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Regional analysis of slope instability processes along the southern border of the central Tauern Window (Eastern Alps)

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rockfall
slide

Abstract

The central Tauern Window and the adjacent Austroalpine Unit are characterized by complex tectonic, geological and geomorphologic settings that result in a variety of different hillslope processes. Most scientific studies in the literature about slope instabilities in the Tauern Window focus on single slopes only. The present work is a first attempt, to give a regional overview about gravitational mass movements and predispositional factors, which are typical for the Sub-Penninic, Penninic and Austroalpine units. The varying anisotropy in rock material caused by a highly diversified foliation and the presence of brittle fault zones affects the stability of the slopes within the study region significantly, thus leading to spatial pattern of different types of gravitational mass movements. Mountain slope deformations are the most characteristic morphologic feature and occur throughout the study area. The Sub-Penninic and Penninic units show a higher susceptibility of to rockslides and mountain slope deformations in the southwest dipping slopes. The Upper Austroalpine sub-unit is more susceptible to rockfalls in addition to mountain slope deformations. The Lower Austroalpine sub-unit is primarily susceptible to mountain slope deformations, the dominant mechanism being creep. Some areas of the slopes are covered by moraine deposits or scree due to the glacial and postglacial landscape evolution. Rockfall activity, due to the remobilization of boulders caused by erosion processes, mass movements or wind throw, is a common process. Such „secondary“ rockfalls can be triggered nearly everywhere in the study area. Superficial soil slips and flows are quiet common gravitational mass movement types in the Quaternary fillings of the steeply incised valleys.

Das Tauernfenster und angrenzende Ostalpin ist durch komplexe tektonische, geologische und geomorphologische Eigenschaften charakterisiert, was zu einer Anfälligkeit gegenüber unterschiedlichster Prozesse führt. Die meisten wissenschaftlichen Studien im Bereich des Tauernfensters fokussieren auf einzelne Massenbewegungen auf der Hangskala. Die vorliegende Arbeit soll einen regionalen Überblick über gravitative Massenbewegungen und disponierende Faktoren geben, die für das Sub-Penninikum, Penninikum und Ostalpin typisch sind. Die räumlich variierende Anisotropie beeinträchtigt die Stabilität der Hänge im Untersuchungsgebiet maßgeblich, was sich in einer charakteristischen räumlichen Verteilung der unterschiedlichen Typen von gravitativen Massenbewegungen äußert. Die Sub-Penninische und Penninische Einheit weisen eine höhere Disposition gegenüber dem Auftreten von Felsgleitungen und tiefgreifenden Massenbewegungen in Festgestein (Talzuschub und Sackungen) im Bereich nach Südwest einfallender Hänge auf. Das Oberostalpin hingegen ist höher disponiert gegenüber dem Auftreten von Sturzprozessen und tiefgreifenden Massenbewegungen. Das Unterostalpin ist vorwiegend gegenüber dem Auftreten von tiefgreifenden Massenbewegungen anfällig, die als dominanten Bewegungsmechanismus Kriechen aufweisen. Aufgrund der glazialen und postglazialen Landschaftsentwicklung sind viele Hänge durch eine Moränen- und/oder Schuttauflage bedeckt. Steinschlag infolge der (Re-) Mobilisierung von Blöcken/Steinen durch Erosionsprozesse, Massenbewegungen oder Windwurf, ist ein sehr häufig auftretender Prozess. Solch ein sekundärer Steinschlag kann fast überall im Untersuchungsgebiet auftreten. Flachgründige Rutschungen oder Hangmuren sind sehr typische gravitative Massenbewegungen in den quartären Talfüllungen der tief eingeschnittenen Seitentäler.

1. Introduction

Slope instability processes are common in the Eastern Alps. They occur at a wide range of spatial and temporal scales. Occurrences of certain types of gravitational mass movements are linked directly to specific tectonic, geologic and geomorphologic conditions. Various authors have described gravitational mass movements in the Eastern Alps, e.g. Ampferer (1940), Goetzinger (1943), Stini (1941), Zischinsky (1966), Moser (1971), Brückl and Scheidegger (1972), Abele (1974), Poisel and Eppensteiner (1988), Poisel and Eppensteiner (1989), Moser (1994), Rohn et al. (2004), Lotter and Moser (2007), Prager et al. (2008), Agliardi et al. (2009), Gruber et al. (2009), Poscher (1990), Hübl et al. (2009), Sausgruber et al. (2010), Tilch et al. (2011), Melzner et al. (2012), Prager et al. (2012), Patzelt (2012a), Patzelt (2012b), Ostermann et al. (2012), Zangerl et al. (2012), Chifflard and Tilch (2013), Supper et al. (2013) and Melzner and Guzzetti (2014).

Most of the literature discussing mass movements in the central Tauern Window and the adjacent Austroalpine Unit focuses on single slopes e.g. *Egger-Wiesen-Kopf Talzuschub* (Kronfellner-Kraus, 1980; Moser and Glumac, 1982; Weidner, 2000; Brückl et al., 2001; Brückl et al., 2006; Weidner et al., 2011), *Eckkopf Talzuschub* (Pflügler, 1991), *Reißkofel* (Reitner et al.,

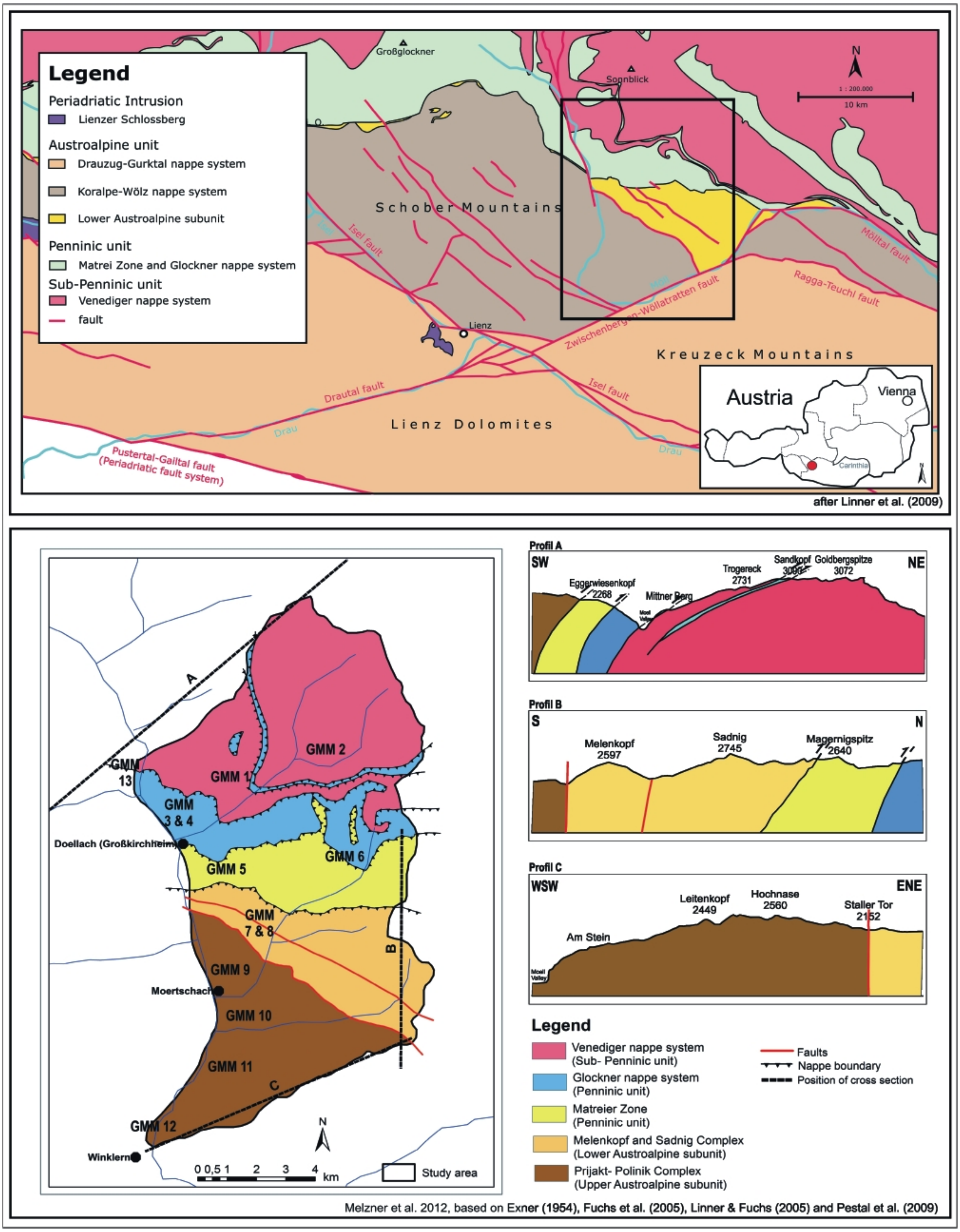

Figure 1: Tectonic map of the southern part of the central Tauern Window and the adjacent Austroalpine unit (Black box in indicates location of study area, modified from Linner et al., 2009) and tectonic map of the study area and cross sections (Melzner et al. 2012 based on Exner 1964, Fuchs & Linner 2005, Pestal et al. 2009). Gravitational mass movements (GMM1-13) discussed in the text are indicated.

1993) and *Oberes Törl* and *Hoher Trog* (Reitner and Linner, 2009). Information about the spatial distributions of these movements is presented in various geological maps e.g. *Geological Map of the Sadnig Group, 1:25.000* (Fuchs and Linner, 2005), *Geological map of the Sonnblick Group, 1:50.000* (Exner, 1962), *Geological Map of Salzburg, 1:200.000* (Braunstingl et al., 2005) and the recently published geological map *Lienz, 1:50.000* (Linner et al., 2013).

The literature does not however include a regional overview of the tectonic, lithologic and geomophological factors that influence the occurrences of different types of mass movements in the central Tauern Window and the adjacent Austroalpine unit. The current study aims to address this issue and provide a profound basis for a more detailed investigation at slope scale, including a detailed kinematic analysis of failure mechanisms respectively.

1.1 Definitions

The term “gravitational mass movements” includes all processes that involve the outward or downward movement of slope material under the influence of gravity (Varnes, 1978). In contrast to other slope processes (e.g. soil erosion), gravitational mass movements do not need a transportation medium such as water, ice or air. Other terms, similar to gravitational mass movements, that are used in the literature include landslides (Cruden, 1991), mass movements (Hutchinson, 1968; Brunsden and Prior, 1984), mass wasting (Yatsu, 1966), slope movement (Varnes, 1978) and deep-seated gravitational slope deformation (Dramis and Sorriso-Valvo, 1994).

The term landslide is often used when referring to any of the above slope movement types. However, the term is considered unsuitable for this purpose because it implies a sliding type mechanism whereas other mechanisms are often applicable. Other authors have expressed similar concerns with the use of the term (e.g. Varnes, 1978; Crozier, 1989).

Gravitational mass movements occur at a wide range of temporal and spatial scales. They may be small localised processes (e.g. single rockfall) or occur over several square kilometres (e.g. rock spread). Their velocities may vary from very-slow (mm/year) to very-fast (m/sec) (Cruden and Varnes, 1996).

