ground throughout the periglacial belt.
MODERATE CONTINENTAL TYPE *arid sub-type* (Central Caucasus, some mountain groups of the Basin and Range Province, United States) *MCa*	e.g. Baksan Valley and Mt. Elbrus, Central Caucasus: MAAT about 0 °C MART 19 °C FI about 1100 Q(FI/TI) about 1.0 MAP about 800 mm (summer maximum)	A.Z. less distinct than in the humid sub-type, mainly because of a less continuous vegetation cover. Transitional position between the MCh- and the Ci-type.	Transitional position between MCh and Ci needs further investigation	
CONTINENTAL TYPE or interior type (Middle Rocky Mts. and parts of the Southern Rocky Mts., U.S.A.; Tien Shan, Southern Changhai Mts., Central Asia) *Ci*	MAAT −1/−4 °C MART 20–28 °C FI 1300–2400 Q(FI/TI) 1.3–2.4 MAP 250–600 mm (Central Asia) 500–1000 mm (Rocky Mts.) (summer maximum)	A.Z. is evident, but the hypsometric change is less distinct and takes place more gradually, whilst the altitudinal limits of the periglacial belt are less clearly defined than in the MCh-type. *Upper sub-belt* with bare blockfields and debris contains considerably less distinct periglacial features than the *Lower sub-belt* with its multiform inventory of	A great variety of active and inactive features of solifluction and patterned ground, including rock glaciers and other permafrost indicators. A decrease of the periglacial landform inventory is observed towards the upper sub-belt.	Continuous permafrost at the highest altitudes. Discontinuous permafrost stretches down to the timberline ecotone and locally even into the forest belt. Deep seasonal and short-term periodic freezing of the ground occurs throughout the periglacial belt and down to the forest or forest-steppe belt.

		active and inactive periglacial landforms. The lower limit of the present periglacial belt is not sharply defined.		
EASTERN CONTINENTAL TYPE (highest mountain groups of New England, U.S.A., mountains near the eastern periphery of Asia, esp. Hokkaido, Northern Japan) *EC*	MAAT −0.9/−3 °C MART 24–30 °C FI 1600–2300 Q (FI/TI) 1.2–2.0 MAP >1000 mm (summer maximum, but plenty of winter snow) Frost action on the ground restricted by deep snow cover and dense vegetation.	A.Z. is not clearly developed and remains incomplete because of the low altitude of the mountains. Local and site-specific factors are more important than the altitudinal variation of macroclimate. The lower limit of the belt with active periglacial features is rather indistinct and reaches down into the forest belt.	The periglacial landform inventory is poorly developed. Turf-banked solifluction garlands or terraces and small-scale patterned ground are dominant. Many inactive periglacial landforms in the New England Mts.	Discontinuous permafrost shows a more limited and irregular distribution than in the mountains of the Ci-type. Some patches of sporadic (fossil?) permafrost occur in the forest belt. Short-term periodic freezing and needle-ice action can be effective down to a very low altitude.

Abbreviations (Climatic data):
MAAT = mean annual air temperature
MART = mean annual range of air temperatures
FI = freezing index (annual total of mean daily temperatures below the freezing point)
Q = quotient freezing index/thawing index
MAP = mean total of annual precipitation

parts of the Southern Rocky Mountains) the general altitudinal zonation of the periglacial belt looks similar to the mountains of Central Asia, though the degree of continentality is less extreme. For the intensively studied Colorado Front Range see e. g. Benedict 1970, Ives 1973, 1980, Höllermann 1980).

The *eastern continental type* presents no clearly developed altitudinal zonation. Active periglacial features as turf-banked terracettes or small-scale patterned ground appear, where the protection of the ground by dense vegetation or deep snow cover is reduced or lacking, even in openings of the forest belt. Thus local and site-specific factors are more important for the distribution pattern than macroclimate or altitudinal variation. Discontinuous permafrost shows a more limited and irregular distribution than in the mountains of the continental (interior) type. Detailed information about the periglacial belt in mountains of the eastern continental type can be taken from the special studies of Antevs 1932, Thompson 1960/61, 1962 a, Koaze 1965, Fukuda a. Kinoshita 1974, Ellenberg 1974, 1976 a, 1976 b, 1977, Koizumi 1980, Nogami et al. 1980, or Ono et al. 1982.

The succession of the different types along the profile (Fig. 3) shows an asymmetric distribution, in which the oceanic to moderate continental types of the periglacial belt occupy the western parts and the continental types hold the central and eastern parts of the continents. Though all the different types of the periglacial belt need a periglacial cold climate as a minimum requirement, the cold climatic conditions are not the direct limiting factors for the periglacial zonation in mid-latitude mountains. This becomes evident from the schematic latitudinal profile for a model continent in Fig. 4. For better comparison all altitudinal limits are drawn relative to the timberline ecotone (= horizontal line in Fig. 4) as the best approximation of lower limit of the

