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LANDFORM EVOLUTION IN MOUNTAIN AREAS

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CONDITIONS OF ALPINE GULLY DEVELOPMENT AS EXAMPLIFIED BY THE AUSTRIAN ALPS

Abstract. Many slopes in the alpine environment are characterized by dense gully systems which provide considerable material transports, e.g. torrential transports and debris flows. Based on map analysis and field studies the importance of erosional slope development is evaluated on a cross section of the Eastern Alps. From the total mountain areas 4 to 13% is controlled by strong developed gully patterns. Characteristics of gully morphometry and associated relief features show that gully develop under a wide range of rock conditions, precipitation regimes, geomorphic predisposition and human influence. Alpine gullies take on an important role in process interactions between slopes and valley bottoms and apart from a vast number of local differentiations process interactions on gully controlled slopes differ essentially between the northern and the southern slope of the alpine chain.

Key words: alpine gullies, debris flows, alpine mountain slopes, channel network, slope processes

INTRODUCTION

Every year the Alps are hazarded by numerous events of debris flows and exceptional events caused by torrents. For this reason, former geomorphologists (e.g. Stiny 1910) have dealt with processes of accelerated slope erosion. These earlier works focussed on origins, effects and processes of debris flows and torrent activities. At the same time mass movements such as rockslides, rock avalanches and other slope failures and finally snow avalanches, endanger also villages and agricultural areas, they became a central topic of investigations directed by institutions of torrent and avalanche control (Bunza et al. 1976; Kronfellner-Kraus 1982). In this connection, for example, H. Aulitzky (1986) stated that in some regions of Austria, the percentage of alpine torrents with debris flows-activity is higher than 60%. In more recent studies, the relationships between mass wasting on slope and processes of linear erosion were given more priority (Briem 1988; Rieger and Becht 1997; Dalla Fontana and Marchi 2001). Debris flows are common single events, but the paths of debris flows are often concomitant with the already existing network of gullies on a slope. With a higher degree of the drainage density on slopes, over a longer period of time, the transports of material considerably increase (Delannoy and Rovéra 1996).

Although many of the steep slopes in the Alps are structured, by linear incisions, the causes of their development, their actual process response systems and also their morphometric attributes still remain obscure and have not been explored, so far. Their particularity is underlined by the fact that most of the gully systems connect the periglacial environment above the upper tree line with the valley bottoms crossing the subalpine and montane belt on generally short courses. Therefore the material transfer can take place rapidly both in isolated ravines and in systems of ravines which will lead to an accentuated slope pattern. The slope areas which are affected by closed patterns of gully systems, vary in size from a few hectares to over 5 square kilometres. Since the knowledge of such ravine systems has been performed only in limited areas with active debris flow events this investigation aims to undertake a large scale study of slopes with strongly developed gully systems along a transversal profile of the Austrian Alps, by examining morphometric data, sequences of forms and interrelationships of processes.

The knowledge about gully development is mainly derived from investigations in semi-humid and semi-arid regions in which the precipitations are determined by a high variability and high intensities. Relief forms of badland-like gully dissection have been also reported from humid regions. Between systems of intense gullying in the Alps and the already well studied badland-gullies have been found surprising similarities (Morawetz 1968; Heede 1974). Part of alpine gullies primarily in areas with accelerated erosion, which result in earth pyramids (Becker 1963) show a tight relationship to badlands, regarding both relief parameters and processes (Briem 1988). The degree of vegetation covering on gully sides generally represents an important indicator for the intensity of erosion.

It can be concluded that the alpine environment exerts particular differentiations of gully parameters, processes and development. Therefore it is a further objective of this study, to elucidate in exemplary regions how the sequences of processes on the sides of the gullies, on gully heads and in the channel ways do occur. Such an investigation will also indicate to the importance of rock-conditions, climatic conditions and human control as parameters for the development of gully systems on alpine slopes.

Regarding the basic considerations about form and development of gullies (Montgomery and Dietrich 1994), it will be a goal of this study to characterise on one hand the sequences of the forms of the incisions, on the other hand to exemplify their hierarchical arrangement. Within the network of gullies, only the first order segments have a specified source area (Marcus 1980). Forms and processes on the channel heads and sides are coupled to those in the main channel by process response systems (Chorley and Kennedy 1971). Every incision of the channel bed causes increases of the slope angles on the sides as well as on the channel head (Dietrich and Dunne 1993) and also increases erosion intensity. Dependent on the density of the gullies and the depth of the incisions a more or less tall slope area is directly connected to the gullies. In this way the erosion on a slope is controlled to high percentage by processes inside the gullies. Such slopes undergo, as reported by A. Wirthmann (1977), an "erosive slope development".

On the steep slope areas of alpine slopes the channels form segments of first to third order. The channel systems can split up, the slope area directed to the valley (exposed), into a variety of parallel stripes which have an orientation that is directed to the channels. Consequently, as important morphometric indices can be classified, the channel gradient (σ), the inclination of the gully sides (θ), the incision-depth of the gullies within the slope (h), the width of the gullies (2w) and the spacing between the gullies (e). Because of the steep channel gradient, an additional increased steepness of the gully side walls is the consequence (Fig 1).

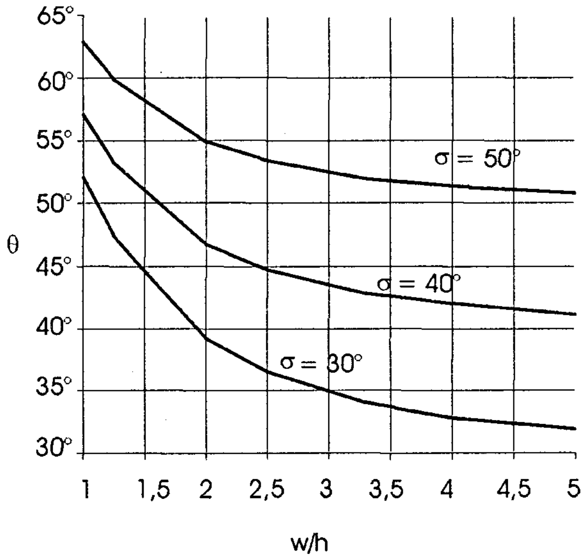

Fig. 1. Gully side slope-angles (θ) related to channel gradient σ, and sharpness of gully incision gully depth (h) and gully width (2w) (Stocker 1997)

J. Büdel (1948) differentiates, regarding the shaping of the mountain ranges, hierarchically dissected slope forms with deeply incised channels from parallel reaches with gradients that equal the accompanying main slopes. Nearly all exact analyses of the channel networks on alpine slopes demonstrated that even in the upper areas of the slopes hierarchically arranged networks of 2 to 3 orders do exist and that the channel gradients deviate only in the deeper parts of the slopes from their general inclination. As soon as the channel gradient strongly deviates from the inclination of the slope, a deep incision develops and a new formation of a valley, corresponding to the d-type drainage described by T. Oguchi (1997).

