Features related to snow avalanches and snow glides, Nordkette range (Northern Calcareous Alps).

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Abstract

The southern flank of Nordkette range near Innsbruck city (Austria) is sculpted by bedrock-incised ravines that, in their upslope portion, are excavated by snow avalanches (also termed snowflows) into avalanche chutes. The downslope portion of the ravines, in contrast, is mainly shaped by fluvial erosion from ephemeral to perennial creeks. Downslope from the starting zone of most snowflows, the avalanche chutes show: (a) an increasing depth of bedrock incision down to a few tens of meters, accompanied by (b) a progressive change of cross-section from an ‚inverted trapeze' to a U-shape, or to a more deeply-incised ‚inverted trapeze' shape; farther downslope, the chutes pass into the lower part of the ravines shaped by stream erosion (V-shaped cross-section). Aside of chute incision, full-depth snow avalanches and snow glides produce smaller-scale features of erosion, such as rip-ups a few meters to a few tens of meters in width of soil and scree; these rip-ups may develop into sub-circular to elliptical depressions similar to nivation kettles. Furthermore, the floor of the avalanche chutes is characterized by grooves and striae excavated from soil. Along some of the chutes, bedrock exposures and surface facets of lithoclasts show polish and striation from by-pass of sediment-laden full-depth snowflows. Clasts with avalanche polished-striated (p-s) surface facets can be distinguished from p-s clasts from basal tills of glaciers by a set of criteria. Polished-striated bedrock and clast surfaces are preservable – in declining quality – over a few tens of years at least, and provide a criterion to identify avalanche activity in areas where snowflows are rare, or where snow cover is absent in season. Along Nordkette, features of avalanche-related sediment transport mainly include scree littered within or alongside the chutes, and scree perched on top of boulders. Aside of the lower part of slope drained by streamlets, snow avalanching is the most active geomorphic agent in shaping the chutes. A comparatively common incidence of large, full-depth, sediment-laden snowflows along the Nordkette is related to: (a) the mountain flank dipping with ~50–30° S, maximizing insolation, and (b) the facing of the flank into a major foehn-wind corridor. Rapid warming during foehn lowers the stability of the snow cover and, in case of sustained thawing, of underlying soil and scree. This favours, both, the formation of sediment-laden full-depth avalanches and the excavation of chutes.

keywords: Alps, snow, snow avalanche, avalanche chute

Zusammenfassung

Die südliche Flanke der Nordkette-Massives bei Innsbruck ist morphologisch durch eine Reihe von Gesteinsrinnen geprägt, deren oberer Abschnitt durch Lawinen-Erosion geformt wird (Lawinenrinnen). Der talwärtige Abschnitt der Rinnen dagegen wird hauptsächlich durch fluviatile Erosion entlang ephemeraler bis perennialer Gerinne gebildet. Talwärts vom Abriss-Gebiet der meisten Schneelawinen zeigen die Lawinenrinnen: (a) eine zunehmende Tiefe des erosiven Einschnitts bis zu einigen Zehnermetern, in Verbindung mit (b) einer allmählichen Änderung des Querschnitt-Profils von einem 'umgekehrten Trapez' zu einer U-Form, oder zu einem tief eingesenkten, steilflankigen 'umgekehrten Trapez'. Weiter hangabwärts, zum unteren Abschnitt der Rinnen mit ephemeralen bis perennialen Gerinnen hin, ändert sich der Querschnitt zu einer V-Form. Abgesehen vom Einschneiden der Rinnen wird durch Grundlawinen und Schneegleitungen eine Reihe kleinerer Erosionsmerkmale erzeugt, wie etwa meter- bis zehnermeter-grosse Ausrisse von Humusschollen und Haldenschutt; diese Ausrisse können sich mit der Zeit zu grob kreisförmigen bis elliptischen Eindellungen entwickeln, die ähnlich aber nicht genau analog zu Nivationskesseln sind. Des weiteren ist der Boden entlang der Lawinenrinnen durch grosse, strömungsparallele Furchen und Striemungen gekennzeichnet. Entlang einiger Lawinenrinnen zeigen sowohl Gesteinsaufschlüsse als auch einzelne Lithoklasten Politur und Striemung, die durch die abschleifende Wirkung unter sedimentbefrachteten Grundlawinen entsteht. Klasten mit polierten und striierten (p-s) Oberflächen, wie sie durch Grundlawinen entstehen, können anhand einer Reihe von Merkmalen von p-s Klasten aus Gletscher-Grundmoränen unterschieden werden. Durch Grundlawinen erzeugte p-s Oberflächen auf Gesteinsaufschlüssen und Lithoklasten sind jahrzehntelang erhaltbar. Damit können derartige p-s Oberflächen Hinweise auf Lawinentätigkeit auch in Gebieten geben, in denen Grundlawinen selten sind. In den Lawinenrinnen der Nordkette beschränken sich Merkmale von Sediment-Transport im wesentlichen auf lose verstreuten Haldenschutt an der Sohle oder entlang der Ränder der Rinnen, und Streu von Haldenschutt auf der Oberseite von Gesteins-Blöcken. Abgesehen vom unteren Teil, in dem fluviatile Abtragung überwiegt, sind Schneelawinen der wichtigste Prozess in der Formbildung der Rinnen. Eine vergleichsweise Häufigkeit von sedimentbefrachteten Grundlawinen am Südhang der Nordkette wird erklärt durch: (a) das etwa 30-50° steile Südfallen der Flanke, welches maximale Sonneneinstrahlung bedingt, und (b) die Tatsache, daß die Nordkette der Prallhang eines der aktivsten Föhnwind-Korridore der Alpen ist. Die sehr rasche Erwärmung während Föhn-Bedingungen verringert die Stabilität der Schneedecke und – im Falle von länger anhaltendem Tauwetter – auch des unterliegenden Bodens und Haldenschutts. Dies fördert die Entstehung von sedimentbefrachteten Grundlawinen sowie die erosive Formung der Rinnen.

1. Introduction

In mountain ranges that are densely populated and an arena for winter tourism, an understanding of the dynamics and risk assessment of snow avalanches (or snow flows; see Blikra and Nemec, 1998, for term) obviously is important. In consequence, an extensive literature exists on physical aspects of snow and snow avalanching, chiefly with the goal to predict formation and runout of snow flows (e. g., Voellmy, 1955; Savage, 1979; Brun and Rey, 1987; Sovilla et al., 2001; Sailer et al., 2002; Sovilla and Bartelt, 2002; Tiefenbacher and Kern, 2004; Sovilla et al., 2006, 2008; Pudasaini and Hutter, 2007; Issler et al., 2008; Thibert et al., 2008; Kern et al., 2009; Christen et al., 2010; Sovilla et al., 2010; Buser and Bartelt, 2011; Vriend et al., 2013). Periglacial geomorphologists similarly are long aware that snow avalanches are major agents of material transport (other than snow) and shaping of landforms (e. g., Rapp, 1959, 1960; Gardner, 1970; Luckman, 1977, 1978, 1988; Thorn, 1978; Corner, 1980; Fitzharris and Owen, 1984; Ward, 1985; Ballantyne, 1987; André, 1990; Bell et al., 1990; Jomelli and Francou, 2000; Jomelli and Bertran, 2001; De Scally and Owens, 2005; Decaulne and Saemundsson, 2006, 2010; Owen et al., 2006; French, 2007; Johnson and Smith, 2010). Although snow avalanching can be important for sediment dispersal on talus slopes and alluvial fans (Blikra and Nemec, 1998; Blikra and Selvik, 1998; Sanders et al., 2009; Freppaz et al., 2010), relative to fluvial sediment transport or debris flows, snow flows hardly received attention from geologists.

