Debris flow-dominated and rockfall-dominated talus slopes: Genetic models derived from GPR measurements

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Abstract

Stratified talus deposits are reported from many different mountain environments. Numerous possible explanations are discussed in the literature; however, the sediment stores are rarely accessible as exposures are sparse. We applied ground-penetrating radar (25, 50 and 100 MHz antennae) to gain insight into the internal sediment structures of 23 alpine scree slopes; ten examples are presented in this paper. The study areas are spread over the Eastern European Alps at altitudes ranging from 1500 to 2900 m. The bedrock type is primarily limestone and dolostone; one area is composed of gneiss and mica–schist.

GPR turned out to be highly suitable for investigating sediment structures of dry talus debris. The results showed that almost all of the deposits investigated are characterized by pronounced stratification. Several different types of layering were identified. Discordant layers which are restricted to confined parts of the talus are probably related to sediment redistribution processes like surficial debris flows or dry grain flows. These features frequently occur at the uppermost part of the slope caused by overland flow from the adjacent rock face, but may also develop in the downhill part of a talus. One talus in the Reintal area showed surface-parallel, persistent layers of different grain sizes which cannot be explained by any known models. We suggest a novel model of talus development which is driven by climatic fluctuations. In periods of enhanced freeze–thaw activity like the Little Ice Age, the delivery of coarse debris prevails. In warmer climate with a higher frequency of rainstorms, the depletion of finer-grained intermediate stores in less inclined rockwall positions leads to delivery of clasts smaller than 2 cm. The type of layering found within a talus is determined by rockwall parameters like height, steepness, topography and dissection of the rock face. The “storage depletion” model applies to high rockwalls with a considerable volume of intermediate storage.

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Keywords: Talus; Rockfall; Ground-penetrating radar; Stratified scree

1. Introduction

Talus deposits in steepland areas collect detached material from adjacent rockwalls and thus, represent the first step in the alpine sediment cascade. Traditional models explain talus evolution as an evolving phenomenon of debris fall activity (0–10 m³) (Whalley, 1984) in response to infinitesimal rockwall retreat (Hutchinson, 1998). If talus slopes are situated in closed basins, e.g. behind moraine ridges, they act as archives of backweathering. Despite this rather straightforward geographical setting, talus deposits are complex sediment stores documenting the transition from Late-Glacial to Holocene sedimentation history as well as process fluctuations within the Holocene. Changes
in the processes and intensity of rockfall generation and subsequent debris redistribution lead to more or less pronounced stratification of talus deposits.

Stratified scree deposits are reported from a steadily increasing number of different mountain environments. Whereas stacked debris was first investigated in the French Pyrenees (Guillien, 1951), recent work has described similar deposits in temperate upland environments (Franco, 1990; Van Steijn, 1997; Gengnian et al., 1999; Hinchcliffe, 1999; Garcia-Ruiz et al., 2001) as well as in cold temperate environments worldwide (Bilkra and Nemec, 1998; Hétu and Gray, 2000). Stratified scree slopes are not only confined to high mountain regions, but also occur in vegetated upland environments (BerTRAN and Texier, 1999; Harris and Prick, 2000; Curry and Black, 2002). In these studies attention is paid to the question of whether the scree strata correspond to climatic fluctuations during the Pleistocene Pleniglacials, the Lateglacial and the Holocene.

Field assessment, laboratory studies and theoretical modelling approaches have established a number of post-depositional processes that can be responsible for the formation of stratified scree. In the view of most authors, the strata in scree deposits are a result of redistribution and sorting processes after a homoge-

eous rockfall deposition. Spatial particle sorting by debris flows is one of the oldest explanations for stratified slope deposits (Guillien, 1951). The frequent occurrence of debris-saturated flows on a scree slope can lead to alternating layers of channel, levee and lobe deposits of different debris flow events (Van Steijn, 1988; BerTRAN and Texier, 1994; Blair, 1999). The stratification of debris flow deposits is often not clearly developed and rather branded by openwork

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**Table 1**

Geographical setting of the study sites

<table>
<thead>
<tr>
<th>Area</th>
<th>Lithology</th>
<th>Elevation [m]</th>
<th>No. slopes</th>
<th>GPR frequency [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arnspitze</td>
<td>Limestone</td>
<td>1200–1900</td>
<td>2</td>
<td>50, 100, 200</td>
</tr>
<tr>
<td>Dammkar</td>
<td>Limestone</td>
<td>1600–2100</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>Hoher Ifen</td>
<td>Limestone</td>
<td>1900–2200</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>Reintal</td>
<td>Limestone</td>
<td>1200–2000</td>
<td>4</td>
<td>25, 50, 100</td>
</tr>
<tr>
<td>Zugspitze</td>
<td>Limestone</td>
<td>2400–2900</td>
<td>2</td>
<td>25, 100</td>
</tr>
<tr>
<td>Parzinn</td>
<td>Dolostone</td>
<td>2100–2700</td>
<td>3</td>
<td>25, 50</td>
</tr>
<tr>
<td>Tegelberg</td>
<td>Dolostone</td>
<td>1500–1800</td>
<td>2</td>
<td>25, 50</td>
</tr>
<tr>
<td>Wolfebner</td>
<td>Dolostone</td>
<td>2100–2500</td>
<td>2</td>
<td>25, 100</td>
</tr>
<tr>
<td>Kar</td>
<td>Gneiss/mica-s.</td>
<td>2400–2800</td>
<td>5</td>
<td>25, 50</td>
</tr>
<tr>
<td>Kühtai</td>
<td>Gneiss/mica-s.</td>
<td>2400–2800</td>
<td>5</td>
<td>25, 50</td>
</tr>
</tbody>
</table>

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Fig. 1. Location of study sites in the Eastern European Alps.
lenses in the proximal part, and by diamicton lenses in the distal part in the dimensions of a few meters (Van Steijn et al., 1995).