1.2 Classification schemes for gravitational mass movement

Gravitational mass movements can vary significantly in form,

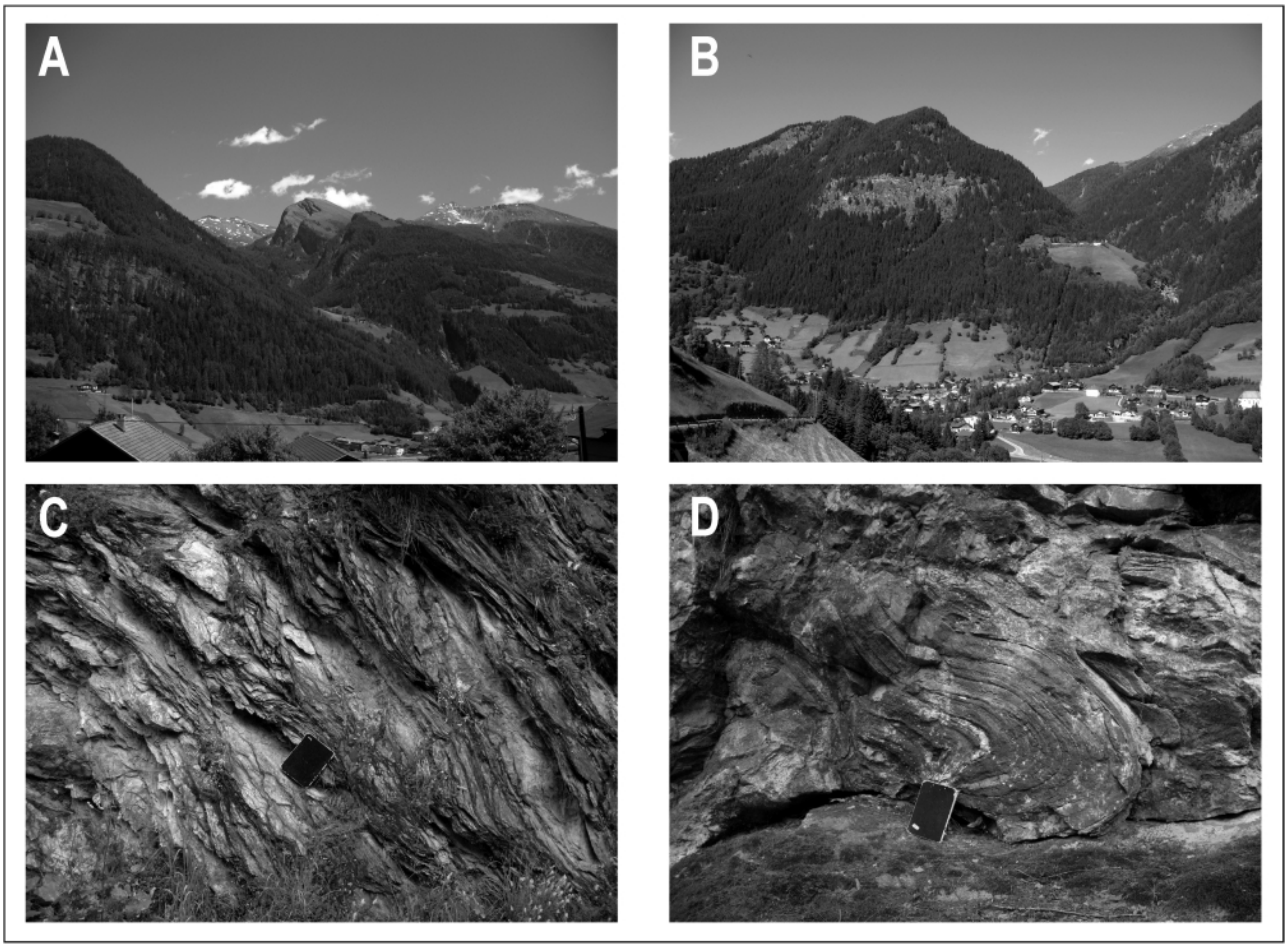

Figure 2: Tectonic and structural settings within the study area: (A) Southwest dipping of Venediger nappe system (Sub-Penninic Unit) and Glockner nappe system (Penninic Unit); (B) Mica- schist within a fault zone in the Glockner nappe system (Penninic Unit); (C) Northeast to southwest dipping of Prijakt-Polinik Complex (Upper Austroalpine sub-unit); (D) Complex rock mass structure within the Prijakt-Polinik Complex (Upper Austroalpine sub-unit) have resulted from several ductil and brittle deformation phases (photos by S. Melzner, 2010).

behaviour, speed, material and volume. They often consist of several sub-processes (Crozier, 1989; Dikau et. al., 1996). Numerous classification systems have been presented in the literature to differentiate gravitational mass movements. Well cited systems include those developed by Hutchinson (1968, 1988), Skempton and Hutchinson (1969), Varnes (1958, 1978), Goodman and Bray (1976), Hoek and Bray (1981), Cruden and Varnes (1996) and Dikau et al. (1996).

Most systems consider the combination of geomorphologic criteria with parameters such as kinematics, type of material or rate of movement respectively. An international unification of landslide classification systems has been promoted by the IDNDR (International Decade for Natural Disaster Reduction). The International Association of Engineering Geology (IAEG) published a Suggested Nomenclature of Landslides (IAEG, 1981); the UNESCO and the International Geotechnical Society (IGS) founded a Working Party on the World Landslide Inventory (WP/WLI). This party published the Multilingual Landslide Glossary (WP/WLI, 1993).

Hungr et al. (2014) reviewed classification systems and subsequently updated the system developed by Varnes (1978). This paper considered this system and those by Cruden and Varnes (1996), WP/WLI (1993), Dikau et al. (1996) and Hungr et al. (2014). These systems distinguish a gravitational mass movement according to mechanism (e.g. fall, topple, slide, flow (incl. creep), spread, complex) and the material involved in the movement.

In relation to mechanism, the term “falls” describes the free fall of material from a steep slope. The term “topple” involves a tilting movement at the base of the mass. Movement along a distinct shear surface are referred to as “slides”, which are subdivided into “rotational” (concave slide surface) and “translational” (planar sliding surface) types. The term “spread” refers to the lateral extension of cohesive material over a deforming mass of softer underlying material (Dikau et al., 1996; Poisel and Preh, 2004). A “flow” is a spatially continuous movement in which surfaces of shear are short-lived, closely spaced and usually not preserved. The distribution of velocities in the displacing mass resembles that in a viscous liquid (Cruden and Varnes, 1996). “Complex” characterises movements that combine different mechanisms (Dikau et al., 1996). Hungr et al. (2014) consider this latter term to be inappropriate because nearly all movements involve more than one type of mechanism (and often more than one type of material).

A “mountain slope deformation” is a large-scale gravitational deformation occurring on steep, high mountain slopes, without fully defined rupture surface and extremely slow rates of movement. The difference between this type of movement and “rock slope deformation” is that the latter type occurs on slopes that are only a few tens or hundreds of meters high and in weak rocks (Hungr et al. 2014).

A “rock compound slide” is characterized by a rupture surface comprising several planes, or a single uneven shaped surface. It also tends to involve significant internal distortion of the moving mass (Hungr et al 2014).

2. Study region

The study area is located in the north-western part of the federal state of Carinthia, Austria. It is part of the geographical unit Goldberggruppe, which occupies a total area of approximately 120 km² along the orographic left-hand slopes of the main valley of the Möll River. It includes the side valleys Zirk-

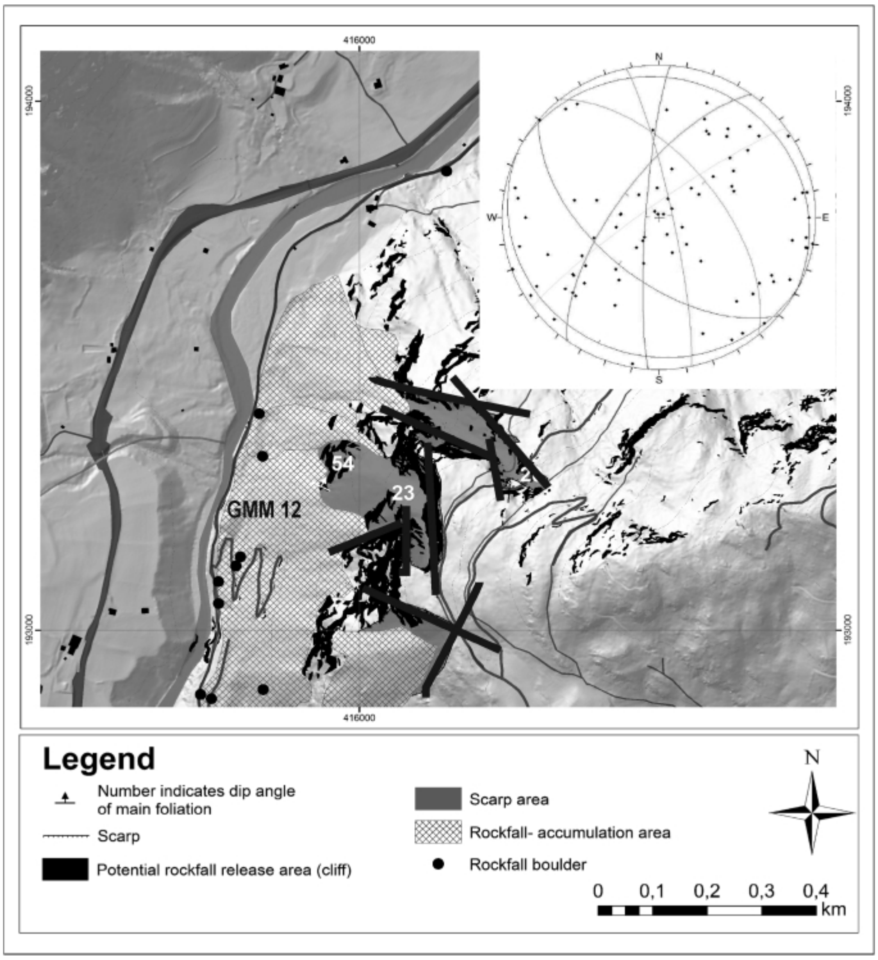

Figure 3: TMap of gravitational mass movements in the Prijakt- Polinik Complex (Upper Austroalpine subunit); map scale 1:5.000 (Melzner, S., 2011). dominant fault planes that strike in WNW-ESE, NNW-SSE, N-S, NNE-SSW and NE-SE directions (pol plot and great circles in equal area projection, lower hemisphere, n. 86) with a high degree of separation are the main cause for large volume rockfalls (GMM 12 in Fig. 1) (mapping by Melzner, S., 2010).

nitz, Asten, and Kolmitzen.

The region is located within the southern part of the central Tauern Window, which is characterized by high tectonic and lithological complexity (Kurz et al., 1998).

From north to south, the region comprises three main tectonic units: Sub-Penninic, Penninic and Austroalpine unit (Schmid et al., 2004; Pestal et al., 2009) (Fig. 1-2). The rocks of the Sub-Penninic and Penninic unit dip towards the south-west, whereas those of the Austroalpine unit dip gently to steeply towards the south-west and, in part, to north-east (Fig. 1-2).

The lowest tectonic unit of the Tauern Window incorporates the sub-penninic Venediger Nappe System (Frisch, 1976; Frisch, 1977; Schmid et al., 2013), which is found in the northern part of the study area (Fig. 1). Rocks of the Zentralgneis, Wustkogel-, Seidlwinkl-, and Brennkogel Formations are the predominant lithostratigraphic units in this area (Pestal et al., 2009).

The Glockner Nappe System (Penninic unit) comprises various lithologies of the Jurassic to Cretaceous Bündnerschiefer Group (Fig. 1) (Pestal et al., 2009; Schmid et al., 2013). In upper tectonic position, the Penninic unit incorporates the Matrei Zone (Fig. 1). In contrast to the Glockner Nappe System in the study area, the Matrei Zone contains meta-sediments of the Bündnerschiefer Group, which are also of Jurassic age.

The southern half of the study area is occupied by the Austroalpine unit, which can be subdivided into a Lower and Upper Austroalpine sub-unit with assigned lithologic complexes (Fig.1). The Lower Austroalpine sub-unit is comprises the Melenkopf Complex and the Sadnig Complex, which is covered by Permian to Triassic meta-sediments. These complexes are tectonically inverted and have thrust over the penninic Matrei Zone to the north. To the south, a steeply dipping, NW-SE striking fault zone marks the border between the Melenkopf Complex and the Upper Austroalpine sub-unit (Fuchs and Linner, 2005) (Fig. 1).

The Upper Austroalpine sub-unit is represented by the Prijakt Nappe (Linner and Fuchs, 2005) as part of the Koralpe-Wölz Nappe System (Schmid et al., 2004; Schuster 2011) (Fig. 1). The Prijakt Nappe, as the tectonic highest unit of the study area, comprises the Prijakt-Polinik Complex.