DATA COLLECTION AND METHODS

The basic elements for the collection of data was the *Austrian Map Version 2.0* (2002) which can be utilized to perform exact and rapid determinations of square areas and lengths; moreover enlargements of the topographical map (ÖK25V) to a scale of 1 : 10,000 can be achieved. The curves with a contour interval of 20 m are very suitable to trace the values of slope inclinations and to determinate the length and widths of segments within a gully system. More detailed analyses, such as the kind of gully heads, the exact course of channels with low incisions or evaluations of the activities of the gully sides were performed by data obtained from aerial photographs and field examination. Indications about the character of discharge (perennial intermittent or ephemeral) require longer periods of field measurements.

If the slope length increases the channel gradient becomes almost smaller than the half of the inclination of the adjacent slopes, and this enable deeply enoched channels. Such areas with V-shaped dissections were excluded. By registration of 20 gully systems on alpine slopes bifurcation ratio R_b and the (R_L) were investigated using the order system of A. N. Strahler (1969).

The density of the network is generally specified as length with reference to the area. By this calculation the channel segments of all the present orders are included. To achieve an improved evaluation in a differentiated network of slope gullies, additional measurements of density referring to the order of the channel trunks were conducted, which result from measurements of the mean distances between the channels, typical for a particular order. The obtained data can be estimated as useful supplementary parameters, because the density of the gullies is strongly related to the depth of incision.

The sharpness of the incisions of the gullies on a slope has an important control function for the intensity of slope erosion (Oguchi 1997) and depends on depth, width and general slope inclination (e.g. Fig. 1). Measurements were applied only for 3rd order channels taking from 5 cross-sections and using the contour intervals of 20 metres. From this data sets, the mean maximum slope angles were derived. For the less incised gullies only an approximate calculation of the side slope angles is achieved (Stocker 1997).

STUDY AREAS

Gully development occurs in the Alps under extremely different conditions. Because of, it has been a point of view to compare first a sufficient number of examples for getting a general idea and than, to analyse more exactly few selected study areas. Therefore only a limited number of rock conditions, climatic conditions and altitudes was taken into account. Of those, study areas were pointed out along a north-south-cross section of the Austrian Alps from the margin of the

Northern Calcarous Alps to the Periadriatic fault on the southernmost border of the Upper Austroalpine cover. Six mountains with an area of nearly 3,800 km² were analysed for to estimate the importance of intense gully erosion. For a total of 237 slope-areas with about 300 km² area, data sets were collected. The study areas are the following (Fig. 2):

area 1: Osterhorn Group in the Northern Calcarous Prealps near Salzburg as the first example from the Upper Austroalpine cover (Tyrolic Nappe Complex),

area 2: Dientner Mts. from the Graywacke Zone,

area 3: Northern Sonnblick Group (between the valleys of Fusch and Großarl) as an example of Penninic unites of the "Tauern Window",

area 4: Sadnig Group and Deferegger Mts. from the southern border of the "Tauern Window" belonging to the higher mountains of the Austroalpine crystalline complexes, respectively,

area 5: Kreuzeck Group, also from the Middle Austroalpine basement, but with lower altitudes than in area 4,

area 6: Gailtaler Alps (central zone between Gailberg-Saddle and Windische Höhe) as the second example for the Upper Austroalpine cover (Drau-range).

RESULTS

IMPORTANCE OF ALPINE GULLY EROSION

Examinations of the study areas (Table 1) show, that in the central part of the Gailtaler Alps (area 6), especially in the zone of the triadic dolomites, c. 13% of the mountain area is affected by intense slope erosion, whereas in the high mountain environments of the Sonnblick-Sadnig Group (area 4) and the central part of the Defregger Mts. this percentage ranges only near 4%. In the centres of these mountain chains in which glacial erosion was strongest, slopes with an intense gully incision are only rarely present. The northern parts of the Hohen Tauern (area 3) have a division into 20 to 25 km long and deep valley bottoms; the slopes with the dominant gully development concentrate along the valley-sides, however, the central Sonnblick region, manly shaped by glacial erosion is nearly free of gully eroded slopes.

Within the Graywacke zone (area 2) the slopes with dominant gully erosion assemble around the crests with the highest peaks in the central parts of the mountain group. The scouring effects of the former glaciers have led to a steepening of the valley heads generating a starting point for the successive development of gully systems. On more flat and long stretched slopes, the fluvial drainage-type prevails. Although the areas of deep-type drainage were not recorded in this analysis, a relatively high percentage of areas, c. 10%, are slope areas with distinct gully erosion.

In the Northern Calcareous Alps, slope assemblages are strongly governed by structure and lithology. Many slopes are divided by cliff faces and often rock

Table 1

Areas controlled by gully patterns along N–S profile of the Austrian Alps

Study areas	Total area [km^2]	n	Gully-slopes [km^2]	Percent	Mean areas [km^2]	Mean length [m]	Top means [m]	Base means [m]	Relative relief [m]	Slope angle
Osterhorn Group	504.92	36	39.77	7.9%	1.11	956	1,540	916	622	33.7
Dientner Mts.	286.75	26	29.68	10.4%	1.14	1,082	1,765	1,249	516	26.3
Sonnblick N	892.92	45	61.89	6.9%	1.37	1,382	2,257	1,382	867	32.1
Sadnig/Defer. Mts.	906.42	24	38.01	4.2%	1.47	1,401	2,487	1,401	867	31.6
Kreuzeck Group	569.28	47	65.64	11.5%	1.40	1,343	2,210	1,343	866	32.2
Gailtaler Alps	631.11	59	82.57	13.1%	1.42	1,071	1,750	1,193	678	29.9
Total	3791.40	237	317.55	8.4%	1.32	1,206			736	31.0