The mountain range – termed Nordkette – adjacent north of the city of Innsbruck (Fig. 1) has a long and dreadful record of avalanche damage to vegetation and facilities, and life toll. Nordkette is riddled with long and steep ravines that were and are by-passed by large, destructive avalanches that, in some cases, literally reached the citys' doorsteps until the 20th century (Schönegger, 2006). Construction of avalanche dams and breakers banned destruction of facilities, but occasional damage to forest and even life toll persist til present. Due to its southward exposition and facing into a foehn-wind corridor, Nord-kette is prone to formation of large full-depth avalanches mainly during late winter and spring (see, e. g., www.avalanches.org/ for snow avalanche terminology). The common incidence of full-depth avalanches implies a high capacity to erode and transport material, and to excavate avalanche chutes from bedrock. This paper presents a first summary of features related to snow avalanches and snow glides on the southern flank of Nordkette. Features are described in order of their scale in space from large to small, from entire avalanche chutes down to single lithoclasts. A set of criteria is presented how to identify snow avalanche activity from diverse indicators, with an application to two areas in the Apennines mountain range in Italy.

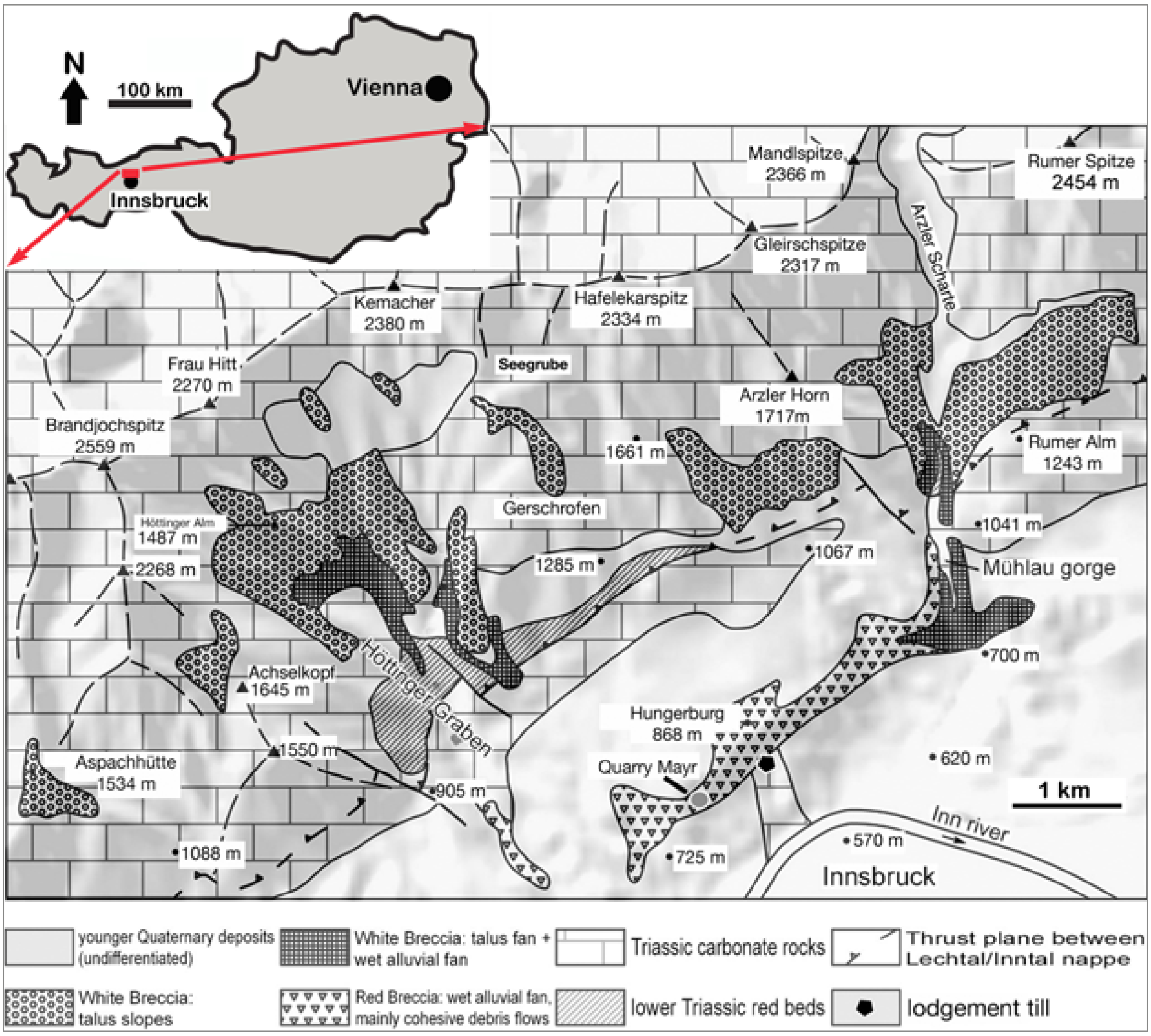

Fig. 1: Position of investigated area in Austria, and simplified geological map of southern slope of Nordkette range.

2. Setting

The southern slope of Nordkette (Fig. 1) range is located along the soutern limit of the Northern Calcareous Alps (NCA) that are built of cover-thrust nappes (Schmid et al., 2004). Nordkette comprises two superposed thrust nappes mainly of Triassic limestones and dolostones. The basal part of the superjacent nappe (Inntal nappe, Fig. 1) consists of Lower Triassic red beds that represent a distinct marker interval; aside of the red beds, practically the entire mountain flank consists of carbonate rocks of neritic environments. Over large areas, the truncated Triassic succession of Nordkette is overlain by an upper Pleistocene package of lithified talus- and alluvial fan deposits ('Hötting Breccia' *Auct.*) (e. g., Ampferer, 1914; Penck, 1921). The Hötting Breccia is traditionally subdivided into the White and Red Breccia, respectively (Fig. 1). The White Breccia comprises deposits of talus slopes and stream-dominated alluvial fans, and consists entirely of clasts of Triassic