Dry grain flows, which provide a further explanation for stratification, are usually initiated by rockfall, gradual loading or over-steepening of talus deposits and culminate in a flow of cohesionless clast material maintained by dispersive forces of particle collisions (Lowe, 1976). The flows move with a speed of 0.5–2 m s \(^{-1}\) and are usually some tens of centimetres in width and some metres in length. Due to the effects of kinematic sieving (Camiel and Scheidegger, 1974) and the vertical increase in the speed of the flow movement, coarse-grained particles are sorted towards the front and upper part of the flow, while the grain size decreases in the lower and back parts of the flow deposit.

Supranival sliding processes have been described as stratification processes (Hétu and Vandelac, 1989; Hétu, 1991, 1995). These processes lead to stratifications exclusively at the bottom of the scree slopes, mostly in protected zones at the intersection of debris cones. Supranival sliding of debris can deposit coarse-grained openwork layers and is often connected to the initiation of minor debris flows during the spring thaw.

A systematic investigation of stratified sediment bodies is hampered by the limited number of exposures. Drillings are mostly impossible on steep and remote talus slopes. In addition it is highly questionable if the limited spatial information that is derived from boreholes is sufficient to distinguish between redistribution and sorting processes that leave stratification patterns on a much larger scale. However, with the widespread use of geophysical techniques in geomorphology, our knowledge of alpine sediment thicknesses and structure has considerably increased. For the investigation of dry and loose debris in arctic and alpine environments, ground-penetrating radar proved to have great potential combining a high penetration depth with an excellent resolution of internal sediment structures (Lønne and Lauritsen, 1996; Berthling et al., 2000; Otto and Sass, 2006; Sass, 2006). Due to the ability of GPR measurements to resolve key factors of scree stratifications such as grain size, internal structure and spatial distribution of sediment bodies as well as their mutual interrelation, they are one of the most

![Fig. 2. Pictures of the scree slopes investigated (1). A) The complex talus cone Blaue Gumpe, Reintal, with the darker rockfall talus on the right (1) and the light, much less steep debris flow talus on the left (2). The backing rockwall is characterized by large amounts of intermediate storage on ledges. Right picture. B) Talus sheet Wolfebner Kar 1. The backing rockwall is a steep dolostone outcrop with many bedding planes.](image-url)
promising geophysical methods for future investigations. Thus, the key questions of this contribution can be summarized as follows:

- Can the inner structure of talus slopes be made visible using geophysical techniques, particularly ground-penetrating radar?

Fig. 3. Pictures of the scree slopes investigated (2). A) Hoher Ifen; B) Reintal/Steingerümpel; C) Kühtai/Neunerkogel; D) Parzinn cones 1, 2 and 3 (left to right); E) Kühtai/Hinterkarle.
Are all talus deposits stratified and are there different types of stratification?
Can these types of stratification be referred to prevailing circumstances of talus formation, e.g. certain pre- or post-depositional processes?

2. Overview of the study sites

Between 2003 and 2005, GPR measurements were carried out at a total of 23 talus slopes in nine investigation areas in the European Alps. The sites are situated in Germany and Austria in the northern and central part of the Eastern Alps (Fig. 1). Rock type, elevation and an overview of the geophysical investigations accomplished are compiled in Table 1.

The presented examples of GPR sections were measured in the areas Reintal, Wolfebner Kar, Hoher Ifen, Kühtai and Parzinn (Figs. 1, 2, and 3).

The Reintal is a deeply incised trough valley towered by steep rockwalls with a vertical extension of up to 1400 m. The contributing rock areas of the talus cones studied reach a height of 600–1000 m and consist of Wettersteinkalk, a very pure and fine-grained, intensely fractured limestone. The rockwalls are characterized by a high amount of intermediate scree storage on prominent ledges and in gullies. The cone “Blaue Gumpe” has a distinct two-part feature: The right part (as seen from below) is a huge, ramp-like talus without any signs of fluvial erosion, while the left part is heavily affected by frequent debris flows (Fig. 2A). At the interface between two debris cones, dissection caused a 40 m high exposure where the stratification of the right talus part could be observed directly (Fig. 4).

The “Steingerümpel” talus cone in the Reintal is distinctly cone-shaped; fresh clasts of all grain sizes indicate a considerable rockfall activity (Fig. 3B). The cone is situated above a 400–600 year old rockfall deposit with boulders up to 20 m in size (Schrott et al., 2002).