Brittle deformation is dominated by two dominant strike-slip fault systems, assigned to the dextral NW–SE striking Isel and Mölltal faults and to the sinistral WSW–ENE-striking Drautal and Zwischenbergen-Wöllatratten faults (Fig.1) (Lin-

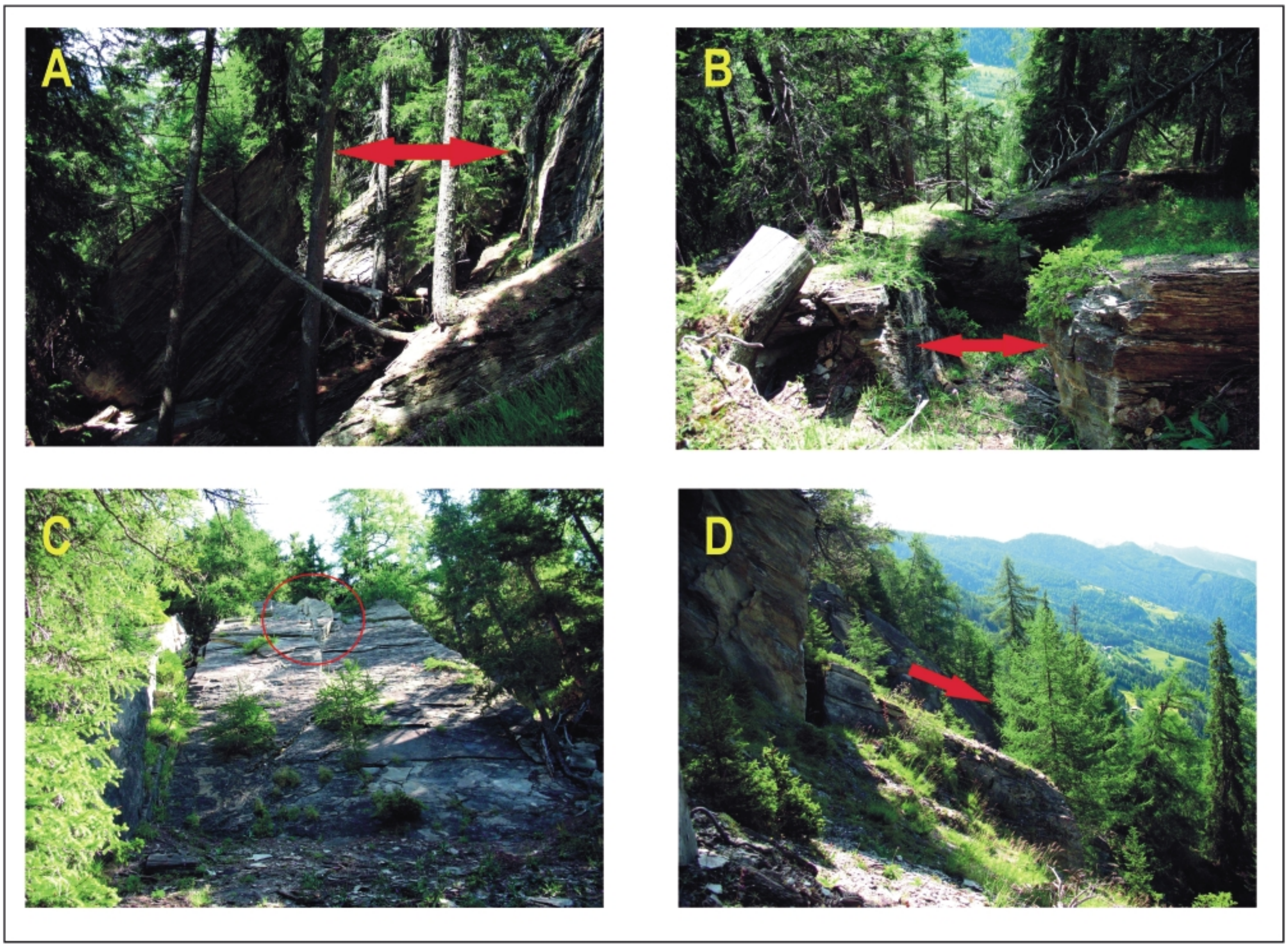

Figure 4: Rockslide in micamarble of the Glockner Nappe System (Penninic Unit). (A) The rockslide (GMM 4 in Fig. 1).shows in the scarp area a displacement of about 20 m and highly loosened zones/caves in the upper part (B) Tension fissures strike slopeward following the main fault directions (317/80) (C) Overturning or folding of rock masses at the toe of the slide; possibly rockfall source (red circle) and topple areas (D) detachment of large rock masses by sliding mechanism (photos by S. Melzner, 2010).

ner et al., 2009).

3. Results

Within the study area, the spatial heterogeneity of the anisotropy in the foliated rocks, as well as the geomorphologic evolution of this region, significantly influences the spatial distributions and occurrences of different types of gravitational mass movements. Structural geologic and geomorphologic mapping were undertaken within the different tectonic units to enable these movements to be characterised within the different tectonic units. Strength assessments of the rock masses involved empirical field identification according to the system of ISRM (1978). Rock type characteristics were based on visual descriptions of hardness and strength anisotropy of each rock type.

3.1 Tectonic and structural geologic factors

The northern part of the study area is characterised by the predominately south-west dipping Sub-Penninic and Penninic Units. Dip slopes are prevalent in these units and hence distinct cliffs are not generally present (Fig. 2A). Cliffs are restricted to those exposures that lie orthogonal to the strike direction of the lithological unit or to areas of significant tectonic structures such as brittle fault zones. The foliation of the rocks of the Glockner Nappe System (Penninic Unit) is highlighted as clusters of discontinuities dipping up to 51° towards the SW. Some steeply SE or NE dipping discontinuities, mainly faults, are dominant orthogonal or sub-orthogonal to the foliation. These structures follow broadly the direction of the Zirknitz Valley. Some very-persistent moderately NNW to NNE dipping discontinuities can also be observed.

The Melenkopf Complex, Sadnig Complex, and the Permian to Triassic meta-sediments (Lower Austroalpine sub-unit) dip steeply towards the south-west. The Prijakt-Polinik Complex (Upper Austroalpine sub-unit) dips as a rigid block gently to the NE or SW. This characteristic has resulted in the formation of distinct cliffs along the orographic left slopes of the Moell Valley between the villages of Moertschach and Winklern (Fig. 2C).

The dextral Isel and Mölltal faults and the sinistral Drautal and Zwischenbergen-Wöllatratten faults (Fig. 1) have produced brittle deformations. These occurrences are prevalent in the study area. The geographic orientations of most of the valleys follow the main faults in NW–SE or WSW–ENE-striking directions (Linner et al., 2009) and also related syn- and antithetic faults, respectively. Only in one section in the Möll valley, between the villages of Mörtschach and Winklern, are these main fault systems not the primary cause for the orientation of the valley. In this section, the Möll glacier has been responsible for the evolution of the landscape (Section 3.4).

The Upper Austroalpine and the Lower Austroalpine sub-units exhibit polyphase Alpine ductile and brittle deformation. Both sub-units were subjected to various brittle periods of faulting; these actions responsible for much of the local strength anisotropy of the rock masses (Fig. 2B & 2D).

Within the Prijakt-Polinik Complex (Upper Austroalpine sub-unit), the highly heterogeneous anisotropy is expressed by (Melzner et al., 2012):

- A significant number of discontinuity sets with each set generally containing discontinuities that have orientations that deviate significantly from the mean orientation of the set.
- Highly persistent faults that are widely spaced and persistent.
- Deep tension structures that follow the main fault systems.
- Rapid transitions in the lithologies and volumetric densities of discontinuities.

The dip-directions of the main foliation vary significantly, but in general dip shallow to moderately (< 30°). In the areas of Moertschachberg and Goaschnigkopf (Fig. 1) a cluster of foliations dip towards the NNW. These orientations correspond to shallow E to NE dipping fold axes of open folds having amplitudes of several tens of metres. The heights of cliffs in the areas are associated with these features. Steeply dipping WNW-ESE to NNW-SSE striking fault planes and their synthetic and antithetic directions are present within the mapped area. The anisotropies of rocks at the Steinerwand, near the village of Winklern (GMM 12 in Fig. 3), are significantly influ-

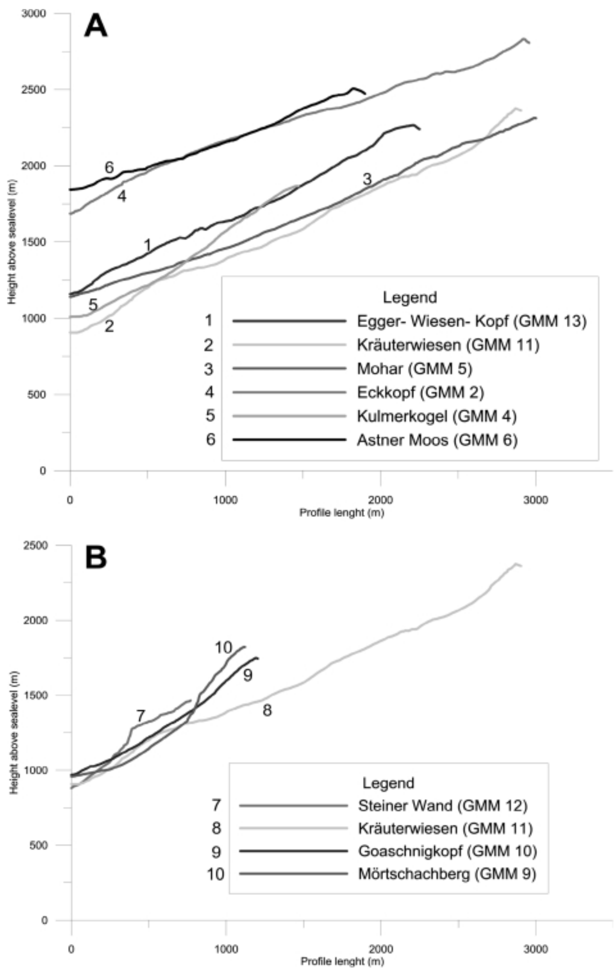

Figure 5: Slope profiles crossing some characteristic types of gravitational mass movements in the study area. The mountain slope deformation in the (A) Sub-Penninic unit, Penninic unit (exclusive GMM 11 in Fig. A) and Lower Austroalpine subunit show much lower slope gradients than it is the case for gravitational mass movements in the (B) Upper Austroalpine subunit.

enced by those fault systems that strike WNW-ESE, NNW-SSE, N-S, NNE-SSW and NE-SE (Fig. 3). A high degree of separation between the faults has resulted in the formation of deeply incised escarpments into the metamorphic rocks.

Similarly, the orientation of the Asten Valley is influenced by the orientations of the faults within the Melenkopf and Sadnig Complex (Lower Austroalpine sub-unit). These faults strike in NE-SW and synthetic and antithetic directions. As occurs in the Upper Austroalpine sub-unit, the dip-directions of the main foliation vary significantly.

3.2 Lithological properties

The sub-penninic Zentralgneis of the Sonnblick area comprises predominantly massive granite gneiss and minor granodiorite gneiss (Exner, 1964). These rock types correspond to the orthogneisses of the western Tauern Window of Carboniferous to Permian protolith ages (Veselá et al., 2011).

The Permian to Lower Triassic Wustkogel Formation comprises predominantly pale-green quartzites and arkosic gneisses. These rock types are stratigraphically followed by Middle and Upper Triassic age Seidlwinkl Formation calcitic and dolomitic marbles. Dark phyllites, dark calc-schists and light calcareous quartzites constitute the Lower Cretaceous Brennkogel Formation.

The Penninic Glockner Nappe System comprises lithologies of Cretaceous age with ophiolite fragments. The predominant lithology within the study area comprises calc-mica schists including mica-bearing marbles.

The penninic Matrei Zone contains meta-sediments of the Bündnerschiefer Group of Jurassic age. Rocks are predominantly comprise dark and light coloured phyllites and, to a lesser extent, calc-mica schists. Notable is the large concentration of intercalated greenschists (Fuchs and Linner, 2005). The highly variable lithology of thise Matrei Zone is completed by Middle and Upper Triassic age calcitic and dolomitic marbles as well as sericite-chlorite schists and pale green quartzites of Permian and Lower Triassic ages.

Figure 6: Rockfall boulder that was released as secondary rockfall at the highly disintegrated front of a mountain slope deformation (GMM 2 in Fig. 1) in coarse-grained granitic gneiss in the Zentralgneis Complex (Venediger Nappe System) (photo by S. Melzner, 2010).

The lithologies of the lower Austroalpine sub-unit resemble those in the Matrei Zone; sericite-chlorite schists and pale green quartzites. Fine-grained micaschist and quartzite are prevalent in the Sadnig Complex. The Melenkopf Complex is more variable, comprising mica-schists and paragneisses as well as granite gneisses and subordinate amphibolites.