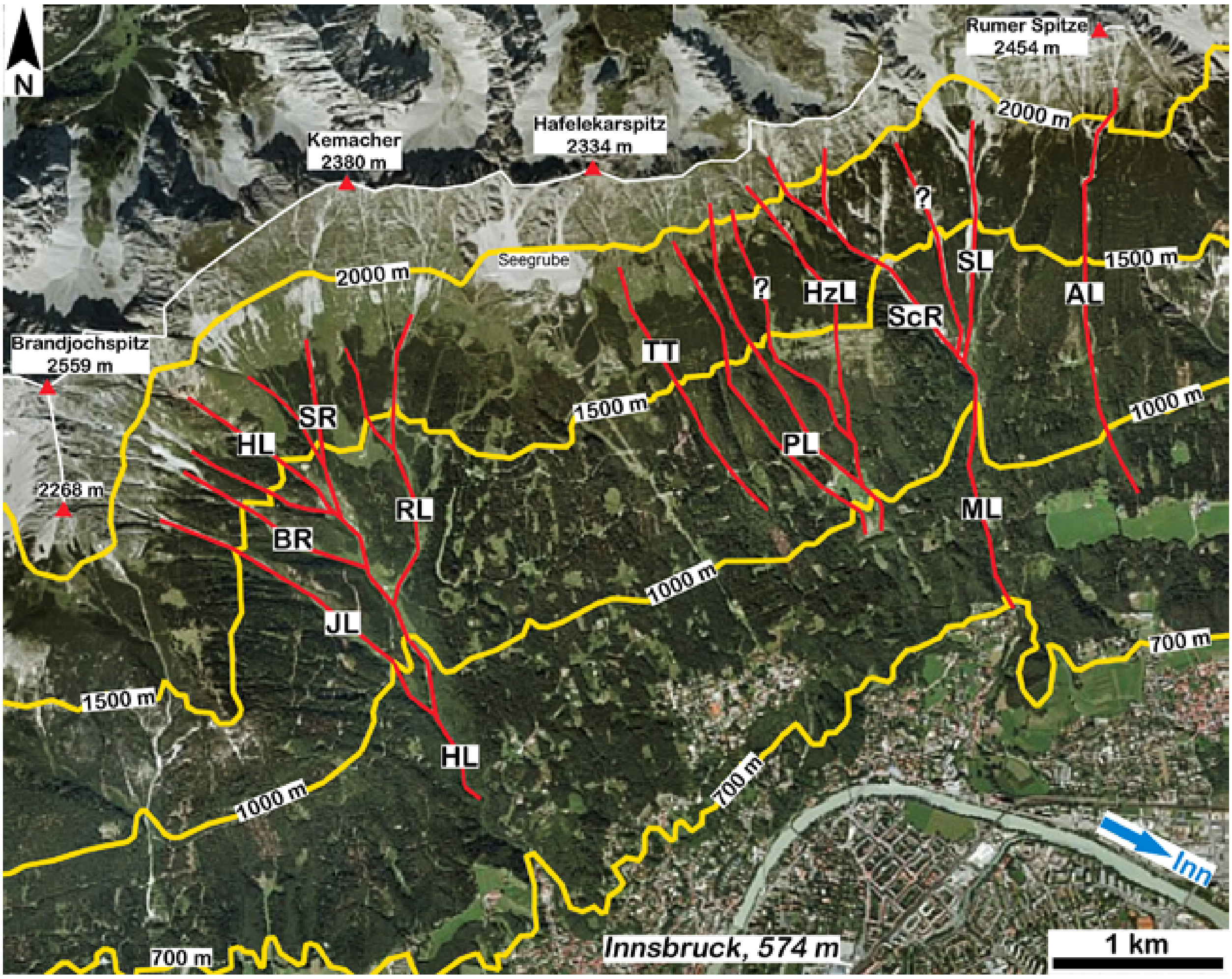

Fig. 2 : Satellite orthoimage showing the main avalanche chutes along the southern slope of the Nordkette range. AL=Alblahner; BR=Breitachreissn; JL=Junger Lahner; HL=Höttinger Lahn; HzL=Herzwiesn Lahn; ML=Mühlauer Lahn; PL=Pfurgegg Lahnen; RL=Rossfall Lahner; ScR=Schusterreissn; SL=Scharten Lahn; SR=Sattelrinner; TT=Taubental; ?=avalanche chutes for which a traded name could not be found out.

carbonate rocks. The Red Breccia, in turn, is rich in lithoclasts derived from the red beds. The Red Breccia consists mainly of deposits of cohesive debris flows and torrential streams. Recent investigations into facies archi-tecture and numerical ages suggest that what is subsumed as Hötting Breccia in fact consists of several lithosomes separated by unconformable contacts (Sanders, 2010). At the present state of investigation, an accumulation of all lithosomes comprising the Hötting Breccia during the late Riss glacial to early Würm appears as the most parsimonious interpretation (see Sanders, 2010, for summary; cf. Gemmell and Spötl, 2009).

The present upper treeline at Nordkette is situated between about 1500 to 1700 m a.s.l.; above, hillslopes are covered by stands of mountain pine (*Pinus mugo*) and by grass. The present altitude of the treeline results from extensive anthropogenic clearing for pasture and use of wood, mainly during the 19th century (Heuberger, 1975); the area became partly re-forested since then. Marked damage to forest was exerted by ground avalanches and, in particular, by rare powder avalanches (Schönegger, 2006, p. 7, p. 10). Comparison with adjacent south-facing mountain flanks of the NCA suggests that the upper treeline ecoline at Nordkette perhaps ranged up to 1800-2000 m a.s.l.

Along the southern slope of Nordkette, a single landform ('Seegrube') is present that represents a nivation cirque (cf. Watson, 1966; Rapp, 1982). Otherwise, the slope is riddled with avalanche chutes (Rapp, 1959) or *rasskars* (Ahlmann, 1919; Luckman, 1977) up to more than three kilometers in length incised into the Hötting Breccia and/or Triassic bedrock (Braunhofer, 2011) (Fig. 2). Depending on avalanche size and runout, the vertical drop and track length of snow flows varies over a wide range, and among individual ravines. Large avalanches, however, are associated with typical vertical drops in the range of approximately 1000 to more than 1500 meters (see also below). The avalanche chutes are paved with grass-covered soil over most of their extent. In their most upslope part, some of the chutes may be littered or thinly veneered with scree derived from partly vegetated talus slopes higher up. These chutes are by-passed by snow avalanches nearly every winter to spring, and at least most of the chutes are dubbed with a popular name (see Fig. 2). For the area considered herein, a fairly reliable and continuous record of snow avalanches goes back to 1855 ('avalanche chronicle'; Schönegger, 2006). Whereas powder avalanches are relatively rare on the southern slope of Nordkette, ground avalanches are common (Schönegger, 2006). Powder avalanches can exert heavy damage to forest, but full-depth avalanches exert most erosion on their substrate and are most effective in transporting soil and scree. The avalanche chro-nicle, and my own observations, suggest that large, full-depth avalanches typically form upon rapid, transient warming during winter (e. g. due to a phase of foehn wind, in some cases combined with rain), and in spring. Despite measures to prevent the formation and/or to block large and highly mobile avalanches, large full-depth avalanches occasionally still do form, such as during the late winters of 1986 (Schönegger, 2006) and 2012. At the beginning of March 2012, after weeks of persistently cold weather, rapid and sustained warming combined with fair weather led to rundown of ground avalanches in each of the chutes within two days from warming; this was a rare situation even for an avalanche-prone slope such as that of Nordkette. A comparable situation, with 14 avalanches descended over five days, is recorded for the winter of 1951 (Schönegger, 2006). Many of the March 2012 avalanches detached along the underlying soil or rock substrate and were rich in scree, chunks of soil, and uprooted vegetation (mountain pine, spruce, beech) (Lorenzi, 2012). The present paper provides a first summary of features related to erosion by snow avalanches and snow glides along the southern flank of Nordkette. In the following, these features are described: (a) from the relatively largest scale of entire avalanche ravines down to small-scale features including single lithoclasts, and (b) in downslope direction following snow transport.

3. Features of erosion

3.1. Avalanche chutes to stream valleys

Downslope from the crest of the Nordkette range, the areas subject to snow avalanching can be subdivided into three parts (Fig. 3, Fig. 4). (1) The uppermost part is the avalanche starting zone. Overall, the starting zone of most avalanches is a slope sector typically 40-45° in steepness, and sculpted with shallow bedrock chutes (sector labeled 1 in Fig. 4). The starting zone for many avalanches descending along Rossfall-Lahner and Höttinger Lahner is an exception: Along this sector of the mountain flank, many snow flows detach along the relatively uniform slope between 2100 to 1800 m a.s.l.; this slope is 35-40° in steepness, and is underlain by loose scree and/or by Hötting Breccia veneered with vegetated soil (Fig. 4B).

Downslope, the starting zone passes into: (2) A straight to low-sinuous chute incised into bedrock (Hötting Breccia and/or Triassic carbonate rocks). The chutes typically are of 'inverted trapeze' shaped cross-section, and increase in depth down slope (cross-sections A and B in Fig. 3; Plate 1A, 1B). For medium to large avalanches, this part represents the upper or uppermost sector of their track. Down slope, some of the larger avalanche chutes deepen and widen to a U-shaped cross-section roughly some 20-80 m in width along their floor (cross-section C in Fig. 3; lower part of Rossfall-Lahner in Fig. 4B; Plate 1C). These U-shaped sectors of the chutes are incised into Hötting Breccia or into Triassic carbonate rocks. Along other chutes, the depth of incision merely increases while the 'inverted trapeze' shaped cross-section is retained. Medium-size avalanches typically stop in this part of the chutes; large avalanches, however, by-pass this sector. Farther downslope, over a distance of a few hundreds of meters, the avalanche chutes show an overall gradual narrowing of their floor, and attain a V-shaped cross-section; this transition marks the onset of prevalent fluvial erosion (transition from cross-section C to D in Fig. 3; Fig. 4C). Part 3 of the avalanche tracks is drained by a semi-perennial to – farther downstream – perennial creek. The large avalanches documented in the avalanche chronicle, and several avalanches observed by the present author stopped only in this, stream-dominated part of the track. A few avalanches, however, are reported to have even reached the inhabited areas along Höttinger Graben and beyond the debouch of Mühlau gorge (Schönegger, 2006) (cf. Fig. 1).