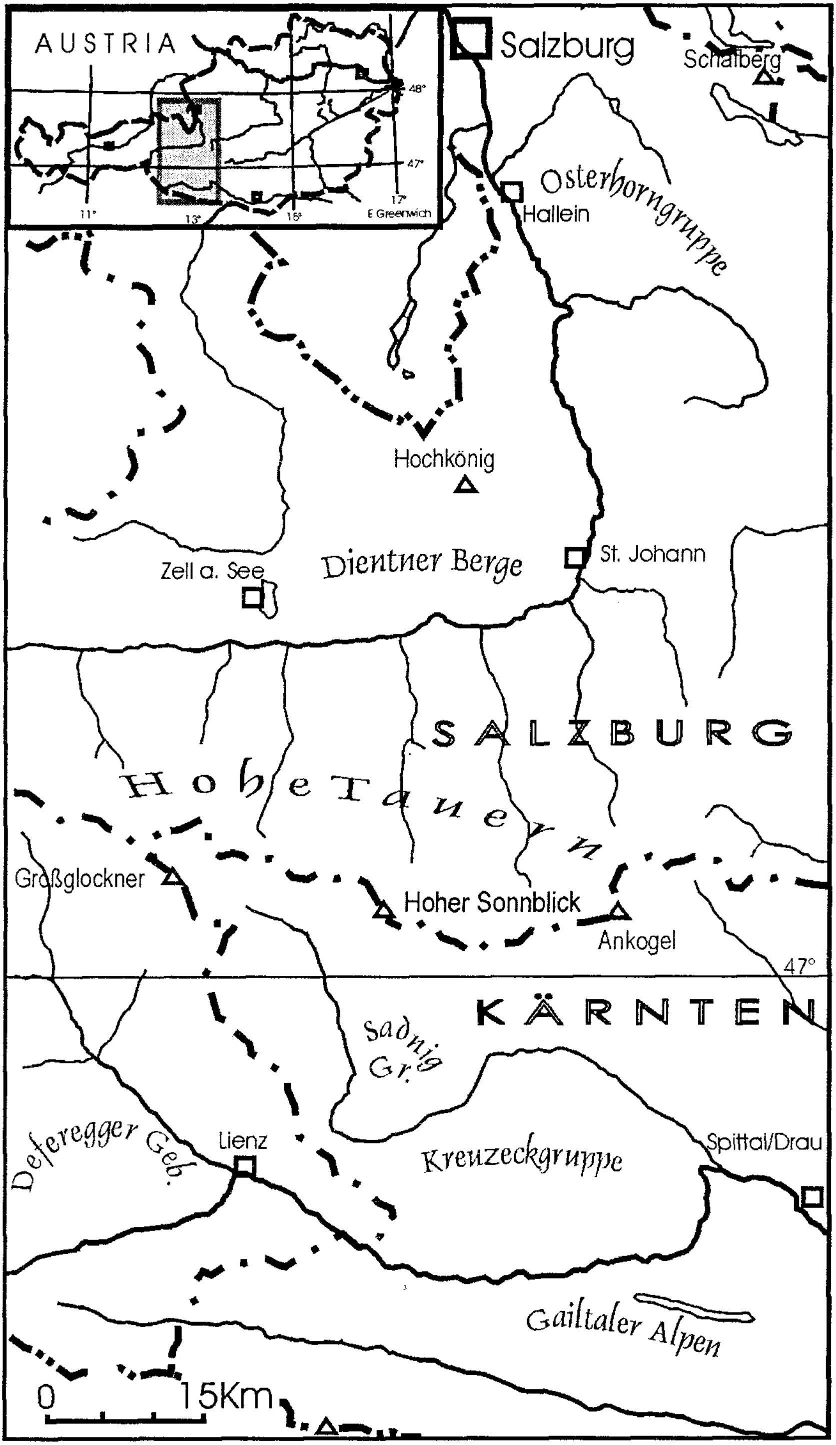

Fig. 2. Study areas

slope failures emerge. Gully development takes place under specific conditions. Therefore, in the present analysis the conditions of erosive slope evolution were limited to the Northern Calcareous Prealps (area 1), where the geological predisposition is simpler and easier comparable with those in the other mountain chains. Like in the Graywacke-Zone, the erosive slope development is concentrated to the central parts of the mountain chain, in which 25% of the total slope area is dominated by intensive gully erosion. Simultaneously, the highest average slope angles (33,7°) were measured there. This is caused by the fact that the valley floors have very low gradients, producing high relative relief in the interior. Extremely steep cirques slopes, between a bottom altitude of about 800 m up to c. 1,700 m on top, are created.

In the Southern Calcareous Alps (area 6) slope areas with prevailing gully erosion concentrate along the main crests. The more complex rock conditions give rise to an exceptional variability of gully development. On the north-eastern slopes, which have part of the schist-zone single gullied slopes, achieve areas up to a dimension of 6 km².

The medium relative relief of all investigated slopes are between 516 and 866 m, although the mountain crests which limit the erosion slopes on top, are in the Central Alps about 1,000 m higher than in the Northern Calcareus Prealps. Very low differences also do exist between the medium areas of the slopes that are affected by gully erosion.

MORPHOMETRY OF GULLY SYSTEMS ON ALPINE SLOPE

Most of the analysed gully systems occur on slopes with a relative relief that is higher than 600 m. Slope lengths are generally between 1,000 and 2,000 meters and the most common slope angles range between 30° and 40°. Well developed gully networks reach a trunk-channel of the 3rd or 4th order, but the majority of area is occupied by 1st or 2nd order gullies. Bifurcation ratios decreasing rapidly from 4–6 between the 1st and the 2nd order to 2–4 between the 2nd and the 3rd order, representing a clear deviation from the usual straight line regression. It can be deduced, that on steep slopes incision of the segments of the respective higher orders occurs stronger than that of the lower orders. Considering a limited slope length, 3rd order segments which have incised deep ravines can hardly meet each other. Mostly they generate torrents. If the basal rocks consist of weaker strata (area 1), the effect of accelerated incision of higher order segments is enhanced and the length of the respective higher segments become smaller. It has been proved that length ratios have considerably smaller values than normally occur in fluvial networks. This implies that gully-segments of the respective lower order have relatively higher lengths than those of the higher orders. The fact that a large number of gully patterns are found on head slopes which have a concave planar form, increases the tendency of extended development of 1st to 2nd order gullies.

Density values are generally between 5 and 12 km/km², locally in gully-networks of the first stages these values are strongly higher than 20 km/km². Density measurements that distinguish between the respective orders of gully gave more characteristic values (though they do not include source areas). Mean values of 22 km/km² for the 1st order gullies and 8 km/km² for the 2nd order gullies were recorded.

The long-profiles of 1st order gullies are generally well adapted to the inclination of the surrounding slope areas (on average 35° to 45°). Equally in the Northern and Southern Calcareous Alps (area 1 and area 6) the long profiles of the 2nd order gullies differ only insignificantly from the surrounding slope-profiles. However in the metamorphic rocks the difference between the channel-long profile of 2nd order gullies become about 5–7° lower that those of the surrounding slopes. The gradients of 3rd order channels are significantly gentle in comparison with the slope profiles, in average hardly above the half slope angles. Especially in soft bedrocks (phyllites, graywacke-rocks) 3rd order channels cannot be estimated fully as parts of the slope system, but as a component of the fluvial system.

CONDITIONS FOR THE DEVELOPMENT OF SLOPE CHANNEL SYSTEMS

Structural conditions

The most important conditions for the development of channel systems on slopes are homogenous, relatively less resistant rocks in combination with a sufficient slope stability. In area 1 flat to moderate dipping of marly limestones (Oberalm-strata) underlet by thin bedded marls and slates (Tauglboden-strata) grant high stability. Oberalm-strata which are about 600 m thick, contain two or tree resistant up to 20 m thick beds of turbidites (olistostromes) (Plöchinger 1983). Turbidite formations produce free faces and can locally influence the gully-network. There is tendency to unite or to initiate new channels and to design channel heads as a consequence of springs arranged along bedding planes. In the underlying soft Tauglboden-strata the gully and ravine incisions become significantly strong and cause reinforced denudation of the side slopes (Photo 1). Maximum side-slope angles show specific differences dependent on the type of rock (in limestones values are found around 60°, in less resistant Tauglboden--strata the values are about 40–50°. Antidip slopes of homoclinal ridges favour the development of steep funnel-like cirque walls (Fig. 5).