The predominant lithologies of the Prijakt-Polinik Complex are coarse-grained paragneisses and mica-schists (Fig. 1) with frequent layers of orthogneisses, amphibolites and eclogites.

3.3 Geotechnical properties of lithological units

The lithological units in the Sub-Penninic and Penninic Unit show a wide range of strength ranging from weak to very strong rock:

The Venediger Nappe System (Fig. 1) represents the Sub-Penninic Unit in the study area. The main lithologies are coarse-grained biotitic granitic gneiss and to a minor extent granodioritic gneiss. These lithologies are characterized by very hard, very compact rocks that are highly resistant to weathering. The rock mass structure of these lithologies is relatively free of pregnant foliations and has a tendency to form sets comprising widely spaced discontinuities, including joints and faults.

The Glockner Nappe System and the Matrei Zone (Fig. 1) represent the Penninic Unit in the study area. The Cretaceous limestone mica-schists of the Bündnerschiefer Group (Glockner nappe) is a rather strong, platy limestone, forming mica-bearing marbles. Depending on the carbonate contents, the lithology can form boulders having volumes of several tens of m^3 (Fig. 4A). The strong rock mass is pervaded by weak layers of mica-schists. These layers have closely spaced foliation, ranging in thickness from a few millimetres to several centimetres. This characteristics results in the formation of very small-to-small blocks. Huge boulders can fail by sliding along to a certain extent, these weak interlayers can cause failure of huge boulders as a consequence of initial sliding along the foliation planes (see chapter 4).

The Penninic Matrei Zone comprises predominantly weak and strongly foliated rocks that are less resistant to weathering than those rocks described previously. From a morphologic perspective, the phyllites of the Bündnerschiefer Group are usually associated with gentle, rolling landscapes and do not tend to form steep cliffs. The lithology comprises, to a lesser extent, calcareous mica-schists and quartzites. These rocks can form significant rockfall source areas, such as those in the southern scarp of the Mohar rock avalanche (GMM 5 in Fig. 1). Alpiner Verrucano and Lantschfeldquarzit are typical lithologies within the Matrei Zone. They comprise as well weak to medium strong phyllites and quartzitic phyllites of Permo

Triassic age (Alpiner Verrucano) and thin platy, pale-green strong quartzites of Lower Triassic age (Lantschfeldquarzit).

Lithological units in the Austroalpine Unit have a wide range of strengths from low to very-high.

The Sadnig Complex (Lower Austroalpine sub-unit) in general contains fine-grained mica-schists with layers of quartzites. This complex is unspectacular; characterized by weak to medium-strong foliated rocks. These rocks are less resistant to weathering than are those rocks described previously. These lithologies are usually associated with a gentle, rolling landscape containing some small cliffs. The main foliation is usually densely spaced and forms the dominant set of discontinuities. In combination with sets of joints, the rock mass characteristically comprises small blocks. The Melenkopf Complex (Lower Austroalpine sub-unit) contains predominantly weak rocks, but also some rocks of high to very-high strength. The Prijakt-Polinik Complex (Upper Austroalpine sub-unit) is characterized by very-high strength, weathering resistant, rocks. High cliffs in the area are associated with these rocks (Fig. 2).

3.4 Geomorphologic factors

The Möll Valley takes the form of a typically wide U-shaped alpine trough, due to intense glacial erosion during the Würmian glacial maximum. The altitudinal difference is over 1,000 metres from the bottom of the main valley to the peaks of the mountains. After the Last Glacial Maximum, during the Gschnitz stadial and Egesen stadial, the Möll Valley and the side valleys were subject to several glacier advances, albeit with restricted regional extent. An associated sequence of terminal moraines has remained within the study area. The side valleys occur at notably higher elevations, which has promoted post-glacial fluvial erosion processes and the formation of steeply incised gorges.

Due to the young landscape evolution, an almost preserved, over-steepened glacial and post-glacial relief can be recognized throughout the study area. Nearly all of the lithological units form cliffs, having 48° to 50° of slope inclination. The higher strength rocks (e.g. Prijakt-Polinik Complex) result in a greater proportion of the steep terrain (e.g. GMM 9 in Fig. 1) than do the lower strength rocks (e.g. Matrei Zone, GMM 6 in Fig. 1). The development of deep-seated gravitational mass movements likely started during the late glacial or post-glacial period after the breakdown of the net of glacial streams and exposure of the glacially over-steepened relief.

3.5 Types of slope instability processes

Rocks within the Sub-Penninic and Penninic units show a high susceptibility to failing according to planar and rotational type sliding mechanisms and large-scale deformation of mountain slopes or rock compound slides.

An example of mountain slope deformation occurs near to the confluence of the Small Zirknitz and Large Zirknitz Rivers (GMM 2 Fig. 1) within the Venediger Nappe System (Sub-Penninic unit). The combination of rock spread and creep (terms according to Varnes, 1978) is in its initial stage of development. The scarp area of the mass movement has developed more-or-less completely, whereas an over-steepened front has not yet formed distinctly (Fig. 5). A sequence of minor

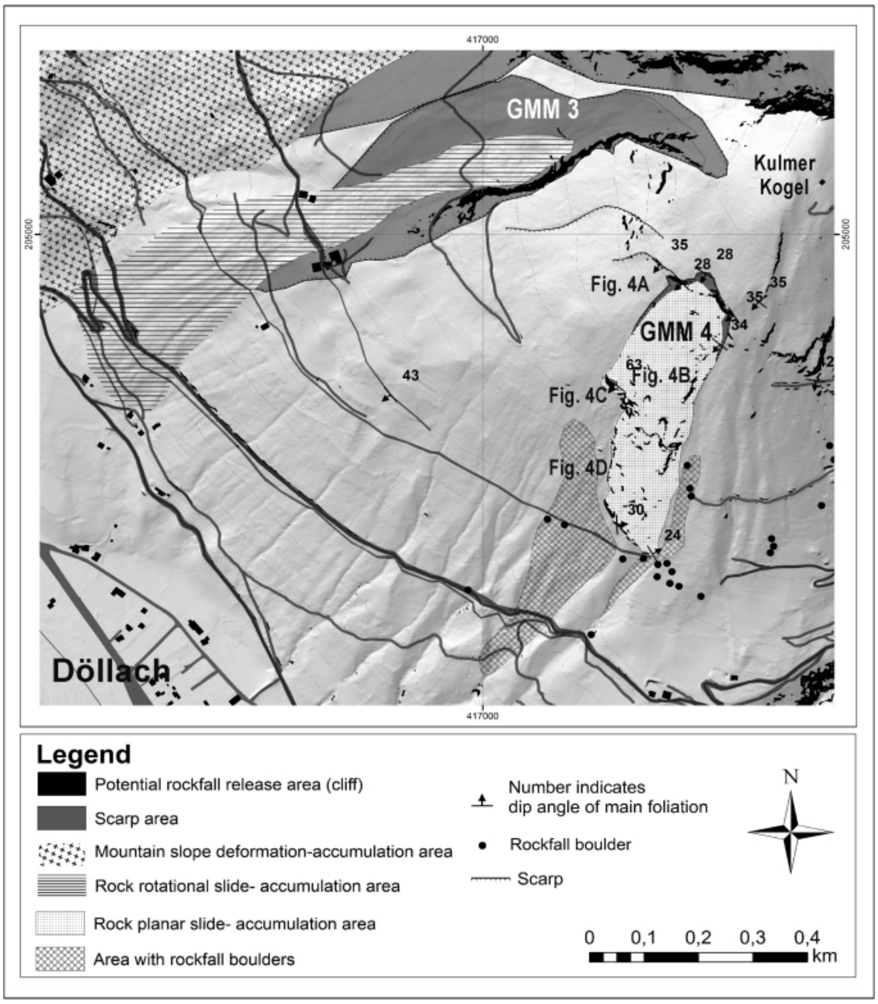

Figure 7: Map of gravitational mass movements in the Penninic unit (Glockner Nappe System), map scale 1:5.000 (mapping by Melzner, S., 2010). A rotational rock slide has developed next to the strongly degraded mountain slope deformation in the area of Mitten (Mittner Berg-Talzuschub) in the Glockner Nappe System. Beneath Kulmer Kogel,the dominant geomorphologic feature in this area is a rock planar slide in its initial stage of development (GMM 4 in Fig. 1). This feature has displaced material with an approximate volume of 350,000 m³. Sliding, rockfalls and block toppling occur as secondary processes at the front and/or along the eastern side of the slide (Fig. 4 C & 6 D).

scarps around the toe indicates an increasing disintegration of rock down the slope, which makes the slope highly susceptible to rockslides and rockfalls as secondary processes (Fig. 6). In other parts, deformations are characterized by recent secondary debris slides and small debris flows on the highly disintegrated surfaces (e.g. the 2005 event in Rupitschkaser). These events can be hazardous for road users and infrastructure.

A rotational rock slide has developed next to the strongly degraded mountain slope deformation in the area of Mitten (Mittner Berg-Talzuschub) (Fig. 7) in the Glockner Nappe System. The lower part of the mass comprises a soil flow (GMM 3 in Fig. 1). The ability for the lithologies of the Glockner Nappe System to form cliffs depends on the characteristics of the materials and the specific glacial and post-glacial erosion processes. These processes have resulted in dominant relief along pre-existing joints and faults (Section 3.1).The south-west dipping slopes beneath Kulmer Kogel do not form steep cliffs as a result of the lithological units dipping parallel to the slopes (Fig. 2A). The dominant geomorphologic feature in this area is a rock planar slide in its initial stage of development (GMM 4 in Fig. 1). This feature has displaced material with an approximate volume of 350,000 m³ (Fig. 7). The underlying rupture surface developed along foliation and dips at approximately 40° towards the southwest (160° to 230°). The upper part of the slide has moved approximately 20 m (Fig. 4A). In the area of the scarp, the foliations in the mica-marble dip at 26° to 35° towards 203° to 272° (Melzner et al. 2012). The upper part of the mass is characterized by highly loosened zones containing caves and tension fissures that strike orthogonal to foliation (Fig.4B). In the toe area (eastern side), the foliation dips at 24° to 45° towards 052° to 078°; opposite to the dip of the slope. This orientation has resulted in overturning or folding of the mass at the toe of the slide (Fig. 4C). Sliding, rockfalls and block toppling occur as secondary processes at the front and/or along the eastern side of the slide (Fig. 4 C & 6 D).