At the Wolfebner Kar (=cirque), two loose talus slopes under steep dolostone rockwalls were investigated. The slopes are slightly concave with a maximum inclination of 33–35° each (Fig. 2B). The first slope ends downslope at a hummocky rockfall deposit while the second one gradually passes over to a slightly more compacted, rolling scree surface which is probably of glacial origin. The bedrock is a medium-grey dolostone named Hauptdolomit which is, on the whole, intensely fractured and brittle. However, exposed bedding planes are very compact and reflect a very wide joint spacing. The rockwall above talus 1 is one of the described compact, almost vertical bedding planes without any recognizable intermediate storage, while the wall at talus 2 is slightly more inclined and dissected by several furrows.

The Parzinn is the local name of a wide, north-exposed cirque in the Lechtaler Alps (Austria). The very steep and loose talus cones (33–35°) are backed by Hauptdolomit rockwalls with a vertical extension of 300–500 m (Fig. 3D). Due to the almost vertical Hauptdolomit beds, the rockwalls are characterized by an alternation of compact bedding planes and heavy dissection by small ravines. The talus cones show no deep dissection but signs of moderate, superficial sediment redistribution.

The Hoher Ifen talus sheet is situated under a long limestone escarpment which reaches a height of 100–150 m (Fig. 3A). The “Schrattenkalk” limestone is very pure and rather resistant towards frost-weathering, the debris fall rates are comparatively...
low. Along the escarpment medium-sized rockfalls occur; large, rectangular boulders have accumulated in a small valley at the foot of the talus sheet.

– The lithology of the Kühtai area is characterized by paragneiss and mica–schist rockwalls (Fig. 3C,E). The gneissic rock outcrops have a rather wide joint spacing (ca. 1 m) and a very low debris fall activity (Sass, 2005). The grain size distribution on the surface of the talus slopes is dominated by both coarse rockfall debris (few decimetres) and clasts of boulder size (approx. 1–2 m). The top positions of the talus cones are dominated by fresh rockfall material, while the debris near the talus foot and most of the boulders are lichen-covered. The rockwalls at mica–schist outcrops (Plenderlesee, Neunerkogel) show a slightly higher joint density and produce smaller clasts.

Details on rockwall and slope parameters are shown in Table 2. However, each rock face and each talus has an

### Table 2
Parameters of the rockwalls and talus slopes investigated

<table>
<thead>
<tr>
<th>Rockwall</th>
<th>Talus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>Slope (°)</td>
</tr>
<tr>
<td>Reintal Gumpe Line1</td>
<td>700</td>
</tr>
<tr>
<td>Reintal Gumpe Line2</td>
<td>700</td>
</tr>
<tr>
<td>Steingerümpel</td>
<td>1000</td>
</tr>
<tr>
<td>Hintere</td>
<td>1200</td>
</tr>
<tr>
<td>Kühtai Neunerkogel</td>
<td>200</td>
</tr>
<tr>
<td>Plenderlesee</td>
<td>200</td>
</tr>
<tr>
<td>Vorderkarle 1</td>
<td>160</td>
</tr>
<tr>
<td>Vorderkarle 2</td>
<td>100</td>
</tr>
<tr>
<td>Hinterkarle</td>
<td>250</td>
</tr>
<tr>
<td>Parzinn Cone 1</td>
<td>280</td>
</tr>
<tr>
<td>Parzinn Cone 2</td>
<td>220</td>
</tr>
<tr>
<td>Parzinn Cone 3</td>
<td>300</td>
</tr>
<tr>
<td>Wolf. Talus 1</td>
<td>170</td>
</tr>
<tr>
<td>Kar Talus 2</td>
<td>120</td>
</tr>
<tr>
<td>Zug- SF 1</td>
<td>360</td>
</tr>
<tr>
<td>Spitze SF 2</td>
<td>220</td>
</tr>
<tr>
<td>Damm Viererkar 1</td>
<td>300</td>
</tr>
<tr>
<td>Kar Viererkar 2</td>
<td>120</td>
</tr>
<tr>
<td>Arn- Cone 1</td>
<td>400</td>
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<td>Spitze Cone 3</td>
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<td>Tegel Talus 1</td>
<td>160</td>
</tr>
<tr>
<td>Berg Talus 2</td>
<td>60</td>
</tr>
<tr>
<td>Hofer 100</td>
<td>59</td>
</tr>
</tbody>
</table>

Note:

a Slightly bent.
b One prominent couloir.
c Flattened by debris flows.
d Plus bergsturz scarp.
e Plus boulders.
penetration depth, while 100 MHz profiles yield a clearer picture of the typical reflection patterns of certain sedimentary units. The total number of measured profiles and the frequencies applied are shown in Table 1.

