Berichte der Geologischen Bundesanstalt, 91

Sandra Melzner, Michael Lotter, Nils Tilch & Arben Koçiu

Rockfall susceptibility assessment

at the regional and local scales as a basis for planning site-specific studies in the Upper Moelltal (Carinthia, Austria) INTERREG IV A, Proj. 1381-277

KÄRNTEN WWW.KTN.GV.AT · REGIONE DEL VENETO · REGIONE AUTONOMA FRIULI VENEZIA GIULIA · Interreg IV

Geological Survey of Austria

INTERREG IV A

Project No. 1381-277

"Minimal requirements for compilation of danger maps like landslides and rock fall as a tool for disaster prevention" (Acronym MassMove)

Rockfall susceptibility assessment at the regional and local scales as a basis for planning site-specific studies in the Upper Moelltal (Carinthia, Austria)

Sandra Melzner, Michael Lotter, Nils Tilch & Arben Koçiu

Berichte der Geologischen Bundesanstalt, Nr. 91

Geological Survey of Austria

Cover: Rockfall event on 8th July 2009 endangered the road between Moertschach and Asten (Photo by S. Melzner)

Citation: MELZNER, S., LOTTER, M., TILCH, N. & KOÇIU, A. (2011): Rockfall susceptibility assessment at the regional and local scales as basis for planning site-specific studies in the Upper Moelltal (Carinthia, Austria). – Ber. Geol. B.-A., **91**, 105 p, Vienna.

For details on the project see: www.massmove.at

ISSN 1017-8880

Medieninhaber und Verleger: Geologische Bundesanstalt, Neulinggasse 38, A 1030 Wien
www.geologie.ac.at
Layout: Dido Massimo
Verlagsort: Wien
Herstellungsort: Wien
Ziel der „Berichte der Geologischen Bundesanstalt“ ist die Verbreitung wissenschaftlicher Ergebnisse.
Für den Inhalt sind die AutorInnen verantwortlich.
Satz: Geologische Bundesanstalt
Druck: Offset-Schnelldruck Riegelnik, Piaristengasse 8, A 1080 Wien

Contents

1 Introduction

1.1 Challenges and goals of the project

Many regions in Austria and Italy are affected by rockfall processes which pose a significant hazard to settlements and infrastructure. Decision makers in Federal State Governments and Local Authorities depend heavily on methods, techniques, and adequate data in order to delineate potentially endangered areas and to plan further more detailed investigations so as to implement preventive measures.

In Austria, legislation relating to rockfall susceptibility and hazard zoning is covered by the *Forstgesetz 1975*, *Wasserbautenfoerderungsgesetz BGBl. 148/1985*, *Gefahrenzonenplanverordnung BGBl. 436/1976* and the *Wildbachverbauungsgesetz BGBl. 54/1959*. The Austrian Torrent and Avalanche Control provides a hazard zoning method that defines yellow and red hazard zones for torrential and avalanche processes only. Within these hazard maps, a so-called *brown hazard indication zone* indicates areas that may be affected by gravitational mass movements. Unfortunately, the criteria used to define those areas potentially endangered by rockfall are largely subjective and depend greatly on the knowledge and experience of the surveyor. At the Austrian Torrent and Avalanche Control, ongoing work is attempting to define an Austrian standard rule of *Technical Rockfall Protection* (see ONR 24810) at the slope scale.

In northern Italy, an adapted version of the Swiss BUWAL method (*Piani di Assetto idrogeologico – PAI*) is stipulated by law in the provinces of Friuli and of Veneto. In the former, this required the generation of spatially-continuous hazard maps at the scale of 1:5,000 whereas in the latter it required spatially-continuous hazard maps in scales 1:10,000. However, in order to apply this method, it is crucial that a large number of areas are defined as highly endangered (Level P4). Consequently, Italian decision makers and governmental institutions are interested in refining this method.

Within this context, an INTERREG IVA project was initiated between the Austrian Federal State Government of Carinthia (Project leader: Mr. Richard Baek, Division 15: Environment) and the Italian Regione Autonoma Friuli-Venezia Giulia (Project partner: Mr. Fabrizio Kranitz, Direzione Centrale Ambiente e Lavori Pubblici-Servizio Geologico & Project partner: Mrs. Mariateresa Torresin, Servizio Gestione Territorio Rurale e Irrigazione) and Regione del Veneto (Project partner: Mr. Rocco Mariani, Segreteria Ambiente e Territorio Direzione Difesa del Suolo) in Italy. The project is entitled *Minimal standards for compilation of danger maps like landslides and rock fall as a tool for disaster prevention* (Acronym: *MassMove*, Project Code 1381-08-1). The main aim of this co-operative project is to evaluate different methods and define the minimum requirements relating to susceptibility and hazard assessment for two massmove types, landslides and rockfalls. To achieve these goals, the lead and project partners assigned external experts to investigate different study areas in Austria and Italy.

The Department of Engineering Geology at the Geological Survey of Austria (GBA) was commissioned by the project leader (Federal State Government of Carinthia) to assess the occurrence of rockfalls within a specific part of Austria. The investigated site is situated in the *Upper Moelltal* in Carinthia, and covers an area of about 120 km². Due to the large extent of the area and the stated project objective to produce spatially-continuous susceptibility maps for the entire area, it was decided that the assessment strategy should be undertaken at the regional and local scales. This decision was made with regard to the project budget and available data. The Italian experts (UNIMIB: University of Milano and UNITS: University of Trieste) investigated potential rockfall endangered areas in the provinces of Friuli and Veneto. These investigations were undertaken within a few far smaller study areas at the local and slope scales. Therefore, the MassMove Project covers all spatial scales (regional, local and slope scale). As a result, the project examines a variety of methods that are potentially applicable and assesses the quality of available sources of data.

In this report, the presented results relate to the rockfall susceptibility assessment conducted in the "Upper Moelltal" in Carinthia, Austria.

Chapter 2 provides an overview of the study area in terms of its geomorphic, tectonic, and lithological settings. Furthermore, the data availability at the beginning of the project is discussed. These are very important topics, because the complex settings of the study area and low amount of project relevant data were important issues for the choice of the assessment strategy.

Chapter 3 summarises the multi-scale assessment strategy applied during the course of this project. In the assessment of the Upper Moelltal, slope scale assessments have not been undertaken as these were conducted by partners in Italy (for details, see reports of the Italian rockfall experts). The three-dimensional runout simulations were undertaken by another project team (for details, see DORREN et al., 2011). The MassMove Handbook for Rockfall presents detailed descriptions of the techniques/methods and minimum requirements for data collection.

Chapter 4 presents the results of data collection and analysis obtained across the entire area at the regional scale. This chapter focuses on information regarding the geotechnical behaviour of the lithological units, the spatial distribution of potential rockfall source areas, and a chronicle of historical rockfall events and preventive measures. From this information, the areas to be investigated in detail at the local scale are defined.

Chapter 5 presents the results of data collection and analysis obtained through detailed investigations of specific areas at the local scale. This chapter focuses on information regarding the factors that determine onset and runout susceptibility. It has to be stated that a large amount of data was collected during the course of the project, not all of which could be included into this report due to space considerations. Therefore, this chapter only provides examples from the different areas of detailed investigations.

Chapter 6 summarises the findings of the susceptibility assessments and also suggests places in which more detailed runout simulations at the local scale or site-specific studies for the planning of preventive measures may be required.

Chapter 7 describes how the various data and maps can be applied. Furthermore, recommendations are presented that should be taken into account when defining an assessment strategy for a regional study within the alpine area.

1.2 Acknowledgements

The Department of Engineering Geology at the Geological Survey of Austria (GBA) is grateful to the following people and institutions for their contribution to the success of this project:

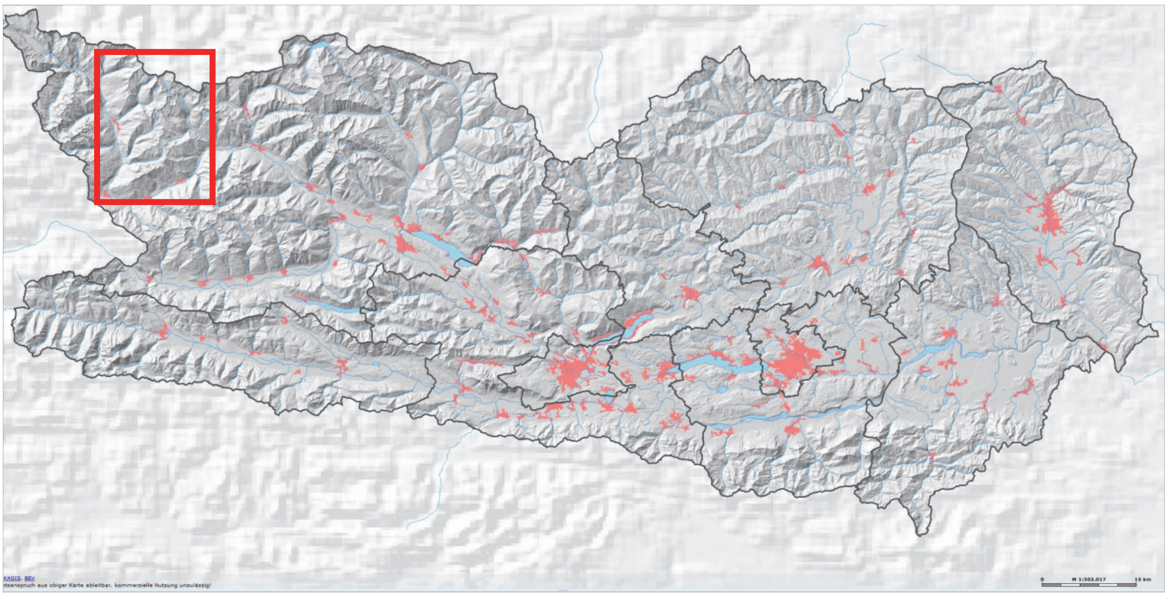
- MassMove Project leader Richard Baek at the Austrian *Federal State Government of Carinthia* and partners Rocco Mariani at the *Regione del Veneto* and Fabrizio Kranitz and Mariateresa Torresin at the *Regione Autonoma Friuli-Venezia Giulia* in Italy for initiating and coordinating the project.
- L. Dorren, F. Agliardi, E. Castelli, P. Frattini, and G.B. Crosta for their rockfall expertise and for sharing knowledge and experience through fruitful discussions.
- S. Bensi, L. Bigot, M. Borga, F. Goldschmidt, P. Manca, A. Missio, W. Poltnig and P. Saccon for the various discussions about minimum requirements.
- I. Baron for field support, G. Posch-Trözmüller for administrative support of the project leader and P. Lipiarsky for developing the project meta-database.
- I. Speiser for financial management and organising the workshops held in Austria.
- M. Mölk and T. Sausgruber at the Geological Service of the Austrian Torrent and Avalanche Control (WLV) in Innsbruck for valuable rockfall discussions.
- E. Ferlan, W. Klaus, and K. Kulterer at the “Drautal und Mölltal” Regional Office of the Austrian Torrent and Avalanche Control (WLV) for the provision of data.
- The communities of Großkirchheim, Moertschach, and Winklern for the provision of data and their support during the field investigations.

Last, but not least, we would like to especially thank the members of staff at the Geological Survey of Austria (GBA) who were not directly involved in the project but with whom significant scientific discussions and software developments were conducted: M. Linner, G. Pestal, R. Schuster, R. Supper, J. Reitner, J. Reischer and H. Heger.
Furthermore, we would like to thank M.D. Rowberry at the Institute of Rock Structure and Mechanics in Prague for language proof reading of the final report.

2. Study area and available data

2.1 Geography and geomorphology

The study area is located in the northwestern part of the federal state of Carinthia, Austria (Text-Fig. 2.1). It is part of the geographical unit *Goldberggruppe*.



Text-Fig. 2.1: Location of the study area in northwest Carinthia, Austria (red box). (From: http://gis.ktn.gv.at/atlas/%28S%28c0tvam45eek5glvntszenor2%29%29/init.aspx?karte=atlas_basiskarten&ks=kaernten_atlas).

The area falls within three communities, *Doellach (Großkirchheim*), *Moertschach*, and *Winklern*. It occupies a total area of approximately 120 km^2 along the orographic left-hand slopes of the main valley of the *Moell River* and includes the side valleys of the tributaries *Zirknitz*, *Asten*, and *Kolmitzen* (Text-Fig. 2.2).

Permanently inhabited houses and settlements, in addition to the main infrastructure, are concentrated within the main valleys of the *Moell* and *Asten Rivers* and around the confluence of the *Zirknitz River* into the *Moell River* (Text-Fig. 2.2). A KELAG AG building is situated within the valley of the *Zirknitz River*, a little to the east of the confluence of the *Great Zirknitz River* and the *Little Zirknitz River*. Throughout the study area a number of temporary roads and temporarily inhabited cottages can be found, such as those below *Moharspitz* and *Eckkopf*.

The study area is characterised by two main strike-slip fault systems, assigned to the dextral *Iseltal Fault System* and to the sinistral *Zwischenbergen-Wöllatratten Fault System* (Text-Fig. 2.3 and LINNER et al., 2009). These tectonically predisposed zones of weakness have been subjected to glacial or glacio-fluvial/fluvial erosion processes. The valleys presently follow these main faults in NW–SE or WSW–ENE striking directions and very probably in the associated synthetic and antithetic directions, respectively.

Text-Fig. 2.2: The geographical location of the study area (Fig. by S. MELZNER, GBA). Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609)

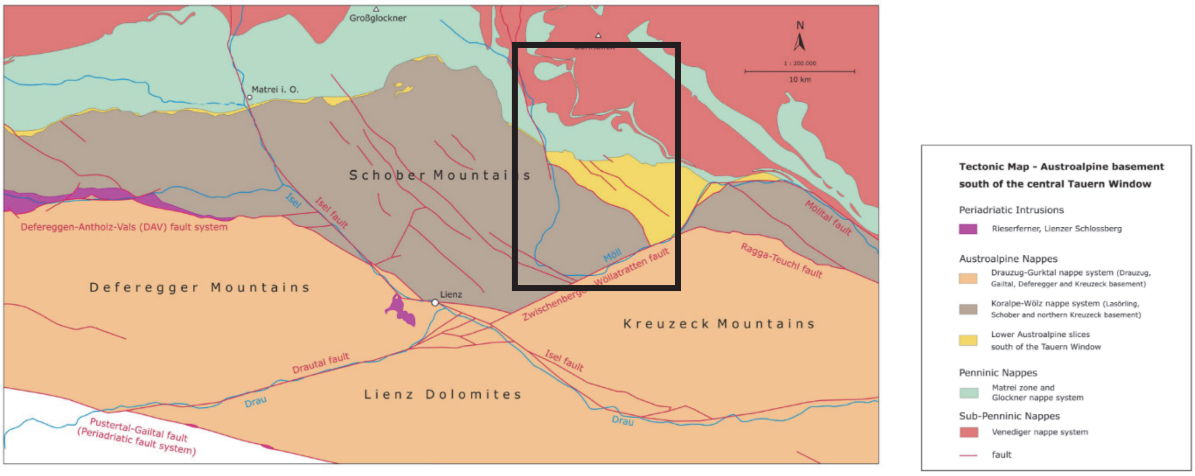
Due to glacial erosion by the former Moell Glacier during the last ice age, the Moell Valley takes the form of a typically wide U-shaped alpine trough. The altitudinal difference is over 1,000 meters from the bottom of the main valley, at 970 m asl, to the mountain peaks, at between 1,803–2,605 m asl, The highest peak is that of *Goldbergspitze*, at 3,076 m asl. The typical glacial valley form can also be partly recognised in the side valleys, especially that of the *Great Zirknitz*. These side valleys occur at notably higher elevations than the main Moell Valley, a consequence of the considerably more limited erosional capabilities of the smaller glaciers. These elevational differences have promoted post-glacial fluviatile erosion processes, whose strong erosive forces can presently be recognised in form of steeply incised gorges.

During the Würmian glacial maximum, the Moell Valley was filled with ice up to 2,300 m asl (LGM: 29–21 ka BP). The subsequent ice melt between 21–19 ka BP led to the formation of ice reservoirs and kames terraces along the shrinking glaciers until such time as the main valley was completely ice-free. The area was later subject to occasional glacial advances and retreats. These occurred within both the main valley itself, and in the adjacent side valleys (pers. comm. J. REITNER, GBA, work in progress). During the Gschnitz period (16–15 ka BP), the Moell Glacier advanced through the study area and the resulting terminal and side moraines are still visible. It is debateable as to whether any glaciers encroached from the side valleys at this time. During the Egesen period (12,5–11,6 ka BP), glaciers only encroached from the side valleys during the advance. However, as a consequence of these late glacial advances and retreats, a sequence of terminal moraines has formed. As the glaciers retreated and stabilised, the permafrost also moved to higher elevations; this is documented by relict rock glaciers (Chapter 4.2.3).

After glacial retreat and exposure of the glacially over-steepened relief, the development of deep-seated slope deformations probably started during the post-glacial or late glacial stadial (for a detailed description, see Chapter 4.2.2). These complex mass movements are the most characteristic morphologic feature of the study area. The trough valleys have been modified and appear today as asymmetric valley forms. In some parts of the study area, these mass movements have narrowed the valleys and led to the development of gorges (e.g. *Judenbrücke*).

2.2 Geological and tectonic overview

The study area is located within the southern part of the central *Tauern Window* and adjacent *Austroalpine Nappes*. It is characterised by high tectonic and lithological complexity (Text-Fig. 2.3). From north to south, it comprises the main tectonic units *Sub-Penninic*, *Penninic* and *Austroalpine* (SCHMID et al., 2004, PESTAL et al., 2009). The Sub-Penninic and Penninic Units dip towards the southwest, whereas the Upper Austroalpine Sub-Unit dips gently to deeply towards southwest and, in part, to northeast (Text-Fig. 2.4 and Text-Fig. 2.5).



Text-Fig. 2.3: Tectonic map of the southern part of the central Tauern Window. (Source: LINNER et al., 2009):

Text-Fig. 2.4: The southwest dip of the lithological units. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

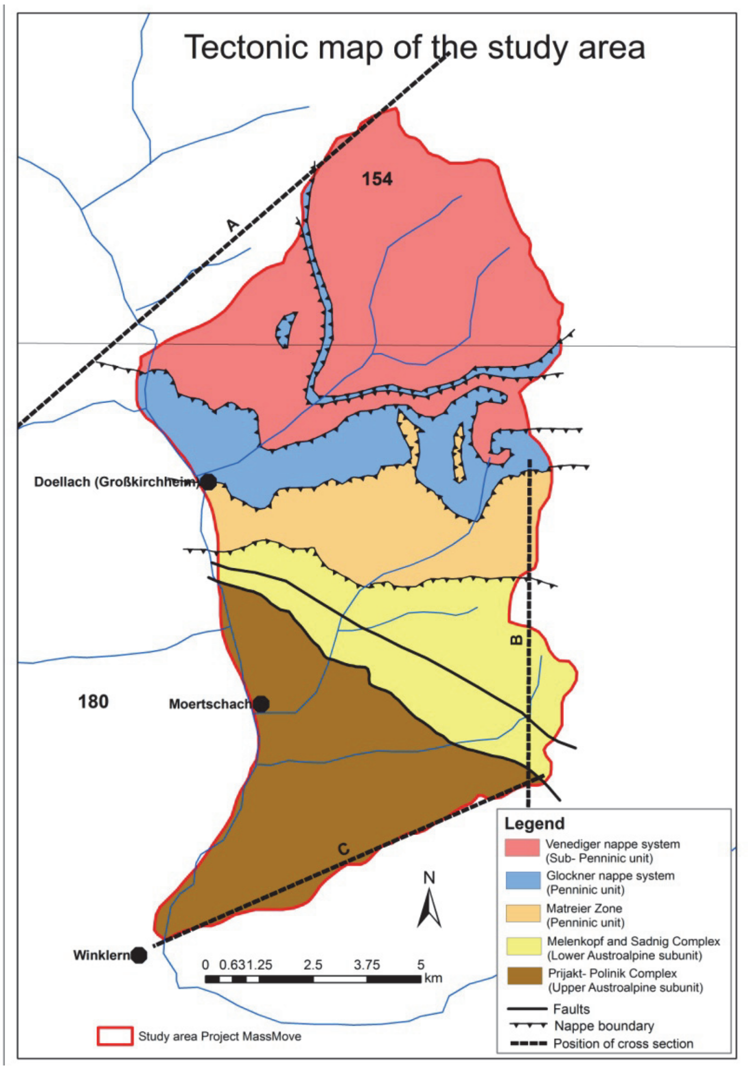
2.2.1 Sub-Penninic Unit

The lowest tectonic unit of the central Tauern Window incorporates the *Venediger Nappe System* (FRISCH, 1976, 1977; SCHMID et al., 2004). This is found in the northern part of the study area (Text-Fig. 2.5 and Text-Fig. 2.6). These nappes comprise overformed continental crust of Variscian age and a metasedimentary cover from the Late Carboniferous, Permian, and Mesozoic. These sediments were previously part of the former European Margin (Helvetic Shelf) (PESTAL et al., 2009).

Based on the most recent scientific findings, the following lithostratigraphic units and rocks occur within the study area:

- The Lower Paleozoic *Metabasit Complex* (predominately prasinite and amphibolite).
- The Lower Paleozoic – Carboniferous *Habach Group* (albitic gneiss, light phyllite, sericite schist, chlorite schist, porphyric schist, biotite-epidote gneiss, and prasinite).
- The Upper Paleozoic *Draxel Complex* (black schist, dark albite-/biotite blast schist, and graphitic quartzite).
- The Upper Paleozoic *Zentralgneis Complex* (granitic gneiss with minor granodioritic gneiss).
- The Permian – Lower Triassic *Wustkogel Formation* (phengite bearing quartzite and arkoses bearing gneiss).
- The Middle and Upper Triassic *Seidlwinkl Formation* (calcitic and dolomitic marbles).
- The Cretaceous *Brennkogel Formation* (dark phyllite, dark calcareous micaschist, and light calcareous quartzite).

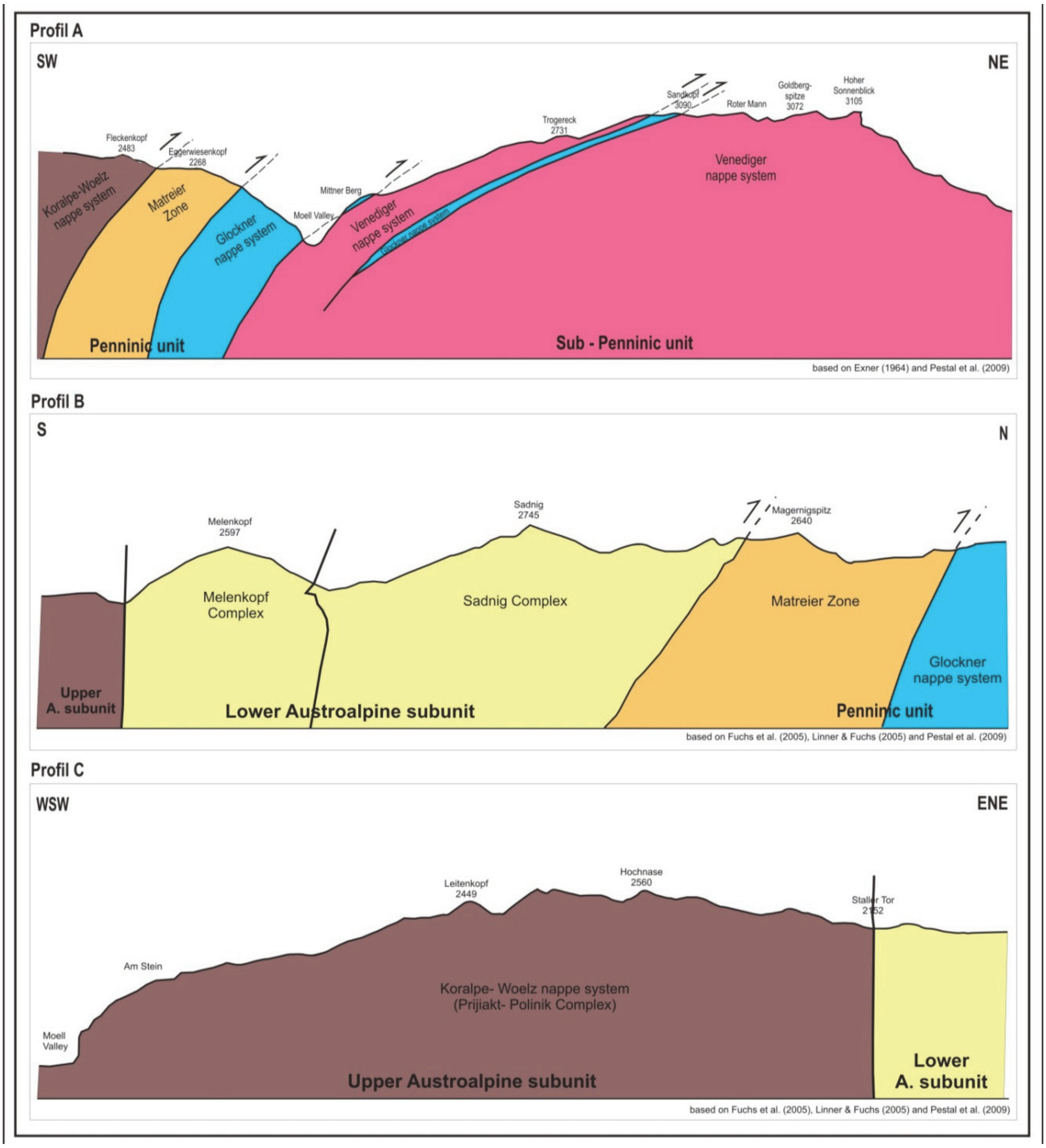
Within the study area, the rocks of the *Zentralgneis Complex*, *Wustkogel Formation*, and *Brennkogel Formation* are the most commonly occurring lithologies of the Sub-Penninic Nappe.