The largest gravitational mass movements (Fig. 8) within the

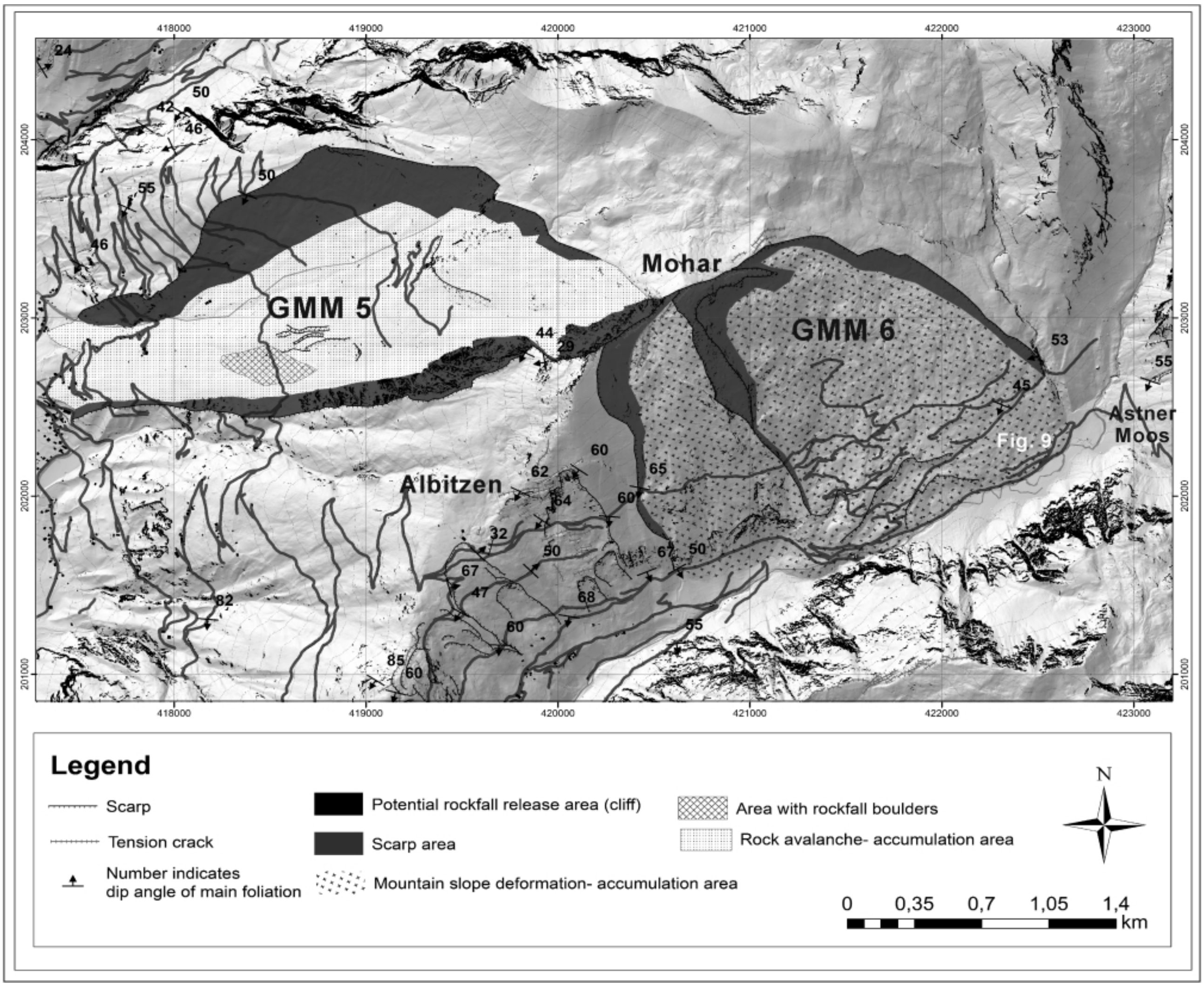

Figure 8: Geotechnical map of gravitational mass movements in the Penninic unit (Matrei Zone), map scale 1:15.000 (Melzner, S. 2011). The mountain slope deformation Mohar – Asten Valley (GMM 6) dammed the Asten River and favoured the development of the Astner Moos. In contrast, the mass movement from the Mohar ridge towards the Möll Valley (GMM 5) developed as a result of a completely different process mechanism: the morphology of the transportation and accumulation zone and the lithological composition of the deposited material in the accumulation zone represent the flow-like motion of a rock avalanche, resulting from a large rock slide/fall at the peak area (mapping by Melzner 2010, Lotter 2013).

study area are located along the Mohar peak/ridge, in the transition between Glockner nappe (Penninic Unit), Matreier Zone (Penninic Unit) and Lower Austroalpine Unit. A mountain slope deformation has developed towards the Asten Valley (GMM 6 in Fig. 1, Fig. 8 & 9). In contrast, towards the Möll Valley, the process mechanism was a rock fall which turned into a rock avalanche.

The mountain slope deformation of the Kräuterwiesen ("Talzuschub", GMM 11 in Fig.1, Fig. 12) shows considerable mass depletion in the scarp area at approximately 150 m. This process has resulted in a typical concave-convex shaped terrain profile. The rocks are highly disintegrated within the over-steepened frontal toe of this mass movement creating potential source areas for rockfalls.

Depending on the mass movement type (e.g. rock slide, large-scale mountain slope deformation/"rock creep", rock slope spread, etc.) and its stage of development, secondary rockfall occur either within the scarp area, along and within the body and along the oversteepened front part of the slope deformation (Melzner et al., 2012). A mountain slope deformation in terms of Hungr et al. (2014) (e.g. GMM 2 in Fig. 1) may already have a high degree of disintegration and loosening in an initial development stage, thus favouring the occurrence of secondary rockfalls and rockslides. The mountain slope deformations Mittnerberg (north of GMM 3 in Fig. 1) or Kräuterwiesen (GMM 11 in Fig. 1) are in the final stages of development and are associated with rockfall processes.

Most of the slopes are covered by moraine deposits or scree due to glacial and postglacial landscape evolution. The remobilization of boulders by erosion processes such as mass movements or wind throw are common. Such "secondary" rockfalls can be triggered nearly everywhere in the study area.

4. Interpretation

The highly variable anisotropies in the foliated rock at the southern border of the central Tauern Window and the adjacent Austroalpine Unit influence significantly the stabilities of the slopes. In particular, it influences the spatial pattern of different types of gravitational mass movements:

- The Sub-Penninic and Penninic units show a high susceptibility to rock planar and rotational sliding modes and mountain slope deformation in southwest dipping slopes with a predominance of sliding processes due to the predisposed dip-slope situation.
- The Lower Austroalpine sub-unit is primarily associated with mountain slope deformation, most likely associated with poorly defined rupture surfaces ("rock creep").
- The Upper Austroalpine sub-unit is highly susceptible to rockfalls. Mountain slope deformation, with no clear dominance towards sliding or "creeping" processes, is also prevalent depending on the structure of the rock masses and the orientations of the slopes.

Figure 9: Mountain slope deformation in the Penninic Unit (Matrei Zone), damming the Asten River in former days and thus resulting in the development of the Astner Moos (photo by M. Lotter, 2013).

Deep-seated and large-scale mountain slope deformations are therefore the most characteristic morphologic features in the study area. The kinematic mechanisms of these mass movements and their developing stage from initial (e.g. GMM 2 in Fig. 1) to final shapes (e.g. GMM 11 in Fig. 1) are different; varying according to the lithologies and geomechanical characteristics of the tectonic units.

4.1 Sub-Penninic and Penninic Unit

The structural, lithological and geomorphic factors that influence the spatial distribution of slope failures within the Sub-Penninic and Penninic Units are as follows:

The tectonic settings are not conducive to the development of distinct cliffs (Fig. 2A) in the areas comprising south-west dipping slopes. These areas are predominantly susceptible to rock planar slides (Fig. 3 & 5) and mountain slope deformation (GMM 1 & 2 in Fig. 1) when suitable tectonic structures are present. Cliffs, and hence potential rockfall source areas, are generally restricted to those areas that lie orthogonal to the strike direction of the lithological units (GMM 1 in Fig. 1), areas of significant tectonic structures, or areas of deep-seated gravitational mass movements (Fig. 7). The geographic location of GMM 2 (Fig. 1) in the Zirknitz valley between the confluence of the "Große Zirknitz" and "Kleine Zirknitz" rivers likely favour lateral movements of the mass movement bodies. The confluence of the two over-steepened glacial valleys is likely to be the primary cause for this slope failure (GMM 2 Fig. 1).

The mountain slope deformation in the Mohar – Asten Valley (GMM 6 in Fig. 1) dammed the Asten River and favoured the development of the "Astner Moos" (Fig. 9). In contrast, the mass movement from the Mohar ridge towards the Möll Valley (GMM 5 in Fig. 1) developed as a result of different mechanisms. These mechanisms include the morphology of the transportation and accumulation zone (Fig. 8) and the lithological composition of the deposited material in the accumulation zone. The latter mechanism resulted from a large rock slide/fall in the area of the peak. It represents the flow-like motion of a rock avalanche. Field mapping indicated that this avalanche is overformed by secondary slides and younger rockfall processes due to differences in lithology. In particular, the steep southern scarp comprises high to very-high strength rocks (Alpiner Verrucano and Lantschfeldquarzit, metabasic rocks) and consequently is more susceptible towards rockfall processes. Parts of the northern scarp area comprise calcareous mica-schists that dip in the directions of the slopes and hence are more susceptible to sliding.

The mountain slope deformation in the Sub-Penninic unit, Penninic unit and Lower Austroalpine sub-unit have lower slope gradients than do the gravitational mass movements in in the Upper Austroalpine sub-unit (Fig. 4). The difference is due mainly to the geomechanical properties of the different lithologies; primarily strengths that range from low to very-high resulting in different characteristics of late tectonic fracturing. In addition, the orientations of the foliations in the tectonic units are very different, ranging from moderately to steeply dipping towards the SW (Sub-Penninic and Penninic Unit, Lower Austroalpine sub-unit) to shallow to moderately dipping towards the NE and SW (Upper Austroalpine sub-unit). The orientations of the main foliation and steeply dipping major faults favour the development of mountain slope deformation involving predominantly sliding and/or creeping mechanisms. Despite the tectonic locations, nearly all mountain slope deformations in the study area have similar slope angles even though the slopes developed differently (final versus initial) (Fig. 4). In contrast, the rock slide at Kulmer Kogel (GMM 4 in Fig. 1) has a relatively steep slope gradient, because the rock is generally of high strength and each failure occurs primarily along a single weak zone formed by the foliation of an intercalated mica-schist layer (Fig. 3).

The Penninic Matrei Zone has been

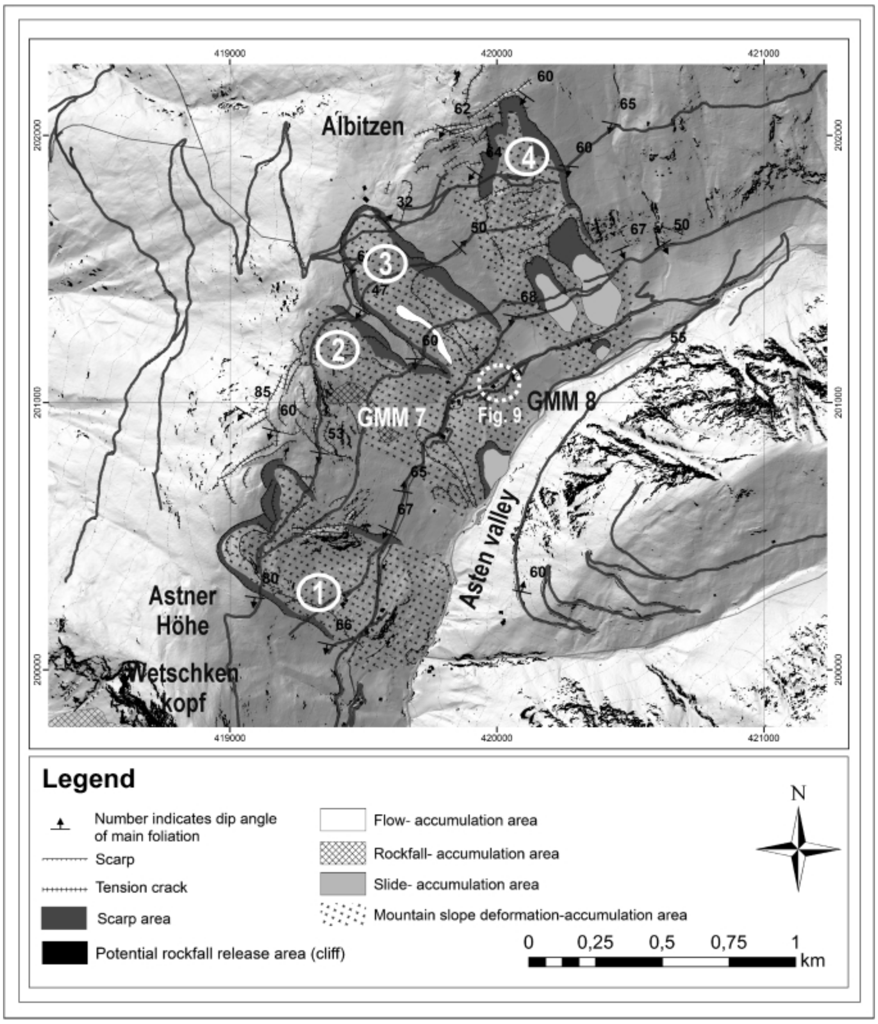

Figure 10: Map of gravitational mass movements in the (Lower Austroalpine subunit), map scale 1:10.000 (Lotter, M., 2013). On the orographic right side in the Asten Valley (GMM 7), a total of four mountain slope deformations), exhibiting a dominance of rock creep, evolve from deep tension cracks above the scarp areas into a significant vertical mass loss downslope (mapping by Lotter 2013).

subjected to intense ductile deformation and brittle faulting. As a result, the local anisotropy of this tectonic melange zone tends to be characterized by strongly foliated low to medium-strength rocks. Predominantly homogeneous and moderate slope inclinations are associated with this characteristic (Fig. 4). This characteristic and the orientations of the tectonic unit/main foliation (SW) relative to the slope exposition (S-SE) of the orographic right slopes of the Asten River do not favour the development of fully defined rupture surfaces. Rock creep tends therefore to be more prevalent than sliding. Furthermore, the geographic locations of the mass movements (GMM 6 in Fig. 1) within the Asten Valley, where the relief energy and thus the erosional power of the Asten River is limited, are likely associated with the relatively low amount of movement.