The propagation velocity of the radar waves is widely dependant upon the dielectric constant \( \varepsilon \) of the subsurface. The reflectivity (percentage of reflected energy) also depends upon contrasts in \( \varepsilon \). The dielectric constant of a substrate is primarily controlled by water and clay mineral contents. The velocities in typical substrates in the study areas were measured individually at each site by WARR measurements (measuring with stepwise increasing antenna distance) indicating that the established velocities are largely similar to the observed sedimentary units. For debris flow deposits, fluvially redistributed sediments and glacial till, a velocity of ca. 0.1 m ns\(^{-1}\) was measured, while loose talus debris recorded slightly faster wave propagation (0.11–0.14 m ns\(^{-1}\)). This very narrow range of velocities (and thus, \( \varepsilon \) values) means that there is not necessarily a distinct dielectrical contrast at the interface between two sedimentary units or at the sediment/bedrock interface. However, the distinction between different subsurface units is often facilitated by typical internal reflection patterns of individual units. To include this additional type of information on stratification, 100 MHz profiles on typical locations (talus, debris flow deposits, moraine and bedrock) were provided. At a total of ten sites in the five different study areas, a cross-check between GPR and other geophysical methods (2D-geoelectrics and seismic refraction) was carried out (Otto and Sass, 2006; Sass, 2006, in press-a). The results showed that GPR is a reliable method whose results match well with those from other techniques of subsurface investigation.

At the “Blaue Gumpe” site in the Reintal, a vast exposure of 13 m height in a more than 30 m deep gully enabled a direct verification of the GPR results. In this exposure, two vertical profiles of scree layers were examined along two abseiling transects and their sedimentological information was recorded in detail. The two profiles were fitted together and show fourteen different rockfall layers. A sample (1000–2000 g) of material smaller than 10 cm grain size was taken for each layer and evaluated using sieve analysis. The proportion of stones with long and medium axes longer than 10 cm, 20 cm and 30 cm was registered for a 1 m\(^2\) representative area of each layer, and their proportion of weight was calculated separately.

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**Fig. 5.** Radargram (50 MHz) of the Blaue Gumpe talus cone 1 (line 1 in **Fig. 2A**). A) Longitudinal profile; B) cross profile; C) interpretation of the longitudinal profile. 1 tick=10 m.
4. Results and interpretation

4.1. Complex talus cone “Blaue Gumpë” (Reintal)

Fig. 4 shows the stratified scree deposits at the large exposure of the Blaue Gumpë cone (left of line 1 in Fig. 2A). The layers can only be well assessed on freshly carved surfaces and are sometimes partly covered by deposits from upper layers. The stratified layers begin in direct contact with the rock face; at a distance from the rock face continuous bedding is found. The typical, 0.5–0.7 m thick pronounced coarse-grained layer indicated by the lines in Fig. 4 is a continuous planar layer. The exposure does not cut the layers in the dip direction, and the slope angle of a layer alternates between openwork layers and fine-grained layers, so angles and thickness of layers appear slightly distorted. The general dip angle of 26° is almost the same as the present orientation of the scree cone.

The layers visible in Fig. 4 vary considerably in grain size and can easily be attributed to two clearly distinct clusters: 1) coarse-grained layers bearing a weight proportion of more than 70% of particles larger than 2 cm, and 2) fine-grained layers with a proportion of less than 70% of particles larger than 2 cm. The grain size proportion is not dominated by a single diameter class but includes various particle fractions. Variations of other sediment characteristics, such as imbrication or particle rounding, have not been detected.

At the Blaue Gumpë talus, we had the opportunity to compare the stratigraphic record of the scree exposure with GPR measurements at the same site. The radarograms reveal an obvious layer structure. Straight, surface-parallel reflectors can be traced along the entire profile line 1 (Fig. 5). In some places, the reflections are slightly weaker; but without doubt the lines are consistent throughout almost the entire talus body. In cross profile, these layers also appear to be almost surface-parallel (Fig. 5/inset), giving the three-dimensional impression of extensive, persistent layers which stretch across large parts of the cone. Right underneath the straight-line reflectors, hook-like reflections can be recognized in the 100 MHz profiles (Fig. 6B). These “hooks” are due to reflection hyperbolae originating from large clasts (approximately >30 cm). Thus, we assume that the observed radar patterns are caused by the reflection of the coarse debris layers that have been found at the exposure.

In the 100 MHz longitudinal profiles, the debris strata of the rockfall talus (line 1) presented in Fig. 5 are
characterized by continuous layers which are orientated parallel to the present scree cone surface (Fig. 6B). However, within the part of the talus cone subject to intense sediment redistribution by debris flows (see Fig. 2A), rather different radar facies were recorded (Fig. 6A,C). In the longitudinal profile of line 2 (Fig. 6A), stacked debris flow tongues are recognizable for the partly layered structure with obvious discordances. In contrast to the adjacent rockfall talus, parts of the layers are not surface-parallel; the inclination of some reflectors (ca. 14°) is smaller than the surface inclination (25°). These layers probably witness the distal parts of former debris flows which were subsequently buried by debris. In the cross profile across both of the neighbouring sedimentary units (Fig. 6C), the different inner structure becomes clearly visible. While the rockfall talus illustrates a widely surface-parallel layering also in the cross profile, the debris flow part exhibits numerous arched, interlaced structures which point to the lenticular deposits of flow tongues.

The distinct reflector at a depth of 22–28 m at the right part of Fig. 6C is probably the bedrock surface. Due to the higher distortion and a higher portion of fine grain sizes, the penetration depth is lower on the left part. Thus, the talus base cannot be clearly identified under the debris flow part.