In the northern mountain chains of the Hohe Tauern (area 3) the systems of erosion are characterised by overall small textured drainage systems and refer to series of schist's (Bündnerschiefer), which are components of the Austroalpine Cover (Frasl and Frank 1966; Neubauer and Handler 2000). In average, the resistance of the existing metamorphites (sericite-mica-schists, calcareous mica-schists, greenschists and gneisses) is medium. Considering a relative relief between the mountain crests and the main valley bottoms of about 1,500 m, gully systems develop to deeply incised ravines in the lower slope sections. Mainly in the zone of the very hard "central-gneisses", gully-systems occur exclusively on very steep flanks, glacial trough-walls and cirque-walls. In contrast, on the moder-

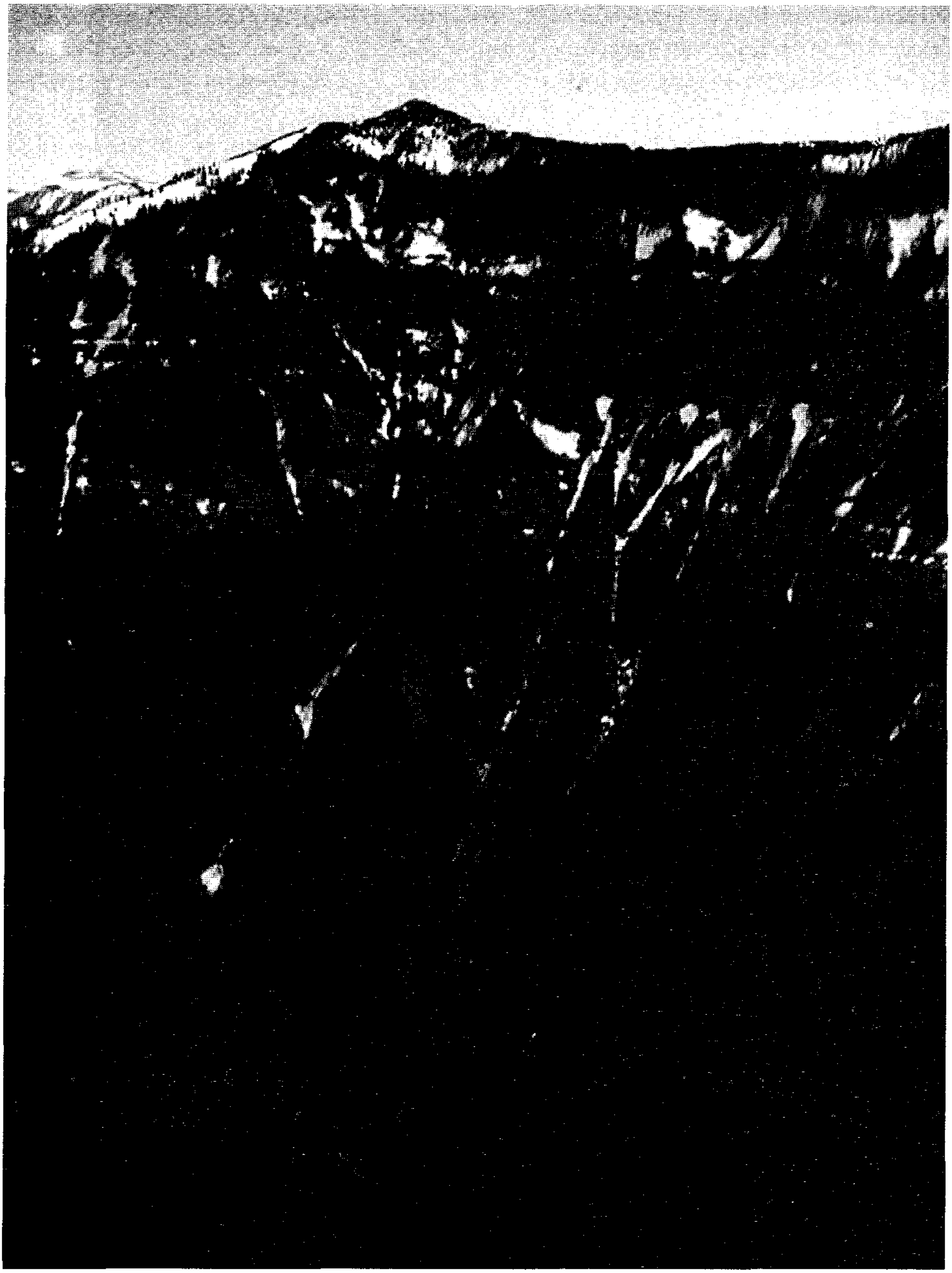

Photo 1. Gully system Osterhorn N. Top 1,746 m, valley bottom about 1,000 m. On the upper slope flat layered jurassic marly limestones (Oberalmer limestones with thick Barmstein-layers of resistent limestones), below weaker series of thin layered marls (Tauglboden-strata). Source areas in oval swales (steep avalanche-slopes), below dense gully system with strongly incised channels in the Tauglboden-strata. Channels and gully sides correspond to avalanche paths and are exposed to intense avalanche scouring

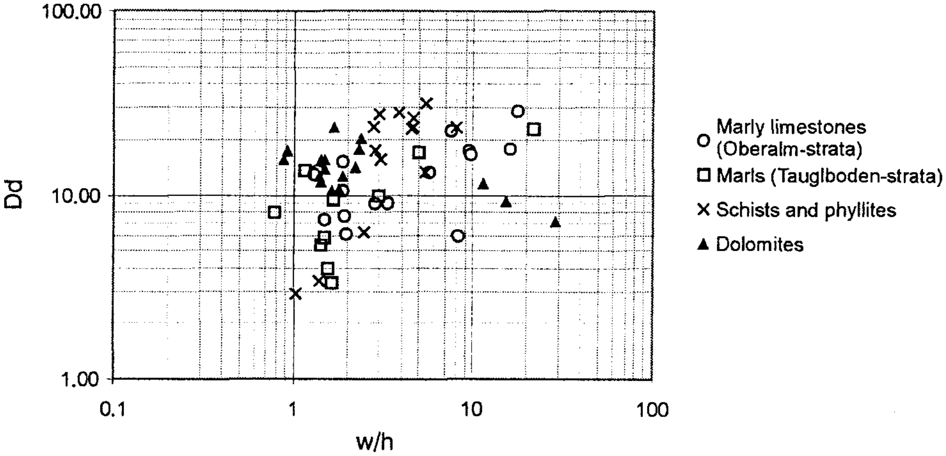

Fig. 3. Relation of density of channels-sharpness and incision measured on 55 examples from of different rock units

ately inclined slopes of the Graywacke-Zone (area 2) with dominant sericite-phyllites a high tendency for fluvial dissection does exist and gully patterns are limited to favourable relief conditions. Both in the southern side of the Hohen Tauern (area 4) and in the mountain chains (area 4–5) of the Middle Austroalpine basement related rock conditions are effective, although rock resistance changes considerably. Similar to area 2 of the Graywacke-Zone, slopes are affected by widespread gravitational rock movements, which resulted in strong slope deformations, on which gully systems are hardly developed.

In the southern Calcareous Alps (area 6), gully development on slopes arises primarily from susceptible mesozoic stratas and the strong tendency that the ridges strike from west to east. A considerable number of gully formations of the badland-type, agree with the extend of the “Hauptdolomit”, the “interposed dolomites” and also with muschelkalk formation of Anis which are part of the Drau-range (Schönlaub 1989). Generally, the beds dip moderately to strong towards south, generating homoclinal ridges and hogbacks. Therefore, 54% of all of the investigated gully-slopes are situated on north-faced antidip slopes (Fig. 5). The gully features are influenced by rock structure, such as dipping, jointing or fault-lines. Especially, the steep walls of the gully heads are extending along increased jointing and the weak rock zones contribute to an extension of the intensely incised gully area. Correlations between the sharpness of gully incisions and gully-density show typical spreading in relation to the different rock types (Fig. 3).