3.2. Rip-up scars, grooves

Rip-up of soil and scree is a common feature of erosion associated with snow glides. Snow glides are indicated by crescentic open fissures in the snow cover, giving rise to 'snow mouths' (see www.avalanches.org/, for term). Snow glides are particularly common on the slopes above Höttinger Alm and east of Seegrube (cf. Fig. 1), where rip-ups are common and diverse in shape and size. Many rip-ups are of rectangular to subcircular shape in plan view, and about a meter to a few tens of meters in width. Rip-ups not planed by by-pass of full-depth avalanches typically are associated with small accumulations of scree and soil (Plate 1D). Where slopes in the avalanche starting zone are underlain by Hötting Breccia, the rip-up marks are in many cases associated with subcircular to elliptical depressions a few meters

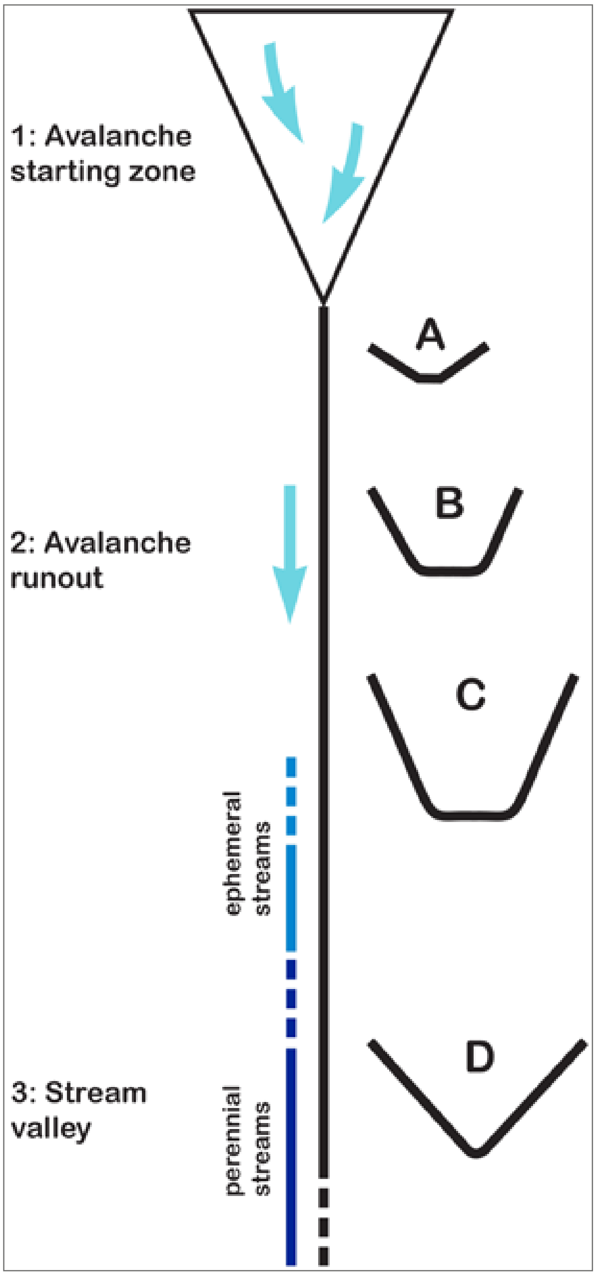

Fig. 3: Scheme of avalanche tracks, not to scale. See text for description and discussion.

to about 20 m in width. The upslope side of the depressions is a crescentic scar that may be sculpted with rip-ups. The floor ahead of the scars is vegetated by grass, and/or littered with scree (Plate 1E). By-pass of full-depth avalanches and/or snow gliding over a number of seasons give rise to rip-ups associated with downslope-elongate scree tails (Plate 1F). More rarely, rip-ups of typically a

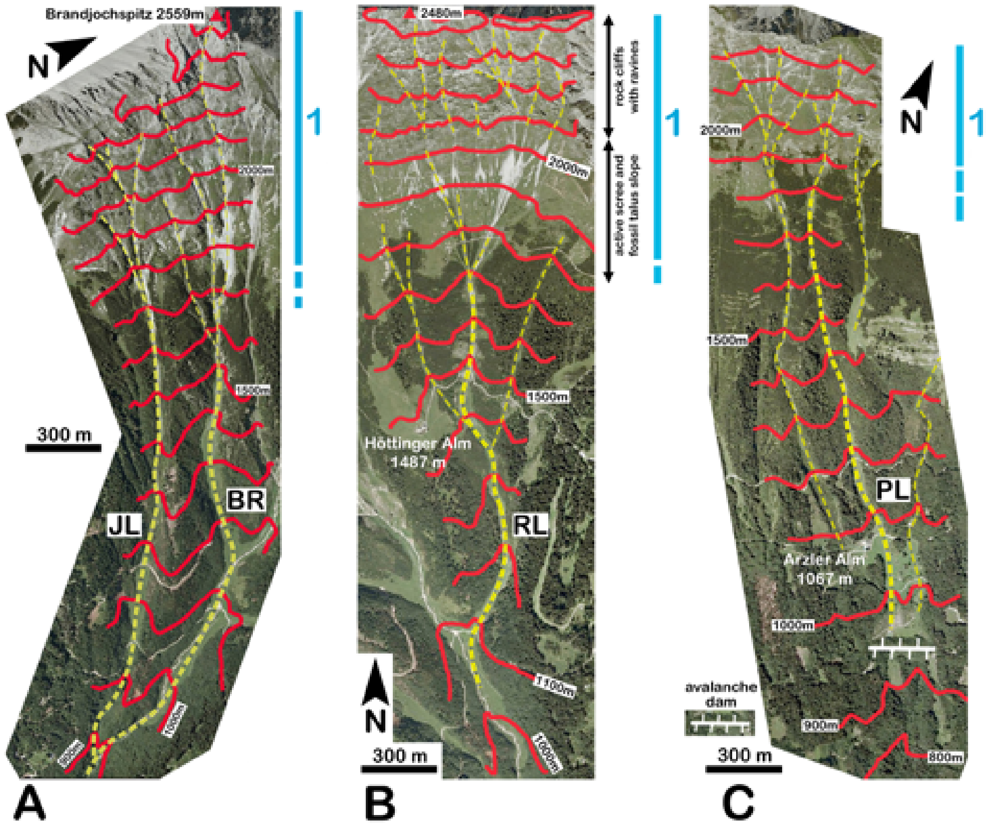

Fig. 4: Some major avalanche chutes along Nordkette, from west (A) to east (C) (compare Fig. 2) (**A**) Along Junger Lahner (JL) and Breitachreissn (BR), most avalanches start between 1900-2300 m a.s.l. (**B**) Rossfall-Lahner (RL) and its tributaries are associated with a comparatively wide avalanche starting zone, between 1700 to 2100 m a.s.l. The slope from Höttinger Alm up to 2100 m a.s.l. is underlain by Hötting Breccia. On this slope, snow glides indicated by snow mouths are common. (**C**) The Pfurgegg-Lahnen (PL), with a starting zone of most avalanches between 1800 to 2200 m a.s.l., have been tamed by an array of concrete avalanche breakers (not indicated), and a terminal dam at approximately 950 m a.s.l.

few decimeters in diameter of soil and scree were observed also along the avalanche tracks (Plate 2A). Along the avalanche chutes, the surface is locally sculpted by grooves excavated from soil and scree (Plate 2B, 2C). The grooves may be associated with scars produced by drag of boulders and/or logs along the base of full-depth avalanches (Plate 2D).