4.2. Stratified and non-stratified talus deposits (Wolfebner Kar)

At the upper part of both profiles from the Wolfebner Kar (right part of Fig. 7A,B), bedrock is indicated by the fading of the scree reflections and by typical weak, intersecting reflections (Sass, in press-b). At the lower (=left) side, rockfall deposits or glacial till form the terrain surface at the foot of the talus slopes. These sediments can be distinguished from the talus deposits for their typical uneven reflections. The talus bodies themselves are characterized by rather different reflection patterns. Talus 1 (Fig. 7A) shows only weak stratification. The reflectors are not strictly surface-parallel and cannot be traced over the entire profile. The few reflectors are clearer recognizable near the base of the talus (e.g. 30–50 m distance, ca. 5 m depth). Apart from a surface-near reflection which is influenced by the direct ground wave, there is almost no continuous reflector in the upper 40 m of the talus (profile distance of 70–100 m).

By contrast, talus 2 reveals evidently stratified debris (Fig. 7B). The layers are rather continuous, start directly at the talus–rockwall interface and are mostly surface-parallel. However, the deeper layers are slightly less inclined forming an acute-angled discordance with the superficial layers (e.g. 100 m distance, 4 m depth). We
attribute the difference between taluses 1 and 2 mainly to a higher influence of redistribution processes at talus 2, caused by higher amounts of concentrated overland flow from the less steep and more dissected rockwall (cf. Table 2).

4.3. Examples of deposits subject to debris redistribution processes (Kühtai and Parzinn)

The radargrams in Fig. 8 provide further examples of reflection patterns which we relate to characteristic types of layered structures.

– Kühtai “Neunerkogel” (Fig. 8A): The radargram shows apparent stratification in the upslope (=right) part of the talus body. The talus body is very shallow near the rockwall; further downslope, obvious stratification can be recognized between approximately 60 and 120 m profile distances. The layers are not strictly surface-parallel and show small-scale discordances. Near the talus foot (0–60 m) almost no stratification can be found. The bedrock surface is indicated by a distinct reflection at a maximum depth of 10–12 m; the bedrock itself is characterized by typical bedding structures slanting diagonally to the left.

– According to field evidence and lichenometric results, the upper part of the talus (right half) is covered with finer-grained material with some indication of fluvial redistribution. Small clasts are obviously washed down from the inclined rock face leading to small-scale debris flow structures on the upper part of the talus. These structures can be clearly recognized in the radargram. By contrast, the lower part (left half) is characterized by larger clasts originating from rockfall with redistribution by avalanches. No apparent stratification can be found in this part of the radargram.

– Parzinn “cone 1” and “cone 2” (Fig. 8B, C, D): An obvious stratification can be recognized in the 25 MHz radargrams from the Parzinn area which is, however, not persistent across the entire cones (note that the resolution is much poorer in the 25 MHz profiles). In the cross profiles, the layers are bent and not surface-parallel (see Fig. 8C as an example). The layered structures are even clearer in the 50 MHz section at a part of cone 2 (Fig. 8D). The rest of the 50 MHz profile at cone 2 was unfortunately not properly recorded due to an antenna malfunction. However, the short profile shows apparent small-scale discordances between the debris layers (e.g. between 5 and 15 m depth). No evidence for large-scale debris

Fig. 8. Examples of talus radargrams from the Kühtai area (A: 50 MHz) and the Parzinn area (B, C: 25 MHz; D: 50 MHz). 1 tick=10 m.
flows is found on the very steep and loose talus surface; thus, we attribute the observed structures to surficial redistribution processes like small-scale debris flows, dry grain flows, frost-coated flows or solifluction (see the discussion chapter for details).

4.4. Examples of the influence of large rockfalls (Hoher Ifen, Reintal and Kühtai)

In the three study areas, evidence for the influence of boulder fall on talus formation was found.

- **Hoher Ifen** (Fig. 9A): Rockfall boulders of up to 10 m in size are found in a small valley along the foot of the talus slopes. The talus sheet itself is composed of smaller clasts. At the lower end of the slopes finer debris is deposited on and between the large boulders. This setting can also be observed in the radargrams. The very loose and dry talus results in a strong air wave between transmitter and receiver which masks almost every talus structure in the superficial 5–10 m. However, the big rockfall boulders can be clearly recognized from the arched, hyperbolic reflection structures between 10 and 25 m in depth.

- **Reintal “Steingerümpel”** (Fig. 9B): The presented section of the Steingerümpel cone shows obvious stratification in the depth range between 5 and 12 m. The layers are partly discordant at an acute bias angle; the most prominent reflector at the upper (right hand) side is slightly steeper (33°) than the surface (31°). The angle of dip points to a rockfall layer rather than debris flow redistribution processes, as found at the adjacent Blaue Gumppe cone. The surface-near parts of the radargram (0–3 m depth) appear to be severely distorted; the layers are cluttered and interrupted. We attribute this distortion to the impact of the large Steingerümpel rockfall which tumbled down over the talus surface 500 years ago (Schrott et al., 2002).

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Fig. 9. Examples of talus deposits influenced by major rockfalls. A: Hoher Ifen (25 MHz); B: Reintal, “Steingerümpel” (50 MHz); C: Kühtai, “Hinterkar” (50 MHz), circles: irregular structures. 1 tick = 10 m.
impact of the rockfall boulders partly destroyed the layered structures. Given sufficient time before the next major event, a new rockfall layer might develop on top of the distorted zone.