Relief conditions

The correlation between the relative relief and slope inclination (as expressed in the proportion of difference in altitude and slope length) show typical

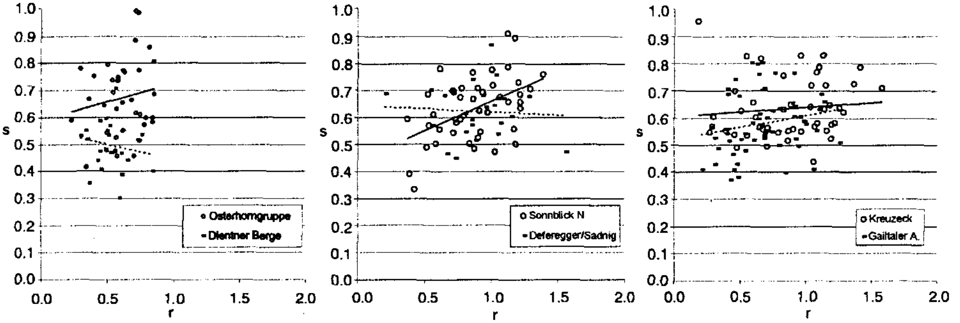

Fig. 4. Relations of relative relief (r) — slope (s) from 237 slopes dominated by gully erosion

distribution patterns for the analysed mountain areas. For example, between area 1 and area 2 remarkable differences are visible (Fig. 4). From correlations result further substantial differences between areas 5 and 6. Stable gneisses and micaschist of part of the Kreuzeck-group enable high relative relief together with high values of slope inclination.

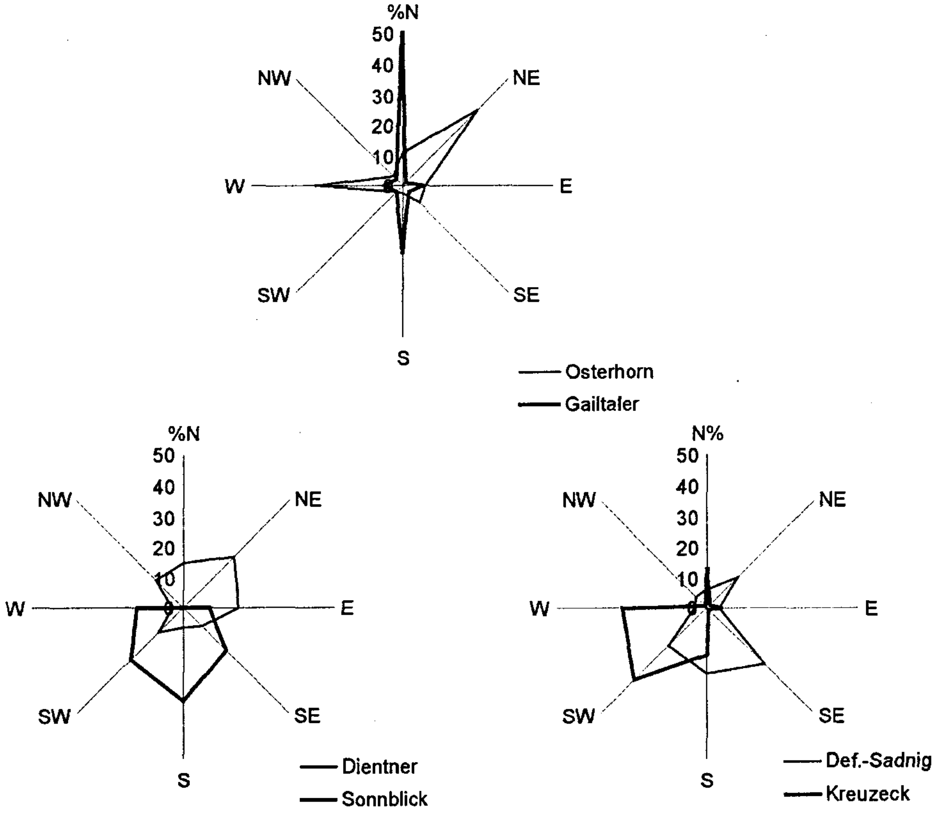

Fig. 5. Distribution of aspects (percent of area)

In the area 1 remnants of a ancient land surface are only present in the eastern part, where mountain plateaus still exist. The central chain is dissected by a radial pattern of valleys which reached a mature stage of development. Valley heads are pronounced, with slope angles up to 50°. Some of the walls of the valley heads show oneself to be a glacial cirque. Most of the gully-systems which drain the funnel-shaped or cirque-shaped valley heads, are connected with the fluvial channel system; on steep valley side slopes young stages of mostly discontinuous gullies have been established (E. Stocker 1997).

The example of the Southern Calcareous Alps (area 6) show partially similar landform conditions for gully development. Cirques are disposed on the north-faced slopes of the W–E-striking hogbacks and give rise to a number of gully-patterned slopes. In contrast to the area 1, gully systems are frequently extended as isolated areas with very sharp incisions disposed in gentle sloping mountain environments, sometimes near the base of the mountains. The gully relief is identified by sharp crests with natural bridges and castellated rocks (Photo 4).

In the northern and southern Central Alps (area 3–5) the distribution of aspects of slopes affected by ravines shows a preference of SE to SW faced slopes, were glacial cirques are not well developed. Frequently gullied slopes do occur in the peripheral parts of the mountain chains with an increased relative relief. They are nearly absent both on the central mountain areas, which are strongly reworked by glacial erosion, and on slopes deformed by gravitational slope-movements. From this relief predispositions arise two types of gully development: denditric patterns of deeply incised high-order ravines which occupy slopes with high relative relief and dense parallel patterns of first to second order gullies, preferably on cirque walls in lesser resistant rocks. The latter are related to intense debris-flow activity.

Climatic conditions

For the gully development the characteristics of precipitation play an important role: three meteorological stations provided the data for the period of 1981–1990 (Hydrographischer Dienst in Österreich 1994); Hintersee (685 m) is situated in the inner part of a valley in area 1, Teuchl (1,260 m) is located in a valley in area 5 and Weißbriach (800 m) is situated in the central zone of area 6. On the northern margin of the Alps, despite of low altitudes, precipitations achieve the highest values (more than 1,900 mm) and in the central Alps the lowest values (1,171 mm at an altitude of 1,260 m). The seasonal patterns of precipitation vary remarkably (Fig. 6). At Hintersee the winter precipitations (November to March) reach the double quantity (648 mm) than at Teuchl (323 mm). The precipitation maximum during the summer at Hintersee amount to about c. 100 mm more than those in the mountains south of the Hohe Tauern. In the Gailtaler Alps the precipitation maximum is postponed to October as a consequence of Mediterranean influence.