4.2 Austroalpine Unit

Typical gravitational mass movements in the Lower Austroalpine subunit involve mountain slope deformations with dominant "rock creep" processes and, to a lesser extent, progressive developing "sliding" mechanism in terms of the development of clearly defined rupture zones. Four mountain slope deformations (1-4 in Fig. 10) can be seen on the orographic right side in the Asten Valley (GMM 7 in Fig. 1). These features exhibit a dominance of rock creep which evolves from deep tension cracks above the scarp areas into a significant vertical mass loss downslope. The two mass movements located in the middle (2 & 3 in Fig. 10) developed in different zones of depletion, joining up into a common zone of accumulation in the lower part of the slope. Mass movement "1" and "2" in Fig. 10 developed in the Melenkopf-Complex. Mass movement "3" developed primarily in the Melenkopf-Complex but it is bordered and tectonically controlled to the northeast by a dominant NW-SE striking fault. This fault separates the Melenkopf-Complex from Permian to Triassic metasediments. Mass movement "4" is mainly developed in high to very-high strength quartzites and, to a lesser extent, in low to medium strength phyllites that form the frame of this mass movement. All of the four mass movements are strongly tectonically controlled by a set of NW-SE striking faults. In contrast to most of the mountain slope deformations in the other tectonic units, these movements show a high number of tension cracks and several minor scarps at the crown, indicating a high degree of loosening in this area.

The side valleys, Zirknitz, Asten, and Kolmitzen, occur at notably higher elevations than does the Möll Valley, a consequence of the considerably more limited erosional capabilities of the smaller glaciers. These differences in elevation have promoted post-glacial fluvial erosion processes. The steeply incised gorges are evidence of the strongly erosive forces associated with these processes. The nearby toe part of the

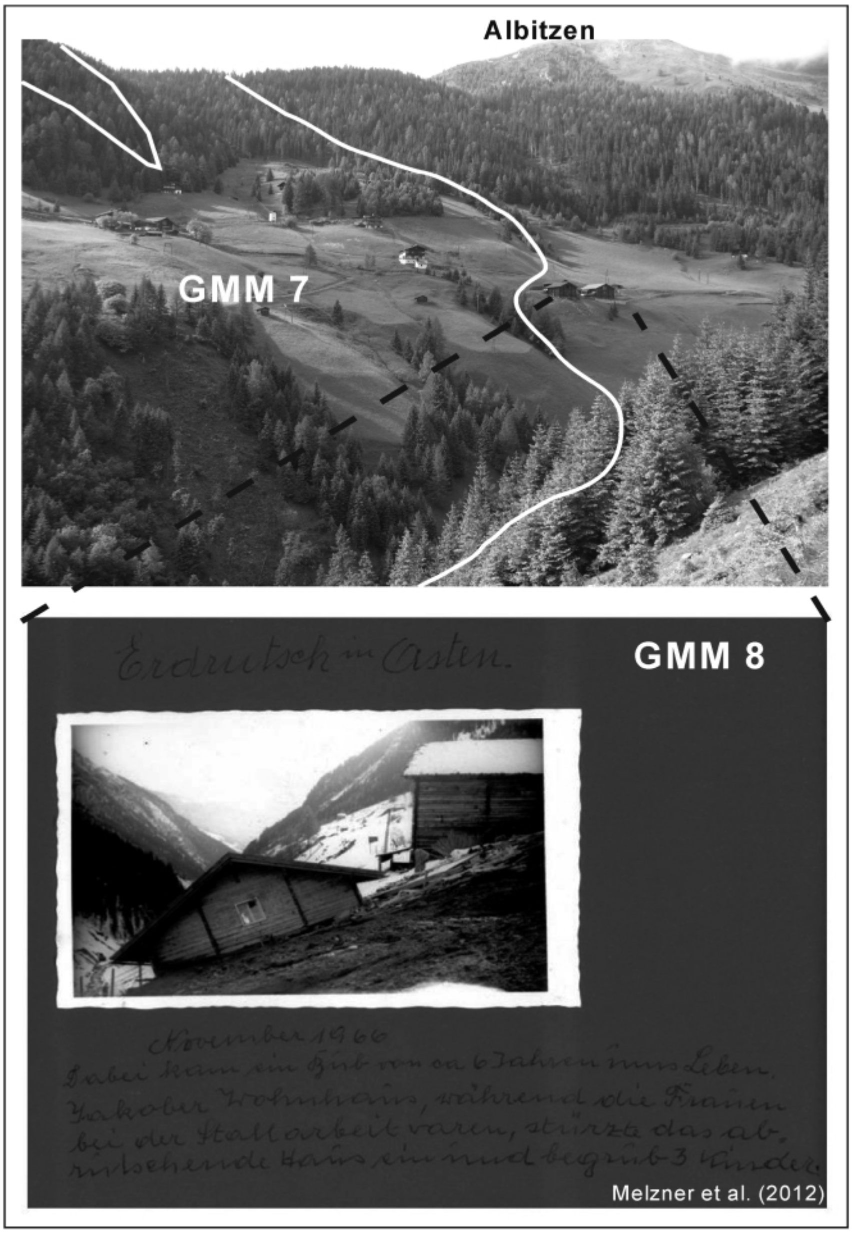

Figure 11: On the orographic right side in the Asten Valley (GMM 7), a total of four mountain slope deformations), exhibiting a dominance of rock creep, evolve from deep tension cracks above the scarp areas into a significant vertical mass loss downslope. In 1966 a child got killed by a slide (GMM 8) in quaternary sediments, documentation of landslide fatality by a habitant (upper photo by S. Melzner, 2010; lower photo by unknown photographer).

mountain slope deformation “3” (GMM 7 in Fig. 1, “1-4” in Fig. 10), which comprise quaternary sediments, mobilised in 1966 resulting in a child being killed (GMM 8 in Fig. 10 & 11). Similar surficial soil slips and flows are common in these sediments in the side valleys. They are generally triggered by very intense and/or long duration rain fall and/or snowmelt.

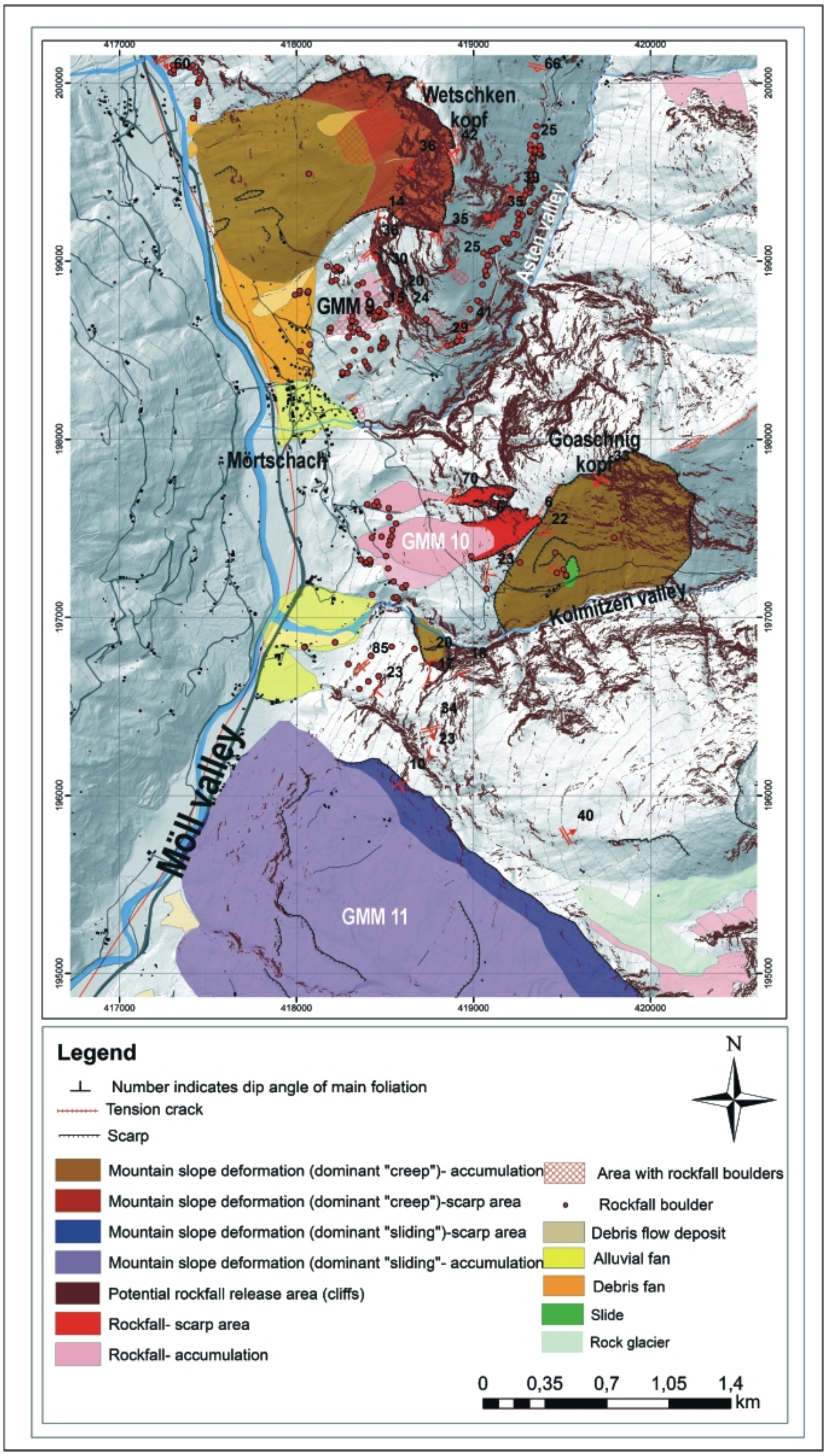

Figure 12: Map of gravitational mass movements in the Prijakt-Polinik Complex (Upper Austroalpine subunit), map scale 1:15.000 (mapping by Melzner 2010). The Upper Austroalpine sub-unit is highly susceptible to rockfalls and also to mountain slope deformation (GMM 9-11). There is no clear dominance towards sliding or “creeping” processes, the mode depends on the structures of the rock masses and the slope orientations. Some cliffs developed from a sequence of scarps subsequent to several large volume rockfall events (GMM 10). Rockfall are endangering houses and infrastructures.

An expanded brittle fault zone characterizes the boundary between the Prijakt- Polinik Complex towards the Melenkopf Complex. This zone is a rockfall source area comprising highly fractured and loosened material.

The Upper Austroalpine sub-unit is highly susceptible to rockfalls and also to mountain slope deformation (GMM 9-11 in Fig. 12). There is no clear dominance towards sliding or “creeping” processes, the mode depends on the structures of the rock masses and the slope orientations. Some cliffs developed from a sequence of scarps subsequent to several large volume rockfall events (GMM 12 in Fig. 1). These scarps have similar orientations to some of the dominant faults that occur with a high degree of separation. Field mapping indicated that the landforms are controlled significantly by significant brittle fragmentation associated with faulting. The high degree of separation and the wide spacings have resulted in the main scarps being deeply incised into the metamorphic rocks. The cliffs are associated with former active scarp areas; their spatial distributions being associated with these tectonic structures (Fig. 3).

The Prijakt- Polinik Complex (Upper Austroalpine Unit) is very susceptible to rockfalls due to the heterogeneous anisotropy caused by variations in the characteristics of foliations and joints. A significant number of different discontinuity sets and faults are frequently associated with high degrees of separation, wide spacings and deep tension cracks that follow the main faults (Melzner et al. 2012). These features have caused large volume rockfalls (GMM 10 & 12 in Fig.1, Fig. 3 & Fig. 12). Small-scaled transitions between medium strength and high to very-high strength rocks and the ongoing process of detachment along a few widely spaced discontinuity sets are likely to cause selective weathering and subsequent susceptibility to comparatively large volume rockfalls (GMM 9 & GMM 10 in Fig. 1, Fig. 12). The heterogeneous anisotropy may result in different failure mechanisms as well as considerable diversity in block size and shape (Melzner et al., 2012).