Text-Fig. 2.5: A tectonic overview. Used nomenclature based on PESTAL et al., 2009. See Text-Fig. 2.6 for details on cross sections. (Fig. by S. MELZNER & G. PESTAL, Geological Survey of Austria).

2.2.2 Penninic Unit

The lowermost tectonic unit of the Penninic Unit within the central Tauern Window incorporates the *Glockner Nappe System* (SCHMID et al., 2004; STAUB, 1924). This nappe system comprises the numerous lithologies of the Jurassic–Cretaceous *Bündnerschiefer Group*. However, within the study area, the *Glockner Nappe System* only comprises lithologies of Cretaceous age (Text-Fig. 2.5 and Text-Fig. 2.6). It consists of remnants of oceanic crust (ophiolite) and sediments from the former Piedmont-Ligurian Ocean to the south of the European Shelf. These sediments represent the metamorphic metasediments of the *Bündnerschiefer Group* (PESTAL et al., 2009).



Text-Fig. 2.6: Geological cross sections through the Sub-Penninic Unit, Penninic Unit, and Upper Austroalpine Unit. See Text-Fig. 2.5 for the cross section locations (Fig. by S. MELZNER & G. PESTAL, Geological Survey of Austria).

Based on the most recent scientific findings, the following lithostratigraphic units and rocks occur within the study area:

- Cretaceous *ultrabasic* rocks (serpentinite partly accompanied by metagabbro, talcum schist, and ophi-carbonatic rocks).
- Lower Cretaceous *metabasic* rocks (prasinite and amphibolite).
- Cretaceous *limestone micaschist* (mica bearing marbles and, to a lesser extent, calcareous phyllite and garnet-muscovite schist).

Within the study area, the *limestone micaschist* (*micamarble*) forms the dominant lithology.

The uppermost tectonic unit of the Penninic Unit incorporates the *Matrei Zone*. This also comprises the predominant metasediments of the *Bündnerschiefer Group* (PESTAL et al., 2009). In contrast to the lower Glockner Nappe System, the Matrei Zone (Text-Fig. 2.5 and Text-Fig. 2.6) contains the younger elements of the Bündnerschiefer Group that had formed during the Dogger and Malm Periods. Metamagmatites, which originated from the former oceanic crust, form a significant ophiolite band running from the Moell Valley to the southern edge of *Schöbertörl*. Rocks of Permian, Triassic, and Lower Cretaceous age are also quite frequent, and these share lithological similarities to the rocks of the Lower Austroalpine *Radstädter Tauern*. These metasediments originated from the Austroalpine continental margin and have been transported due to various tectonic processes within the *Matrei Zone.*

Based on the most recent scientific findings, the following lithostratigraphic units and rocks occur within the study area:

- Permian – Lower Triassic *Alpiner Verrucano* and *Lantschfeldquarzit* (sericite-chlorite schist, arkoses bearing gneiss, and quartzite).
- Middle and Upper Triassic *carbonate* rocks (calcitic and dolomitic marbles).
- Jurassic – Lower Cretaceous *metabasic* rocks (prasinit and chlorite schist).
- Jurassic – Lower Cretaceous *Phyllitic Bündnerschiefer* (dark and light phyllite and, to a lesser extent, calcareous micaschist and quartzite).
- Jurassic–Cretaceous *limestone micaschist* (calcitic and mica marbles and, to a lesser extent, calcitic phyllite).

Within the study area, the *Phyllitic Bündnerschiefer* is frequent within the *Matrei Zone*. Also notable are the large concentrations of metabasic (greenschist) and the rocks of the *Alpinen Verrucano*.

2.2.3 Austroalpine Unit

The southern half of the study area comprises the *Austroalpine Unit* (Text-Fig. 2.5 and Text-Fig. 2.6), which predominantly consists of high-grade metamorphic rocks with some (meta-) sediments of Paleozoic and Mesozoic age. The *Austroalpine Units* were thrust over the *Penninic Unit*s during the Eoalpine and Alpine Event (PESTAL et al., 2009). The *Austroalpine Unit* can be differentiated into an *Upper Austroalpine Sub-Unit* and a *Lower Austroalpine Sub-Unit* (SCHMID et al., 2004; FROITZHEIM et al., 2008).

2.2.3.1 Lower Austroalpine Sub-Unit

The Lower Austroalpine sub-unit comprises those elements of the Austroalpine Units that were previously part, during the Jurassic and Cretaceous, of the former shelf of the southern margin of the Piedmont-Liguria Ocean. During opening and closing of the ocean, these rocks were subject to intensive structural and/or metamorphic deformations (LINNER & HEJL, 2009). Within the study region, the Lower Austroalpine sub-unit is characterised by *“slivers along the southern margin of the central Tauern Window”*. These slivers comprise typical Lower Austroalpine metasediments of the metamorphic equivalents of the *Alpine Verrucano* and *Lantschfeldquarzit* (TOLLMANN, 1977). Complexes of crystalline rock only occur in the southern *Goldberg Group* (FUCHS & LINNER, 2005). LINNER & FUCHS (2005) term these nappe fragments the *Stall Nappe* and differentiate it into the *Melenkopf Complex* and *Sadnig Complex* (Text-Fig. 6). The aforementioned metasediments were deposited on to the *Sadnig Complex*. In the previous tectonic model of this area, all these metasediments were considered to belong to the *Lower Austroalpine Matrei Zone*. The new tectonic model uses the occurrence of rocks such as prasinite and serpentinite to indicate profound nappe margins (LINNER & HEJL, 2009). Aside from the basite lithology, the metasediments of the Matrei Zone and the slivers of Lower Austroalpine are quite similar and can hardly be distinguished from one another.

Based on the most recent scientific findings, the following lithostratigraphic units and rocks occur within the study area:

- *Melenkopf Complex* (predominately micaschist and paragneiss, sometimes granitic augengneiss and, to a small extent, amphibolite).
- *Sadnig Complex* (fine-grained micaschist and quartzite).
- *Permian – Lower Triassic Metasediments (sericite-chlorite schist,* quartzite meta-arkoses, schistose breccia). This lithology was deposited on the pre-alpine metamorphic Sadnig Complex.

Within the study area, the Lower Austroalpine *Stall Nappe* has a much more homogenic lithology in comparison to the Sub-Penninic and Penninic Nappes. Nevertheless small intercalations in the *Melenkopf* and *Sadnig Complexes* are not detailed on the *Geological Map of the Sadnig-Group 1:50,000* (FUCHS & LINNER, 2005). For the *Melenkopf Complex*, signature marks are used to indicate the presence of intercalations such as augengneiss and amphibolites. Outside the study area, these lithologies outcrop over larger areas and are shown as discrete polygons.

The largest fragment of the Lower Austroalpine Nappe (Melenkopf and Sadnig Complex covered by metasediments), along the edge of the central Tauern Window, is tectonically inverted and has thrust over the Penninic *Matrei Zone* to the north. To the south, steeply dipping faults indicate its border with the Upper Austroalpine Sub-Unit.

2.2.3.2 Upper Austroalpine Sub-Unit

The Upper Austroalpine Sub-Unit is an eoalpine nappe stack of Upper Cretaceous age, which developed due to subduction and subsequent extrusion processes within the northeastern part of the Apulian Plate (SCHUSTER et al., 2009). After SCHMID et al. (2004), the Upper Austroalpine Nappe can be differentiated into different nappe systems.

Within the study region, the tectonic highest unit comprises the *Prijakt Nappe*, part of the *Koralpe-Wölz Nappe System*. The *Prijakt Nappe* is characterised by the absence of transgressive, overlying, sedimentary rocks of Permian–Mesozoic age. This cover was sheared from the *Koralpe-Wölz Nappe System* during eoalpine tectonic processes.

The Prijakt Nappe comprises the *Prijakt Polinik Complex*. The predominant lithology is:

- Micaschist and paragneiss, sometimes quartzitic and, to a very small extent, pegmatitic gneiss.
- Eclogite, eclogitic amphibolite, and amphibolite.
- Orthogneiss, sometimes with augentexture, and biotite-orthogneiss.

The most frequent lithology are the coarse micaschist and paragneiss. It was not possible to delineate and geologically map these rocks separately due to the smooth transition (FUCHS et al., 1996). In addition, amphibolite and orthogneiss are widespread.

2.3 Available data and data quality

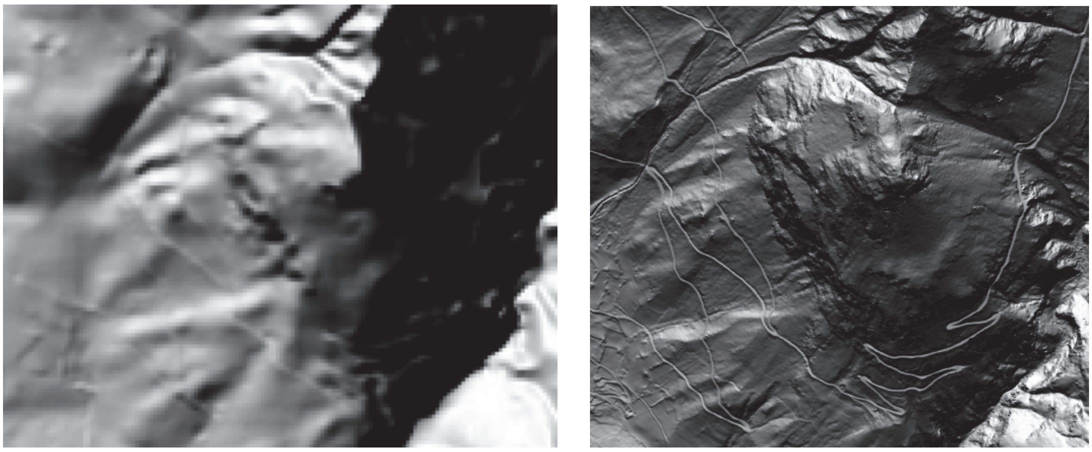
Table 2.1 presents those data that could be collected or provided by the Geological Survey of Austria and the Federal State Government of Carinthia at the beginning of the MassMove Project.

2.3.1 Basic topographic data

The basic topographic data for the study area were available in the form of a topographic map at a scale of 1:50,000 and a digital terrain model (DTM) with a resolution of 10 m (Source: BEV). The high resolution Airborne Laser Scan (ALS) data, with a resolution of 1 m, were provided in the second year of the project by the Federal State Government of Carinthia. By this time, most of the field investigations had already been completed. Text-Fig. 2.7 highlights the difference in accuracy between the 1 m and 10 m DTMs, respectively. The ALS data are clearly more suitable for data analysis and for the generation information that is relevant to the project (Chapter 4). For example, it is possible to construct very accurate base maps from automatically calculated isolines. These maps could then have been used during the field mapping.

Data Type	Title/Content	Scale/Resolution	Date	Format
Topography	Topographic Map	1:50,000	unknown	TIFF Format
	Digital Terrain Model (DTM)	10 m	unknown	Raster Format
	Digital Terrain Model (DTM)	1 m	2010	Raster Format
Geology	Geological Map of the Sadnig Group	1:50,000	2005	TIFF/Vector Format
	Geological Map of the Sonnblick Group	1:50,000	1962	TIFF
	Geological Map of Salzburg	1:200,000	2005	TIFF
	Tectonic Map of Austria (based on SCHMID et al., 1904)	1:200,000	2004	Vector Format
	Geological Map of Carinthia	1:50,000	2005	Vector Format
Land Use	Digital Land Use Map	1:2,880	unknown	Vector Format
	Digital Surface Model (DSM)	1 m	2010	Raster Format
	Orthophoto	0.25 m	2006	TIFF Format
Process Data/ Event information	Event register of the Federal State Government of Carinthia	Spatially variable	2009	Vector Format
	Web-application for mass movements of the Geological Survey of Austria	Spatially variable	2009	Vector Format
	GEORIOS database of the Geological Survey of Austria	Spatially variable	2009	Vector Format

Table 2.1: An overview of the data available for the study area "Upper Moelltal" at the beginning of the MassMove Project.



Text-Fig. 2.7: A comparison of the 10 m DTM (left) and the 1 m ALS data (right) (Source DTM: BEV and Federal State Government of Carinthia).

2.3.2 Basic geological data

In the vicinity of the study area, no *Geological Map of the Republic of Austria within the sheet line system at the map scale of 1:50,000* has thus far been published. At present, geological mapping is ongoing and it is expected to be finished with the publication of map sheets *Rauris* (Sheet 154) and *Lienz-Ost* (formerly *Winklern*, Sheet 180). (For details, see www.geologie.ac.at).

Fortunately a number of regional geological maps are available for the study area. The map scales of these ranges from 1:50,000 to 1:200,000. However, the most recent lithological nomenclature for the various units and their modern tectonic explanation is presented only on the *Geological Map of Salzburg* (1:200,000). This is significant because the older geological maps need to be reinterpreted in respect to the most recent nomenclature and tectonic explanation before they can be used for geotechnical investigations and susceptibility assessments (Chapter 4.1 and 5.2).

Regional Map: Geological Map of the Sadnig Group (1:25,000)

An important and very accurate geological map of the southern part of the study area is the *Geological Map of the Sadnig Group* by FUCHS & LINNER (2005) with corresponding explanatory notes. This map formed the basis of the modern tectonic framework, and although the nomenclature and framework have been modified over the past few years, it was possible to transfer the old nomenclature to the modern concept of *Austroalpine Unit* without difficulty (Chapter 2.2.3). However, reinterpretation of those lithological units now within the so-called *Matrei Zone* (Chapter 2.2.2) was far more complex. This was primarily due to the fact that the lithological units were not necessarily classified into the same tectonic units (*Lower Austroalpine Unit* versus *Penninic Unit*). The presentation of the lithological units had also changed, in places significantly, over the past few years.

Regional map: Geological map of the Sonnblick Group (1:50,000)

The *Geological Map of the Sonnblick Group* by EXNER (1962), with corresponding explanatory notes by EXNER (1964) and PREY (1964), contains geological information about the northern part of the study area (Sub-Penninic and Penninic Units). The underlying tectonic concept and thus the definition of the tectonic boundaries are obsolete. However, this map was of great value during the project as it contains highly detailed information about the bedrock geology. In contrast, information about superficial deposits and mass movements are highly generalised and the associated nomenclature is completely obsolete. In addition, different lithological units are sometimes displayed with the same colours. Without detailed knowledge of the study area, it would not have been possible to reinterpret these units.

National map: Geological Map of Salzburg (1:200,000)

At present, the most recent lithological nomenclature for the various units and their modern tectonic explanation is only presented on the *Geological Map of Salzburg* by BRAUNSTINGL et al. (2005), with corresponding explanatory notes by PESTAL et al. (2009). It is, unfortunately, impossible to use this map in order to achieve the project goals due to its coarse resolution; zooming-in to an adequate scale for a regional assessment (1:25,000 or 1:50,000) is neither appropriate nor possible because the geology (shape and number of polygons) and position of the tectonic boundaries (e.g. between the Penninic and Upper Austroalpine Unit) need to be adjusted significantly.

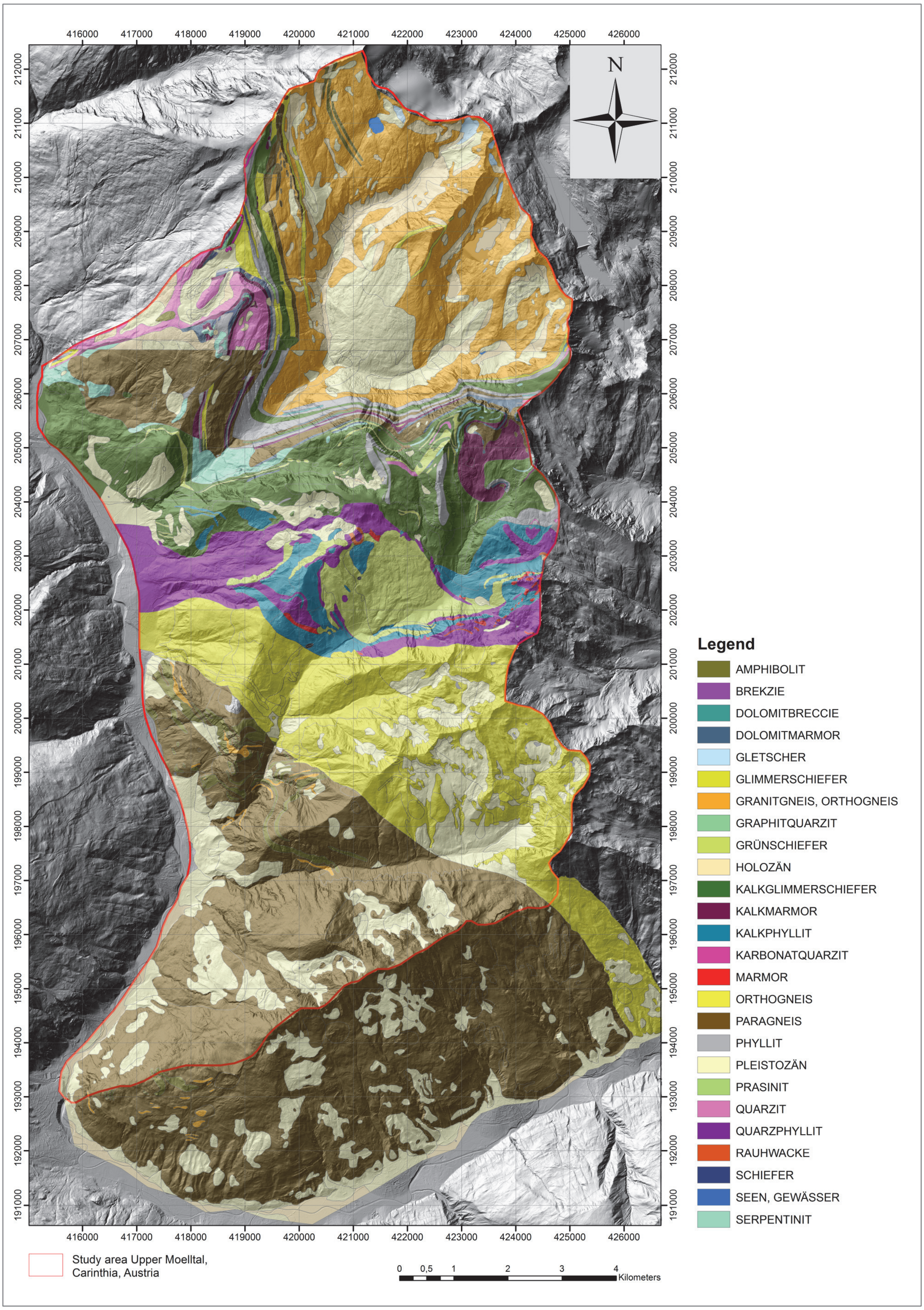
The explanatory notes for this map (PESTAL et al., 2009) were mainly used to understand the lithological and structural nomenclature and tectonic development of the study area. This detailed knowledge was essential in order to improve and reinterpret the geological map used during the assessment and detailed field investigations (see next section).

Geological Map of Carinthia (1:50,000)

The only spatially-continuous digital geological information available for the entire study area is the *Geological Map of Carinthia* by LETOUZÉ-ZEZULA et al. (2005), see Text-Fig. 2.8. This map was compiled during the KC-25 Project. It is an extensive compilation of a range of existing geological information, taken from a variety of sources that depicted different contents and with varying accuracies. Consequently, it does not incorporate the modern tectonic framework and is not consistent in terms of its lithological and structural nomenclature. The authors recognise these drawbacks, and state that the map is a *"... compilation, which is not free of visible and scientific inhomogeneity"* (LETOUZÉ-ZEZULA et al., 2005). Furthermore, they state that it should be understood as a "work in progress", especially *"for the crystalline areas in the northwest of Carinthia a homogeneous status is not existent so far and adjustments are expected to be postponed until the future"*.

Due to the numerous data sources, the map contains a large variety of lithological names. In some instances, different names may describe the same type of rock. In others, the same name may describe different types of rock. Especially on the older maps, antiquated names and lithological descriptions do not conform to present tectonic interpretations.

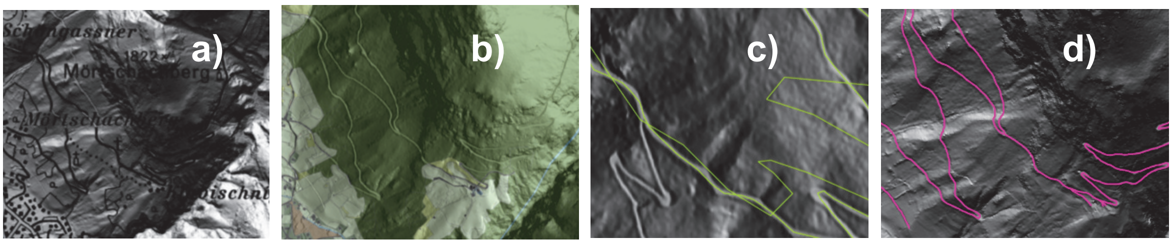
Despite these shortcomings, this geological map was used for the regional assessment because its southern part was based on information from the accurate *Geological Map of the Sadnig Group* (FUCHS & LINNER, 2005). It was not possible to construct a more "refined" digital compilation of the additional geological information for the entire area as this would have been too time intensive and, therefore, not practical during the course of the MassMove Project.



Text-Fig. 2.8: The geological map of Carinthia, at a scale of 1:50,000 (LETOUZÉ-ZEZULA et al., 2005) (Fig. by S. MELZNER, GBA). Source DTM: BEV and Federal State Government of Carinthia.

2.3.3 Basic land use data

Land use data are available across a range of scales and resolutions. Text-Fig. 2.9 demonstrates that there are large differences between the datasets in terms of the quality of their content. The 1:50,000 topographic maps are highly generalised and do not include all buildings and infrastructure (Text-Fig. 2.9a). The 1:2,880 digital cadastral land use maps are far more accurate but even these are not always reliable as they occasionally omit important buildings and infrastructure (Text-Fig. 2.9b-red circle) and Text-Fig. 2.9c). These inaccuracies are probably due to the fact that orthophotos have been automatically or visually interpreted, and during this process not all the objects were recognised (or, in the case of automated analysis, the objects were not post-processed sufficiently). The Airborne Laser Scan data (DTM and DSM), with a resolution of 1 m, provide the most accurate information. These data delineate settlements, infrastructure, and land cover with a high degree of precision (Text-Fig. 2.9d).