- Kühtai “Hinterkar” (Fig. 9C). The thick talus body shows clear but frequently interrupted debris layers. Between the almost surface-parallel reflectors, irregular, hook-like structures appear (circles in Fig. 9C). Considering the double-peak grain-size distribution found at the talus surface, we assume that the linear reflectors are due to finer-grained layers which indicate moderate activity of small-scale rockfalls. The irregular areas are in all probability due to boulder-size material originating from medium-size rockfalls. These episodic rockfall events distort and partially destroy the stratification.

5. Discussion

All talus slopes we investigated (not only the examples presented) turned out to be stratified to a certain degree. The GPR results permit the clear distinction of characteristic stratification features which are of central importance for the recognition of stratification processes involved. According to the results, the stratification observed in the talus radargrams differs in thickness, dip angle, distinctness and continuity of the layered units. Thus, different models of scree slope development apply.

5.1. Validity of previous models of stratified debris formation

Numerous models have been developed to describe the generation of strata of lenticular appearance in scree deposits. These models involve creep in Alpine solifluction lobes (Bertran et al., 1993), dry grain flows (Lowe, 1976), frost-coated flows (Hétu et al., 1994), debris flows and hyper-concentrated flows (Van Steijn, 1988; Bertran and Texier, 1994; Blair, 1999) as well as vegetational binding (Bertran and Texier, 1999). Centimetre-thick layers generated by supranival debris sliding and nivo-aolian transport (Hétu and Vandelac, 1989; Hétu, 1991, 1995) are too thin to be identified in the applied GPR resolution, and thus these processes should be excluded from our interpretation of GPR imagery.

The occurrence of Alpine solifluction lobes is determined by altitudinal and material restrictions such as the presence of finer-grained sediment. Solifluction sheets and lobes resulted from periglacial processes in matrix-rich material lead to a two-fold stratification: a surficial layer of coarse clasts on a matrix-rich heterogeneous layer, and the latter rests on a former layer of coarse clast. In Alpine conditions layer dimensions are likely to reach a few tens of centimetres in thickness and a few metres in width and length (Francou, 1990; Bertran et al., 1993; Van Steijn et al., 1995). Thus, this type of layering is also too fine to be responsible for the observed GPR reflection patterns. Furthermore, solifluction processes are rather unlikely because of the very dry, matrix-poor character of the scree slopes investigated.

Only one of the scree slopes investigated (Blaue Gumpe line 2, Fig. 6) shows evidence of intense sediment redistribution by debris flows. The radar reflection patterns in this part of the Reintal slope are clearly different from the adjacent rockfall talus as well as all other talus slopes investigated. Moreover, the dip angle of the sediment bodies (approximately 14°) indicates their debris flow origin (Fischer, 1965). Thus, intensive debris flow processes which cut deeply into the upper talus and led to large-scale sediment redistribution can be identified from the radargram. Accordingly, large-scale debris flows as an agent of talus formation can be excluded for most of the other sites investigated.

However, smaller-scale, surficial debris flows were frequently observed in the study areas. These processes may be initiated by overland flow from furrows in the rockwall (Fryxell and Horberg, 1943), heavy rainfall or snowmelt leading to over-saturation of the debris (Wilkinson and Schmid, 2003), over-steepening of the talus slope (dry grain flows, Lowe, 1976), or may occur as frost-coated grain flows (Hétu et al., 1994). The layering effect is probably due to kinematic sieving (Carniel and Scheidegger, 1974) and the vertical increase in flow velocity. We summarize these processes under the term “surficial debris flows” no matter whether these are triggered by over-steepening, heavy rainfall or frost coating. These processes are likely to cause more or less surface-parallel, slightly discordant layers (see Wilkinson and Schmid, 2003, Fig. 3) which, in most instances, do not extend across the entire talus. Thus, this explanation probably applies to the Parzinn (Fig. 8B–D) and the Wolfebner Kar (Fig. 7B). Continuous, often undulating beds with a clear stratification which are preferably developed in the lower scree slope sections are traced to the final deposition zone of dry grain flows and frost-coated clast flows, perhaps sometimes modified by nival transport or supranival debris sliding. The reflection patterns in the Wolfebner Kar 1 talus (layers predominantly developed in the lower talus section; Fig. 7A) may point to this type of redistribution process, while the upper part of the talus is apparently built up by continuous rockfall with only moderate post-depositional redistribution. By contrast, at the Neunerkogel site (Fig. 8A), the stratification is
restricted to the upper section of the talus adjacent to the rockwall. Thus, we assume that overland flow and downwash from the inclined rock face is responsible for the layered structure in this position. Furthermore, pre-depositional sorting processes may contribute to the layering, as discussed below.

5.2. A model of talus slope development

The processes discussed above account for many of the stratification features found in the radargrams. It can be presumed that all these models explain the stratification as a result of post-depositional processes such as redistribution and sorting. However, while these models provide numerous possible explanations for layered structures in a spatially confined part of the scree slope, few convincing ideas for the development of large-scale structures in a spatially confined part of the scree slope, few convincing ideas for the development of large-scale structures in a spatially confined part of the scree slope. However, while these models provide numerous possible explanations for layered structures in a spatially confined part of the scree slope, few convincing ideas for the development of large-scale structures in a spatially confined part of the scree slope.