The mountain slope deformation of the Kräuterwiesen (GMM 11 in Fig. 1 & 12) was likely initiated by glacial erosion and loading and unloading phases during the periods of glaciation. Due to the large rock displacement of the mountain slope deformation Kräuterwiesen, it is highly likely that the dominant failure mechanism is progressive developed sliding. A continuous sliding surface could not however be observed during field investigations.

5. Discussion

Various ductile and brittle deformation phases have a significant influence on the local strength anisotropy of the foliated rocks in the study area. Zangerl et al. (2012) discussed this characteristic and polyphase deformation processes that have occurred in the area of the Engadiner Window. These characteristics are responsible for the formation of ductile and brittle structures that have influenced the rock mass strength and anisotropy significantly. Agliardi et al. (2009) showed that in the central Eastern Alps deep-seated gravitational mass movements mainly develop in anisotropic, medium strength fractured rock masses cut by recent fracture systems.

No absolute dating methods could be undertaken for the gravitational mass movements considered in this study. Prager et al. (2008) prepared an inventory of about 480 fossil deep-seated landslides in Tyrol (Austria). Analysis of the spatial and temporal distribution of these events indicated that they were primarily controlled by fault-related valley deepening and the coalescence of brittle discontinuities. Furthermore they concluded that the deep-seated landslides were not directly caused by deglaciation processes but needed at least a preparation time of some 1000 years before the slopes collapsed.

The mass movement Egger-Wiesen-Kopf at the orographic left slope of the Graden River (GMM 13 in Fig. 1) is an example for a mountain slope deformation. The event involves the slope of the river valley from the valley floor up to the ridge covering an area of about 2 km². Mass movements in the study area are indicated by the steeper slope inclinations (Fig. 5) and a significantly higher degree of activity than in other recent large-scale deformations. This characteristic is due mainly to the mass movement being located close to the confluence to the Möll Valley, which has a lower elevation. The difference in the elevations of each valley influences the localised erosional power of the Graden River which constantly undercuts the adjacent slopes. According to Weidner (2000), the orientations of the lithological units of the orographic left slope are towards the south-west to south-south-west dipping at 30° to 59°. The lithology is characterized by sudden changes of phyllites, mica-schist-phyllonites and chlorite phyllites. The mechanism of motion of the Egger-Wiesen-Kopf sagging slope is related to rock creep, sliding movements and combinations of the two modes (Weidner et al., 2011). The upper part of the slope is characterized by translational sliding along steeply dipping sliding planes. The movement in the lower part is characterized more by rotational sliding due to high rock decomposition (Moser and Glumac, 1982; Moser, 1994; Weidner et al., 2011). Although the mountain slope deformation at the Astner Moos (GMM 6 in Fig. 1) is situated in the same tectonic unit, it shows in contrast to the Egger-Wiesen-Kopf (GMM 13 in Fig. 1), less displacement in the direction of the slope. This characteristic is associated with there being less defined rupture surfaces (i.e. predominance of rock creep versus the development of sliding zones) and a significantly lower slope angle (Fig. 16).

Moser (1994) investigated some geotechnical characteristics of several sagging slopes in the Alpine region. The author concluded that strong anisotropy in gneisses and phyllites are typical predisposition factors for the occurrence of complex gravitational mass movements. Analysis of the mass movements showed most to be associated with slope angles of approximately 25° to 30°. A comparison of these angles with those in the study area shows similarities, slopes ranging from 22° (GMM 2 in Fig. 1) to 27° (GMM 10 & 12 in Fig. 1).

The rock slide of Niedergallmigg (Tyrol) is characterized by a large rock displacement similar to the mountain slope deformations (with most likely dominant sliding movement) of the Kräuterwiesen (GMM 11 in Fig. 1). This mechanism significantly influences the mechanical and hydrogeological characteristics of the rock masses and the in-situ stress conditions in the over steepened front part (Zangerl et al., 2012). The high susceptibility towards the formation of secondary slides and rockfalls in the over-steepened front part is common in such highly fragmented mass movement bodies. Moser (1994) and Hermann (1996) noted that deep-seated gravitational mass movements in an initial development stage may be a significant hazard to infrastructures due to the susceptibility towards secondary slides and rockfalls. Madritsch and Millen (2007) noted, on the basis of the results form hydrogeologic analysis at a deep-seated gravitational slope deformation in the Innsbruck Quartzphyllite Complex, that a continuous basal shear zone of clay gouge-bounded kakarites are underlain by higher strength and less disturbed rocks. In case of the Egger-Wiesen-Kopf mountain slope deformation, more than one sliding plane is most likely (Poscher, 1990). Sausgruber et al. (2010) found similar structural conditions associated with complex slope failures at Bunzkögele in Tyrol. The dominance of these mass movements towards sliding indicates that most of the displacements likely occur along the main foliation.

In contrast, the rock avalanche at Mohar (GMM 5 in Fig. 1) shows a significant longer runout distance (Fig. 16). The orientations of the foliations and/or the tectonic units towards the SW and secondary sliding on top of the rock avalanche indicates that the initial failure mechanism could have been sliding. Prager et al. (2012) noted that the (pre-) historic rock avalanches Fernpass and Tschirgant in Tyrol are also clearly structurally controlled, initially characterized by a sliding mode. According to the authors, these rockslides transformed to rock avalanches with considerable run-out lengths. The post-kinematic secondary failures may be attributed to gravitational spreading of the accumulated debris. The accumulation zone of the Mohar rock avalanche doesn't show material to have collapsed but more flow-like motion of fragmental rock. Prager et al. (2009) noted that the largest crystalline mass movement of the Alps, the Holocene Köfels rockslide (Tyrol, Austria) in the Oetztal basement, is highly structurally controlled by deep tension cracks in the upper part, creep along dominant discontinuity sets and final collapse of some part of the material as a rockslide. The active Hochmais-Atemkopf rockslide in the Kaunertal and complex mass movement Steinlehnen (Sellraintal) with dominant failure mode creep (and secondary rockfall processes) detach along east dipping fracture sets (Prager et al., 2008).

Failure mechanism such as flexural toppling in the vicinity of the study area, as examined by Reitner and Linner (2009) and Sausgruber et al. (2010), are not considered to be of significance. The rock mass in the area is either too strong or, where it is of low to medium strength, structural requirements for the mechanisms to develop are not satisfied.

6. Conclusion

The varying anisotropy of the foliated rocks in the southern border of the central Tauern Window and the adjacent Austroalpine Unit affects significantly the stability of the slopes. This characteristic results in certain spatial pattern of different types of gravitational mass movements.

The Sub-Penninic and Penninic units show a higher susceptibility towards rock planar slides and mountain slope deformations in the south-west dipping slopes, with a predominance of sliding processes due to the predisposed dip-slope situation.

The Lower Austroalpine sub-unit is subject primarily to mountain slope deformations involving poorly defined rupture surfaces (dominance of rock creep).

The Upper Austroalpine sub-unit is highly susceptible to rockfalls and mountain slope deformations with no obvious dominance of sliding or creeping mechanisms.

The slopes are in part covered by moraine deposits or scree due to glacial and postglacial landscape evolution. Rockfall activity, due to the (re-) mobilization of boulders caused by erosion processes, mass movements or wind throw, is a common process. “Secondary“ rockfalls can be triggered from nearly anywhere in the study area. Superficial soil slips and flows are common gravitational mass movement types in the Quaternary fillings of the steeply incised valleys.

7. Outlook

Most of the literature about gravitational mass movements in the central Tauern Window and adjacent Austroalpine Unit focuses on single slopes. The present work attempts to link tectonic, lithologic and geomorphic factors that influence these movements. Further studies should include more detailed structural and kinematic analysis of the failure mechanisms. These studies are considered to be important because specific types of slope instability mechanisms have different impacts on the environment. These influences result in different hazards and hence risk levels for different infrastructures and populations. Decision makers in the Federal State Governments and local authorities may benefit from such data to delineate potentially endangered areas (i.e. hazard zones) and to plan detailed investigations to implement preventive measures.

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References

Abele, G., 1974. Bergstürze in den Alpen- ihre Verbreitung, Morphologie und Folgeerscheinungen. Wissenschaftliche Alpenvereinshefte, Heft 25, 230 pp.

Ampferer, O., 1940. Zum weiteren Ausbau der Lehre von den Bergzerreißungen. Sitzungsberichte Akademie der Wissenschaften, mathematisch-naturwissenschaftliche Klasse, 149, 51-70.

Agliardi, F., Zanchi, A. and Crosta, G.B., 2009. Tectonics vs. gravitational morphostructures in the central Eastern Alps (Italy): Constraints on the recent evolution of the mountain range. Tectonophysics, 474, 250-270. http://dx.doi.org/10.1016/j.tecto.2009.02.019

Braunstingl, R., Pestal, G., Hejl, E., Egger, H., Van Husen, D., Linner, M., Mandl, G., Reitner, J., Rupp, C. and Schuster, R., 2005. Geologische Karte von Salzburg 1:200.000. Geologische Bundesanstalt, Wien.

Brückl, E. and Scheidegger, A.E., 1972. The rheology of spacially continuous mass creep in rock. Rock Mechanics, 4, 237-250.

Brückl, E., Brückl, J. and Heuberger, H., 2001. Present structure and prefailure topography of the giant rockslide of Köfels. Zeitschrift für Gletscherkunde und Glaziologie, 37/1, 49-79.

Brückl, E., Brunner, F.K. and Kraus, K., 2006. Kinematics of a deep-seated landslide derived from photogrammetric, GPS and geophysical data. Engineering Geology, 88, 149-159. http://dx.doi.org/10.1016/j.enggeo.2006.09.004

Brunsden, D. and Prior, D.B., 1984. Slope instability. John Wiley and Sons, Chichester, UK, 620 pp.

Chifflard, P. and Tilch, N., 2013. Learning from Nature – Mapping of Complex Hydrological and Geomorphological Process Systems for More Realistic Modelling of hazard-related maps.- 44. Jahrestreffen des Arbeitskreises Hydrologie in Lunz am See, 15.-17. November 2012, Geographica Augustana, 134-137.

Crozier, M.J., 1989. Landslides: causes, consequences and environment. Routledge, London, 252 pp.

Cruden, D.M., 1991. A simple definition of a landslide. Bulletin International Association for Engineering Geology, 43, 27-29.

Cruden, D. M. and Varnes, D.J., 1996. Landslide types and processes. In: A. K. Turner and R.L. Schuster (eds.), Landslides: investigation and mitigation. Transport Research Board, Special Report, 247, pp. 36-75.

Dramis, F. and Sorriso-Valvo, M., 1994. Deep-seated gravitational slope deformations, related landslides and tectonics. Engineering Geology, 38, 231-243.

Dikau, R., Brunsden, D., Schrott, L. and Ibsen, M.-L.,1996. Landslide recognition- Identification, Movement and Causes. John Wiley and Sons Ltd., 251 pp.

Exner, Ch., 1962. Geologische Karte der Sonnblickgruppe 1: 50.000. Geologische Bundesanstalt, Wien.

Exner, Ch., 1964. Erläuterungen zur Geologischen Karte der Sonnenblickgruppe. 170 pp.

Frisch, W., 1976. Ein Modell zur alpidischen Evolution und Orogenese des Tauernfensters. Geologische Rundschau, 65/2, 375-393.

Frisch, W., 1977. Der alpidische Internbau der Venedigerdecke im westlichen Tauernfenster. Neues Jahrbuch für Geologie und Paläontologie Monatshefte, 11, 675-696.

Fuchs, G. and Linner, M., 2005. Die Geologische Karte der Sadniggruppe: Ostalpines Kristallin in Beziehung zur Matreier Zone. Jahrbuch der Geologischen Bundesanstalt, 145, 293-301.

Götzinger, G., 1943. Neue Beobachtungen über Bodenbewegungen in der Flyschzone. Mitteilungen der Geographischen Gesellschaft Wien, 1986, 201-234.

Goodman, R.E., and Bray, J.W., 1976. Toppling of rock slopes. Proceedings ASCE speciality conference on rock engineering for foundation of slopes, Boulder, Colorado, Vol. 2, 201-234.

Gruber, A., Strauhal, T., Prager, C., Reitner, J. M., Brandner, R. and Zangerl, C. 2009. Die “Butterbichl-Gleitmasse”- eine große fossile Massenbewegung am Südrand der Nördlichen Kalkalpen (Tirol, Österreich). Swiss Bulletin für angewandte Geologie, 14/1+2, 103-134.