Considerable differences result as well from values of the duration type of intensity of precipitations (Fig. 6). Whereas at Hintersee storm precipitations are characterized by longer duration (values of more than 300 mm and a precipitation period of up to more than 10 days; but only about 94 mm within one day), at Weißbriach short-term maxima are typical (diurnal maxima reach 190 mm). Moreover, in the central Alps, high intensities of precipitation, but for only short terms, do occur, dependent on convective rain events, especially in the summers. Generally, the erosivity of precipitations can be estimated as higher in the southern alpine areas. Caused by the remarkably higher snow-precipitations north of the main chain of the Alps, snow-avalanche activity attain an important role in the northern and northern central Alps.

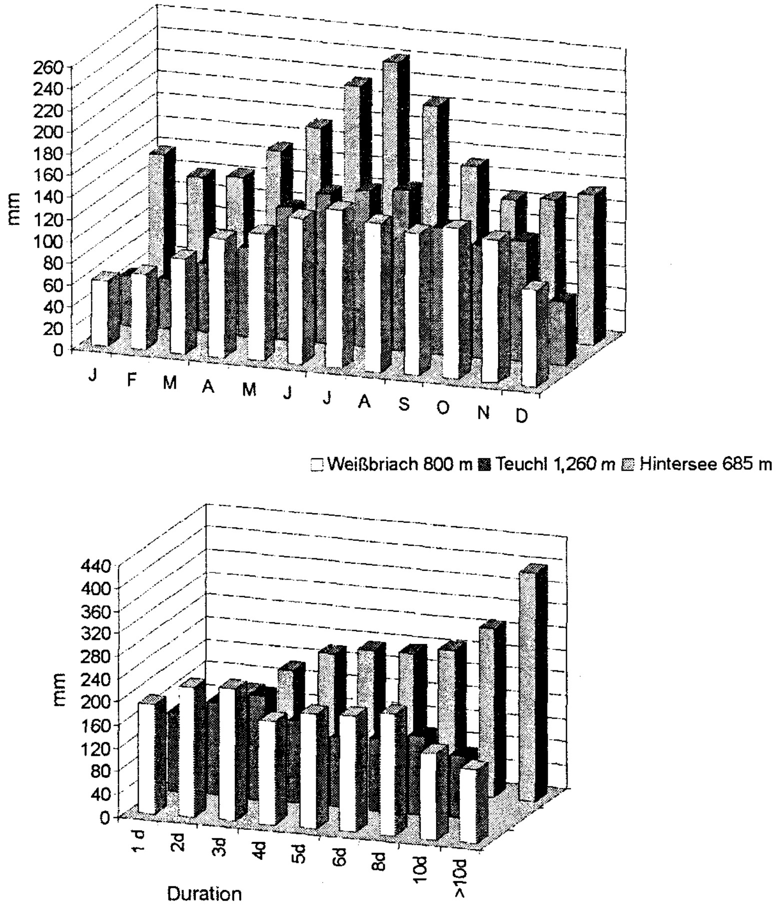

Fig. 6. Seasonal patterns of precipitations and duration of storm precipitations 1981–1990 (data from Hydrographischer Dienst in Österreich, 1994). Higher annual precipitations in the Northern Calcareours Alps combined with high intensity of long term precipitations then in contrast in the Gailtaler Alps, were precipitation maximum is in autumn. High intensities of short term precipitations are typical for the Southern Alps

Actual processes and human control

From the Northern Calcareous Alps to the northern Hohe Tauern (areas 1–3) snow and avalanche scouring plays an important role both on slopes above and below the upper tree line. Avalanches originate in the source areas of gullies, mostly in swales, below free faces and on steep ravine side slopes (Photo 1). Avalanches procure widespread patches of bare surface, strips and scratches by carving of coarse debris and especially, in the Northern Calcareous Alps reworking of the debris slopes they develop avalanche tongues, avalanche garlands and surface sorting patterns (Luckman 1992). Patches of bare surfaces have a similar appearance like translational slips, but investigations in the Northern Calcareous Alps of Bavaria show that soil covers are slipping together with avalanche glide-off under special conditions of high pressure and water availability (Stahr 1996). The recurrence of these phenomena is annual and occurs in the snow melting period. As a consequence of this widespread action of wet-snow avalanches, the development of a pattern of patches caused both by scouring and by slipping, underlies annual changing by successions of vegetation. In area 1, the mayority of the gully-areas are situated in the subalpine and montane environment. Originally closed woodlands were cleared partially for purposes of enlargement of pastures since the Middle Age and for purposes like the production of fire-

Photo 2. Southfacing slopes near Kühkarlkopf (2,267 m), Northern Sonnblick-Group. Widespread snow-avalanche scouring provides direct material transfer to the valley. Despite considerable weathering intensity in weak phyllites, regolith cover and material deposits within the gully-channels maintain to be modest. Features of avalanche scouring are clearly visible. Slope angles are about 36–41°

wood for salt works in 18th century (Stehrer 1987). Continued denudation of soil material from the upper slope led to overall thinner and coarser regoltihs and therefore to a high surface runoff. Following the main tracks of avalanches, gully erosion initiates to establish with mainly discontinuous channels with small incisions.

In the weak phyllites and calcareous mica-schists of area 3, on steep slopes gully systems are arranged by dendritic patterns with mostly short, first-order channels. Their heads are conditioned by joint-induced small springs not far from the divides. Nearly all the total slope areas steeper than 33–35° and above the treeline is affected by phenomena of snow avalanche scouring. Similar to the area 1, the pattern of patches with bare ground, streaks and other carving tracks are widespread and are subjected to annual change in consequence of scouring processes and vegetation successions (Photo 2). As a result of this thorough material transfer by snow avalanches, deposits of loose material (from the upper slopes within the gully channels) are very rare. Perennial water discharge provide the transportation of the remnants of debris in the channels. The environment of the numerous springs favour weathering processes (high soil-water content) in the fine textured phyllites and therefore the production of regolith. Nevertheless, the regolith cover remains thin and this indicates a nearly total removal of the produced material by avalanche scouring. This fact can explain the pronounced development of gully heads. Incision of gullies is controlled by weathering and erosion processes in the narrow rocky channels. Such events provide V-shaped cross-sections. Local process interactions between slope and channel processes clearly stand back, as direct material transfer is conditioned by avalanches.