The exposure and the radargrams of the Blaue Gumpe talus (Figs. 4–6) have shown that the scree layers are all orientated parallel to the present scree surface, continuous across almost the entire talus, and branded by a contrast in the grain size distribution of the debris. None of the models presented so far can account for this type of layering.

Therefore, we have developed a new model for the generation of continuous strata in scree slopes for mountain areas in warm temperate conditions. At the Blaue Gumpé talus the scree layers are absolutely surface-parallel with a maximum dip angle of 26°. We understand that the present angle of the scree surface, which is lower than the maximum angle of repose according to the Statham–Kirkby-Model (Statham, 1976), is an expression of active rockfall deposition. The resemblance of the layers’ orientation, internal structure, dip direction and especially the dip angle to present active rockfall deposits provides strong evidence for their rockfall origin. This means that the layers have not been formed due to post-depositional reorganisation of scree but due to temporal fluctuations in the rockfall grain size input from the rock face. High-magnitude rockfalls can be excluded as a source of the layers as no impact structures are apparent in the fine-grained layers underlying the coarse debris. Furthermore, no evidence of distortion of the layers can be found in the radargrams.

A four-year quantitative rockfall study that has been conducted in Reintal has offered an explanation for temporal fluctuations in rockfall clast size (Krautblatter, 2003; Krautblatter et al., in press). During periods of intense freeze–thaw activity, predominantly coarse-grained (>2 cm) particles with a weight proportion of 80% were deposited. This is due to (i) a preferred loosening of larger particles by frost action and (ii) the fact that larger particles are less prone to stop at intermediate storage areas (Rapp, 1960; Bones, 1973; Statham, 1976; Bozzolo, 1987; Erismann and Abele, 2001). While this coarse-grained deposition is confined to a few days of wet freeze–thaw conditions in spring and autumn, the rockfall deposition during the other days is dominated by the accumulation of fine-grained debris during extreme summer precipitation. During the four years of rockfall measurements at this site, more than 90% of rockfall was deposited by “gross secondary rockfall events” (Krautblatter and Moser, 2005; Krautblatter et al., 2006), which were defined as a short-term mass deposition of fine-grained rockfall material supplied from intermediate storage areas on the rockwall due to fluvial processes and debris-saturated flows. The short-term intensity of rockfall deposition exceeds the deposition during dry periods without frost by a factor of at least 10 (Krautblatter et al., 2006). The material of gross secondary rockfall events resembles that of intermediate storages with a 14–50% weight proportion of fines (<2 cm). Thus, we assume that fine-grained layers indicate periods of preferred depletion of intermediate storages by intense rainstorm activity. In conclusion, the coarse-grained layers of Fig. 4 resemble the grain size distribution of predominantly frost-induced rockfall with selective filling of intermediate storage.

In this model two external climatic factors influence the grain size of small-scale rockfall supply: magnitude and frequency of intense summer rainstorms and the abundance of intense (wet) freeze–thaw conditions. According to McCarroll et al. (1998, 2001), the intensity of frost-induced rockfall activity in Norway increased up to seven times in the Little Ice Age, because of more frequent effective freeze–thaw conditions. The activity of frost-weathering is directly linked to the number of effective frost cycles (Matsuoka, 1990; Sass, 1998) whose frequency in the study areas declined since the Little Ice Age (Hauér, 1950). This argument can easily be transferred to the extraordinarily climate-sensitive Reintal, whose glaciers show a pronounced response to the warming after the Little Ice Age (Hera, 1997). In contrast, the frequency of intense rainstorms has evidently more than doubled since the end of the Little Ice Age (DWD, 2001). We expect such climatic fluctuations lead to an oscillation between two steady states. Cooler periods such as the Little Ice Age with a high frost activity and low rainstorm frequency provide rockfall inputs for coarse-grained scree layers. Warm periods with little frost action and enhanced rainstorm activity deplete intermediate storages and produce fine-grained scree layers. This inference is supported by the
estimation that the transition between the present uppermost fine-grained layer and the underlying coarse-grained layer corresponds to 1870–1900 on the basis of present rockfall deposition rates. Although no absolute dating is available, these deposition rates were derived independently in four separate rockfall collectors at the specific site with a measurement of more than 20 t of rockfall deposits from 1999 to 2003 and were adjusted to average 20th century environmental conditions (Krautblatter et al., in press). They are, thus, believed to be highly representative.

The model outlined above does not explain all types of debris stratification found at scree slopes. It only applies to slopes with large rockwalls with prominent intermediate storages (cf. Table 2) which can keep fine-grained rockfall debris for centuries, in a climatically sensitive setting. A typical example of this is the Blaue Gump site having the exceptional thickness and continuity of the scree layer deposits supplied from the large rockwall. The formation of equally continuous but thinner layers may reflect the same mechanism but lower debris availability. Thus, the outlined model may also apply to the Wolfenbner Kar 2 talus and partly to the Kühtai and Parzinn cones.