3.3. Polished–striated surfaces, impact marks

Where bedrock is exposed along the avalanche chutes, upstream-protruding portions of the rock surface may be polished and striated (Plate 2E). Along the ravines, polished and striated (p-s) rock surfaces were observed in two settings: (a) at bedrock steps across the entire width of a ravine (e. g. Rossfall-Lahn, Höttinger Lahn; Plate 2B), and (b) along bedrock-incised flanks of the ephemeral upper part of streams. In the latter setting, the p-s surfaces are present, both, at the upslope face and at protruding ledges of rock. On downslope-directed rock faces, polish and striation were never observed. Patches of polished bedrock surfaces were observed along very steep to subvertical exposures at a vertical distance of up to eight meters above the thalweg of the adjacent creek. Another indication of snow-avalanching is represented by lithoclasts of gravel to boulder size, firmly embedded in soil, that show polished and striated surface patches (Plate 2F). Depending on clast size and overall shape, only the projecting or the higher-positioned parts of the clast surface are polished and striated whereas receding

Plate 1: White arrows in photos indicate downslope direction (see Fig. 2 for location of avalanche chutes). (**A**) View up from 1540 m a.s.l. into Sattelrinner chute, incised into Hötting Breccia. (**B**) View from 1360 m a.s.l. down along Rossfall-Lahner chute. Note wide floor paved with partly vegetated, extremely poorly-sorted, bouldery to pebbly scree. Along this sector, the chute is incised into Hötting Breccia. (**C**) View up from 1080 m a.s.l. into Rossfall-Lahner chute. Note deep, steep incision of the chute into Hötting Breccia, and wide floor littered with scree. (**D**) Rip-up scar at 1860 m a.s.l. above Höttinger Alm. The rip-up scar is excavated from weathered Hötting Breccia. Note scree tail in downslope direction. Yellow bar is 1 m in length. (**E**) Cuspate depression excavated from Hötting Breccia, 1840 m a.s.l. Dashed white line highlights the slope line. White stipples indicate the upper brink of the depression. Width of depression is approximately 15 m. (**F**) Satellite orthoimage showing rip-up scars on soil-covered, weathered Hötting Breccia. Note also downslope elongate scree tails associated with the rip-ups.

Plate 2: White arrows in photos indicate downslope direction (see Fig. 2 for location of avalanche chutes). (**A**) Rip-up scar, littered with scree, on the floor of Pfurgegg ravine. (**B**) View onto downslope grooves within Rossfall-Lahner chute. White stipples indicate the brink of a bedrock step a few meters in height. Width of view in middleground approximately 25 m. (**C**) View up along a Pfurgegg-Lahner chute. Note elongate grooves moulded from soil (underlain by scree). Person for scale. (**D**) Avalanche striae in stony soil produced by a spring 2012 snow avalanche. Walking stick is 1.3 m in length. (**E**) Lithoclast within Hötting Breccia, showing polished and striated surface. Outcrop is located approximately 6 meters vertically above the thalweg of the ephemeral upper part of Höttinger Bach streamlet. Höttinger Graben, 1020 m a.s.l. (**F**) Boulder on floor of Höttinger Graben ravine. Note light grey, polished and striated projections of boulder surface; depressions of the boulder surface, in turn, are 'normally' weathered, medium grey or blackish. Pen is 14 cm in length.

parts of the surface are 'normally' weathered and lichenized (Plate 2F, Plate 3A). For smaller clasts, the entire surface facet may be polished and striated (Plate 3B). Excavation of all types of clasts showed that it is only the upper, daylit surface that shows polish and striation. In addition, the striae all run into the same direction, consistent with downslope flow. Clasts with facets or with surface patches showing polish and striation are found in the lower and middle part of the avalanche ravines. Boulders with surfaces abraded and rounded by numerous impact marks are present at sites where avalanches jump over rock steps (Plate 3C). In addition, impact marks are concentrated on 'upflow' or protruding edges of boulders overridden by avalanches.

4. Features of sediment transport and deposition

On downmelting full-depth avalanches, patches of scree a few decimeters in width are common (Plate 3D). There is no sharp limit in size between patches of scree a few decimeters in size to scree patches tens of meters in lateral extent (Plate 3D, 3E). In all observed cases, the scree patches and the topmost layer of avalanche snow mixed with scree are underlain by pure avalanche snow. In at least many cases, the pure avalanche snow that underlies the scree-laden snow: (a) was deposited during the same avalanche event, and (b) comprises the majority of avalanche volume (Lorenzi, 2012). Scree-laden snow avalanches may be accompanied, or not, with damage to vegetation. Variable relative amounts of soil (fine-grained sediment) and scree are transported downslope in avalanches together with uprooted vegetation (Plate 3F, 4A). The middle and lower part of most ravines is variably littered with gravels to small boulders (Plate 4B). Along Rossfall-Lahner (cf. Fig. 4B), elongate accumulations of boulders to gravels are locally present along the margins of the ravine (Plate 4C).

5. Interpretation

If the bedrock-incised chutes had been excavated by glacial erosion, or mainly so, each ravine should terminate upslope in a cirque followed downslope by a glacial chute (see, e. g., Benn and Evans, 2010). Except for the nivation cirque of Seegrube that is not associated with a chute down slope, however, no cirques are present along the southern flank of Nordkette. As mentioned the typical width of the lower, U-shaped part of the ravines is in the range of a few tens of meters; conversely, practically all glacial chutes of the NCA are distinctly wider. If the comparativey long and distinctive part 2 of the chutes (cf. Figs. 3 and 4) were excavated by fluvial processes, it should display a V-shaped rather than U-shaped cross-section. The chutes are similar in shape, length and downslope change of cross-section to chutes excavated by snow avalanching (e. g., Rapp, 1960; Gardner, 1970; Luckman, 1977). In the starting zone and in the upper part of a few of the avalanche chutes, aside of snow avalanches, episodic downslope transport of scree is also sustained by ephemeral surface runoff. In addition, in the upper part of Junger Lahner and Breitachreissn (Figs. 2 and 4A), avalanche snow may be preserved til July or August, promoting deepening of the chutes by nivation. The observation that the present sector 2 of the avalanche chutes is paved by grass-covered soil, underlain by scree or bedrock, suggests that at least the 20th-century avalanches are no longer of an erosive capacity for substantial incision. Overall, however, snow flows clearly are the most significant process in downslope material transport and excavation of the chutes.
Rip-ups form where soil or another type of unlithified substrate is subject to drag exceeding