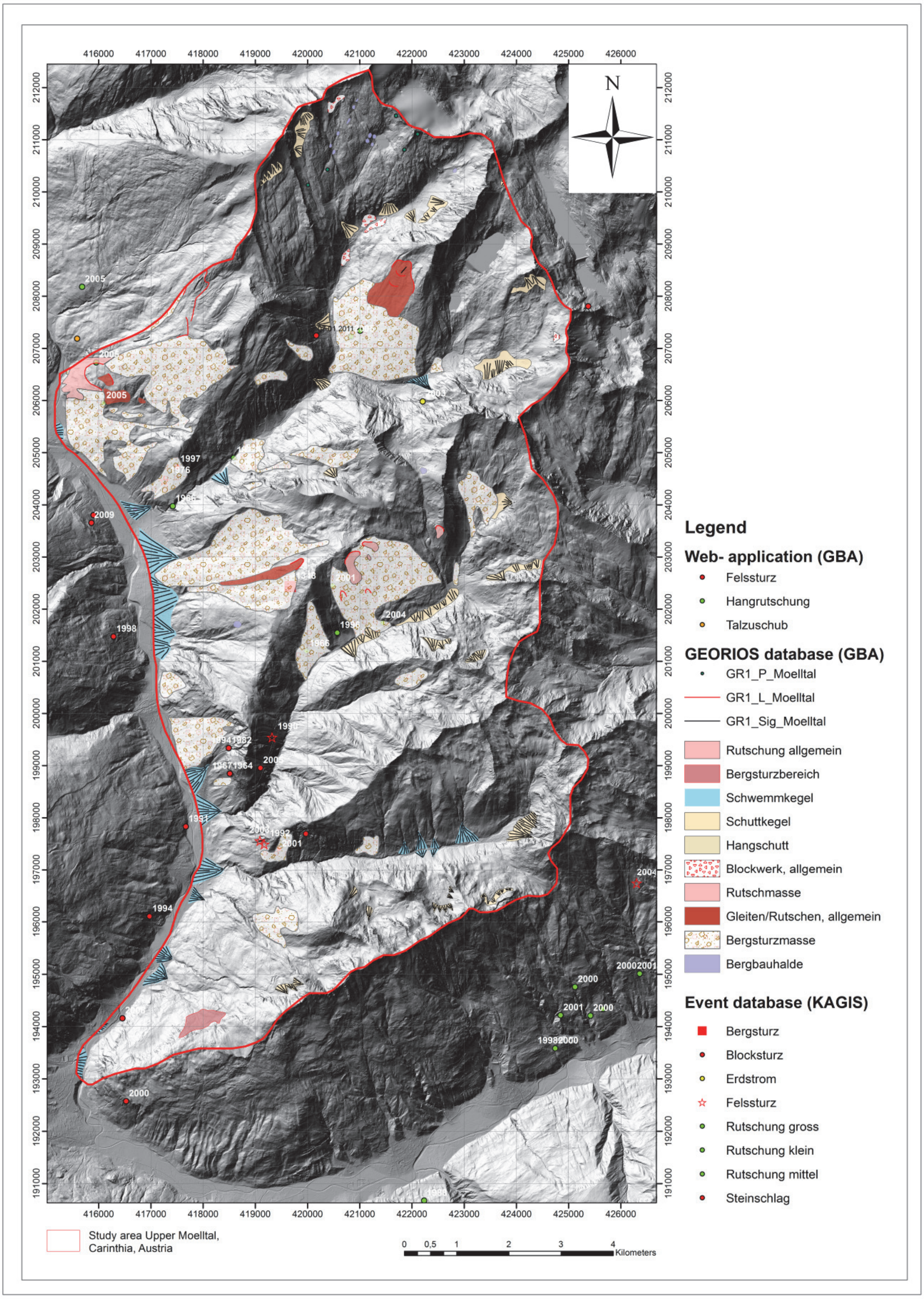


Text-Fig. 2.9: The locational accuracy of buildings and infrastructure according to different datasets: (a) TK 50 versus ALS; (b) DKM versus ALS; (c) Roads of KAGIS (green lines) versus ALS; (d) manually digitised roads based on ALS data (Source data: BEV and Federal State Government of Carinthia). Source of situation data: BEV ().

2.3.4 Process and event data

In 1978, the Geological Survey of Austria (GBA) began collecting meta information (photos, maps, and reports) that related to geogenic natural hazards. Since 2000, this information has been compiled in digital format within one of the core programs of the Geological Survey, Georisiken Österreich or GEORIOS (Georisk of Austria). At present, the GEORIOS data management system comprises information relating to more than 30,000 gravitational mass movements. This information ranges from GIS datasets to digital documents (for further details, see Tilch et al., 2011a). Many of these data are published on the homepage of the Geological Survey (www.geologie.ac.at) within the mass movement application (http://geomap.geolba.ac.at/MASS/index. cfm). Prior to the initiation of the MassMove Project, the database only contained a very small amount of information relevant to the study area. As of September 2009, the web application recorded eight mass movement events (Text-Fig. 2.10) These were distinguished into three process types: rockfall (5 entries); slides (1 entry); and deep-seated slope deformation (2 entries). The extensive GEORIOS database, which is not available in the internet, also contains more detailed information for expert use. In the study region, this information refers mainly to other deep-seated slope deformations, intensely loosened areas, and areas of deposition.

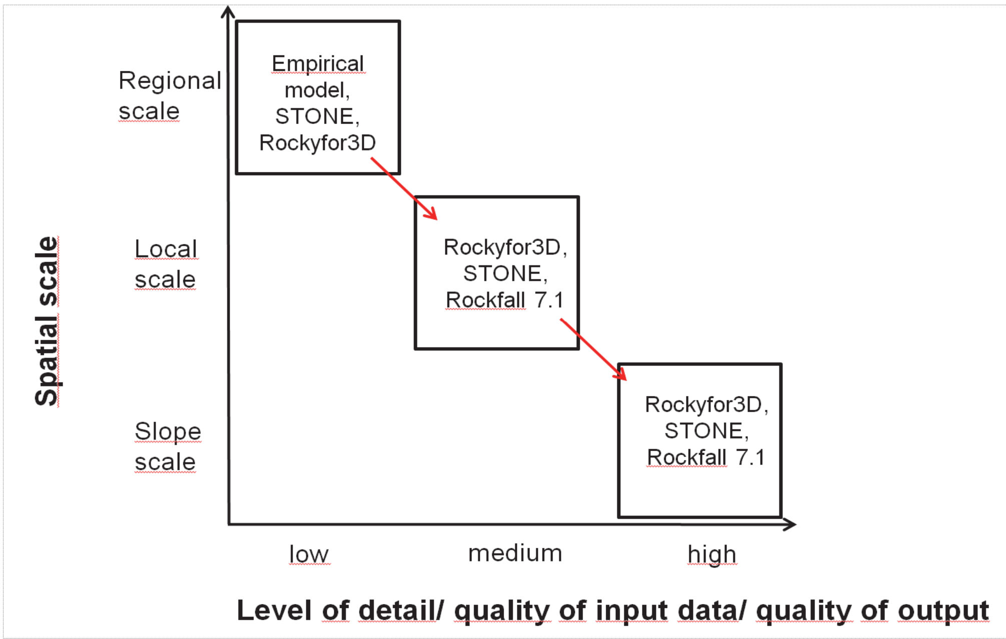
The homepage of the Federal State Government of Carinthia also includes a web application called Geology and Natural Hazards (KAGIS Extranet). This application contains, predominately, information about mass movement events. The underlying database was developed in 2005 by the Geological Survey within a project established by the Federal State Government of Carinthia. As of September 2009, the web application recorded forty-six relevant mass movement events (Text-Fig. 2.10). These were distinguished into four process types: rockfall (22 entries); earth flow (2 entries); rock avalanche (1 entry); and slides (21 entries).



Text-Fig. 2.10: The information available regarding events in the study area at the beginning of the MassMove Project (September 2009). Events recorded in the GEORIOS database of the Geological Survey of Austria and in the KAGIS database of the Federal State Government of Carinthia (Fig. by S. MELZNER, GBA). Source DTM: BEV and Federal State Government of Carinthia.

3. Assessment strategy

It is both expensive and time-consuming to undertake a spatially-continuous rockfall susceptibility assessment across a large area such as that required for a regional study. Indeed, in remote areas, it is often not possible at all. The cost and effort for the susceptibility assessment has to be adjusted according to the project framework (its financial and time constraints). To follow an efficient strategy, a regional susceptibility assessment needs to integrate a range of spatial scales (slope, local, and regional) and incorporate different methods, data types, and data qualities (MELZNER et al., 2010c; MELZNER et al., 2011b; TILCH et al., 2011b). It is, therefore, important to adopt a so-called multi-scale assessment strategy. This type of assessment strategy is shown schematically in Text-Fig. 3.1, with the different scales investigated sequentially from regional through local and down to slope.



Text-Fig. 3.1: A multi-scale assessment strategy for a regional susceptibility assessment. This example shows the application of different runout approaches in relation to three spatial scales (regional, local, and slope). It includes different data qualities in terms of both content and scale/resolution. (Source: MELZNER et al., 2010c, 2011b).

A wide variety of data types and methods can be used during a multi-scale rockfall assessment (see the MassMove Handbook for Rockfalls). The choice of method depends specifically on the size of the investigated study area and the overall project goals. Also important is the availability of different data types and, especially, their quality (scale/resolution). For example, the application of course data (1:50,000 to 1:200,000) is not appropriate for investigations at the slope scale; such site-specific studies require input data with a high resolution (Table 2.1). Thus, the quality (data validity domain) of the resulting output data from an assessment has to always be evaluated according to the quality of the input data (Table 3.1) and, if necessary, adjusted to the input accuracy (for details, see Chapter 5.3.2).

Analysis Scale	Scope	Type of maps	Indicative map scale	DEM cell size
R: Regional	Recognition of potentially endangered areas	Inventory maps/ susceptibility maps	1:50,000 – 1:10,000	≤ 30 m
L: Local (e.g. municipality)	Land use planning	Landslide susceptibility maps/ hazard maps/ hazard zone maps	1:10,000 – 1:5,000	≤ 5 m
S: Specific areas or slope scale (site specific study)	hazard and risk analysis, design of countermeasures	Hazard map/hazard zone maps	1:5,000 – 1:500	≤ 2m

Table 3.1: The defined spatial scales and the associated map scales or data resolution. (Source: MassMove Handbook for Rockfall).

As described, a vital first step to developing an adequate assessment strategy is in the evaluation of existing analogue and digital datasets. Table 2.1 in Chapter 2.3 summarises the datasets that were available for the “Upper Moelltal” at the beginning of the project. On first inspection, it appears that the majority of the data were of low quality in terms of their scale/resolution and that only a small amount of information exists regarding past rockfall events (Chapter 2.3). The high resolution 1 m Airborne Laser Scan data (DEM and DSM) only became available in the second year of the project.

With respect to this framework, the first phase of the project applied various methodologies at the regional scale in order to gain sufficient knowledge regarding the spatial distribution of rockfall source areas and to define potentially endangered areas within the study region. The second phase of the project then used these potentially endangered areas as the basis for further comprehensive susceptibility assessments at the local scale (Melzner et al., 2010c; Melzner et al., 2011a, 2011b). The third phase of the project evaluated rockfall susceptibility at the local scale in order to plan further detailed site-specific studies at the slope scale (Melzner et al., 2011c).

Project Phase 1

The identification of potentially threatened areas at the regional scale

The initial stage of the project collated all existing datasets for the study area including digital terrain models, topographic maps, geological maps, and orthophotos (Chapter 2.3). The acquired data were incorporated into preliminary field investigations in order to define potential rockfall source areas (Chapter 4.2 and Chapter 4.3). During this phase, the lithological units were also characterised according to their geotechnical/geomechanical behaviour (Chapter 4.1).

Information about past rockfall events and other processes were taken from existing digital databases maintained by the Geological Survey of Austria and the Federal

State Government of Carinthia (Chapter 2.3). The main morphostructural features such as lineaments, deep-seated slope deformations, talus slopes, and other morphological features were manually mapped throughout the study area using the high resolution DTM. These features were then verified during field investigations (Chapter 4.2). Furthermore, slope aspect and slope angle maps were generated from the DTM. These formed important datasets during the project (Chapter 5.2). Potential rockfall runout distances were determined by applying a simple empirical model (the reach angle approach or "Geometrisches Gefälle") and by undertaking a three dimensional simulation using Rockyfor3D (Chapter 4.4 and Chapter 5.3.2). The results of these modelling approaches were overlaid with information about buildings and infrastructure. From this, it was possible to define potentially endangered areas at the regional scale. These areas were then used for further detailed mapping at the local scale (Chapter 4.4 and Chapter 5.3). Thus, a variety of data were collated or generated for the entire study area at the regional scale. These form an important basis for the planning of detailed investigations at the local scale.

Project Phase 2

The specification of rockfall susceptibility (local scale)

The second phase of the project used the areas identified as potentially endangered in order to undertake detailed investigations of existing rockfall susceptibility. In effect, this phase of the project examines the extent to which rockfall processes occurred in the past and, thus, may reoccur in the future, thereby endangering settlements. This required, on the one hand, an evaluation and analysis of the dominant lithological-structural geological characteristics (Chapter 5.1 and chapter 5.2.) and, on the other hand, the mapping of past rockfall events (Chapter 5.3). Research activities also focused on an investigation of archival material relating to past mass movement events. Records examined included those kept by borough councils, police departments, and the private archives of residents. This research was carried out alongside the field investigations in order to obtain further information regarding previous rockfall events, damage, and fatalities (Chapter 5.3).

Although the work undertaken during this phase is necessarily much more detailed than it is during the initial phase of the project, spatially-continuous mapping is still unfeasible as the required effort would be too great in relation to an efficient assessment strategy. Partially mapped information within the source, transport, and accumulation zones had to be interpolated in order to generate spatially continuous parameter maps. These parameter maps were then used for the analysis of the onset and runout susceptibility of larger areas (Chapter 5.2 and 5.3). It should be noted that the application of runout models was not part of the remit of the Department of Engineering Geology at the Geological Survey of Austria within the MassMove Project. For this reason, required model parameters such as e.g. surface roughness and surface elasticity were not mapped in detail during the field investigations. MELZNER

(2011b) has subsequently undertaken a three dimensional simulation for a small part of the study area (local scale) within the framework of a follow-up study. Thus, a variety of data were collated or generated at the local scale. These form an important basis for the planning of detailed investigations at the slope scale.

Project Phase 3

The evaluation of rockfall susceptibility at the local scale as a basis for planning detailed site-specific studies

Results at the local scale were then used to define areas that should be subject to further investigations at the slope scale (Chapter 6). These site-specific studies should incorporate detailed and spatially-continuous mapping (>1:5,000) and the application of more quantitative assessment methods (Text-Fig. 3.1 and Table 3.1). Within the MassMove Project, the Austrian rockfall study area is much larger (120 km²) than the Italian study sites (a few km²). Consequently, site-specific studies at the slope scale were not undertaken by the Geological Survey of Austria. Instead, these were undertaken by partners in Italy. Nonetheless, the MassMove project covers a wide range of spatial scales (slope, local, and regional) and examines a variety of methods that are potentially applicable as well as assessing the quality of the available data sources (for detailed descriptions, see the MassMove Handbook for Rockfalls).

4. Results of data collection and analysis at the regional scale

4.1 Geotechnical properties of the lithological units

Due to the fact that the study area is located within the southern part of the central Tauern Window, the tectonic and lithological setting is highly complex (for details, see Chapter 2.2). As a consequence, many areas within the study region are characterized by different lithological and structural anisotropies and are associated with a range of geotechnical properties.

The engineering geological interpretation of the lithological units according to their geotechnical behaviour was based on the compiled "Geological Map of Carinthia at 1:50,000" (Chapter 2.3 and LOTTER et al., 2010). The classification scheme of TILCH & KOÇIU, 2007, was then used to categorise the lithological units in relation to their geotechnical-lithological properties (GTL). (see Table 4.1 and Text-Fig. 4.1). This was done for both homogeneous classes (2,000, 3,000 and 4,000) and heterogeneous classes (23,000, 24,000 and 34,000). (For a detailed description on classification scheme, see TILCH & KOÇIU, 2007; TILCH & SCHWARZ, 2010).

	homogeneous classes			mixed classes		
	2000	**3000**	**4000**	**23000**	**24000**	**34000**
Rock hardness	Very hard	Hard	Soft	Mostly hard	Mostly soft	Mostly soft
Weathering resistance	Very resistant	Resistant	Less resistant	Resistant	Less resistant	Not resistant
Size of rock blocks	Medium to large	Medium	Small	Small to large	Small to medium	Small to medium
Size of rock blocks	≤10 m³	≥1 m³	≥0.2 m³	1-10 m³	0.2-1 m³	0.2-10 m³
Compact/ less compact	Compact	Compact	Less compact	Compact	Less compact	Less compact
Forms rock faces	Yes	Mostly yes	No	In some parts	Mostly no	Mostly no

Table 4.1: The geotechnical properties (GTL) of the lithological units within the study area.

4.1.1 Homogeneous metamorphic rocks of GTL class 2000

Class 2000 is characterised by very hard, very compact rocks that are, consequently, highly resistant to weathering (Text-Fig. 4.1 and Text-Fig. 4.15). These lithologies may form significant cliffs especially where combined with glacial and post-glacial erosion processes. The rock mass structure of these lithologies is relatively free of pregnant foliations and has a tendency to form widely spaced discontinuity sets such as joints and faults. Despite their presence in the vicinity of the main fault zones, they mainly form medium to large rock blocks.

The following lithologies belong to this GTL class:

- The Upper Paleozoic *Zentralgneis Complex* (Sub-Penninic Unit, Venediger Nappe System): coarse grained biotite granitic gneiss.
- The Permian and Lower Triassic *Wustkogel Formation* (Sub-Penninic Unit, Venediger Nappe System): predominately quartzite and paragneiss.
- The Middle and Upper Triassic *Seidlwinkl Formation* (Sub-Penninic Unit, Venediger Nappe System): competent, massive to bedded limestone/ dolomitic marbles.
- The Lower Cretaceous *metabasic* rocks and Cretaceous *ultrabasic* rocks (Penninic Unit, Glockner Nappe System): prasinite, amphibolite, and serpentinite.
- The Jurassic and Lower Cretaceous *metabasic* rocks (Penninic Unit, Matrei Zone): prasinite.
- The *Melenkopf Complex* (Austroalpine Unit, Lower Austroalpine slivers along the southern margin of the central Tauern Window): granitic gneiss (granitic augen-gneiss).
- *Prijakt-Polinik Complex* (Austroalpine Unit, Upper Austroalpine Koralpe-Wölz Nappe System): orthogneiss/granitic, augengneiss and amphibolite.

4.1.2 Homogeneous metamorphic rocks of GTL class 3000

Class 3000 is characterised by hard, compact, weathering resistant rocks. These lithologies may form cliffs similar to those described previously, depending on the properties of the material and the specific glacial and post-glacial erosion processes (Text-Fig. 4.1 and Text-Fig. 4.15). To a certain extent, the foliation of these lithologies can cause failure. Therefore, when combined with other discontinuities sets, they mainly form medium rock blocks.

The following lithologies belong to this GTL class:

- The Lower Paleozoic and Carboniferous *Habach Group* and the Upper Paleozoic *Draxel Complex* (Sub-Penninic Unit, Venediger Nappe System): predominately relatively competent, coarse-grained, dark and light schist along with less common quartzite and paragneiss.
- The Cretaceous limestone micaschist of the *Bündnerschiefer Group* (Penninic Unit, Glockner Nappe System): relatively competent, platy, limestone forming mica bearing marbles.
- *Prijakt-Polinik Complex* (Austroalpine Unit, Upper Austroalpine Koralpe-Wölz Nappe System): coarse grained mica-bearing marbles and paragneiss, with thin layers of amphibolite and granitic augengneiss. It frequently forms cliffs, especially in the vicinity of thick layers of orthogneiss and amphibolite (see GTL 2000).

4.1.3 Homogeneous metamorphic rocks of GTL class 4000

The rocks of GTL class 4000 are characterised by soft incompetent to friable rocks that are, consequently, less resistant to weathering than those described previously. From a morphological perspective, these lithologies are usually associated with gentle, rolling, landscapes and do not form steep cliffs (Text-Fig. 4.1 and Text-Fig. 4.15). The dominant foliation is usually densely spaced and forms most mechanically exploited discontinuity. In combination with other dense joint sets, the rock mass structure characteristically forms small rock blocks.

The following lithologies belong to this GTL class:

- The Cretaceous *Brennkogel Formation* (Sub-Penninic Unit, Venediger Nappe System): dark, partly calcareous phyllite (black phyllite) and, to a lesser extent, layers of calcareous quartzite.
- The Jurassic – Lower Cretaceous *Phyllitic Bündnerschiefer* (Penninic Unit, Matrei Zone): dark and light phyllite and, to a lesser extent, calcareous micaschist and quartzite.
- The *Sadnig Complex* (Austroalpine Unit, Lower Austroalpine slivers along the southern margin of the central Tauern Window): fine-grained, partly phyllitic micaschist (metapelite) with layers of quartzite. The complex is very monotonic and incompetent following brittle tectonic deformation.

4.1.4 Heterogeneous metamorphic rocks of GTL class 23000

The rocks of GTL class 23000 are heterogeneous, silicate-dominated facies. These rocks comprise GTL classes 2000 and 3000, and are characterised by spatially variable changes in stratigraphy or lithology. The more competent rocks are more apparent at the surface as these form cliffs whilst the foliation, in combination with other joint sets, is mechanically operative to varying degrees (Text-Fig. 4.1 and Text-Fig. 4.15). As a consequence, rock blocks may span a range of very different sizes, although blocks of medium size are dominant in those areas where the rocks of class 3000 crop out. As these rocks are not displayed on the geological based map, it is not possible to identify these areas specifically.

The following lithologies belong to this GTL class:

- The *Melenkopf Complex* (Austroalpine Unit, Lower Austroalpine slivers along the southern margin of the central Tauern Window): relatively incompetent micaschist alternating with relatively competent paragneiss. Also common are highly competent granitic gneiss (granitic augengneiss) and amphibolite, forming of cliffs especially in areas with thick layers of granitic gneiss (separately delineated on map with 2000 code).

4.1.5 Heterogeneous metamorphic rocks of GTL class 24000

The rocks of GTL class 24000 are also heterogeneous, **silicate-**dominated, facies (Text-Fig. 4.1 and Text-Fig. 4.15). In contrast to GTL class 23000, this class also includes GTL class 4000. Where the latter comprises the dominant lithologies, the morphology is usually characterised by rounded ridges and lower slope angles; steep cliffs are rare. It is not possible to delineate those areas specifically, due to the previously described shortcomings of the geological map. These shortcomings are particularly acute in relation to the cliff forming units.

The following lithologies belong to this GTL class:

- The Permian – Lower Triassic *Alpiner Verrucano* and *Lantschfeldquarzit* (Austroalpine Unit, Lower Austroalpine slivers along the southern margin of the central Tauern Window and Penninic Unit, Matrei Zone): relatively incompetent phyllite/quartzitic phyllite of Permo-Triassic age (fine grained volcaniclastic; Alpiner Verrucano) and, to a lesser extent competent, thin platy, pale green quartzite of Lower Triassic age (Lantschfeldquarzit).
- A compilation of the different rocks of the *Venediger Nappe System* (Sub-Penninic Unit) and the Matrei Zone (Penninic Unit): mainly incompetent phyllites as well as relatively competent micaschists and quartzites).

4.1.6 Heterogeneous metamorphic rocks of GTL class 34000

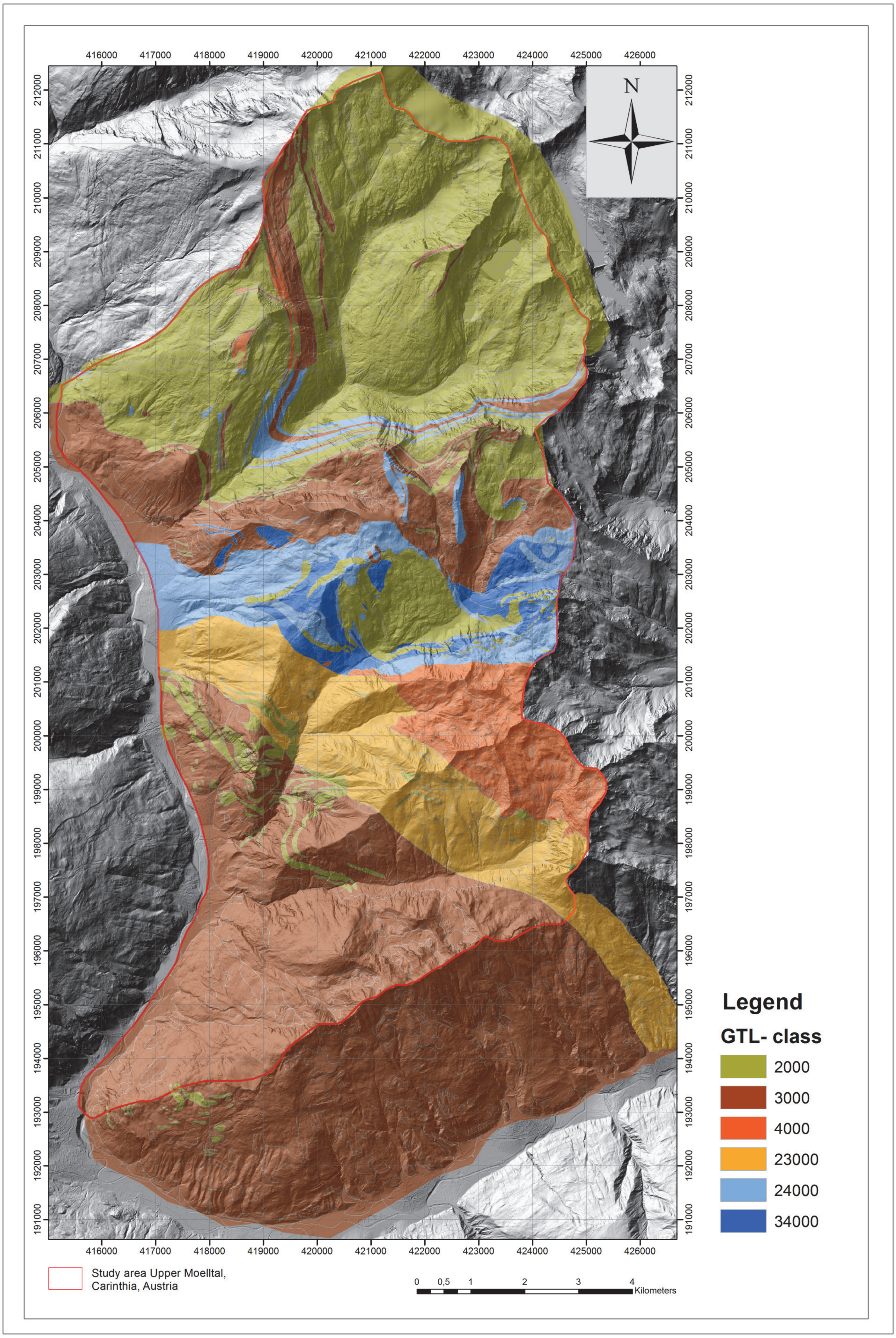
The rocks of GTL class 34000 are heterogeneous, **carbonate**-dominated facies (Text-Fig. 4.1 and Text-Fig. 4.15). These rocks comprise GTL classes 4000 and 6000, and are characterised by spatially variable changes in stratigraphy or lithology; the rocks of class 4000 are generally incompetent whereas the carbonate rocks of class 6000 are generally competent. Where cliffs have formed, they often reflect relatively small changes in lithology within the rocks that comprise class 6000. Class 4000 is normally associated with gentle, rolling, relief. Due to the fact that these units have not been mapped separately on the geological map, it is not possible to constrain these spatial relationships more closely.