In the metamorphic mountain chains ("Austroalpine basement units") south of the Hohe Tauern (area 4–5) morphometric parameters of gully systems are partially similar to those of the area 3. However, field observations show that avalanche scouring is of less importance. The thickness of regolith covers is generally higher and underlies various processes of erosion which increases with altitude. In addition, from detailed geomorphological mapping (1 : 10,000) in the Rottensteiner-valley, for area 5 is concluded, that processes of accelerated slope erosion are tied to gully sides and gully head-areas (Stocker 1996). Direct material transfer from the slopes to the valley-bottom by snow avalanches is prevailed by local process interactions between the gully-channels and gully-side-slopes. Avalanche scouring certainly exerts removal and destruction of soil and vegetation covers on exposed localities. On the other hand soil destruction in alpine environments are also starting from solifluction processes (frost creep, gelifluction, needle-ice activity) and human activity (forest clearing, local intensification of alpine pasture). On the steep gully heads and gully sides, soil destructions often enlarge and primarily, needle-ice triggers a further turf exfoliation. Bare surfaces increase with seasonally conditioned effect on surface wash and rill-development as well as gelifluction; they trigger material transfers to the gully channels. Storages of debris within the channels are therefore common and feed episodic

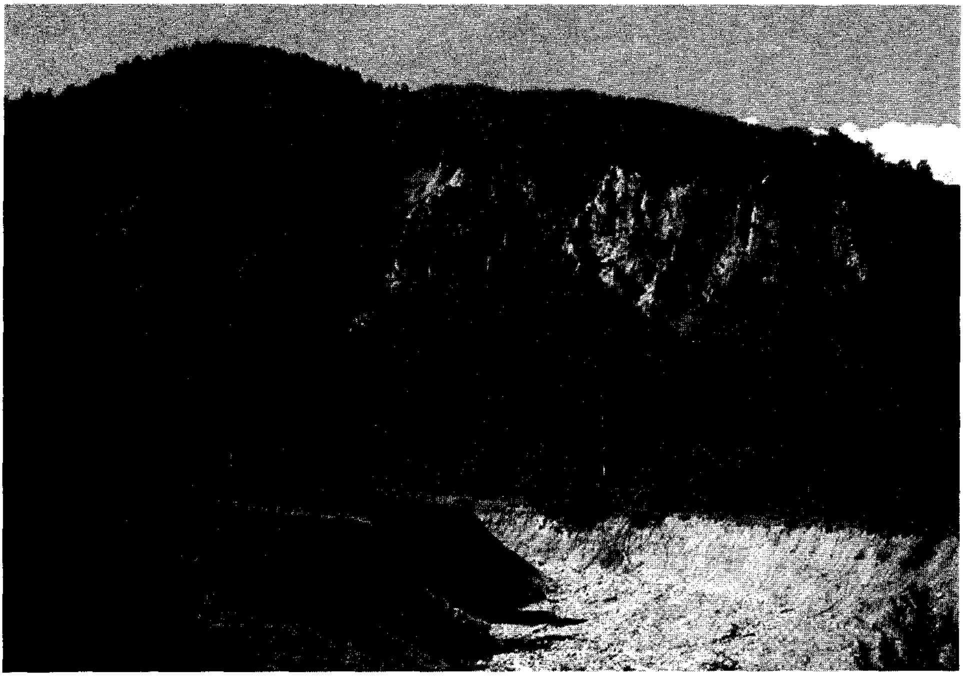

Photo 3. Deeply incised and sharp gullies near Castle of Stein (Gailtaler Alps) at about 700–800 m in Triassic dolomites. High production of small-sized weathering materials together with high rainfall intensities provide accelerated material transports and channel deposits as can be seen in the foreground

debris flows, which favour channel incision and steepening of channel walls, giving rise to further acceleration of slope erosion and debris production by weathering (Photo 3). Weathering and denudation processes are supported by a widespread instability of the metamorphic rocks. Creep induced structural changes by gravitation (toppling, overturning, deep sited down slope bending of schist foliation) are very common and support the retreat of channel heads and the development of ravine side-walls (Fig. 7).

In the area 6 gully erosion takes place both at sides of rounded mountain ridges at low altitudes and also on high mountain slopes above the upper treeline. Actual processes are triggered by channel erosion and occur in dolomites with fine-textured joints. Weathering produces a high amount of cub-shaped, relatively fine-grained debris, which is rapidly transported from the steep ravine sides within the channels and additional high rainfall intensities provide frequent moving and transport of channel deposits during flood-events. By this way the higher-order channels could incise deep gorges. Their sidewalls and valley-heads are developed by funnel-shaped steep gullies, which similar to badlands are nearly bare of vegetation (Photo 4). On the glacial cirque walls and on slopes which reach above the upper tree line, avalanche scouring and frost induced processes

Photo 4. SW-facing slope near Lackenbichl (Kreuzeck-Group), tops between 2,250 and 2,460 m. Gully develop in instable phyllites and schists rapidly. High rates of production of loose material triggers episodic debris flows. Material transfer occurs in several cascading subsystems

similar to those in the mountains of the "Austroalpin basement units" support gully development.

CONCLUSIONS

Since gullies, especially in the central-alpine mountain ranges, are descending, mainly from the periglacial belt into the forest belt, by crossing more then 600 metres of relative relief, process-interactions between altitudinal belts should be taken into consideration. A. M. Harvey (1994) distinguished different styles of coupling between the parts of geomorphic systems. If the coupling of the systems is strong, the sediment throughput can rapidly take place, although the sediment storages on gully sides and within the gully channel are rather small. An overview, by regarding the 237 slopes affected by dense gully systems, allows us to presume a strong coupling, especially, on slopes which are subjected to snow avalanche scouring. First information result from aerial photographs and geomorphological mapping. Therefore, the avalanche activity provides both the transfer of on-slope material deposits in the source area zones and also storages on the gully-sides and the gully channels.

Examples of geomorphological mapping show that on alpine slopes with accentuated gully patterns the coupling between on-slope processes and fluvial pro-

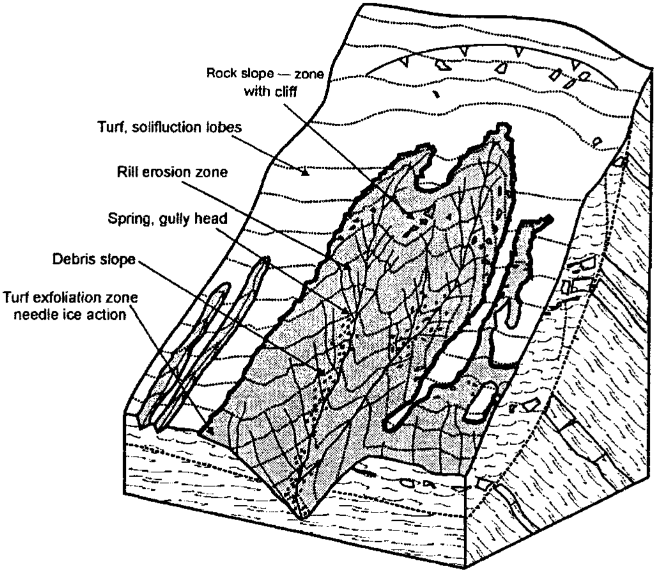

Fig. 7. Gully head from an example with instable metamorphic rock conditions. Gravitation leads to overturning, and gliding of rock unites near the surface. Fracturing of the rocks favours weathering processes, incision and retreat of gully heads. Different seasonal process-interactions take place. Especially frost action in spring-time combined with turf exfoliation and weathering of cliffs produce a high amount of material. Surface wash by rill erosion and material transports within the gully channels occur in summer

cesses on the slope basis can be considered as relatively high. Cascading systems are very differently developed, according to relief features, altitude, climatic influences, material and human influences. The distribution of aspects of the analysed slopes reflects this variety of conditions. About half of all considered slopes is faced from the south to the west. However, 54% of all the gullied slopes in the area 6, are N-faced slopes, as an effect of the general S-dipping of the layers and the E–W striking of the mountain ranges. Moreover many steep slopes that are patterned by shallow and dense gully systems, have been established after the glacial evolution of cirques, particularly the ones on north- to east- faced slopes (areas 1–3) which have reached only an initial stage. Snow avalanche scouring provide a relatively strong coupling between the slope erosion on the gully sides and the gully heads, by including the source areas and debris flow processes in the channels. Similar conditions can be found on the sides of trough valleys; steep valley sides in stable rocks however, are concerned at the most frequent one of erosive slope evolution.