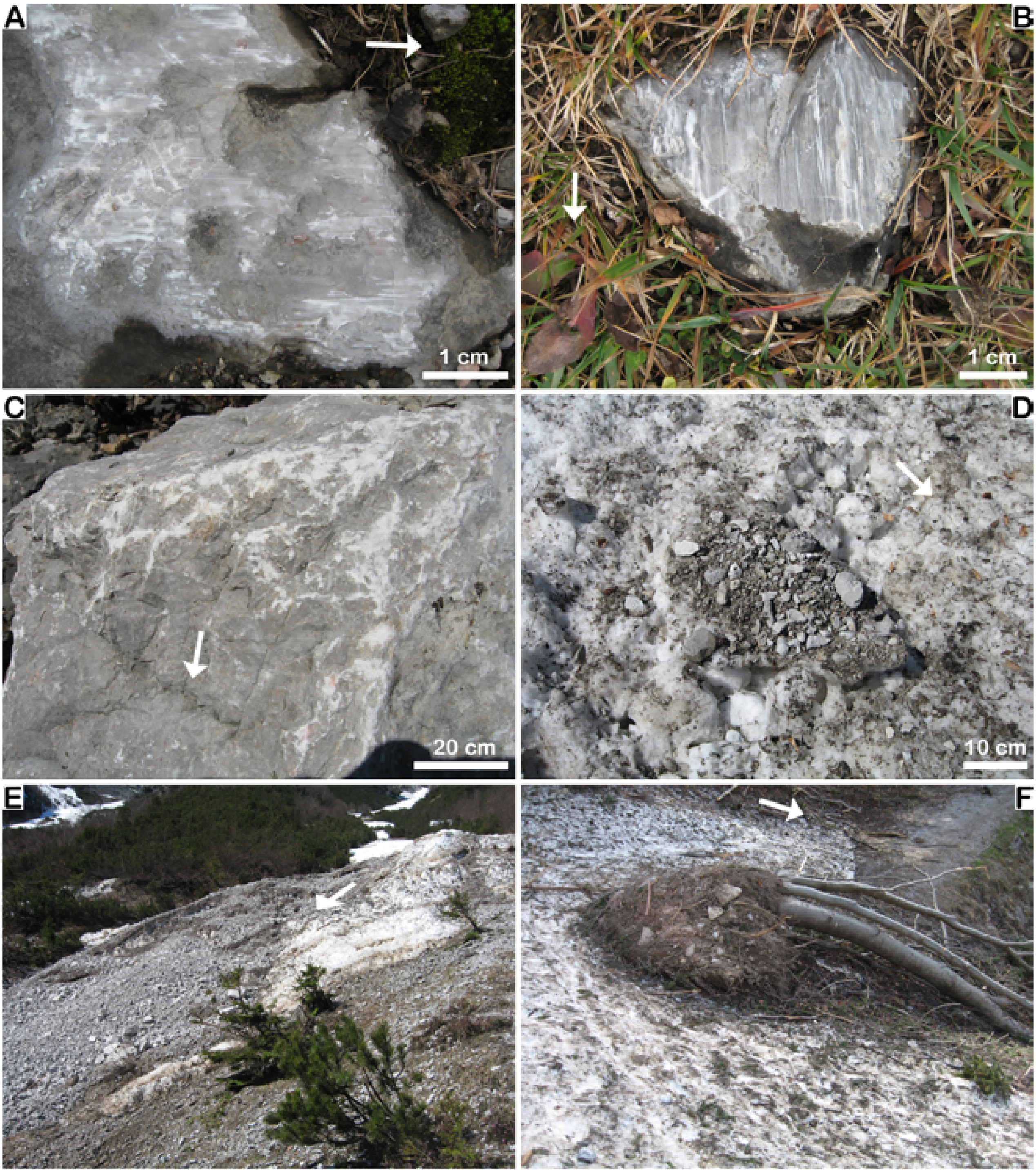

Plate 3: White arrows in photos indicate downslope direction (see Fig. 2 for location of avalanche chutes). (**A**) Detail of boulder shown in Plate 2F. Note polished and striated projections of surface, and medium grey, 'normally' weathered depressions in between. (**B**) Coarse pebble with polished and striated surface, Höttinger Graben. (**C**) Boulder riddled with whitish impact marks on parts of the surface that face upstream into snow avalanches. Rossfall-Lahner chute, 1170 m a.s.l. (**D**) Patch of scree on downmelting avalanche snow, Alblahner. (**E**) Large patch of scree underlain by avalanche snow, Arzler Reisse ravine. (**F**) Bunch of uprooted beeches, bearing soil and scree in the root stock. Rossfall-Lahner, 1090 m a.s.l. Width of view approximately 4.5 meters.

Plate 4: White arrows in photos indicate downslope direction (see Fig. 2 for location of avalanche chutes). (**A**) View downslope onto right flank of Höttinger Graben ravine. In spring 2013, an highly mobile avalanche laden with uprooted trees, soil and scree vertically ran up the right flank, then turned down into the ravine. Along this path, this part of the snow avalanche toppled numerous trees. (**B**) Floor of Pfurgegg ravine, littered with scree, 1220 m a.s.l. (**C**) Downslope-elongate trail of cobbles to boulders along right margin of Rossfall-Lahner ravine, 1110 m a.s.l. (**D**) Google Earth® image of part of western flank of Maiella massif, Italy. The mountain slope is sculpted with an array of snow-avalanche chutes. (**E**) Polished and striated surface of the flank of a ravine incised into a Quaternary slope breccia, Gran Sasso, Italy. Pen for scale is 14 cm in length. (**F**) Pink-coloured, striated surface of a Quaternary slope breccia along the flank of a ravine, Gran Sasso, Italy. Note contrast of light-pink, striated surface with dark grey surface with moss patches on top. Pen is 14 cm long.

the shear strength of the material. On soil-covered slopes, the necessary drag to detach parts of the substrate can be exerted by snow glides and full-depth snow avalanches. Snow glides can exert significant shear on their substrate (Thorn, 1978). In addition, when full-depth avalanches detach on unfrozen water-logged soil, rip-up of part of the substrate is widespread. Large rip-up marks are best developed where vegetated soil is underlain by Hötting Breccia. Rip-ups thus are most common along the mountain flank between Seegrube and Achselkopf (Plate 1D–F). This is also the location where the subcircular to elliptical depressions such as that illustrated in Plate 1E are most widespread. In laserscan images, depressions and rip-up marks can not be distinguished. The association of large rip-ups (= surface forms recording active erosion) with the depressions (=surface forms of similar size and shape, but covered with soil) strongly suggests that these two forms are of the same origin. The elliptical depressions most probably start from rip-ups that are continually deepened by snow glides and snow avalanches; once developed to size, the depressions are shaped further by: (a) nivation and (b) by focussing vadose percolation, thus promoting carbonate dissolution and eluviation of matrix. The depressions, however, are not strictly identical to nivation kettles. It is suggested that the development of large rip-ups and elliptical depressions in areas underlain by Hötting Breccia is related to the combined effects of erodability and lithification of the breccia. Thus, the breccia is lithified enough to sustain the very steep upslope rims of rip-ups; on the other hand, the breccia weathers easily enough to allow for further excavation of the exposed parts of the rip-ups. Extensive surveys of laserscan images and satellite orthophotos by the author in the Eastern Alps and in the Apennines indicate that: (a) elliptical depressions are a characteristic (but not strictly diagnostic) erosional landform of vegetated mountain flanks that dip between ~20 to 45°, (b) are underlain by verified fossil talus successions, and (c) subject to snow glides and snow avalanches.

The described bedrock surfaces and lithoclasts with polished and striated (p-s) patches consistent with avalanche flow can form only upon bypass of a sediment-laden, full-depth avalanche. Other types of avalanche (e. g. ground avalanches overriding a basal snow cover at site) that do not directly slide along the bedrock or clast surfaces are ineffective. This is shown by a large ground avalanche descended in March 2012 from Rossfall-Lahner: This avalanche was heavily laden with uprooted trees, soil and scree (Plate 3F, 4A), but exerted no damage to the soil cover and shrubby vegetation at the sites the photographs were taken. After snowmelt, practically no erosion of soil along this part of the avalanche track was observed, and the grass cover was fully intact and flowers blossomed; this indicates that the avalanche did not hug soil, at least in this sector of the ravines. I assume that this was due to the fact that, at the site of observation, the avalanche overrode a pre-existing snow cover. It can be assumed, in turn, that much or most of the soil and scree transported downslope by this avalanche stems from the process of uprooting trees. In the ravines of Nordkette, the upslope disappearence of polished and striated clast surfaces suggests that an avalanche must have a minimum volume and content in 'grinding agents' (lithoclasts, soil) to produce polish and striae. In addition, in the downslope part of the chutes, large spring avalanches may run over bare ground devoid of snow, providing conditions suited for direct contact between sediment-laden snow flows and bedrock or clast surfaces.

The described litters of scree along the chutes (Plate 4B), and the elongate accumulations of boulders to gravels along their flanks (Plate 4C) provide evidence for avalanche-related downslope transport. In avalanche deposits freighted with scree or scree patches the mode of pickup, transport and emplacement of scree and/or scree-laden snow still is largely unclear. At present, three explanations seem possible for this type of avalanche deposit. (1) A larger rockfall into snow that triggers a scree/snow avalanche. This type of combined scree/snow transport is only very rarely directly observed (Sanders et al., 2013). (2) The upper, scree-laden layer of a snow avalanche originally represented the *tailing* part of a full-depth avalanche, and became telescoped onto the already stopped, pure-snow, heading part of that same avalanche. (3) A scree-laden avalanche may be emplaced during a separate event onto an older, pure-snow avalanche deposit (Jomelli and Bertran, 2001; Lorenzi, 2012). Because rockfalls of a volume sufficiently large to forcefully trigger a snow avalanche are relatively rare, it is suggested that possibilities (2) and (3) are the most common. Along most of the chutes of the Nordkette, the present downslope flux of scree by snow avalanching seems to be relatively low. Due to the ephemeral and highly variable nature of avalanche-related scree transport (cf. Freppaz et al., 2010), and due to the patchy distribution of scree also within individual sediment-laden snow flow deposits, however, the flux is difficult to quantify. In addition, as mentioned, depending on avalanche volume and type, individual snow flows stop in a wide range of altitudes, and the deposits of a single avalanche event may extend over hundreds of meters to approximately one kilometer in length. Nevertheless, future investigations should strive to achieve quantitative estimates of avalanche-related sediment transport.