The following lithologies belong to this GTL class:

- The Jurassic–Cretaceous limestone micaschist of the *Bündnerschiefer* Group (Penninic Unit, Matrei Zone): a mainly incompetent, dark calcitic schist/phyllite, more competent, platy, dark calcitic marbles, and a relatively competent, light mica marble (Bretterich-marble on the Exner Map)

4.1.7 Quality of the resulting GTL map

The geotechnical interpretation was undertaken as a result of the shortcomings associated with the geological base map (Chapter 2.3.2). This proved to be a very time-consuming task, which required some scientific compromise. The complex interpretation could only be achieved thanks to the detailed knowledge of experts within the hard rock mapping section (M. Linner, G. Pestal, and R. Schuster), specifically in relation to the structural-geological setting of the study area and the most recently published geological literature. As a result, it has been possible to generate a high-quality map that rectifies many, if not all, of the inconsistencies on the geological base map. Users need to be aware that the spatial distribution of the lithological units presented on the map may differ slightly from that found in the field. If that is the case, clearly the associated geotechnical areas will also differ. This is especially important to remember with regard to the heterogeneous GTL classes. Nonetheless, the geotechnical characterisation of these areas is thought to be of generally good quality. This quality derives from the amount of information obtained during field surveys in addition to the highly detailed and accurate explanatory notes from the Geological Map of Salzburg.



Text-Fig. 4.1: A map of the geotechnical-lithological homogeneous areas. (Source: LOTTER et al., 2010). Source DTM: BEV and Federal State Government of Carinthia.

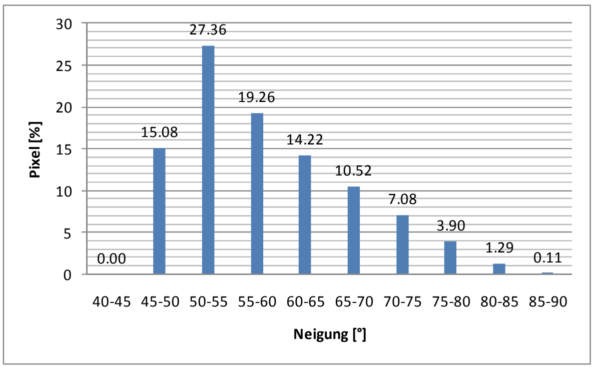
4.2 The spatial distribution of rockfall source areas

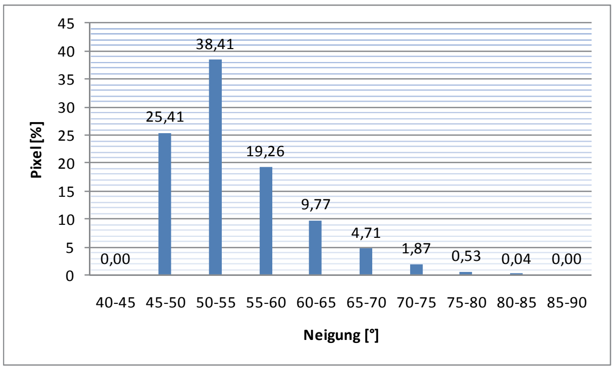
Within the study area, the spatial heterogeneity of the lithological and structural anisotropies greatly affects the spatial distribution of potential rockfall source areas.

4.2.1 Cliffs

Due to the recent erosion processes that have come to construct the present landscape, oversteepened glacial and post-glacial forms are readily identified in the relief. As a result, nearly all the cliffs in the study area are initiated on slopes at angles of between 48° and 50°. This occurs irrespective of the specific lithological unit (Text-Fig. 4.13).

However, the more competent rock types have a greater proportion of steeper terrain than those that are less competent (Text-Fig. 4.2). For example, steep cliffs are typically found within the Upper Austroalpine *Prijakt-Polinik Complex* (Chapter 2.2). This complex crops out within the study area on the orographic left slopes of the Moell Valley, close to the settlements of *Moertschach* and *Winklern*. It is likely that significant rockfalls will have their source areas in this unit due to the competent properties of the rock and the orientation of the rock mass structure, which dips gently in a NW to NE direction (Chapter 5).





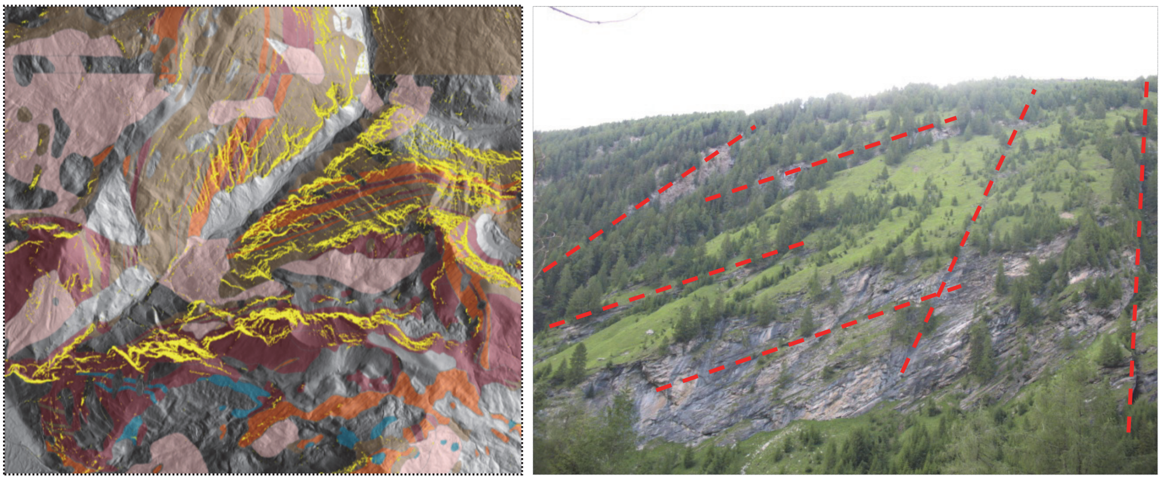
Text-Fig. 4.2: The proportion of steep terrain according to the lithology. Left: the competent rocks of GTL 2000 have a greater proportion of steeper terrain than the less competent rocks of GTL 23000. (Source: MELZNER & KOÇIU, 2010).

However, potential rockfall release areas occur across all the lithological units when the glacial or post-glacial relief is conducive and faults or main joint sets are present (Text-Fig. 4.3). In some places, the change from competent to incompetent GTL classes is reflected in the spatial distribution of potential rockfall source areas.

4.2.2 Deep-seated slope deformations

Several rockfall areas are associated with deep-seated slope deformations (Text-Fig. 4.14, Text-Fig. 4.15). This type of mass movement shapes the landscape in this region. In terms of location and mechanism, they originate as a result of the varying rock anisotropy described above. Depending on the type of mass movement (e.g.

rock slides, rock creep/sagging slopes, rock spreads, etc.) and its stage of development (initial, developed, or final stage), rockfalls either occur within the scarp area, along/within the body, or along the oversteepened front parts of the slope deformation.



Text-Fig. 4.3: Potential rockfall source areas mainly follow dominant discontinuity sets, which strike broadly SW–NE, NW–SE, NNW–SSE, and WSW–ENE. Left: yellow polygons indicate the spatial distribution of the source areas. Right: tension cracks and potential source areas in the area of *Stanziwurten.* (Source: S. MELZNER, photographic archive of the Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia.

A deep-seated slope deformation (*Eckkopf-Talzuschub*) is situated close to the confluence of the *Small Zirknitz* and *Large Zirknitz Rivers*. This rock spread (in combination with rock mass creep) is in its initial developmental stage. The scarp area of this mass movement has already developed more or less completely, but an oversteepened front part has not yet formed so distinctly. Despite this, it is the front part that is subject to rockslide and rockfall processes due to the very loosened rock hereabouts (Text-Fig. 4.4).

Text-Fig. 4.4: Rockfall boulders close to a building that belongs to KELAG AG, at the front of the sagging slope *Eckkopf-Talzuschub.* (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

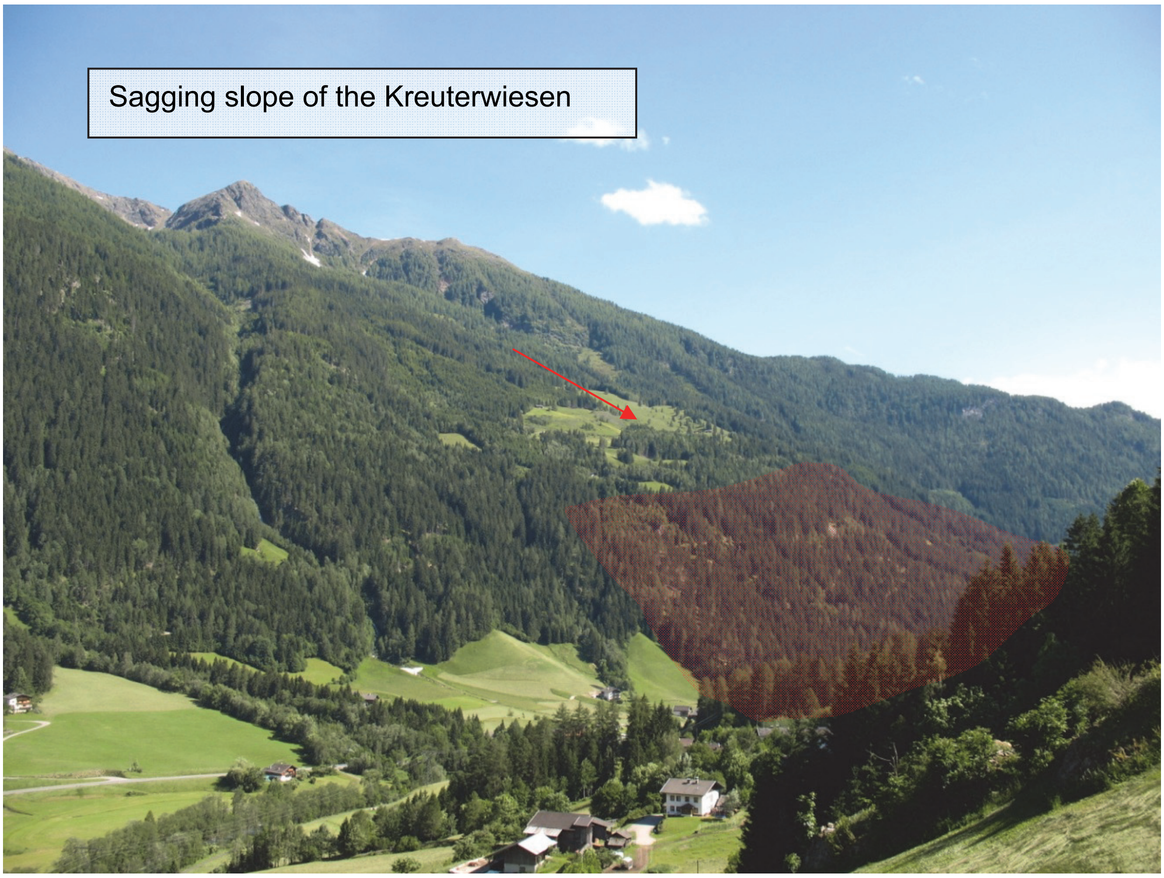
A sagging slope (*Wetschkenkopf Talzuschub*) is located near the settlement of *Moertschach*. This mass movement is further developed than the previous example and has a far more pronounced morphological form. Rockfalls mainly occur within the scarp area (Text-Fig. 4.5), while the front part is predominately subject to secondary sliding processes.

Text-Fig. 4.5: The talus slope beneath the scarp area of the sagging slope *Talzuschub Wetschkenkopf* (photograph, left) and a rockfall boulder located in the rock creep accumulation on the forest road; the boulder has been moved anthropogenically. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

This sagging slope is bound on both sides by dominant faults. These zones of weakness are subject to headward erosion, which has led to the formation of deep gullies. Material derived from erosion processes and rockfalls is repeatedly transported into these deep gullies, in form of debris flows in direction of the Moell Valley. These can be seen in the field through the numerous levees and debris flow scarps. As a consequence, the *Brennerbachl* is regulated by a retaining basin. This gully forms the southern border of the creep and is located within the settlement of *Moertschach*. The retaining basin was constructed because the main state road, the B12, was often affected by the debris.

The sagging slope of the Kreuterwiesen *(Kreuterwiesen-Talzuschub)* already shows considerable mass depletion in the scarp area (Text-Fig. 4.6). Within the resulting over-steepened frontal part (toe) of this mass movement, the rock is highly disintegrated and large rock masses represent potential rockfall source areas. The extent of these displaced rock masses ensure that they may result in large volume rockfalls in the future.

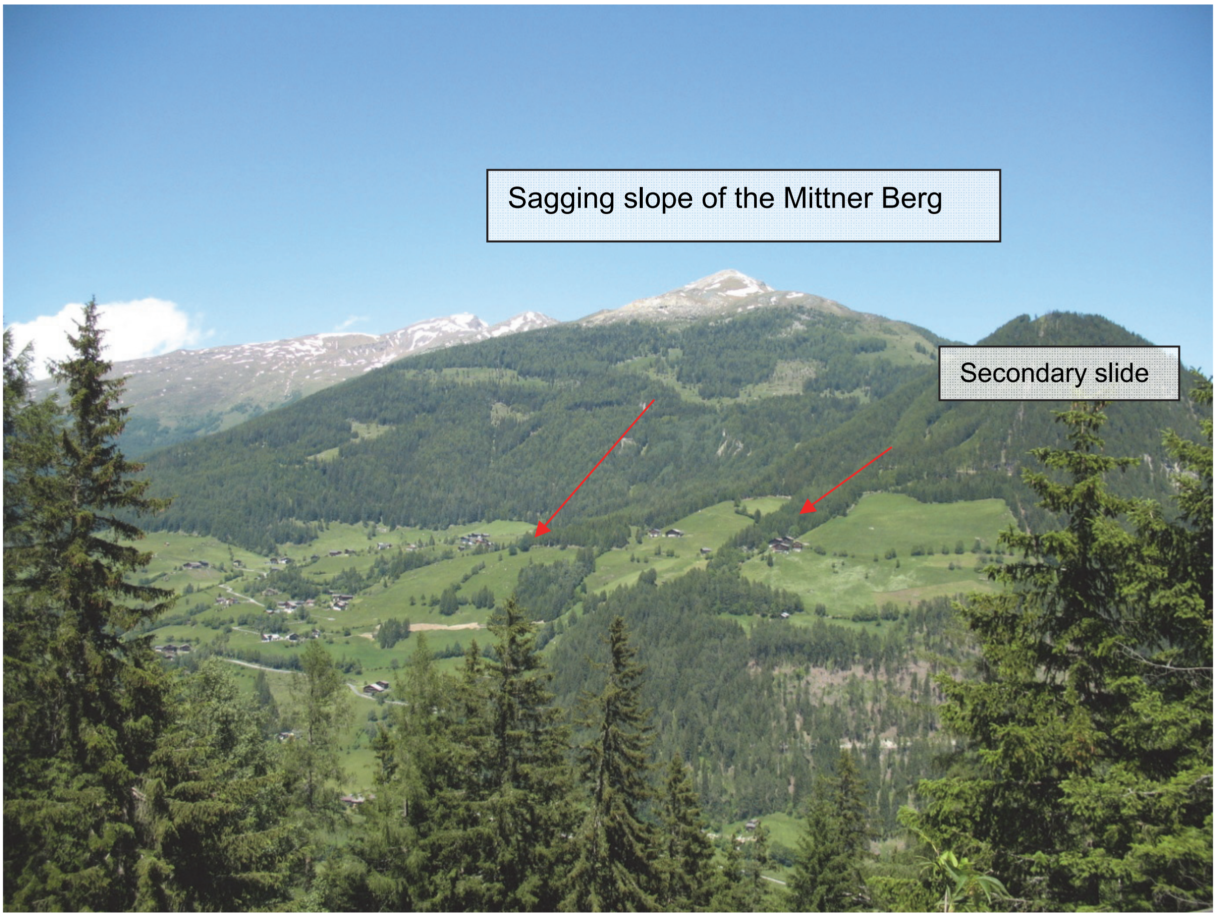
It is conspicuous that the sagging slopes of the *Wetschkenkopf (Talzuschub Wetschkenkopf)* and the *Kreuterwiesen (Talzuschub Kreuterwiesen)* are located in the undercut slope of the former Moell Glacier. It is probable that the slope failure was initiated by this glacial slope undercutting a number of loading and unloading phases during the course of glaciation.



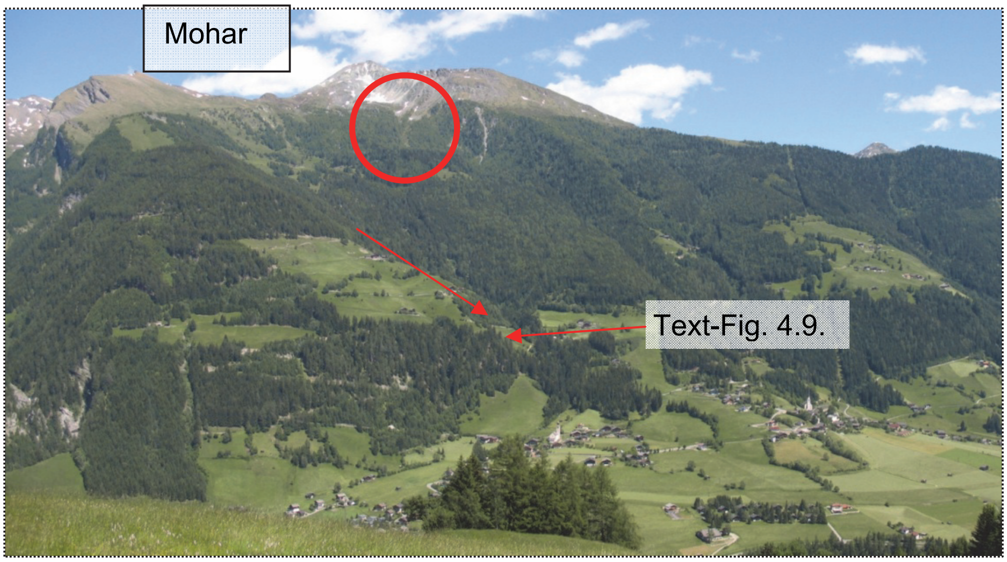
Text-Fig. 4.6: The sagging slope of the Kreuterwiesen (*Kreuterwiesen-Talzuschub*). Within the over-steepened toe (red area), displaced rock masses represent potential rockfall source areas that may result in large volume rockfalls. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

In addition to the previously mentioned mass movements, within the study area some deep-seated slope deformations have highly eroded accumulation zones. An example of this occurs in the degraded sagging slope located near Mitten *(Mittner Berg-Talzuschub).* The volume of the accumulation does not reflect the large scarp area. The borders of this slope deformation are subject to secondary sliding and rockfall processes (Text-Fig. 4.7 and 4.14).

The largest deep-seated slope deformation within the study area is located near the *Moharspitz*. This deformation has developed in two directions at an angle of 90°. In the direction of the *Asten Valley*, this mass movement has developed as a sagging slope. Along the loosened surface, rockfalls may endanger houses and/or the Asten Road (see Text-Fig. 4.10, left). In contrast, in direction of the Moell Valley, the movement developed as a result of a completely different process. The morphology of the transportation and accumulation zones and the lithological composition of the deposited material (Text-Fig. 4.9) in the accumulation zone represent a sturzstrom or rock avalanche (Text-Fig. 4.8). As is the case with the sagging slope near *Mitten* (*Mittner Berg-Talzuschub*), it is probable that some parts of the accumulation have already been eroded. Text-Fig. 4.8 (red circle) shows that rockfalls can only occur within the scarp areas and may endanger houses (Text-Fig. 4.10, right photo).



Text-Fig. 4.7: A strongly degraded sagging slope near Mitten (*Mittner Berg-Talzuschub*). The photograph shows a secondary slide along its southern boundary. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).



Text-Fig. 4.8: The sturzstrom or rock avalanche developed in the direction of the Moell Valley, part of the complex deep-seated slope deformation located near Moharspitz. Rockfalls occur within the scarp areas (red circle). (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 4.9: Block accumulations within the deposit zone of the sturzstrom located near Moharspitz. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 4.10: Left: The potential rockfall hazard along the Asten Road, caused by the sagging slope within the deformation near Moharspitz. Right: Rockfall boulders close to houses on the upper slope of the sturzstrom Moharspitz towards the Moell Valley. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

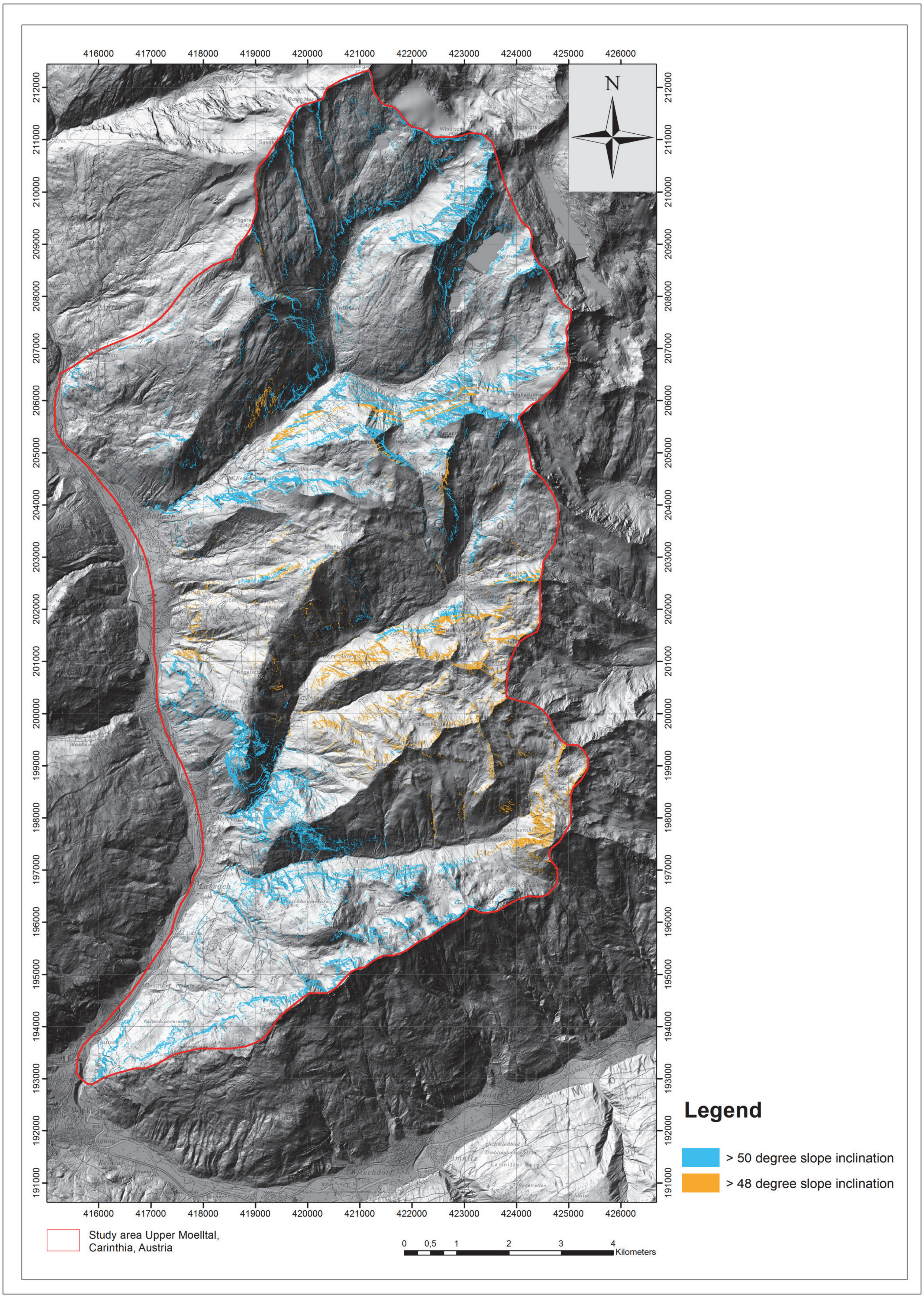
4.2.3 Scree and glacial/periglacial depositional forms

Due to the glacial and post-glacial landscape evolution, most of the slopes are covered by scree or moraine deposits. Within the study area, it is very common for boulders to be mobilised or remobilised by erosion processes, mass movements or windthrow (Text-Fig. 4.11). These types of "secondary" rockfalls may be triggered nearly everywhere across the entire study area. It is, therefore, impossible to constrain their potential source areas with any accuracy.