The soft phyllites of Graywacke Zone (area 2) frequently are subject to ravine incisions on the funnel-shaped valley bottoms. Their gully network is connected with the fluvial channel system of the valleys and the coupling between slope and channel processes in the valley bottoms are estimated to be strong.

Processes of slope erosion can be particularly conditioned by features resulting from gravitation, especially in weak schists and phyllites (areas 2–5). In such

Table 2

Morphometric parameters for selected slope channel systems

Osterhorn Group	A ha	R	s	B	R_b 1/2	R_b 2/3	L_1	L_2	L_3	R_L 1/2	R_L 2/3	Dd	Dd_1	Dd_2	σ_1	σ_2	σ_3	θ
Tauglboden	275.1	900	43	1,070	3.86	3.50	223	364	709	1.63	1.95	5.5	17	7.6	44	43	26	58.3
Schmittenstein	99.6	880	45	1,300	5.50	4.00	276	431	775	1.56	1.80	8.6	20	8.6	49	48	17	56.4
Schlenken N	113.7	840	43	1,240	3.71	3.50	159	234	625	1.47	2.67	5.6	23	10.5	48	45	23	60.8
Osterhorn	102.0	880	43	1,150	3.40	2.50	176	285	358	1.62	1.26	10.2	18	8.7	44	39	24	52.8
Hochthron	108.9	860	32	1,500	5.67	2.00	254	300	543	1.18	1.81	12.0	20	6.4	35	31	21	50.0
Gugelanbrett	29.1	420	40	500			200					28	28		40			
Gennerhorn	34.8	460	33	600			257					21	21		34			
Sonnblick Group N	A ha	R	s	B	R_b 1/2	R_b 2/3	L_1	L_2	L_3	R_L 1/2	R_L 2/3	Dd	Dd_1	Dd_2	σl	σ_2	σ_3	θ
Kühkarlkopf	126.3	840	37	820	4.00	4.50	106	322	465	3.04	1.44	6.84	20	5.5	36	30	19	44.4
Breitebenkopf	192.0	860	35	1,400	3.75	2.67	163	388	733	2.38	1.89	5.88	15	4.1	35	29	20	41.0
Schwarzwand	118.2	1100	41	850	4.38	2.67	151	319	443	2.11	1.39	8.94	19	7.3	41	35	20	46.4
Deferegger/ Kreuzeck Mts.	A ha	R	s	B	R_b 1/2	R_b 2/3	L_1	L_2	L_3	R_L 1/2	R_L 2/3	Dd	Dd_1	Dd_2	σ_1	σ_2	σ_3	θ
Reisachspitze	98.9	980	39	1,400	6.00	4.00	149	408	1630	2.74	4.00	6.91	18	5.4	39	33	23	61.6
Paterskopf	107.9	700	42	1,800	4.00	2.00	244	455	575	1.87	1.26	7.28	34	12.5	42	32	23	47.0
Lackenbichl	37.1	600	40	850	4.50	3.00	119	267	600	2.24	2.25	16.21	34	13.7	40	34	16	46.0
Karlhöhe N	12.8	300	41	600	5.75		144	213		1.48		32.53	33		41	31		
Moscheg	68.6	700	43	950	4.33	3.00	145	317	380	2.19	1.20	4.69	13	8.9	43	36	26	54.4
Neuberg	137.2	1,040	41	1,700	4.14	3.50	103	271	675	2.63	2.49	5.09	17	9.5	41	38	24	53.0
Gailtaler A.	A ha	R	s	B	R_b 1/2	R_b 2/3	L_1	L_2	L_3	R_L 1/2	R_L 2/3	Dd	Dd_1	Dd_2	σ_1	σ_2	σ_3	θ
Weißengraben	49.9	780	41	1,200	3.67	3.00	181	333	780	1.84	2.34	7.56	19	9.5	41	30	23	58.0
Eckwand	83.9	720	39	1,100	5.00	5.00	164	156	600	0.95	3.85	6.53	15	8.5	39	38	25	55.4
Latschur	104.8	640	40	1,100	3.60	5.00	178	280	780	1.57	2.78	5.14	19	9.1	40	35	20	
Donnerspitz	18.8	300	43	540	9.50	1.00	91	150	300	1.65	2.00	12.39	25	9.8	43	45	21	56.8

areas the majority of slopes are modified by large-scale gravitational spreading, which causes uphill facing scars and deformations of slope profiles together with flat slope segments in the middle of the slopes, sequences of scarps and evidence of bulging near the base of the slopes. On such slopes the gully network is not, or only partially established. In the same areas, deformation takes place by deep seated bending and fracturing of the rocks, which also promotes increased erosion. On steep slopes, gully erosion combined with accelerated seasonal varying denudation processes (e.g. surface wash with rill development, frost action, avalanche scour on the gully sides) can take place. In these areas the cascading systems are composed of a chain of subsystems and storages.

Moreover, it appears that the dolomites of the Triassic, in area 6, are predestined for the evolution of very fine textured gully systems Weathering processes of dolomites also control the denudation of the gully sides and the erosivity of the precipitations favours the evolution of very dense and sharp systems of incisions.

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STRESZCZENIE

E. Stocker

WARUNKI ROZWOJU ROZCIĘĆ EROZYJNYCH NA STOKACH ALPEJSKICH NA PRZYKŁADZIE ALP AUSTRIACKICH

Wiele stoków alpejskich charakteryzuje się rozczłonkowaniem przez systemy rozcięć erozyjnych, które dostarczają materiału podlegającego przemieszczaniu przez potoki górskie i spływy gruzowe. Opierając się na analizie map w skali 1 : 10 000 i badań terenowych oceniono stopień i wielkość erozyjnego przekształcenia stoków na przekroju Alp Wschodnich. Jako obszary testowe wybrano postępując od północy fragmenty masywów: 1) Osterhorn, w północnych Prealpach Wapiennych koło Salzburga, 2) Dienter, 3) Sonnblick, 4) Sadnig i Deferegger, 5) Kreuzeck, oraz 6) Gailtaler. Obszary te zajmują powierzchnię prawie 3 800 km^2, a analizy rozczłonkowania stoków wykonano na 237 powierzchniach stokowych. Intensywny rozwój rozcięć erozyjnych udokumentowano na 4 do 13% powierzchni ogólnej obszaru badań. Określono cechy morfometryczne rynien erozyjnych i towarzyszących im form, uwzględniając w analizie rodzaj skał podłoża, reżim opadowy oraz wpływ działalności człowieka. Procesy rozczłonkowania stoków stanowią istotny element we współczesnej ewolucji rzeźby gór, są bowiem pierwszem ogniwem w systemie obiegu zwietrzelin w systemach stokowych i w dnach dolin alpejskich. Praca pokazuje różnice w modelowaniu północnych i południowych stoków masywu alpejskiego.