Hermann, S., 1996. Initiale Bergzerreißung als Gefahrenherd für Bergstürze, Nährgebiet für Muren und Großrutschungen. Beispiele aus dem Naturpark Sölktaäler, Österreich. 1996, 1, 409-418.

Hoek, E. and Bray, J.W., 1981. Rock Slope Engineering, 3rd ed. Institute of Mining and Metallurgy, London. 358 pp.

Hübl, J., Kociu, A., Krissl, H., Lang, E., Länger, E., Rudolf-Miklau, F., Moser, A., Pichler, A., Rachoy, Ch., Schnetzer, I., Skolaut, Ch., Tilch, N. and Totschnig, R., 2009. Alpine Naturkatastrophen- Lawinen-Muren-Felsstürze-Hochwässer, 120 pp.

Hungr, O., Leroueil, S., Picarelli, L., 2014. The Varnes classification of landslide types, an update. Landslides, 11, 167-194. http://dx.doi.org/10.1007/s10346-013-0436-y

Hutchinson, J.N., 1968. Mass movement. In: R.W. Fairbridge (ed.), The Encyclopedia of Geomorphology, Rheinhold, New York, pp. 688-695.

IAEG, 1991. International Association of Engineering Geology, Commission on Landslides. Suggested nomenclature for landslides. Bulletin of the International Association of Engineering Geology, 41, 13-16.

ISRM, 1978. Suggested Methods for Quantitative Description of Discontinuities in Rock Masses; Determining Tensile Strength of Rock Materials and Determining Hardness and Abrasiveness of Rocks.

Kronfellner- Kraus, G., 1980. Neue Untersuchungsergebnisse in Wildbächen- Der Talzuschub in Abhängigkeit von Niederschlägen. International Symposium Interpraevent Bad Ischl, 1, 179-192.

Kurz, W., Neubauer, F., Genser, J. and Dachs, E., 1998. Alpine geodynamic evolution of passive and active continental margin sequences in the Tauern Window (eastern Alps, Austria, Italy): a review. Geologische Rundschau, 87, 225-242.

Linner, M. and Fuchs, G., 2005. Das Ostalpine Kristallin der Sadnig-Gruppe- mit einem Fragment einer unterostalpinen Decke am Südrand des Tauernfensters. Arbeitstagung Geologische Bundesanstalt. Gmünd 2005, 155-158.

Linner, M., Habler, G. and Grasemann, B., 2009. Switch of kinematics in the Austroalpine basement between the Defereggen-Antholz-Vals (DAV) and the Pustertal-Gailtal fault-Eastern Alps. Alpine Workshop 2009,Cogne/Italy 16.-19. September 2009.

Linner, M., Reitner, J.M. and Pavlik, W., 2013. Lienz, Blatt 179, Geologische Karte der Republik Österreich, 1:50.000, Wien.

Lotter, M. and Moser, M., 2007. Die Massenbewegungen der Naßfeldregion. Abhandlungen der Geologischen Bundesanstalt, 61, 159-173.

Madritsch, H. and Millen, B. M. J., 2007. Hydrogeologic evidence for a continuous basal shear zone within a deep-seated gravitational slope deformation (Eastern Alps, Tyrol, Austria). Landslides, 4, 149-162. http://dx.doi.org/10.1007/s10346-006-0072-x

Melzner, S., Lotter, M., Tilch, N. and Kociu, A., 2012. Rockfall susceptibility assessment at the regional and local scales as a basis for planning site-specific studies in the Upper Moelltal (Carinthia,Austria). Berichte der Geologischen Bundesanstalt, 91,105 pp.

Melzner, S. and Guzzetti, F., 2014. A comparison of rockfall inventories in Austria and Italy. Geophysical Research Abstract, 16, EGU 2014.

Moser, M., 1971. Zahl, Form, Vorgang und Ursache der Anbruchsbildung und ihre Beziehungen zum geologischen Untergrund im Bereich des mittleren Lesachtales (Kärnten). International Symposium Interpraevent 1971, 1, 35-48.

Moser, M. 1994. Geotechnics of large-scale slope movements („Talzuschübe") in Alpine regions, 7th International IAEG Congress, 1533-1542, Lisboa.

Moser, M. and Glumac, S., 1982. Zur Kinematik von Talzuschüben, dargestellt am Beispiel des Talzuschubes Gradenbach. Allgemeine Vermessungsnachrichten, 89/5, 174-193.

Ostermann, M., Sanders, D., Ivy-Ochs, S., Alfimov, V., Rockenschaub, M. and Römer, A., 2012. Early Holocene (8.6 ka) rock avalanche deposits, Obernberg valley (Eastern Alps): Landform interpretation and kinematics of rapid mass movements. Geomorphology, 171-172, 83-93. http://dx.doi.org/10.1016/j.geomorph.2012.05.006

Patzelt, G., 2012a. Die Bergstürze vom Tschirgant und von Haiming, Oberinntal, Tirol- Begleitworte zur Kartenbeilage. Jahrbuch der Geologischen Bundesanstalt, 152, 13-24.

Patzelt, G., 2012b. Die Bergstürze vom Pletzachkogel, Kramsach, Tirol. Jahrbuch der Geologischen Bundesanstalt, 152, 25-38.

Pestal, G., Hejl, E., Braunstingl, R and Schuster, R., 2009. Erläuterungen zur Geologischen Karte von Salzburg 1:200.000. Geologische Bundesanstalt, 162 pp.

Pflügler, A., 1991. Alpine Massenbewegungen am Beispiel des Eckkopfes zwischen den Zirknitztälern (Kärnten), Master Thesis, University Graz, Graz, 96 pp.

Poisel, R. and Eppensteiner, W., 1988. Gang und Gehwerk einer Massenbewegung. Teil 1: Geomechanik des Systems „Hart auf Weich". Felsbau, 6, 189-194.

Poisel, R. and Eppensteiner, W., 1989. Gang und Gehwerk einer Massenbewegung. Teil 2: Massenbewegungen am Rand des Systems „Hart auf Weich". Felsbau, 7, 16-20.

Poisel, R. and Preh, A., 2004. Rock slope initial failure mechanisms and their mechanical models. Felsbau, 22/2, 40-45.

Poscher, G., 1990. Geotechnische und morphologische Untersuchungen im Bereich des Talzuschubes „Lahnstrichbach"/ Fügenberg (Zillertal, Tirol). Geologische Paläontologische Mitteilungen Innsbruck, 17, 39-49.

Prager, C, Zangerl, C, Patzelt, G. and Brandner, R., 2008. Age distribution of fossil landslides in Tyrol (Austria) and its surrounding areas. Natural Hazard Earth Science Systems, 8/2, 377-407. http://dx.doi.org/10.5194/nhess-8-377-2008

Prager, C., Zangerl, C. and Nagler, T. 2009. Geological controls on slope deformations in the Köfels rockslide area (Tyrol, Austria). Austrian Journal of Earth Science, 102/2, 4-19.

Prager, C., Zangerl, C. and Kerschner, H., 2012. Sedimentology and mechanics of major rock avalanches: Implications from (pre-) historic Sturzstrom deposits (Tyrolean Alps, Austria). In: Eberhardt, E., Froese, C., Turner, K. and S. Leroueil (eds.), Landslides and Engineered Slopes: Protecting Society through Improved Understanding, 895-900.

Reitner, J, Lang, M. and van Husen, D., 1993. Deformation of high slopes in different rocks after würmian deglaciation in the Gailtal (Austria). Quarternary International, 18, 43-51.

Reitner, J. and Linner, M., 2009. Formation and preservation of large scale toppling related to alpine tectonic structures-eastern Alps. Austrian Journal of Earth sciences, 102/2, 69-80.

Rohn, J., Resch, M., Schneider, H., Fernandez-Steeger, T.M. and Czurda, K., 2004. Large-scale lateral spreading and related mass movements in the Northern Calcarous Alps. Bulletin of Engineering Geology and the Environment, 63, 71-75. http://dx.doi.org/10.1007/s10064-003-0201-x

Sausgruber, J.T., Preh, A. and Poisel, R., 2010. Bunzkoegele south slope- a complex failure mechanism shaped by sliding of joints and breaking of rock. Mitteilungen für Ingenieurgeologie und Geomechanik, 9, 1-14.

Schmid, S.M., Fuegenschuh, B., Kissling, E. and Schuster, R., 2004. Tectonic map and overall architecture of the Alpine orogene. Eclogae Geologicae Helvetiae, 97, 93-117. http://dx.doi.org/10.1007/s00015-004-1113-x

Schmid, S.M., Scharf, A., Handy, M.R. and Rosenberg, C.L., 2013. The Tauern Window (Eastern Alps, Austria) – A new tectonic map, cross-sections and tectonometamorphic synthesis. Swiss Journal of Geosciences, 106, 1–32. http://dx.doi.org/10.1007/s00015-013-0123-y

Schuster, R., 2011. Koralpe-Wölz-Deckensystem. In: Rupp, Ch., Linner, M. and G.W. Mandl (eds.), Erläuterungen zur Geologischen Karte von Oberösterreich 1:200.000, 64-67.

Selby, M.J., 1993. Hillslope materials and processes. Oxford University Press, England, 451 pp.

Skempton, A.W., and Hutchinson, J.N., 1969. Stability of natural slopes and embankment foundations. State-of-the-Art Report. 7th International Conference on Soil Mechanics and Foundation Engineering, 2, 378-381.

Stini, J., 1941. Unsere Täler wachsen zu. Geologie und Bauwesen 13, 72-77.

Supper, R., Baron, I, Ottowitz, D., Motschka, K., Gruber, S., Winkler, E., Jochum, B. and Römer, A., 2013. Airborne geophysical mapping as an innovative methodology for landslide investigation: evaluation of results from the Gschliefgraben landslide, Austria. Natural Hazards Earth System Sciences, 13, 1-16. http://dx.doi.org/10.5194/nhess-13-3313-2013

Tilch, N., Kociu, A., Haberler, A., Melzner, S., Schwarz, L. and Lotter, M., 2011. The Data Management System GEORIOS of the Geological Survey of Austria (GBA). In: Moelk, M., Melzner, S., Tartarotti, T. and T. Sausgruber (eds), Interdisciplinary workshop on rock fall protection 2011, book of abstracts- poster presentations, pp. 31-32.

Varnes, D.J., 1958. Landslide types and processes. In: E. B. Eckel (ed.), Landslides and Engineering Practice, Special Report, 29, 20-47.

Varnes, D.J., 1978. Slope movement types and processes. In: R.L. Schuster and R.J. Krizek (eds.), Special Report 176. Landslides. Analysis and Control, pp. 11-33.

Vesela, P., Söllner, F., Finger, F. and Gerdes, A., 2011. Magmosedimentary Carboniferous to Jurassic evolution of the western Tauern window, Eastern Alps (constraints from U-Pb zircon dating and geochemistry). International Journal of Earth Sciences, 100, 993-1027. http://dx.doi.org/10.1007/s00531-010-0596-0

Weidner, S., 2000. Kinematik und Mechanismus tiefgreifender alpiner Hangdeformationen unter besonderer Berücksichtigung der hydrogeologischen Verhältnisse. PhD Thesis, Friedrich-Alexander-University of Erlangen-Nürnberg. Erlangen, 246 p.

Weidner, S., Moser, M. and Lang, E., 2011. Geotechnische und kinematische Analyse des Talzuschubes Gradenbach (Kärnten/Österreich). Jahrbuch der Geologischen Bundesanstalt, 151, 17-60.

WP/WLI, 1993. Multilingual Landslide Glossary. Richmond, Canada, 32 pp.

Yatsu, E., 1966. Rock control in geomorphology. Sozosha, 135 pp.

Zangerl, C., Prager, C., Chawatal, W., Brückl, E., Kirschner, H. and Brandner, R., 2012. Kinematics and internal deformation of a slow deep-seated rock slide in metamorphic rock (Niedergallmigg, Austria). In: Eberhardt, E., Froese, C., Turner, K. and S. Leroueil (eds.), Landslides and Engineered Slopes: Protecting Society through Improved Understanding, London, pp. 653-658.

Zischinsky, U., 1966. On the deformation of high slopes. Proceedings of the 1st intern. Congress of the International Society of Rock Mechanics, Lissabon, 2, 179-185.

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