Within the hanging valleys of the tributaries *Zirknitz, Asten and Kolmitzen*, rock glaciers are a frequently encountered morphological form. These are usually fossil or relic features. The rock glaciers were constructed from material that was derived from rockfall and weathering processes (Text-Fig. 4.12 and Text-Fig. 4.13). No direct rockfall hazard is given for these enormous block accumulations due to their remote location within the hanging valleys. As these valleys are associated with low slope gradients and as the rock glaciers themselves lack fine material, it is highly unlikely that these morphological forms can be sufficiently mobilised to endanger the lower valley floors.

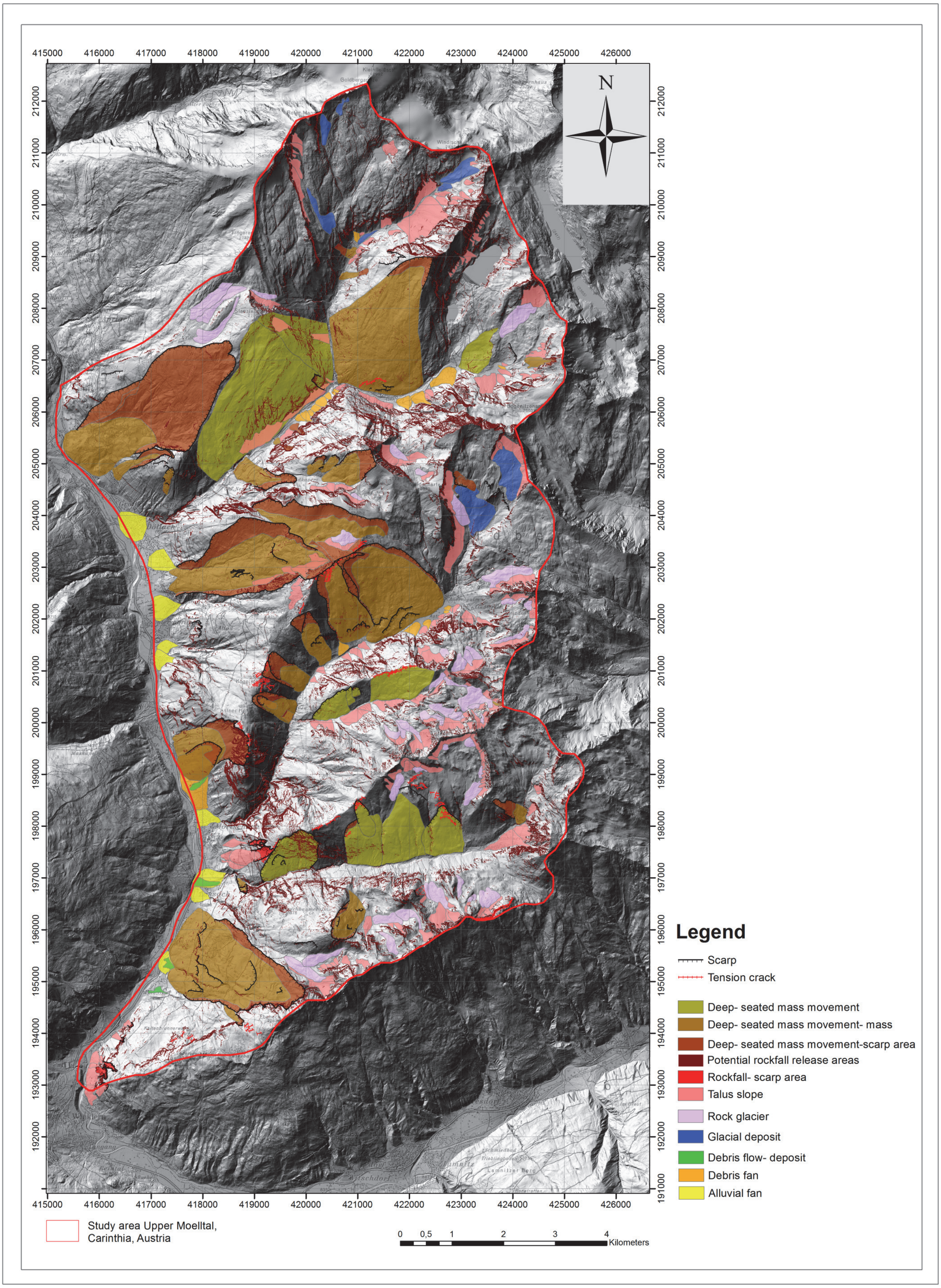
Text-Fig. 4.11: A benchmark on a house (photo, left) caused by the mobilisation of a glacial deposit (photo, right). Information about the event was provided by the owner of the house. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 4.12: The dominant morphological form within the hanging valleys of the study area are huge rock glaciers, example shown here is situated in the *Lienzer Dolomiten* (outside of study area). (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

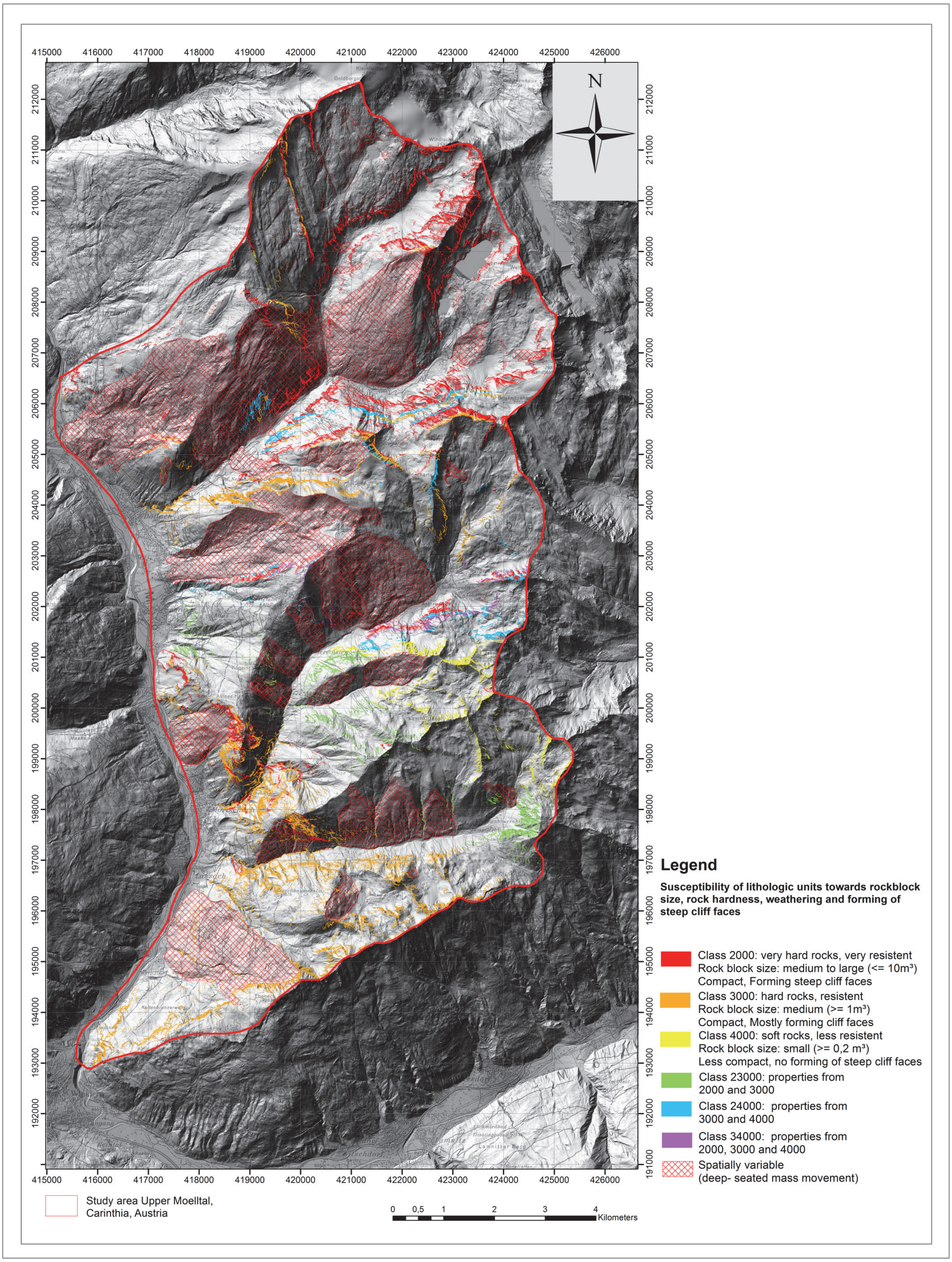


Text-Fig. 4.13: Basic onset susceptibility map (R_01) at regional scale. GTL 2000 & 3000 >50°, GTL 4000, 23000, 24000 & 34000 >48°. (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).

.



Text-Fig. 4.14: Geomorphological map of the study area. (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).



Text-Fig. 4.15: Advanced onset susceptibility map (R_02) at regional scale. (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: BEV ().

4.3 A chronicle of historical events and preventative measures

The initial stage of the archival research focused on collating all the information that is presently available in digital form, through the Geological Survey of Austria and the Federal State Government of Carinthia (Chapter 2.3). Thereafter, during the fieldwork campaign, further relevant information was obtained from a range of institutions and organisations. The majority of these data focused on past rockfall events. However, additional data relating to other types of gravitational mass movement were also obtained.

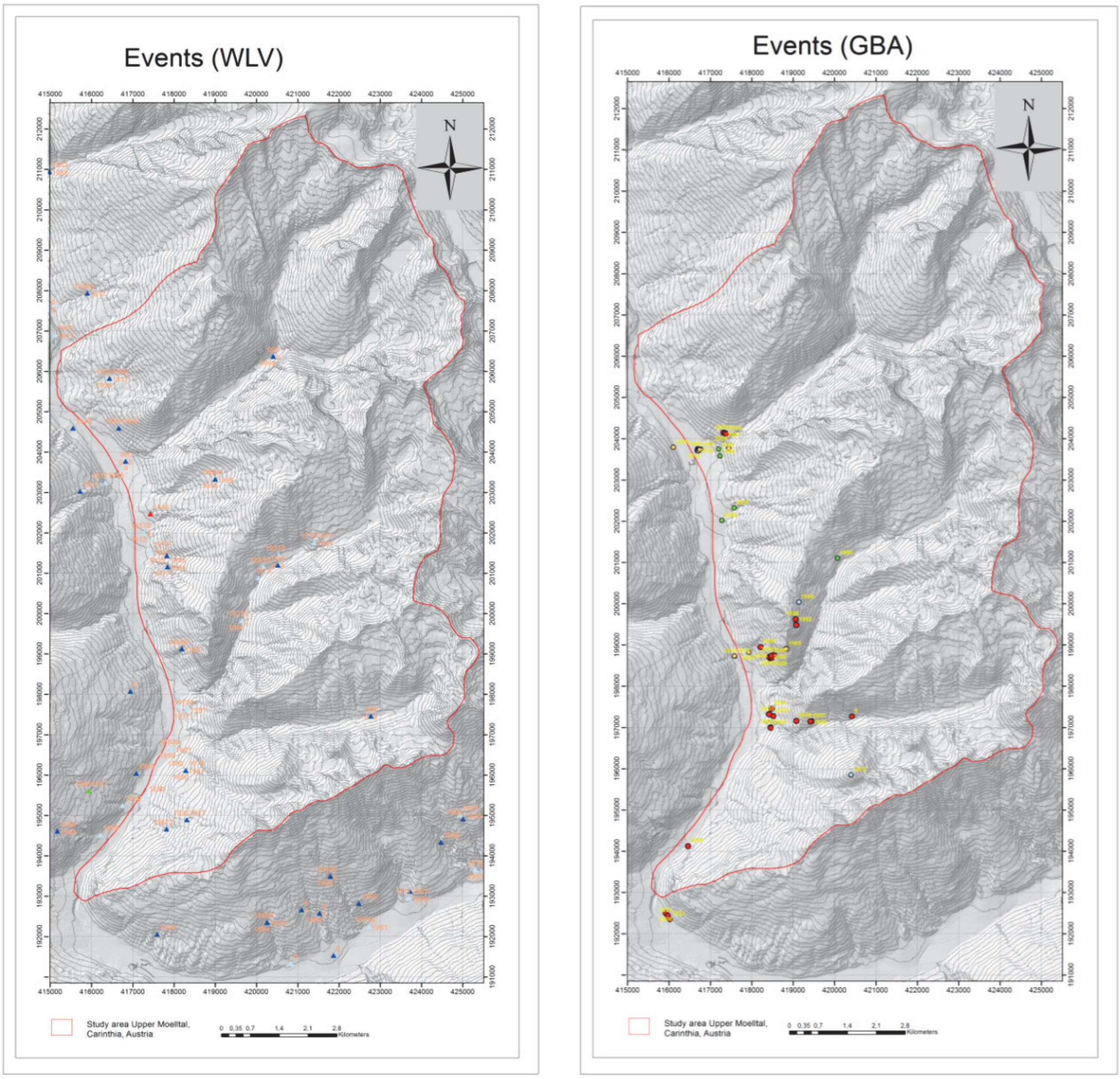
It is known, as a result of the experience gained during other projects that data focused on flood events frequently include information relating to mass movements. Information relating to snow avalanches is also of interest as, in some parts of the study area, this process has transported boulders into settlements (Text-Fig. 5.38 in Chapter 5.3). The local office of the Torrent and Avalanche Control in the *Upper Drau* and *Moell Valley* hosts a digital cadastral torrent and avalanche register (WLK). As of September 2009, this register incorporated a number of events that may be classified as follows: rockfall (3x), landslide (8x), snow avalanches (54x) and fluviatile processes (136x). (Text-Fig. 4.16).

In addition, a number of other documents such as project reports and hazard zone maps were investigated for data that may relate to the project. Again it is known, as a result of the experience gained during recent projects undertaken within the Engineering Department of the Geological Survey that this type of investigation may supplement the data recorded in the digital cadastral torrent and avalanche register (WLK). As a result of this archival research, it is probable that every potential source of information that may be relevant to the project has been exhausted.

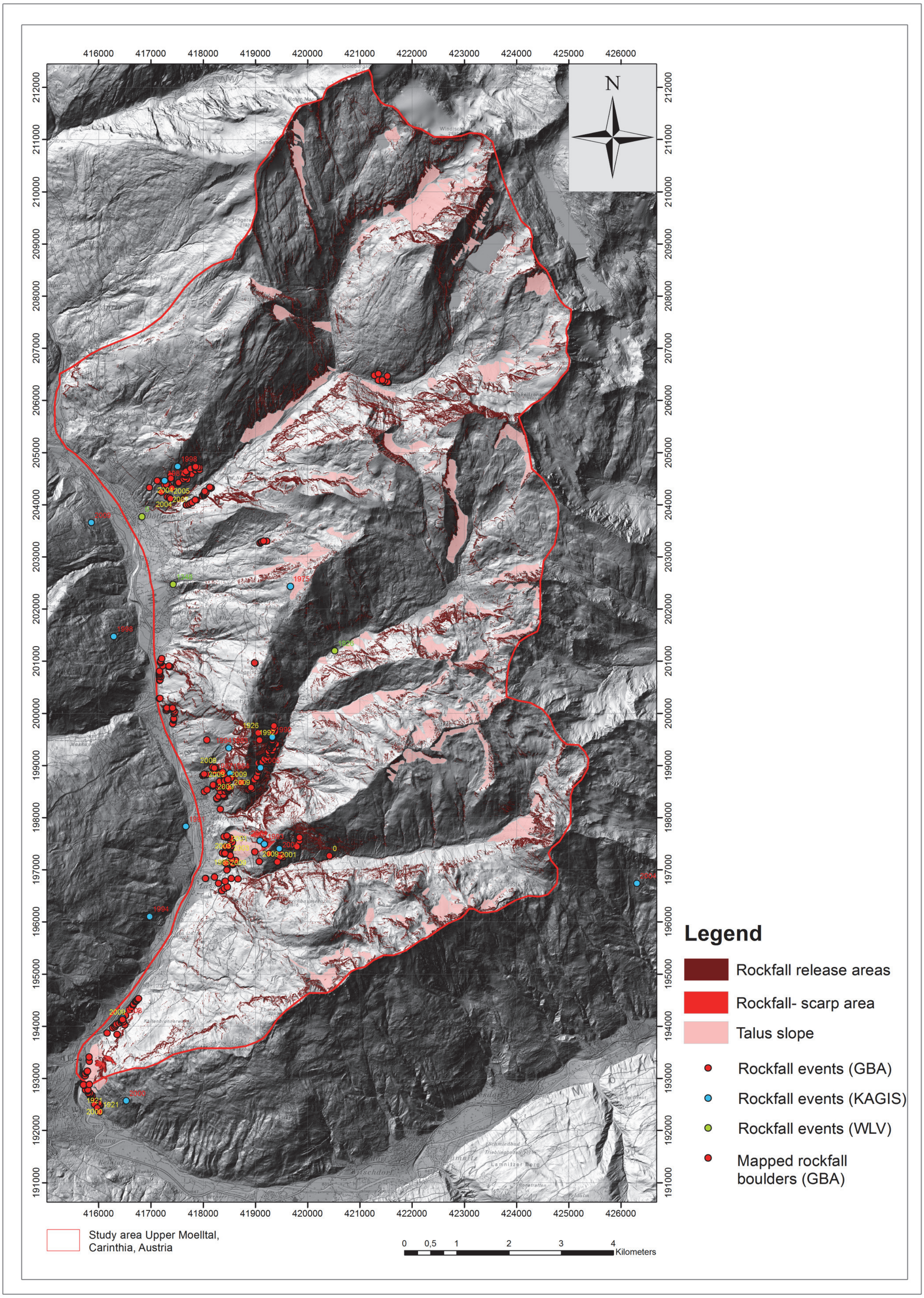
During the course of the fieldwork, data were successfully obtained from a range of local authorities including the municipality, police and church. In particular, previously unrecognised information relating to rockfall events was obtained from the community of *Doellach* and from the police chronicles at *Winklern*; the obtained information was not recorded in any of the available databases. Furthermore, a considerable amount of valuable information was collected from elderly inhabitants.

These inhabitants demonstrated a detailed knowledge of past mass movements and provided much useful data relating to historical events. These events may be classified as follows: rockfalls (20x), large volume falls (2x), rock avalanches (2x), landslides (5x), mudflows (3x), snow avalanches (2x), and flood or debris flows (11x) (see Text-Fig. 4.16). Depending on the obtained information, either the location of the rockfall release area or subsequent block accumulation could be identified. In some cases, both could be determined.

During the fieldwork campaign, four rockfall events occurred in the study area. These were directly investigated by staff member S. Melzner (pers. comm.). In two cases, blocks within slope scree were remobilised; these occurred in the vicinity of the access road to the settlement of *Asten* (*Moertschachberg*) and in the vicinity of the access road to the property of *Goaschnigkopf*. In addition, it was also possible to investigate a substantial rockfall event in considerable detail in the vicinity of *Moertschachberg* (for a more detailed description, see Chapter 6). A further event could be heard by the author close to the *Steinerwand* but it could not be identified in the field, probably because the transported blocks were deposited directly into the *Moell River*. All of these events occurred as a consequence of heavy precipitation. Text-Fig. 4.17 summarises all the rockfall event information compiled by the end of the project. The results show that many rockfall events have occurred within settlements, especially in those areas associated with the *Prijakt-Polinik Complex*. Finally, several events could also be detected in the vicinity of the initial rock slide at the Kulmerkogel.



Text-Fig. 4.16: Information and events relevant to the project, available in September 2009. These data were obtained from the digital WLK of the Torrent and Avalanche Control (left) and during the detailed field investigations of GBA staff (right). Source DTM: BEV and Federal State Government of Carinthia.



Text-Fig. 4.17: Rockfall event database for the study area. (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).

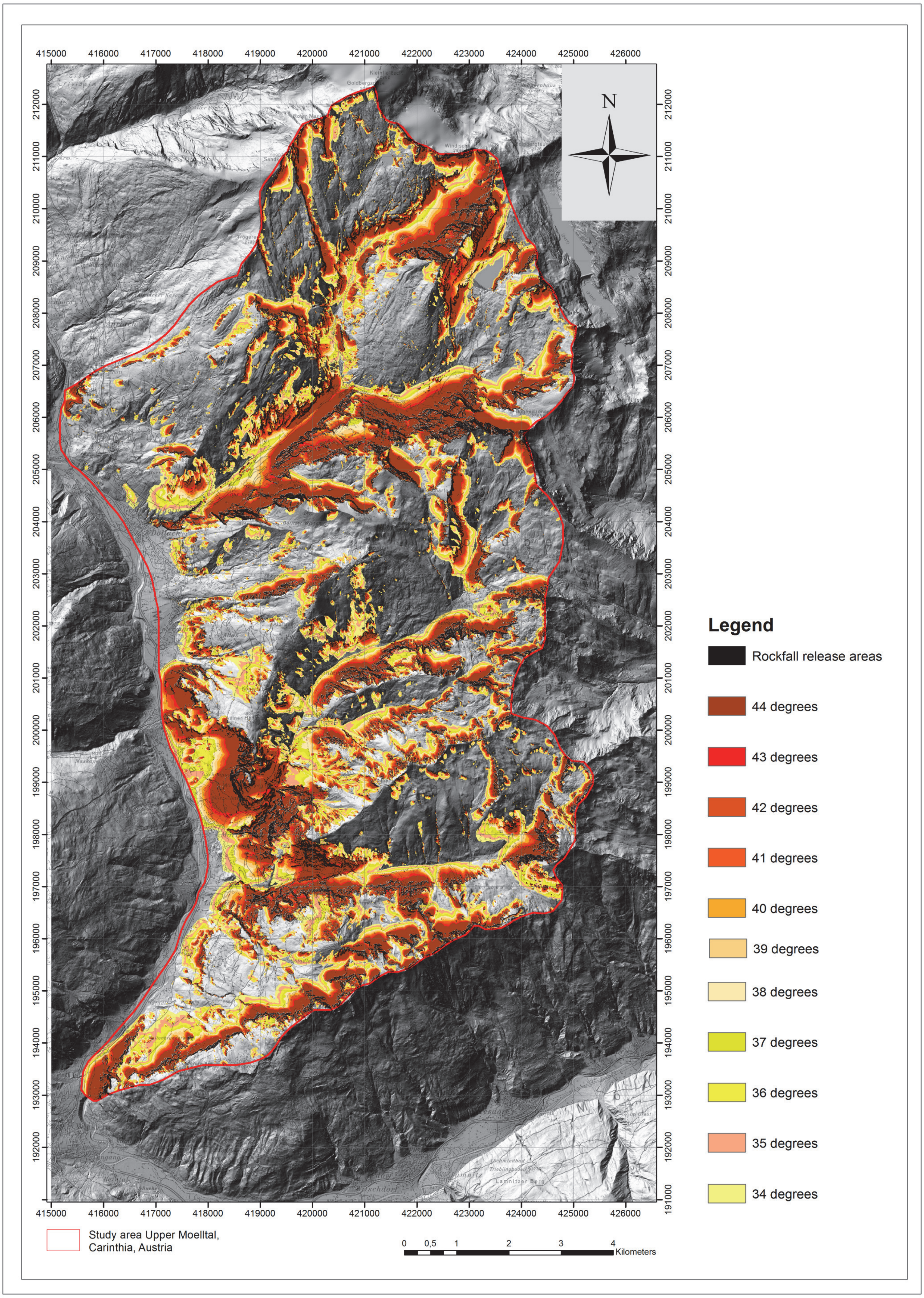
In addition to the compilation of an event chronicle, indications of rockfall activity are also provided by constructed preventive measures; locations that are frequently subject to rockfall events are likely to have been secured by primary and secondary preventive measures. For example, warning signs suggest that infrastructure may be affected by rockfall events in many parts of the study area. Two rockfall nets have been installed in the vicinity of the initial rockslide beneath *Kulmerkogel*. Three rockfall nets and one rockfall embankment have been installed in the vicinity of the southwesterly facing rock cliffs of *Goaschnigkopf*. Two rockfall nets have been installed in the vicinity of the southerly facing slopes of *Goaschnigkopf*. Along the *Asten Road*, some primary protection measures have been installed on the adjacent slopes and three galleries have been constructed within the main failure (fracture) zone. In fact, it is only along the southwesterly facing slopes of *Moertschachberg* that no secondary protection measures have thus far been constructed (for further details, see Chapter 6).