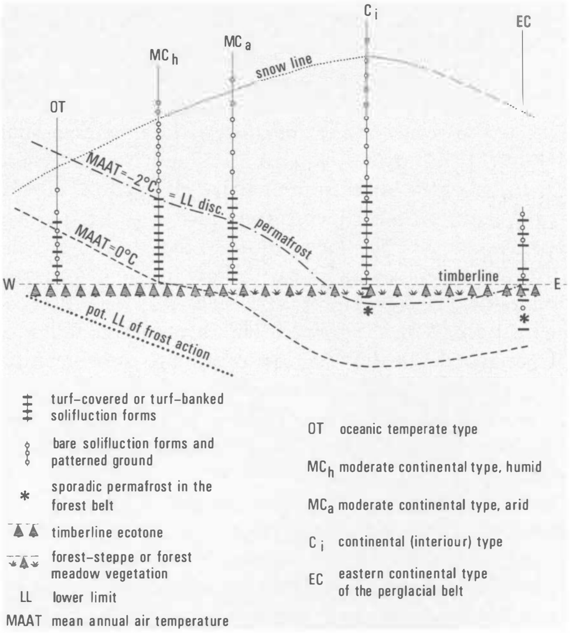

Fig. 4: Schematic profile of the periglacial belt for a model continent at 40–45 °N (all altitudinal lines are drawn relatively to the timberline as base level)

Schematisches Profil der Periglazialstufe für einen Modellkontinent bei 40–45 °N (alle Höhengrenzen sind relativ zur Waldgrenze als Bezugsbasis dargestellt) periglacial belt. The simplified profile illustrates very clearly, that the cold climatic limits have a steeper gradient than the limits of the periglacial belt. Forest growth (or elsewhere aridity) are more effective limitations for active cryogenic processes than the potential lower limit of frost action or other cold climatic thresholds.

The timberline ecotone sets no absolute limit to the periglacial morphodynamics, however. Particularly in arid and continental mountains open forests or forest-meadow stands and active periglacial features can exist side by side in a wide transition belt and the lower limit of the periglacial belt becomes rather indistinct. The altitudinal zonation of the present-day periglacial belt shows a close relation to the vegetation belts. Consequently periglacial zonation is less distinct in continental and arid mountains, where the vegetation factor is less important (Fig. 4).

According to a widely accepted opinion the periglacial belt of the mid-latitude mountains finds its regular vertical expanse between the timberline and the snow line. This general statement should not be mistaken for a definition, however. Both altitudinal limits may be clearly surpassed by the actual distribution of active periglacial features, namely in continental or arid mountains.

Conclusions and final remarks

The study of the present-day periglacial belt of mid-latitude mountains leads to the conclusion, that the existence of a cold climate of one type or another is a minimum requirement only. Contrary to evident expectations the highest altitudinal position of the present-day periglacial belt coincides with the highest intensity of the cold climate and the lowest protection of the ground by the snow cover (Fig. 1 a. 3). The mean air temperature of the warmest month of July (MJAT) comes close to 10 °C nearly everywhere at the level of the lower limit of active solifluction (LLAS). So the natural timberline ecotone proves to be the best approximation of the lower limit of the periglacial belt, with a few exceptions only, particularly in arid-continental mountains. The closed forest belt sets limits to the effects of the frost action on the ground. The altitudinal zonation of the periglacial belt shows a close relation to the vegetation belts. The altitudinal zonation of the periglacial processes and landforms becomes less distinct where the alpine vegetation cover is open or lacking (continental and arid mountains).

Some medium- and large-scale periglacial landforms (as large-sized stone polygons, large non-sorted polygons, active rock glaciers) show a closer and more direct relation to cold climatic limits or thresholds, because their formation needs a permafrost environment (see e. g. Harris 1982, Washburn 1981). Systematic studies on meso-scale landforms of the periglacial belt are rather rare up to now, however (see e. g. Poser a. Schunke 1983).

Different climatic-geoecological types of the contemporary periglacial belt and its altitudinal zonation can be distinguished along a circumglobal latitudinal profile at 42–43° northern latitude (Fig. 3 and Table 2). The classification in the zonal and global dimension is based primarily on the climate-vegetation complex. Here some general rules and distribution patterns become apparent by generalization and comparison.

A closer understanding of the periglacial morphodynamics and the various interacting control factors requires a small-scale, topological research, however. In the topological dimension the structure and small-scale distribution of periglacial phenomena appear to be largely determined by site-specific and local geoecological factors, such as topography, substrate, aspect, wind exposure, soil moisture, etc., as well as by the effects of human activities (Fig. 2). The individuality of the actual distribution pattern in the periglacial belt requires detailed environmental studies and measurements on a geoecological-synoptic basis rather than studies which follow the classical approach of climatic geomorphology in the strict sense.

Periglacial research should make full use of the methodical and substantial instruments of geoecology, following the synoptic approach of Carl Troll, who already explained arctic solifluction features by the interaction of ecological factors ("Zusammenspiel ihrer ökologischen Faktoren") and called for ecological methods to find out different ecotypes of frozen ground (1944, p. 620). These suggestions became realized to some extent only recently, while most of the classical periglacial research in the post-World-War II-period was of descriptive and deterministic rather than of a geoecological character.

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