6. Discussion

In the NCA, bedrock chutes formed by snow avalanches are common, but are less conspicuous in comparison to the more distinct glacial cirques and –chutes. Relative to most other areas in the NCA, an absence of glacial cirques over a lateral distance of ~6 km, such as along the southern slope of Nordkette, is uncommon. This is underscored by the fact that the *northern* slope of the range is sculpted by a laterally continous array of glacial cirques, similar to most other areas in the NCA. The common incidence of large avalanches along Nordkette may be related to two factors, i. e. the relatively uniform, E-W trending mountain flank that: (a) dips more-or-less uniformly with 50–30° towards the South, and (b) that faces directly into the full brunt of a major foehn-wind corridor of the Eastern Alps. According to the World Meteorological Organisation, foehn was defined in 1992 as a wind that occurs on the leeside of a mountain range, and that increases in relative dryness and temperature during sinking. In Innsbruck and environs, with respect to triggering of snow avalanches, the most relevant aspect of southerly foehn is a temperature rise of up to 15–20°C or more within a few hours to a day; such foehn conditions are most common in winter to early spring (Seibert, 1985; Mayr and Armi, 2008; Strobl, 2009). A foehn type that may be particularly relevant for triggering of large, full-depth snowflows is foehn combined with rain ('dimmerfoehn') that may prevail for up to a few days (cf. Kuhn, 1989). Dimmerfoehn is typical for decay or for intermittent weakening/modification of foehn conditions. In the Alps, southerly foehn forms in all N-S striking valleys encroaching the crestline of the orogen (Seibert, 1985). Along the Wipp valley extending from Innsbruck to Brenner Pass, however, foehn is of exceptional frequency and intensity, and positive air temperatures in many cases are sustained overnight (Seibert, 1985; Strobl, 2009). This explains the high frequency and intensity of foehn along Nordkette. Strong foehn combined with high air temperature is confined to the area of Innsbruck and Nordkette (Seibert, 1985). The role of foehn as a potential avalanche trigger is repeatedly indicated in reports of the Nordkette avalanche chronicle (Schönegger, 2006, p. 7; p. 28). Unfortunately, most of the reports do not mention the weather the days before an avalanche event. In addition to the discussed factors, deep incision of avalanche chutes also was favoured by the presence of the relatively easily erodable Hötting Breccia.

From talus slopes in Scotland, Ward (1985) described striated patches produced by snow avalanches on the surfaces of boulders. An obvious prerequisite for the production of p-s clast facets, and of p-s patches on boulders, is that the clast rests stationary or is slowly moved while the sediment-laden avalanche passes by (Ward, 1985). This can be effected by sheer weight, as in case of boulders, or by being firmly embedded in soil, as in case of the gravels to cobbles described herein. Other potential substrates able to sufficiently firmly embed clasts were glacial ice, glacial till, and deposits of cohesive debris flows. P-s clasts most commonly form within basal till of glaciers or ice streams, and typically occur in deposits that prompt little doubt as to their glacial origin. The latter is indicated, for instance, by moraines and/or a diamictic sediment fabric with specific features (e. g., 'overcompaction', horizontal shear bands, vertical joints, etc.) (e. g., Benn and Evans, 2010). A major distinction of glacial versus nival p-s clasts, respectively, is that clasts shaped underneath glacial ice should be more-or-less polished and striated on all of their facets. In contrast, p-s clasts formed by snow avalanches are polished and striated on a single facet or on two facets only, whereas the other facets are 'normally' weathered (lichenized and/or discoloured and corroded surface). A distinction between avalanche- from glacially-produced p-s clasts thus should be no problem within a specific geological and geomorphological context. On the other hand, the presence of a few clasts with p-s surface facets not automatically indicate a glacial origin. In interpretation, it should be established that p-s clasts are compatible with the criteria given in Table 1. A more disguising setting of p-s clasts is realized in deposits of extremely rapid mass movements (ERM) (rock slides, rock avalanches; per definition ≥10^5 cubic meters; Evans et al., 2006). In ERM deposits, lenses up to a few meters thick of cataclastic gouge with floating p-s clasts are fairly common. The gouge is 'overcompacted', and many clasts are polished and striated on *all* of their facets. If exposed on the surface of an ERM deposit, larger lenses of gouge with p-s clasts may appear deceptably similar to basal till. On the Tamins rock avalanche in Switzerland, such a lense gave rise to the interpretation of a separate, post-rock avalanche stadial ('Churer Stadium') that was amended only during the 1990s (Fig. 5A) (see von Poschinger, 2005, for summary). It seems possible that many of the glacial tills mentioned for other ERM deposits of the Alps (Abele, 1974) in fact are lenses of cataclastic gouge with p-s clasts. In sediments supplied from provenance areas containing ERM deposits, the interpretation of p-s clasts may be ambiguous. For instance, the Tamins rock avalanche is overlain by the Bonaduz Gravels; these, in turn, consist of substantial amounts of material reworked from the Tamins rock avalanche, but also of material from other sources (von Poschinger and Kippel, 2009). As a result, a correct interpretation of p-s clasts within the Bonaduz Gravels with respect to environment of formation is difficult (Fig. 5B).

Bedrock-incised avalanche chutes are observed on a wide range of rock substrates. They tend to be best-developed on rock types that: (a) are competent enough to form cliffs (slopes >45° in dip) or very steep mountain flanks a few hundreds of meters in vertical height at least, and that (b) contain sufficiently densely-spaced structural weaknesses such as schistosity, joints or faults to render the rock susceptible to disintegration mainly into pebble-sized scree. Investigations into the correlation between avalanche frequency versus slope dip show that the large majority of avalanches detach on slopes 25–<u>38</u>–55° in steepness (McClung, 1987; Schweizer et al., 2003). It is beyond the scope of this paper to provide a discussion of physical weathering processes producing scree (see, e. g., Sanders, 2012, for summary) which, in turn, is transported down slope by snow avalanches. As a result, snow avalanche chutes are most common on very steep mountain flanks or cliffs composed of schists, or of jointed and faulted/folded sandstones or carbonate rocks. As implied by the avalanche-prone slope of Nordkette, however, the frequency and magnitude of ground avalanches along a given mountain flank is also significantly influenced by slope exposition and micro- to meso-climate. Furthermore, on a scale of thousands of years, snow avalanche activity of course is variable (e. g., Nesje et al., 2007). In the ranges of the central Apennines, Italy, for instance, north- to east-exposed mountain slopes are decorated with glacial cirques, terminal moraines, and rock glaciers. Except for the small retreating relict of the Calderone glacier in Gran Sasso (at present Europe's southernmost glacier), however, all glaciers have vanished from the Apennines (Grunewald and Scheithauer, 2010). South- to west-facing mountain slopes, in contrast, are riddled with avalanche chutes (Plate 4D). Under the present climatic conditions in the central Apennines, talus slopes lower than approximately 2400-2500 m a.s.l. are inactive

(Giraudi, 2005). Snow avalanches, in contrast, are still active and encroach to altitudes down to approximately 1000 m a.s.l. Along the SW face of the Gran Sasso massif, bedrock-incised chutes are rarely by-passed by debris flows or torrential surface runoff; this is indicated by lack or scarcity of pebbly deposits, and by soil cover and bushy vegetation and young trees (e. g. juniper, pine, alder) along the ravines. Exposures of polished and striated bedrock surfaces along these ravines, however, hint on occurrence of large ground avalanches, perhaps with a return period of a few tens of years or more (Plate 4E, 4F). In addition, in the downslope forefields of the chutes, cobbles to small boulders littered on grass-covered soil further hint on snow-avalanche activity. According to reports by local inhabitants, small- to medium-sized snow avalanches descend nearly every winter along these chutes; large avalanches that may inflict damage to facilities and even life toll to cattle and humans are less common.