4.4 Delineation of areas used for detailed investigation

As previously mentioned in Chapter 3, the determination of potential rockfall runout zones using two-dimensional and three-dimensional models was not part of the work of the Engineering Department of the Geological Survey of Austria within the MassMove Project. A 3D simulation for the whole study area has been undertaken by Luuk Dorren using Rockyfor3D (for further details, see Chapter 5.3 and DORREN et al., 2011).

In order to estimate the potential runout zones associated with future rockfall events at the regional scale, it is possible to apply empirical models. Within the framework of the MassMove Project, the reach angle approach was used to calculate the maximum runout zones for the entire study area (HEIM, 1932; MEIßL, 1998). The most significant advantage of this approach compared to other methods (e.g. the *shadow angle approach* and the *Fahrboeschung approach*) is that it can be better verified in the field. The automated calculation of reach angles was programmed in co-operation with the Department of Geophysics in 2008, within the core research program GEORIOS. Similar software (CONEFALL) is available from the University of Lausanne (JABOYEDOFF, 2003).

For the study area, several reach angles (between 32° and 47°) were calculated in steps of one degree (Text-Fig. 4.18). The calculated runout zones and distances were then compared with reach angle values measured in the field (for further details, see Chapter 5.3) in order to determine the characteristic angle range for the study area.



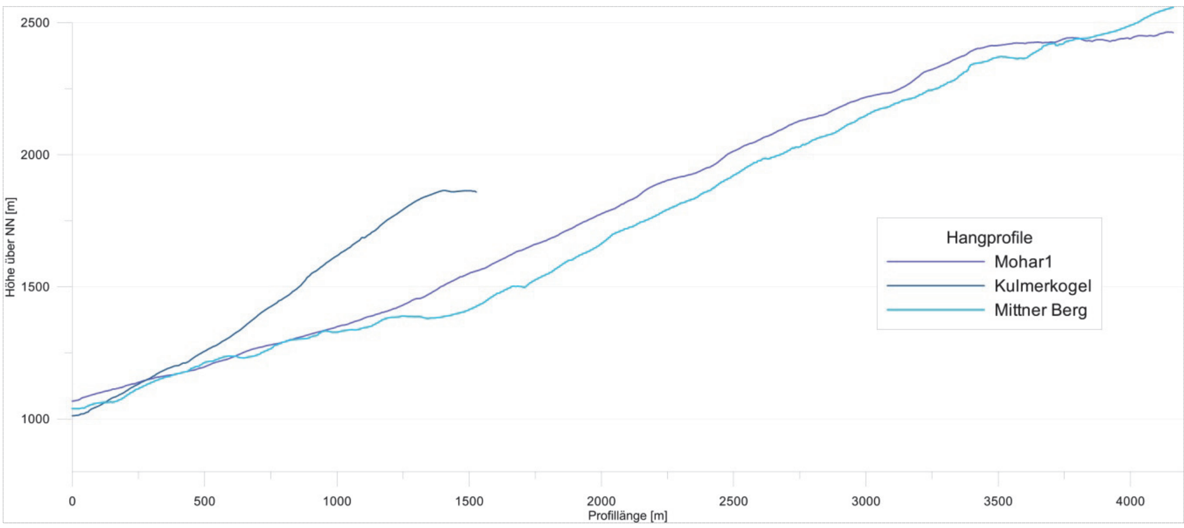
Text-Fig. 4.18: Runout susceptibility map (R_R1) at regional scale derived using an empirical model (reach angle approach). (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).

The derived runout distances were then superimposed onto base maps depicting all the potential elements at risk (e.g. houses and infrastructure). It is important that all requisite information, according to the specific research goal, relating to the elements at risk are included on the base map (i.e. land use map, see Chapter 2.3). The extent of the areas to be used for further detailed investigations depends greatly on whether the endangered areas are associated with settlements and infrastructure or whether they are thus far unsettled.

Following a preliminary field inspection and as agreed upon with the Federal State Government of Carinthia, further detailed assessments at the local scale were only undertaken in those areas in which permanent settlements or major traffic routes may be endangered (Text-Fig. 4.21). Addition areas will need to be assessed in detail if, for example, a settlement becomes notably larger. More detailed assessments may also be required depending on the specific research goals; for example, when examining the potential influence of rockfall material deposited into stream channels.

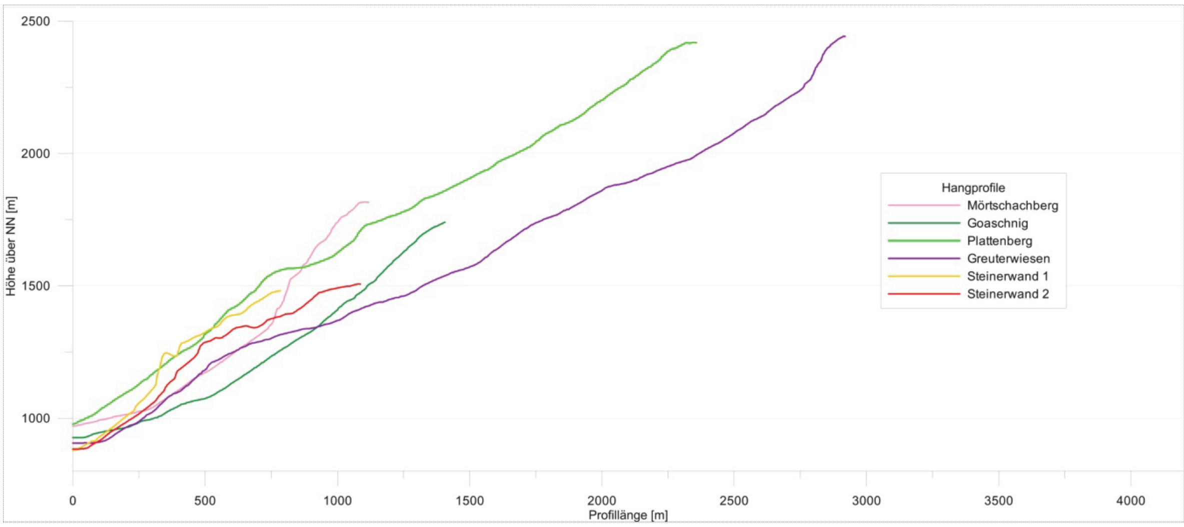
Text-Fig. 4.19 and Text-Fig. 4.20 present slope profiles for each of the detailed investigation areas. These may be used to provide an initial indication of potential rockfall activity. It can be seen that in some places only a very short distance separates potential source areas from a potential element at risk (e.g. Text-Fig. 4.20: yellow, pink, red, and dark green lines). In other areas with lower relief gradients, a far greater distance separates potential source areas from a potential element at risk (Text-Fig. 4.19 and 4.20: light green and purple/violet line).

In case of the sagging slopes of *Talzuschub Kreuterwiese* the oversteepened toe can be seen clearly. In the case of the latter, the heavily eroded accumulation area is also clearly visible (see also Chapter 4.2).

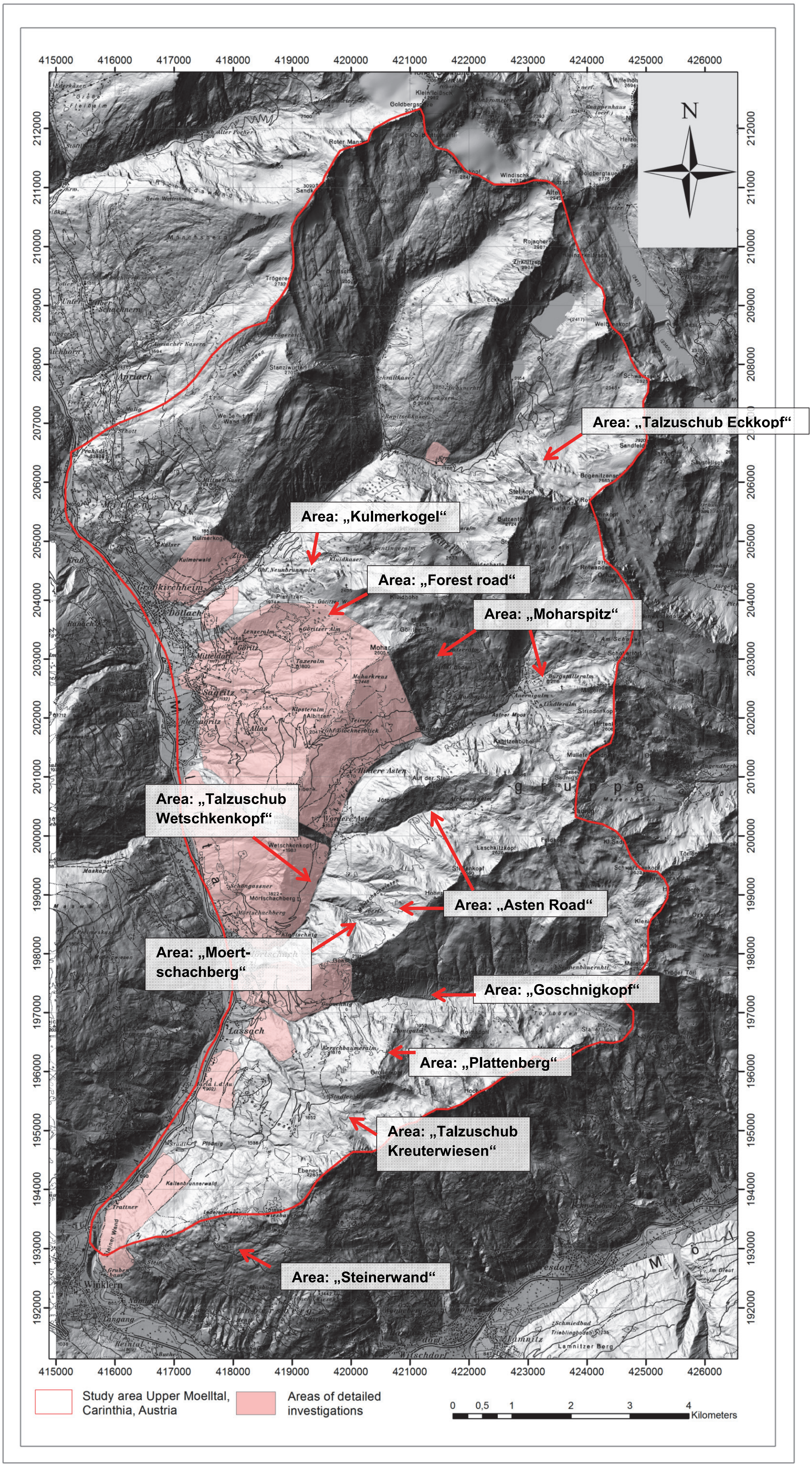


Text-Fig. 4.19: Slope profiles crossing the area of *Kulmerkogel, Talzuschub Mittner Berg*, and *Sturzstrom Mohar*. (Fig. by S. MELZNER, Geological Survey of Austria).

It has to be emphasised that the applied reach angle approach and thorough slope profile analyses are only able to provide a rough estimation of potential runout distances at the regional scale. These results can only, therefore, be used as a basis with which to plan more detailed field investigations or to undertake more detailed modeling at the local scale.



Text-Fig. 4.20: Slope profiles crossing the area of *Moertschachberg*, *Goarschnig*, *Plattenberg*, *Talzuschub Kreuterwiesen*, and *Steinwand.* (Fig. by S. MELZNER, Geological Survey of Austria).



Text-Fig. 4.21: The location of those areas selected for detailed investigation. See for slope profiles Text-Fig. 4.20, 4.21 (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).

5 The results of data collection and analysis at the local scale

At the local scale, detailed assessments have focused on those areas in which rockfall processes may endanger existing settlements or infrastructure (Chapter 4.4). The investigated areas are predominately located along the orographic left-slopes of the *Moell River*, along the *Asten Road*, and in the vicinity of the KELAG AG building in the *Zirknitz Valley* (Text-Fig. 4.21 in Chapter 4.4).

5.1 Geological results

5.1.1 Structural-geological characteristics of the Upper Austroalpine Sub-Unit

Along the orographic left-slopes of the Moell Valley, the Upper Austroalpine Sub-Unit forms very high steep cliffs. This is fundamentally due to the fact that the Prijakt-Polinik Complex (Chapters 2.2 and 4.1) comprises highly competent lithologies. In addition, the entire complex dips as a rigid block gently in a northeasterly direction. In the vicinity of major tectonic structures, deep-seated slope deformations have developed. Examples include the sagging slopes of *Talzuschub Wetschenkopf* and *Talzuschub Kreuterwiesen* (Chapter 4.2.2).

As described in Chapter 2, the Upper Austroalpine Sub-Unit was subjected to several ductile and brittle deformation phases during the Alpidic Orogenies (Text-Fig. 5.1).

Text-Fig. 5.1: The complex rock mass structures within the Prijakt-Polinik Complex have resulted from several ductile and brittle deformation phases. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

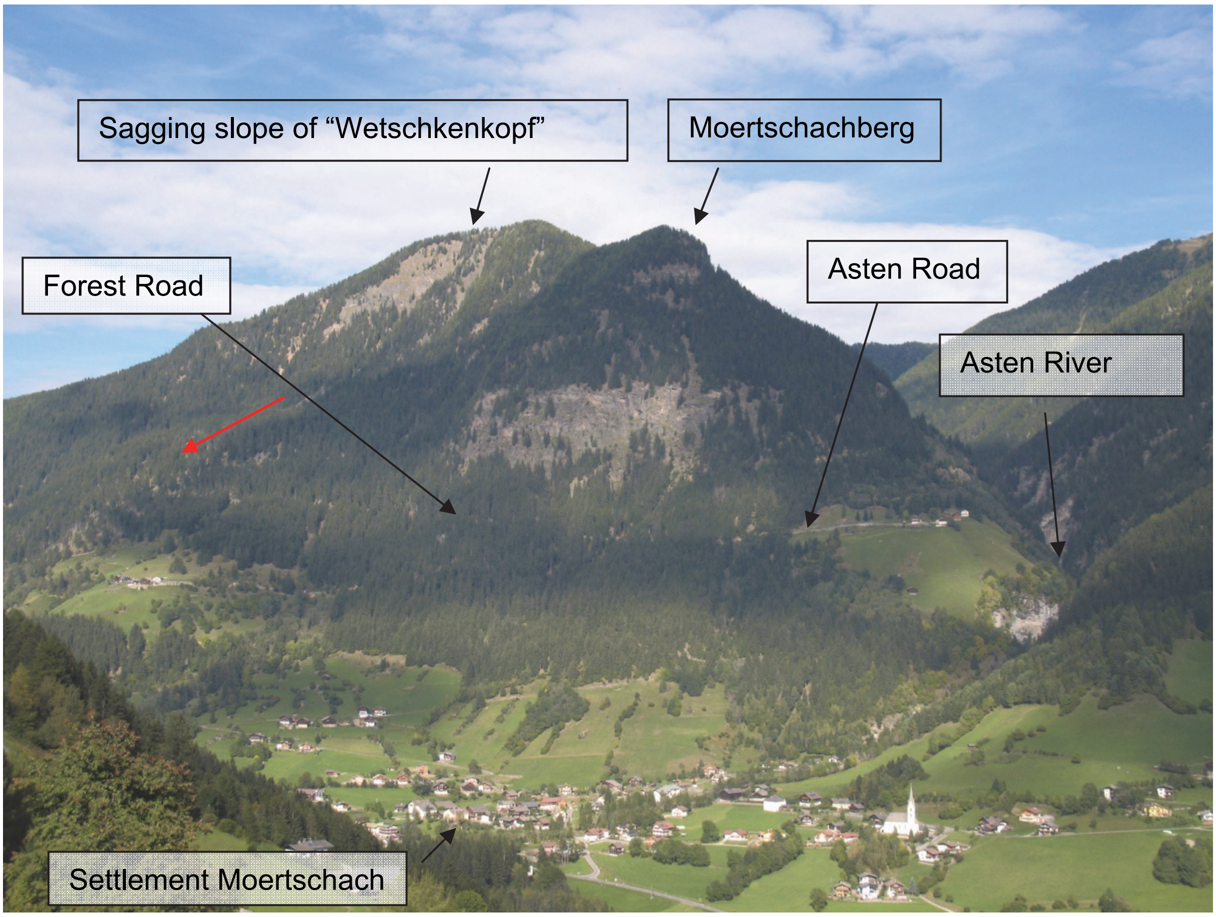
These deformation phases have resulted in various fault systems that exert a major influence. Within this unit, this highly heterogeneous anisotropy is expressed by:

- A considerable number of different discontinuity sets; each set is associated with a high degree of dispersion in its orientation (dip direction/dip angle).
- Significant faults that are frequently associated with a high degree of separation (widely spaced).
- Deep tension structures that follow the main fault systems.
- Rapid lithological transitions and changes in the amount of fracturing.

Within the framework of the MassMove Project, it was not possible to assign the mapped discontinuities to the various ductile and brittle deformation phases (Linner et al., 1909). To achieve this, far more intensive field investigations would have been required so as to better constrain the tectonic evolution of the area. This was not possible due to the restricted time available and the specific project goals.

5.1.1.1 Moertschachberg and the Asten Road

Moertschachberg is located in the community of *Moertschach*. It is delineated to the south by the Asten River and to the north by the sagging slope *Talzuschub Wetschkenkopf* (Text-Figs. 5.2, 5.32, 5.33).

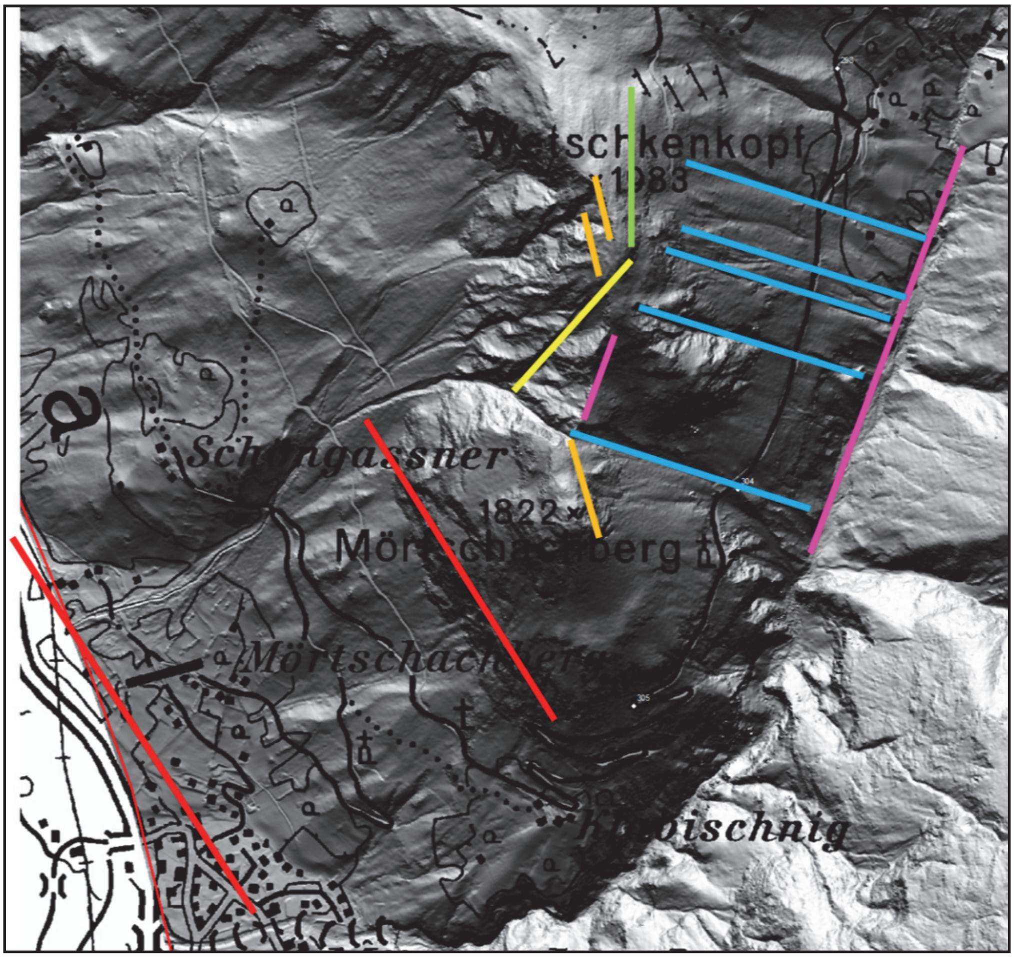


Text-Fig. 5.2: The investigated area of Moertschachberg and the Asten Road. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

In the vicinity of Moertschachberg, a number of fault systems converge. These systems cut the mountain in various directions including, to some extent, sub-orthogonally. The systems are, therefore, significant in determining the slope aspect:

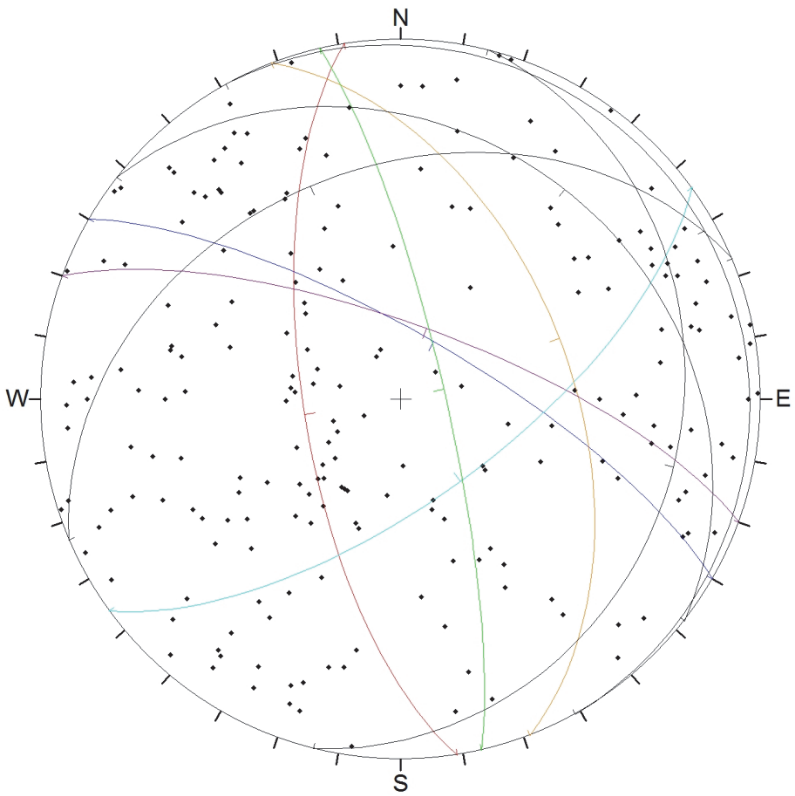
- The main direction of the Moell Valley follows the fault direction NW–SE (Text-Fig. 5.3: red line).
- The main direction of the Asten Valley follows the fault direction NNE–SSW (pink line).
- In between the Moell Valley and Asten Valley, there are two fault directions orientated NNW–SSE (orange line) and N-S (green line).
- A further two fault directions are orientated WNW–ESE (blue line) and ENE–WSW (yellow line).