5.3. Reasons for different types of stratification

Several models which we presume to be responsible for different types of stratified scree deposits are compiled in Table 3. It is evident that dominant processes are independent of study areas, rock types or elevation. A combination of rockwall height, rockwall topography and joint spacing seems to be most influential for the stratification of adjacent talus slopes:

- A narrow joint spacing which allows the production of fine clasts, large extension of the rockwall and topography (ledges) which enables intermediate storage promote the "storage depletion model" outlined above. These preconditions are given for all Reintal cones (e.g. Fig. 5) and, to a lesser extend, for several more talus bodies in different investigation areas.
- A moderate inclination (40–70°) and the presence of furrows and channels on a rock face support the generation of concentrated overland flow (Fryxell and Horberg, 1943). The resulting surficial redistribution processes cause a smaller-scale, discordant layering. Similar stratification patterns may be

### Table 3

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<th>Type of stratification</th>
<th>Process model</th>
<th>Talus examples</th>
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| Pronounced, persistent layers sometimes thick beds sometimes evidence of grain-size variations (1) | Alternating phases of rockfall and intermediate storage depletion (possible modification by surficial debris flows) | Reintal Blaue Gump 1
Reintal Hintere Gump 1
Zugspitze Schneeferner 1
Parzinn cone 3
Kühtai Plenderlesee
Wolfenbner Kar 2 (2) |
| Undulated layers, pronounced discordances, dip angle markedly smaller than friction angle, arched structures in cross profiles (2) | Debris redistribution by large-scale debris flows | Parzinn cone 1+2
Wolfenbner Kar 2
Tegelberg Grüble 1
Zugspitze Schneeferner 2
Arnspitz cone south 1 |
| Layering partly undulated, many small-scale discordances, slightly arched structures in cross profiles (3) | Surfacial debris flows (may be partly connected with periods of storage depletion) | Kühtai Neunerkogel
Kühtai Vorderkarle 1+2
Wolfenbner Kar 1
Hoher Ifen 2 |
| Weak layering (if any), interrupted or only in lower parts (4) | Mainly debris fall possible modification by surficial debris flows in lower parts possible modification by high-magnitude rockfall events | Kühtai Hinterkarle 2
Kühtai Neunerkogel and Vorderkarle (only lower parts) |
| Layering present, but sometimes weak, distorted or interrupted, evidence for boulder-sized clasts (5) | Debris production (maybe alternating rockfall / storage depletion), alternating with high-magnitude rockfall events | Kühtai Hinterkarle 2
Reintal 2
“Steingerümpel”
Hoher Ifen 2 |

Talus examples in italics are presented in this paper.
caused by dry grain flows or frost-coated flows. However, the comparison between the two Wolfebner Kar talus slopes (Fig. 7) suggests that overland flow from an inclined, dissected rockwall promotes the generation of this type of layering. As pointed out before, the two slopes differ mainly in topographical characteristics of the rockwalls above them. While talus 1 is of the un-stratified “debris fall” type, the rockwall above the neighbouring talus 2 is slightly dissected by rockfall couloirs. Thus, the related talus is obviously stratified due to redistribution processes with some intermediate storage depletion.

- If the rockwall is very steep and compact, debris fall is the main agent of talus formation, and layering is only present near the talus foot due to sediment redistribution processes (e.g. Wolfebner Kar 1). The Kühntai taluses (Neunerkogel and Vorderkarle) have a hybrid form with a coarse, un-stratified rockfall talus in the downslope parts and surficial debris flow modification near the rockwalls.

- Sediment redistribution by major debris flows is restricted to certain positions with large furrows cutting deep into the talus body, which concentrate overland flow from a large catchment area (e.g. Blaue Gumpe, Fig. 6).

- The alternation of continuous debris falls with episodic rockfall events provides a further explanation of layered structures which can be recognized from GPR images. However, due to the impact energy and kinematics of a large fallen rock, no continuous layer can be expected. At the Hinterkar talus (Kühntai area), the rockwalls are poor in intermediate storage due to the large grains produced. However, the grain size distribution of the scree slopes and lichen measurements (Sass, unpublished) point to periods of enhanced boulder-sized rockfall alternating with phases of sediment redistribution, finer-grained rockfall and soil development.

6. Conclusions

GPR turned out to be a powerful tool for talus slope investigation, providing new insights into sediment archives which have not been accessible to date. The results of the radar measurements in the Eastern European Alps show that all the talus bodies investigated are stratified to a certain degree. However, a number of quite different processes are probably responsible for the specific type of stratification. Among the numerous post-depositional sorting processes suggested in the literature, we assume that small-scale, surficial debris flows provide the best explanation for the layering observed in many of the talus bodies. To explain the presence of surface-parallel, persistent layers at the Blaue Gumpe site, we developed a novel model of talus slope development which is driven by climatic fluctuations. The delivery of coarse debris prevails in periods of enhanced freeze–thaw activity like the Little Ice Age, whereas warmer periods like today are characterized by the depletion of finer-grained intermediate stores connected with summer rainstorms.

The determining factors for the type of layering found at a specific talus are rockwall characteristics like height, steepness and dissection of the rock face. Narrow joint spacing (causing small clasts), moderate inclination, dissection and intermediate debris storage within the rockwall promote a pronounced layering, while scree slopes adjacent to steep and uniform rockwalls tend to show much lesser stratification.

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