'Fresh' carbonate-rock surfaces produced by fracture or abrasion typically require some 100-150 years to become fully colonized and infested by epi- and endolithic lichens, fungi, cyanobacteria and other bacteria (Chen et al., 2000; Pohl and Schneider, 2002; Hoppert et al., 2004). This implies that avalanche-related polish and striation of clasts and bedrock surfaces should be identifiable – in overall declining quality – over a few tens of years at least. Indeed, in Pfurgegg-Lahner (see Figs. 2, 3, 4C), clasts with striated facets were observed that already were slightly roughened by weathering, and infested by endolithic lichens. More systematic and better-calibrated observations, however, were needed with respect to decay of polished and striated clast/bedrock surfaces in time.

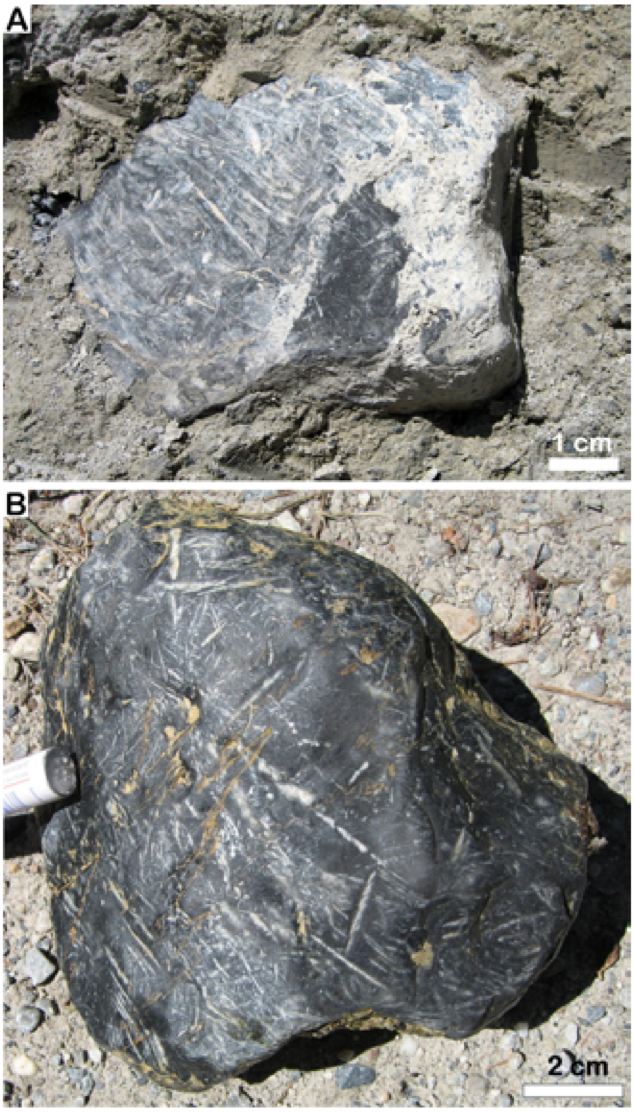

Fig. 5: (**A**) Clast of limestone with polished and striated (p-s) surface, embedded within firm cataclastic gouge. This interval of gouge with p-s clasts is exposed along a roadcut in a shallow level of the Tamins rock-avalanche deposit, Switzerland. Note that striae show different orientations. (**B**) Clast of limestone from the Bonaduz Gravels that directly overlie the Tamins rock-avalanche deposits. Note polished and striated clast surface. See text for discussion.

Table 1: Features of lithoclasts with polished and striated surface (or surface facets) produced in different settings. P-s clasts = clasts with polished and striated surface.

Setting	Clast features	Composition/features of host deposit	Remarks
Snow avalanche track	Clasts with: (a) polish and striation on one or two surface facets, whereas (b) the other surface facets are 'normally' weathered (discoloured, colonized by microbes or lichens) Depressions in p-s clast surface are 'normally' weathered, projections of p-s clast surface are polished and striated All striae are of similar orientation	Extremely poorly- to poorly-sorted, clast-supported scree	Intervals of scree deposited by snow avalanches, and not significantly overprinted by other processes (= snow-avalanche facies *s. str.*), seem to be rare in the NCA
Subglacial setting	Clasts with polish over all or most of their surface, including several surface facets Depressions in p-s clasts are also more-or-less polished Striae typically show in different directions, also on a single facet of a clast surface	Glacial diamicton with 'overcompacted' matrix, with shear fractures and vertical joints Clast- or matrix-supported deposit of cohesive debris flow (redeposited glacial diamicton) May include clasts of remote provenance areas (polymictic clast spectrum)	Distinction from snowflow-produced p-s clasts facilitated by geological and geomorphological context
Extremely rapid mass movements of rock (≥10^5 cbm in volume; 'rockslides, rock avalanches')	Surface characteristics of p-s clasts, sediment fabric and fine-grained matrix all appear similar to glacial diamicton	Diamicton of cataclastic gouge with floating p-s clasts Clast spectrum may be mono- to polymictic	Sediment may be confused with basal till Individual clasts may be mistaken for p-s clasts of glacial origin

Conclusions

(1) The southern flank of Nordkette range is devoid of glacial cirques, but is sculpted by ravines that are mainly formed by snow avalanches (avalanche chutes). Most avalanche pathways can be subdivided into three parts, or sectors: Sector 1, the starting zone, typically is an inverted-triangular, very steep slope facet (with or without shallow ravines) debouching into: Sector 2, a bedrock-incised chute of 'inverted-trapeze' cross-section, that provides the upper part of avalanche tracks; farther downslope, in the lower part of the tracks of most avalanches, the chutes acquire a U-shaped cross-section a few tens of meters in width; still farther downslope, sector 2 grades into: Sector 3, a small valley of V-shaped cross-section drained by a perennial creek; sector 3 provides the stopping zone for the largest avalanches.

(2) In sector 1, both, active and inactive scars up to a few tens of meters in width produced by rip-up of soil, scree and clasts of Hötting Breccia are common. These scars are produced by snow glides, and/or during detachment of full-depth snowflows. Active/inactive rip-up scars of subcircular plan shape, and with a depth of down to approximately 10 meters, are produced by repetitive erosion mainly by downslope transport of snow (glides, avalanches) and, in an advanced stage, by nivation and vadose processes. Arrays of active and/or inactive rip-ups scars are characteristic of mountain slopes underlain by fossil talus.

(3) Along avalanche-track sector 2, gravels to boulders firmly embedded in soil show polished and striated upper, daylit surface facets produced by bypass of sediment-laden full-depth snowflows. In addition, bedrock surfaces exposed along, both, the flanks and steps of the avalanche chutes show smoothened to freshly polished and striated surfaces. Polish and striation of bedrock and clast surfaces, respectively, probably is identifiable over at least a few tens of years after by-pass of a full-depth, sediment-laden snowflow, before being eradicated by weathering and lichenization.

(4) Clasts with surface facets polished and striated by snow avalanches can be readily distinguished from thoroughly polished/striated clasts from the basal till of glaciers by a set of criteria. Conversely, clasts with thorough surface polish and striation, and floating within firm fine-grained rock flour, are also produced by extremely-rapid mass-movements of rock; depending on geological context, these latter clasts may not be straightforwardly distinguished from clasts derived from glacial till.

(5) Along Nordkette, features of avalanche-related sediment transport and -accumulation include: gravels to boulders littered along avalanche chutes and perched on top of larger clasts; elongate, tongue-shaped litters of gravels to small boulders along avalanche flows; clusters of scree probably transported in chunks of ripped-up basal snow layers and/or in frozen state; chunks of soil and soil plus scree; finally, root stocks of trees torn out by avalanches embrace soil and lithoclasts.

(6) Along Nordkette, aside of the topographically lowest part of slope drained by perennial creeks (sector 3, see above), snow avalanching is the most active geomorphic agent in shaping the long chutes that characterize this mountain flank. The common incidence of large and destructive ground avalanches along Nordkette is related to: (a) the mountain flank dipping with ~30-50° S, maximizing insolation, and (b) the facing of the flank into a major foehn-wind corridor. Rapid warming during foehn weather lowers the stability of the snow cover and, depending on circumstances, of underlying soil and scree, as one prerequisite for development full-depth, sediment-laden snowflows.

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