The spatial distribution of potential rockfall source areas reflects these main fault directions, in combination with glacial and post-glacial erosion processes (Chapter 4.2).



Text-Fig. 5.3: The main fault directions within the investigated area. In the vicinity of Moertschachberg and the Asten Road, the spatial distribution of potential rockfall source areas reflects these directions. Red line; NW–SE → Moell Valley direction. Yellow and pink lines: NNE–SSW → Asten Valley direction. Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).

Text-Fig. 5.4 presents a plot of poles and great circles, the latter of which represent clusters of some of the dominant discontinuities measured in the investigated area of Moertschachberg and the Asten Road. It is evident that the main foliation (black great circles) is associated with a wide range of dip directions but predominately gentle to moderate dip (up to 30°). It is possible to recognise a cluster of NNW dip directions. This corresponds to shallow E to NE dipping fault axes of open faults, with amplitudes of several tens of meters that relate to the heights of the cliffs. The mainly steeply WNW–ESE to NNE–SSE to NW–SE striking fault planes, as well synthetic and antithetic directions, are present within the mapped discontinuity system (Text-Fig. 5.4).



Text-Fig. 5.4: A plot of poles and great circles for the discontinuities mapped in the investigation area of *Moertschachberg* and the *Asten Road* (n: 224). The great circles represent clusters of some of the frequently measured discontinuities (equal area projection, lower hemisphere).

Table 5.1 summarises the main orientations of these clusters. It appears that the dominant discontinuity sets reflect a wide range of orientations (dip direction/dip angle). This is predominately due to the fact that the Upper Austroalpine Sub-Unit has been subject to several brittle deformation phases. Consequently, multiple deformation phases overlap within a single discontinuity set.

Cluster	Dip direction	Dip angle	Dip direction (range)	Dip angle (range)
C1	261	68	225-300	45-89
C2	30	75	10-50	65-89
C3	144	67	125-165	40-89
C4	69	51	20-115	45-65
C5	77	80	55-95	65-89
C6	38	27	15-55	20-40
C7	104	23	85-120	10-30
C8	337	36	325-345	25-45
C9	61	4	275-360,0-180	10-45

Table 5.1: The clusters of dominant discontinuities and the range in orientation within each of the discontinuity sets in the investigated area of Moertschachberg and the Asten Road.

5.1.1.2 Goaschnigkopf

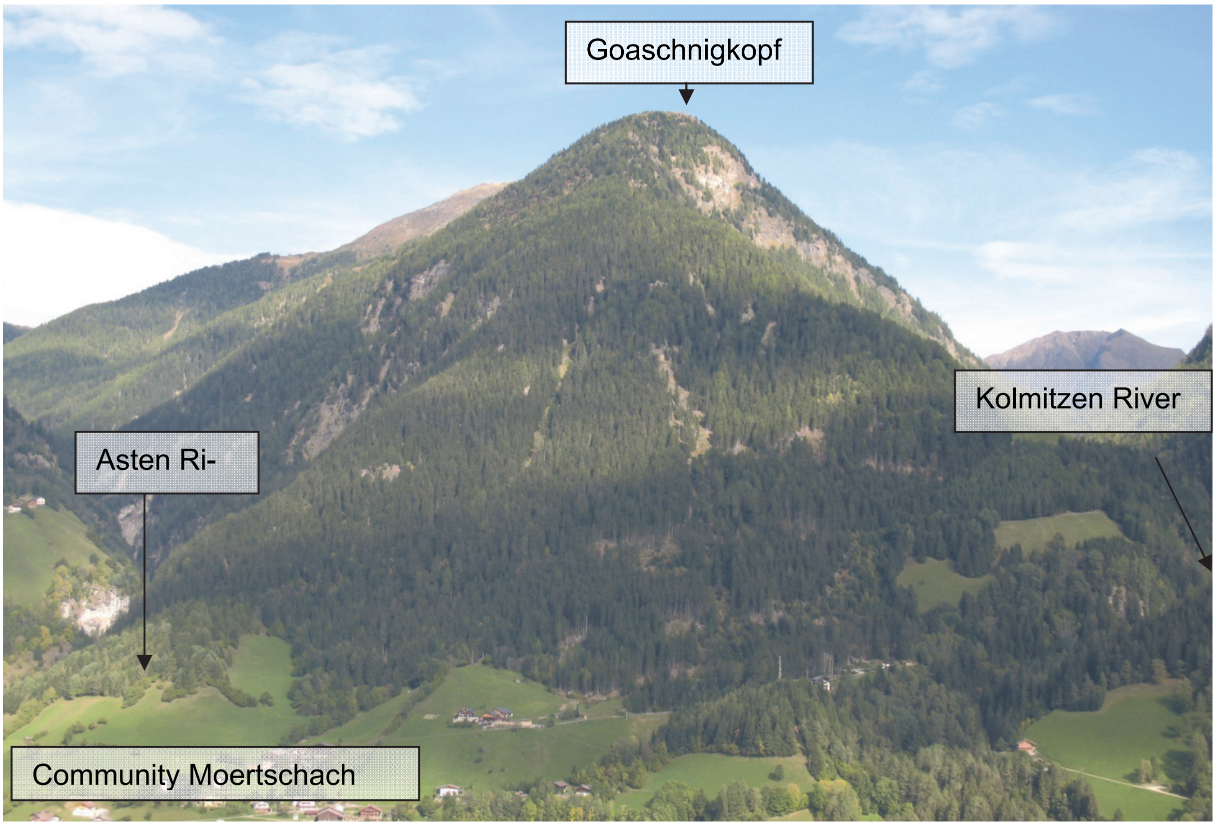
Goaschnigkopf is located in the community of *Moertschach*. It is delineated to the north by the Asten Valley and to the south by the valley of the *Kolmitzen River* (Text-Figs. 5.4, 5.32, 5.33).

In contrast to *Moertschachberg*, the potential rockfall source areas are not so clearly defined and occur across a far smaller area. This is probably due to the fact that two large volume rockfalls or rock avalanches have already altered that which was likely to have previously formed the steepest relief in the area (Text-Fig. 5.5).

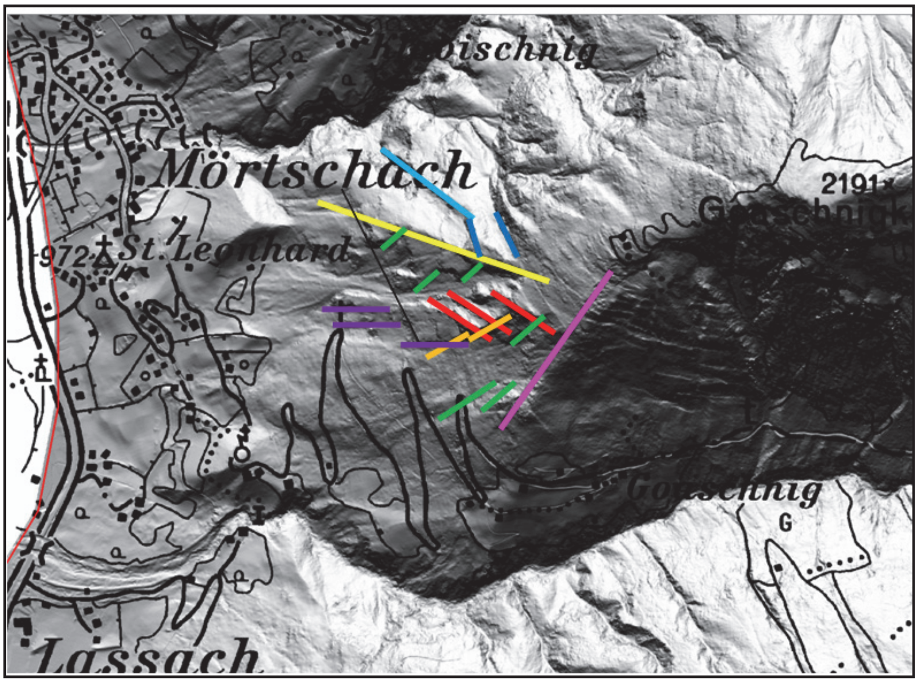
In the investigated area of *Goaschnigkopf*, the dominant fault systems strike as follows:

- The main direction of the Asten Valley follows the fault direction NE–SW (Text-Fig. 5.6: green and pink lines).
- Fault direction NW–SE (red line).
- Fault direction W–E (purple line).
- Fault direction WSW–ENE (orange line).
- Fault direction WNW–ESE (yellow line).

In addition, the influence of two major fault systems is visible in the local lithological anisotropy. These are the *Iseltal Fault System* and the *Zwischenbergen-Wöllatratten Fault System*, which strike NW–SE and WSW–ENE respectively (LINNER et al., 2009).

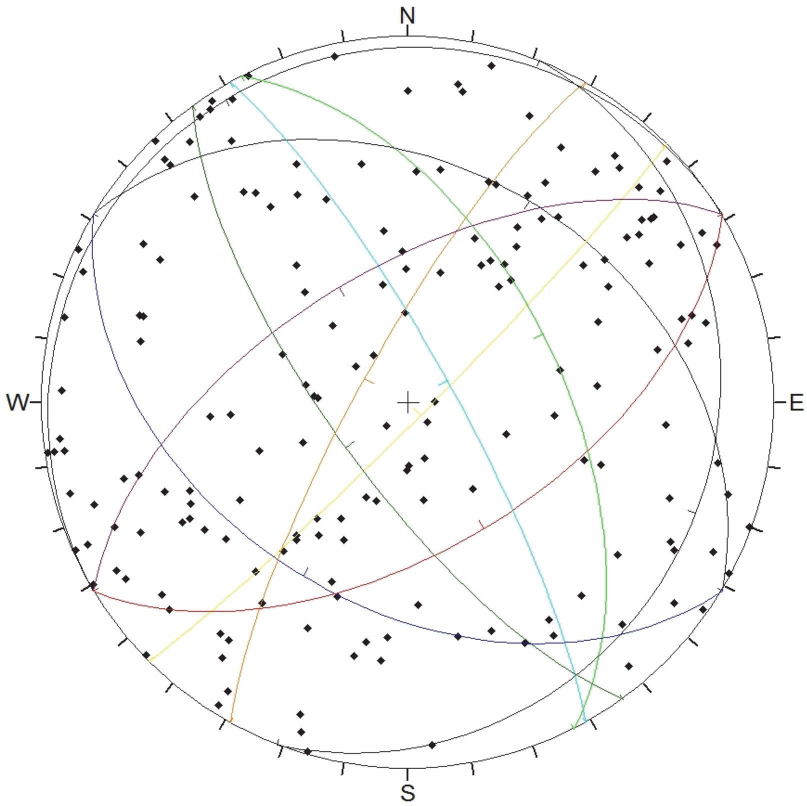


Text-Fig. 5.5: The investigated area of *Goaschnigkopf*. The red areas indicate the accumulations of large volume rockfalls or rock avalanches. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).



Text-Fig. 5.6: The main fault directions within the investigated area. In the vicinity of *Goaschnigkopf*, the spatial distribution of potential rockfall source areas reflects these directions. Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).

Text-Fig. 5.7 presents a plot of poles and great circles, the latter of which represent clusters of some of the dominant discontinuities measured in the investigation area of *Goaschnigkopf*. The main foliation (black great circles) has a slightly more gentle dip than was the case in *Moertschachberg*. However, the NE-dipping axes of the open faults are still recognisable. The dominant discontinuity sets of the main fault systems have strike directions from NE–SW or NW–SE. This reflects the main directions in *Moertschachberg*. This area is characterised by conjugated discontinuity sets (purple and red great circles), which strike orthogonal to the strike of the slope.



Text-Fig. 5.7: A plot of poles and great circles for the discontinuities mapped in the investigation area of *Goaschnigkopf* (n: 184). The great circles represent clusters of some of the frequently measured discontinuities (equal area projection, lower hemisphere).

Cluster	Dip direction	Dip angle	Dip direction (range)	Dip angle (range)
K1	135	86	100-155	80-89
K2	61	80	30-85	65-89
K3	63	56	50-70	50-65
K4	211	44	200-220	30-60
K5	234	73	210-260	60-89
K6	299	79	280-320	65-89
K7	329	60	315-340	55-65
K8	149	57	140-160	50-65
K9 ss	111	17	90-150	10-25
K10 ss	329	4	250-360,0-55	1-10
K11 ss	31	36	15-45	20-50

Table 5.2: The clusters of dominant discontinuities and the range in orientation within each of the discontinuity sets in the investigated area of *Goaschnigkopf*.

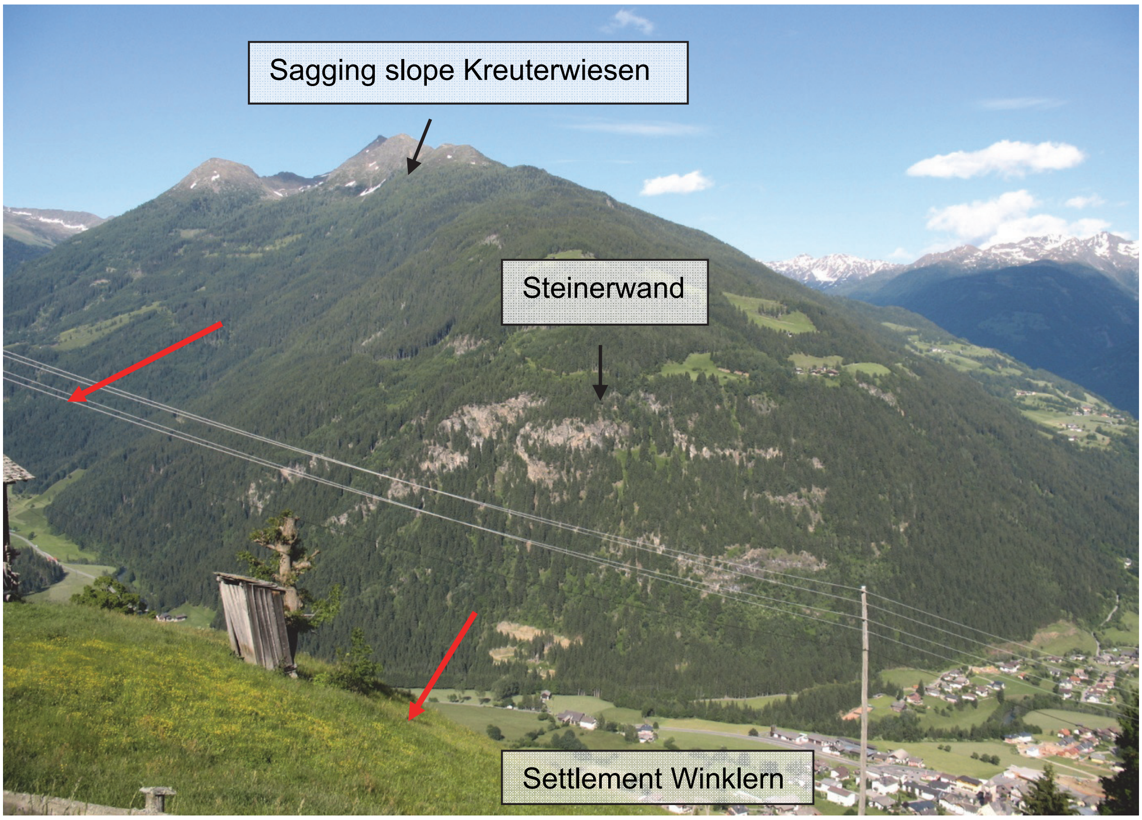
5.1.1.3 Steinerwand

Steinerwand is located in the community of Winklern, in the southern part of the study area. In this area, the direction of the Moell Valley changes from south to northeast following predefined tectonic structures (Text-Fig. 5.8, Text-Fig. 6.3 in chapter 6).

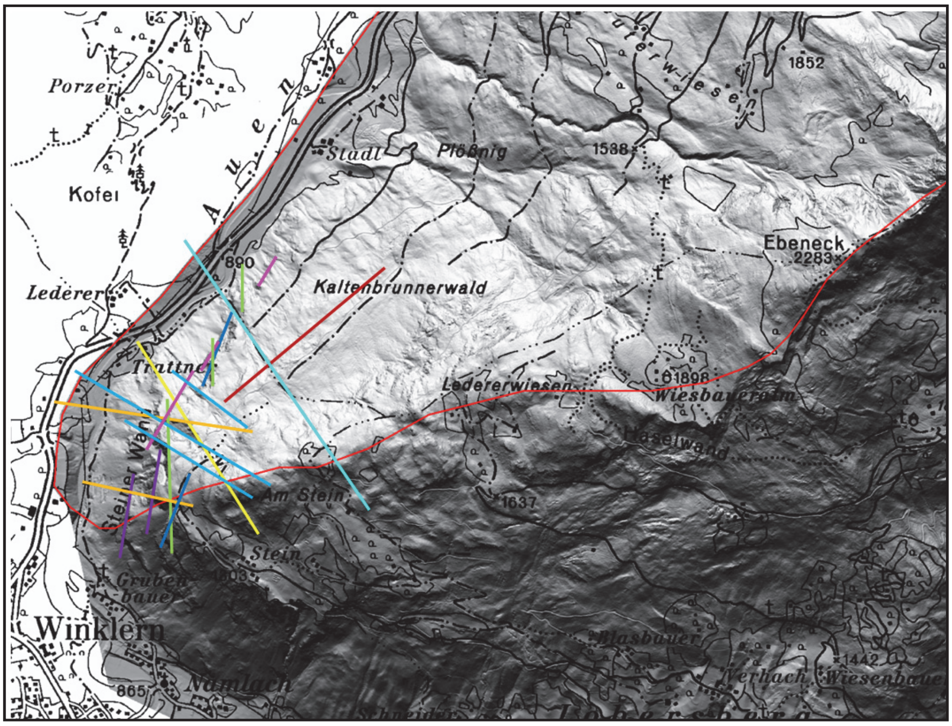
In the investigated area of Steinerwand, potential rockfall source areas are comparatively large and clearly defined. This situation is markedly different to the previously investigated area of Goaschnigkopf. Where the Moell River changes course towards the northeast, the cliffs follow the strike direction of the slope. In the direction of the sagging slope *Kreuterwiesen*, the cliffs are angled acutely to the Moell Valley. As was the case on the southwesterly facing cliffs of Goaschnigkopf, this area is susceptible to rockfalls of large volumes or rock avalanches. These are either caused by, or contributed to, significant faults (Text-Figs. 5.9–5.11).

Steinerwand is also strongly influenced by certain fault systems that strike as follows:

- Fault direction WNW–ESE (Text-Fig. 5.9: light blue and orange lines).
- Fault direction NNW–SSE (dark blue line).
- Fault direction NNW–SSE (yellow line).
- Fault direction N–S (light green line).
- Fault direction NNE–SSW (purple line).
- Fault direction NE–SE (red line).

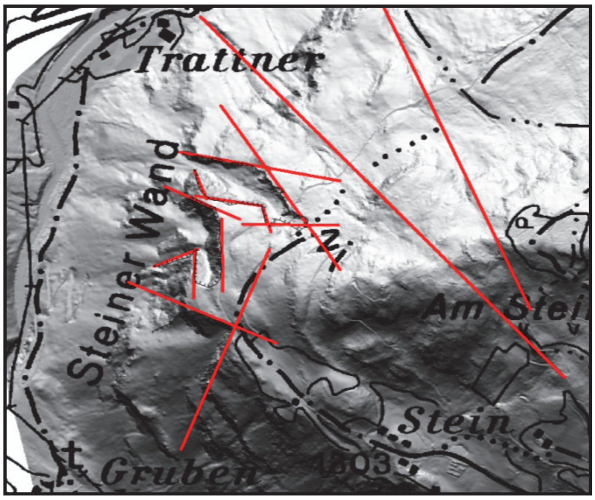


Text-Fig. 5.8: The investigated area of *Steinerwand* (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

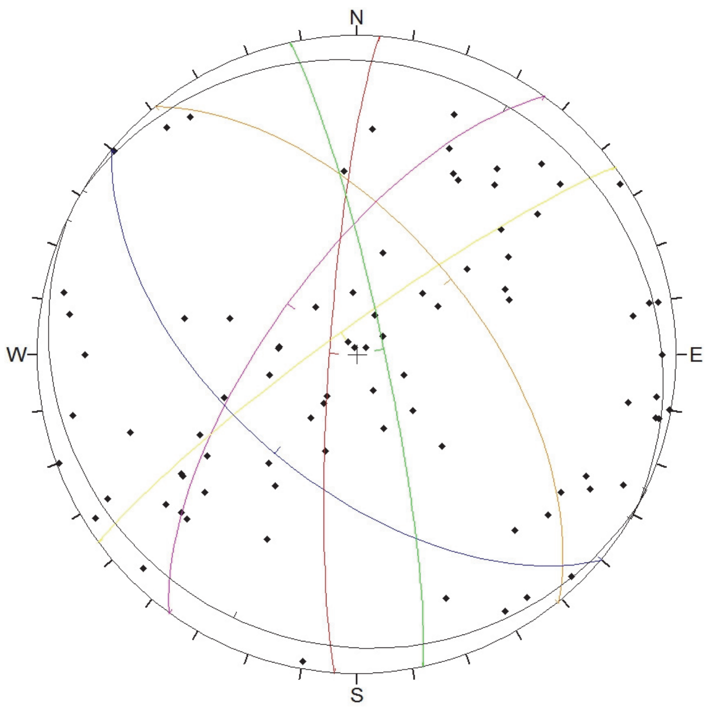


Text-Fig. 5.9: The main fault directions within the investigated area. In the vicinity *of Steinerwand*, the spatial distribution of potential rockfall source areas reflects these directions. Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).

The field investigation demonstrated that the influence exerted by these faults is particularly significant due to their high degree of separation (wide spacing). This separation allows the faults to become deeply incised into the metamorphic rock. The cliffs represent former scarp areas and their spatial distribution follows these tectonic structures (Text-Fig. 5.10).



Text-Fig. 5.10: Map showing fault planes with a high degree of separation. These are the main cause of large volume falls with rockfall source areas situated within the old scarps. Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).



Text-Fig. 5.11: A plot of poles and great circles for the discontinuities mapped in the investigation area of *Steinerwand* (n: 86). The great circles represent clusters of some of the frequently measured discontinuities (equal area projection, lower hemisphere).

Text-Fig. 5.11 presents a plot of poles and great circles, the latter of which represent clusters of some of the dominant discontinuities measured in the investigation area of Steinerwand (see Table 5.3). As was the case in Moertschachberg and Goaschnigkopf, it appears that the orientation of the main foliation is broadly flat and incorporates a range of directions. The other discontinuities dip steeply and their strike directions follow the scarps areas.

Cluster	Dip direction	Dip angle	Dip direction (range)	Dip angle (range)
C1	220	57	200-240	35-70
C2	306	68	295-320	60-75
C3	51	59	40-60	50-70
C4	274	83	255-285	75-89
C5	324	83	310-330	80-89
C6	78	83	55-105	75-89
C7	205	10	130-245	1-25
C8	31	10	285-360	10-25

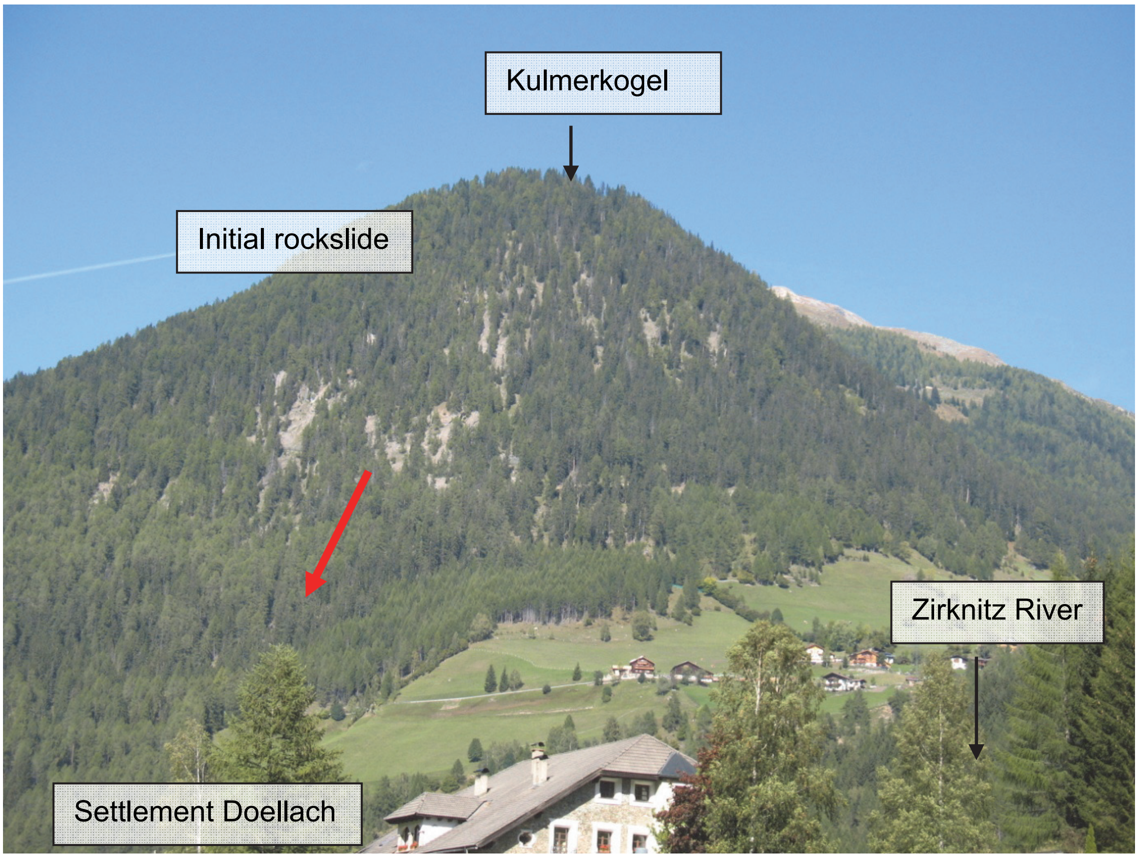
Table 5.3: The clusters of dominant discontinuities and the range in orientation within each of the discontinuity sets in the investigated area of *Steinerwand*.

5.1.2 Structural-geological characteristics of the Sub-Penninic and Penninic Units

The northern part of the study area is characterised by the predominately southwesterly dipping Sub-Penninic and Penninic Units. In marked contrast to that which occurs in relation to the *Prijakt-Polinik Complex*, a so-called dip slope situation exists in these units. As a result these units are not associated with distinct cliffs. Potential rockfall source areas are restricted to those areas that lie orthogonal to the strike direction of the lithological unit, areas of significant tectonic structures, or areas of deep-seated slope deformations (Chapter 4.2). Those settlements and infrastructure that are potentially endangered are predominantly situated within the Penninic *Glockner Nappe System* (Chapter 2.2).
Due to the fact that the orientation of the main foliation within the Sub-Penninic and Penninic Units is parallel to the southwesterly dipping slopes (the dip slope situation), the lithologies hereabouts are susceptible to rockslides and sagging slopes when suitable tectonic structures are also present.

5.1.2.1 Kulmerkogel

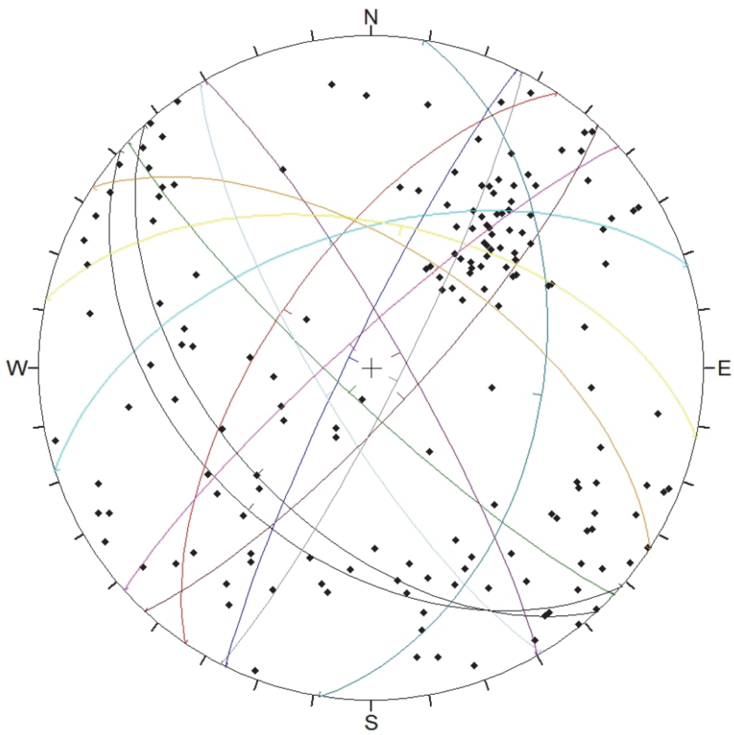
On the southwesterly dipping slopes of *Kulmerkogel*, the dominant morphological feature is that of a rockslide in its initial stage (see Text-Fig. 5.12, 5.13). This rockslide has displaced material with an approximate volume of 4500 m^3. The orientation of the rockslide is towards the southwest (160–230°) and it has a dip of around 40°. With an automatically derived slope criterion of 50°, the main potential rockfall source areas are captured.



Text-Fig. 5.12: The investigated area of *Kulmerkogel*. A red arrow indicates the location of the initial rockslide. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 5.13: Rockfalls along the rockslide in its initial stage beneath *Kulmerkogel*. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 5.14 presents a plot of poles and great circles, the latter of which represent clusters of some of the dominant discontinuities measured within the Glockner Nappe System (Penninic Unit). It is evident that the foliation shows clusters of up to 51° to the SW. Some steeply SE or NE dipping discontinuities, mainly faults, are dominant orthogonal or sub-orthogonal to the foliation. These broadly follow the direction of the Zirknitz Valley. Furthermore, some very significant moderately NNW to NNE dipping discontinuities are also observed.



Text-Fig. 5.14: A plot of poles and great circles for the discontinuities mapped in the vicinity of *Kulmerkogel* (n: 171). The great circles represent clusters of some of the frequently measured discontinuities (equal area projection, lower hemisphere).

Cluster	Dip direction	Dip angle	Dip direction (range)	Dip angle (range)
C1	227	51	200-245	25-65
C2	221	43	205-235	25-65
C3	304	64	295-310	55-75
C4	342	56	325-355	45-65
C5	318	82	310-325	75-89
C6	296	84	290-305	75-89
C7	223	82	220-225	75-89
C8	133	79	125-140	70-89
C9	60	82	55-65	75-89
C10	99	47	90-105	45-50
C11	12	54	5-20	45-60
C12	33	60	25-40	55-70
C13	117	83	105-125	75-89
C14	239	77	230-240	70-85

Table 5.4: The clusters of dominant discontinuities and the range in orientation within each of the discontinuity sets in the investigated area of *Kulmerkogel*, Glockner Nappe System (Penninic Unit).

5.2 Onset susceptibility assessment

5.2.1 Dominant failure mechanisms

Using kinematic analyses, it is possible to identify the mechanisms most likely to be responsible for failure within any given area (toppling, sliding, wedge failure). The aim of these analyses was to recognise those discontinuities that may cause slope instability in the future. Whether a discontinuity has the potential to initiate movement depends greatly on its orientation (dip direction/dip angle) with respect to the slope situation (slope aspect/slope inclination), the rock block morphology, and the condition of the discontinuity along its surface (friction angle). (For further details, see MARKLAND, 1972; HOCKING, 1976; GOODMANN, 1976, 1980; WYLLIE & MAH, 2004).

The rocks that comprise the *Prijakt-Polinik Complex* (amphibolite, orthogneiss, paragneiss, and micaschist) of the Upper Austroalpine Unit are associated with friction angles along the surface of the discontinuity, ranging between approximately 43° and 45°. The minerals within the micaschist and paragneiss are likely to be coarsely crystallised due to their high degree of metamorphosis. This coarse crystallisation leads to comparatively rough discontinuity surfaces. In contrast, the amphibolite is associated with comparatively smooth discontinuity surfaces.

The limestone micaschist within the *Glockner Nappe System* of the Penninic Unit has smoother discontinuity surfaces compared to those of the paragneiss and micaschist. As a result, the friction angles range between approximately 28° and 36°. For the kinematic analysis, a 35° friction angle was applied due to the relatively competent appearance of this lithology.

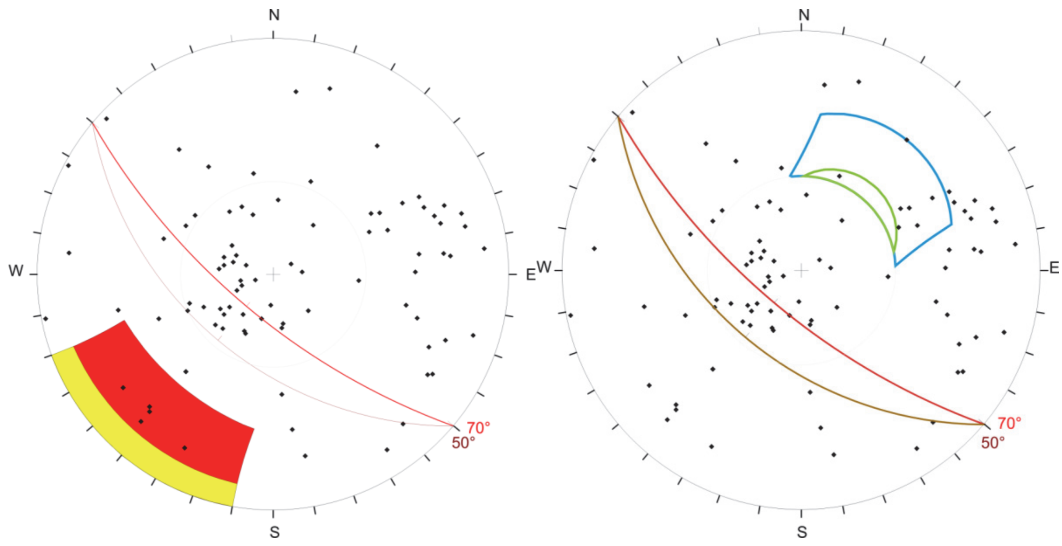
In the following sections, a short summary of the derived results is presented. For further details regarding the various structural-geological settings and dominant failure mechanisms within the study area, see MELZNER (2011a).

5.2.1.1 Moertschachberg and the Asten Road

The southwesterly facing cliffs above the settlement of Moertschach

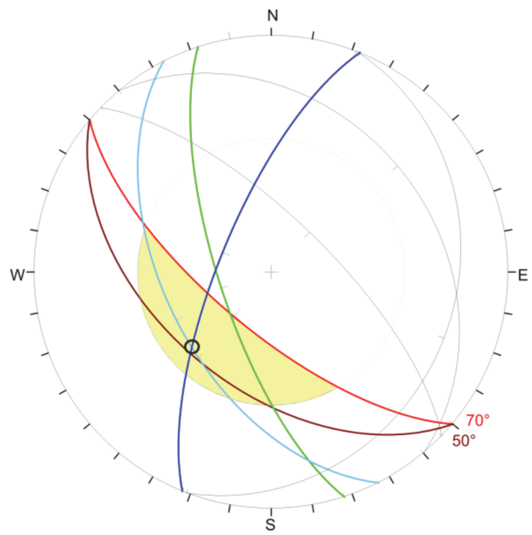
The kinematic analysis of the southwesterly facing cliffs above the settlement of Moertschach was undertaken using two different cliff inclinations (50° and 70°) and a mean dip direction of 220° (ranging from 190° to 250°).

Text-Figs. 5.15 and 5.16 present the results of the kinematic analysis. It is demonstrated that several steep discontinuities dipping NNE to NE may initiate slope failures through the mechanism of toppling, if the cliff face is inclined up to 70° (red area, Text-Fig. 5.15, left). If the cliff face is inclined less or more steeply, toppling is not such a dominant failure mechanism.



Text-Fig. 5.15: The results of the kinematic analysis that examine the failure mechanisms which may cause instability in the southwesterly facing cliffs at *Moertschachberg*: toppling (left) and sliding along one plane (right). These represent the most probable failure mechanisms in this area. The analysis was undertaken using cliffs inclined 220/70 (red great circle) and 220/50 (brown great circle).

Similar results are achieved in relation to the mechanism of sliding along one plane. It is demonstrated that more moderate discontinuities dipping SW may cause slope failures through such sliding, if the cliff face is inclined up to 70° (Text-Fig. 5.15, right). If the cliff face is inclined less steeply, sliding is not such a dominant failure mechanism.



Text-Fig. 5.16: The results of the kinematic analysis that examine the failure mechanisms which may cause instability in the southwesterly facing cliffs at *Moertschachberg*: wedge failure on two intersecting discontinuities. The analysis was undertaken using cliffs inclined 220/70 (red great circle) and 220/50 (brown great circle).

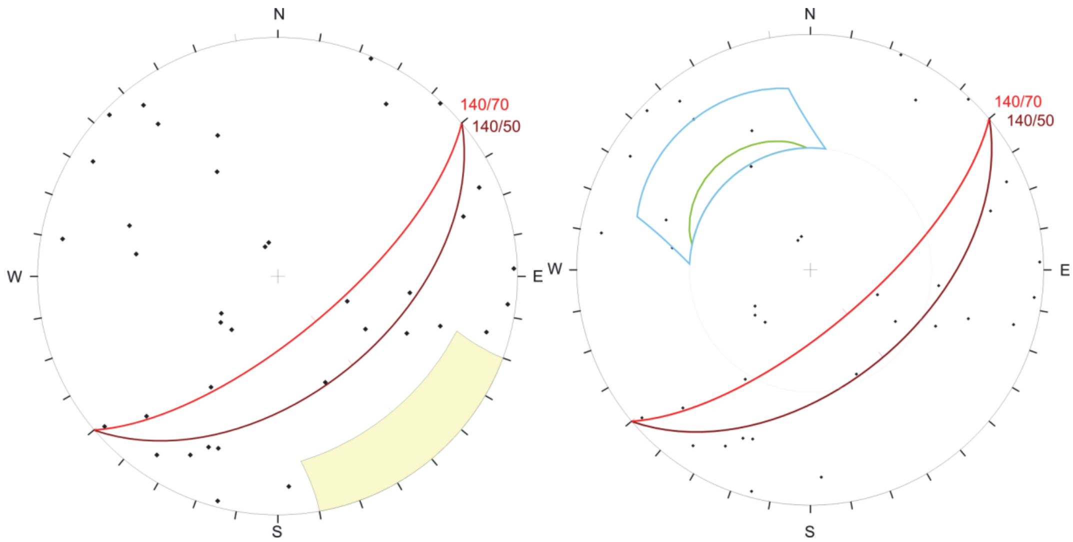
Text-Fig. 5.16 demonstrates that few discontinuities are likely to cause wedge failure in this area. In addition, in some cases it is possible that the lines of intersection incorporate discontinuities that dip in the direction of the slope (the light blue and light green great circles in Text-Fig. 5.16). As a result, failure is more likely to occur through sliding along one plane rather than through wedge failure on two intersecting discontinuities.

The main foliation with its gentle dip from NW to NE may be responsible for detachment above or may act as the base for possible toppling.

The southeasterly facing cliffs along the Asten Road

The kinematic analysis of the southeasterly facing cliffs along the *Asten Road* was undertaken using two different cliff inclinations (50° and 70°) and a mean dip direction of 140° (ranging from 110° to 170°).

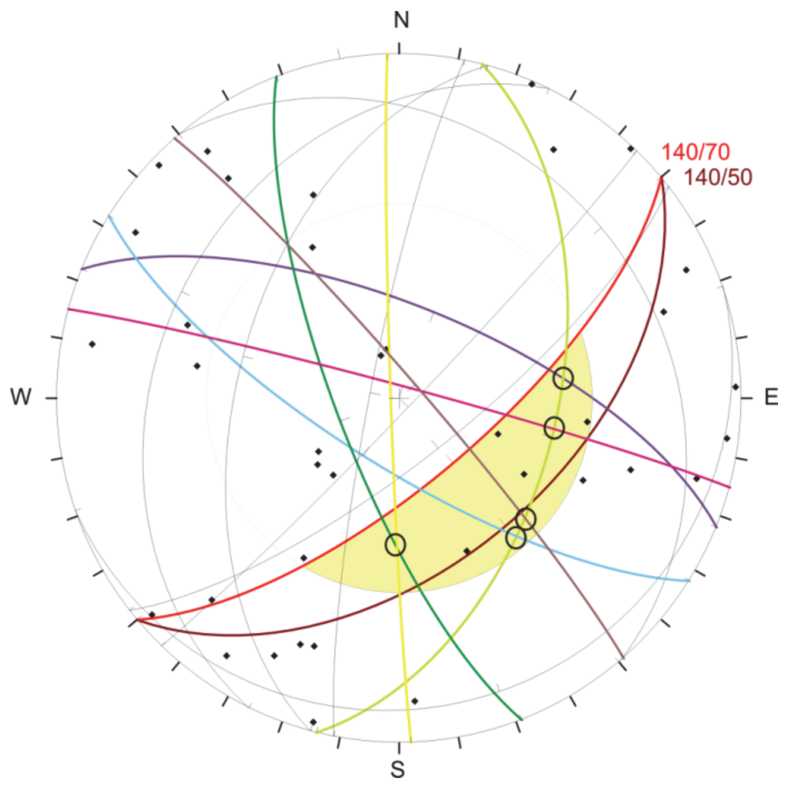
Text-Figs. 5.17 and 5.18 present the results of the kinematic analysis. It is demonstrated that no discontinuities are able to initiate slope failure through the mechanism of toppling, if the cliff face is inclined between 50 and 70° (yellow area, Text-Fig. 5.17, left). Similar results are achieved in relation to the mechanism of sliding along one plane (Text-Fig 5.17, right). Where the cliff face is inclined up to 70°, a very small number of discontinuities exist that may be able to act as slide planes.



Text-Fig. 5.17: The results of the kinematic analysis that examine the failure mechanisms which may cause instability in the southeasterly facing cliffs along the *Asten Road*: toppling (left) and sliding along one plane (right). The analysis was undertaken using cliffs inclined 140/70 (red great circle) and 140/50 (brown great circle).

It is also demonstrated that this area is highly susceptible to wedge failures (Text-Fig. 5.18). As was the case in the previously described area, one dominant discontinuity set dips in the direction of the slope (e.g. the light green great circle). As a result, failure is more likely to occur through sliding along one plane rather than through wedge failure on two intersecting discontinuities.

The main foliation here is not as clearly defined as it is in the southwesterly facing cliffs. It, therefore, has far less influence with regard to the generation of overhanging ceilings and toppling failures.

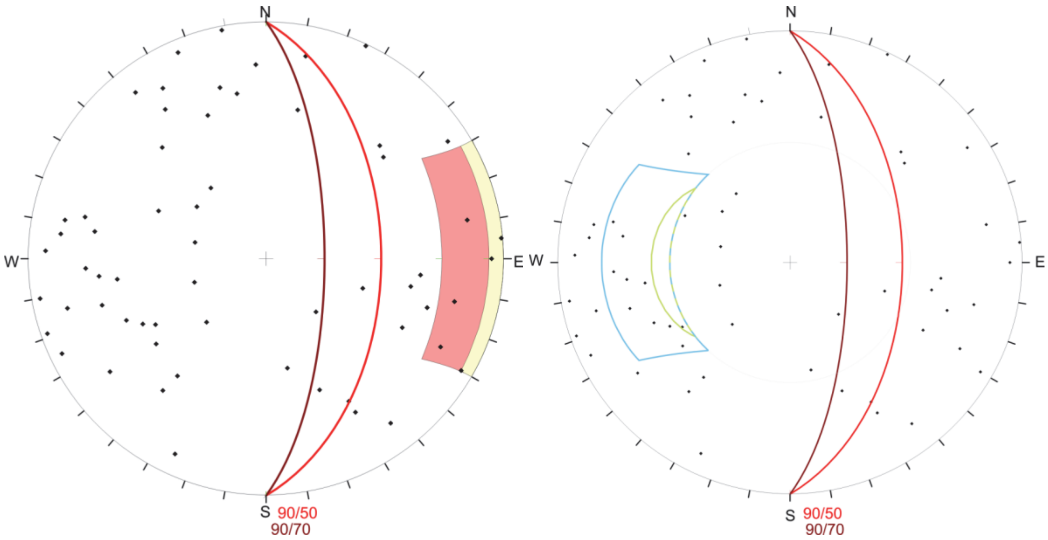


Text-Fig. 5.18: The results of the kinematic analysis that examine the failure mechanisms which may cause instability in the southeasterly facing cliffs along the *Asten Road*: wedge failure on two intersecting discontinuities. The analysis was undertaken using cliffs inclined 140/70 (red great circle) and 140/50 (brown great circle).

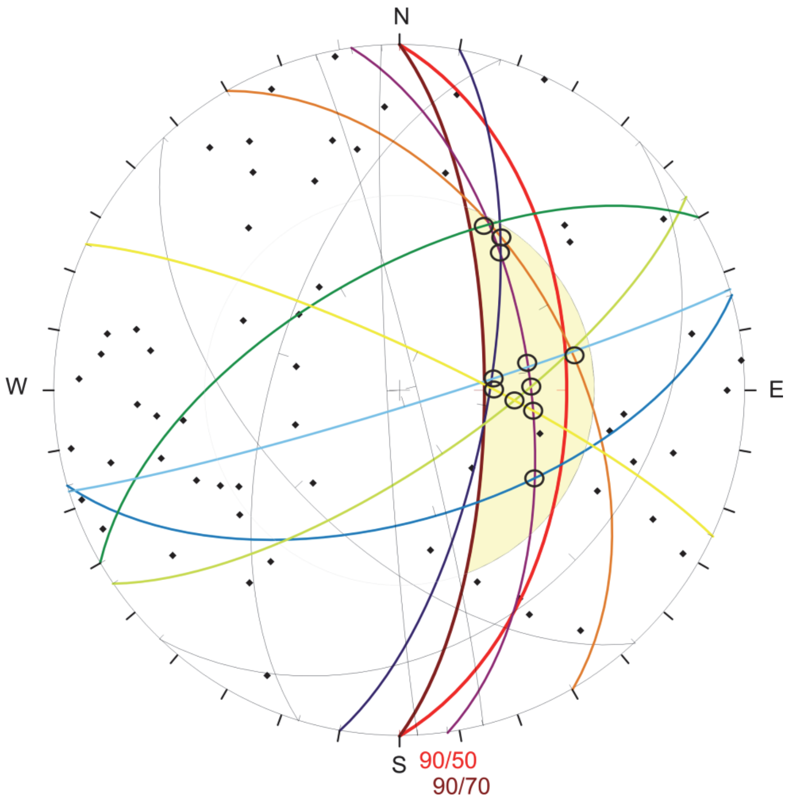
The northeasterly to east-southeasterly facing cliffs along the Asten Road

The kinematic analysis of the northeasterly to east-southeasterly facing cliffs along the *Asten Road* was undertaken using two different cliff inclinations (50° and 70°) and a mean dip direction of 90° (ranging from 60° to 120°).

Text-Figs. 5.19 and 5.20 present the results of the kinematic analysis. It is demonstrated that only a few steep discontinuities dipping WNW may initiate slope failures through the mechanism of toppling, by a slope inclination ranging between 50° and 70° (Text-Fig. 5.19, left).



Text-Fig. 5.19: The results of the kinematic analysis that examine the failure mechanisms which may cause instability in the northeasterly to east-southerly facing cliffs along the *Asten Road*: toppling (left) and sliding along one plane (right). The analysis was undertaken using cliffs inclined 90/70 (red great circle) and 90/50 (brown great circle).



Text-Fig. 5.20: The results of the kinematic analysis that examine the failure mechanisms which may cause instability in the northeasterly to east-southeasterly facing cliffs along the *Asten Road*: wedge failure on two intersecting discontinuities. The analysis was undertaken using cliffs inclined 90/70 (red great circle) and 90/50 (brown great circle).

It is demonstrated that slope failures may occur as a result of sliding along one plane if the cliff face is inclined more than 50° (Text-Fig. 5.19, right) and it may be a frequent failure mechanism if the cliff face is inclined more than 70°. If the cliff face is inclined less than 50°, such sliding does not occur.

Similar results are achieved in relation to the mechanism of wedge failures (Text-Fig. 5.20). This failure mechanism may occur if the cliff face is inclined around 50° and it is a frequent failure mechanism if the cliff face is inclined up to 70°. At these inclinations, sliding and wedge failures are equally important. As mentioned previously, one dominant discontinuity set dips in the direction of the slope. As a result, failure is more likely to occur through sliding along one plane rather than through wedge failure on two intersecting discontinuities.

5.2.1.2 Overview of the failure mechanisms

Chapter 5.2.1.1 presented detailed kinematic analyses of rock mass structures. These were undertaken with respect to the divergent cliff orientations that occur within each of the areas investigated in detail. Table 5.5 summarises the results of these analyses (for further details, see MELZNER, 2011a). It is apparent that the various areas are represented by different dominant failure mechanisms; this is unsurprising given that their rock mass structures and orientations vary considerably.

In order to obtain spatially-continuous information about the failure mechanisms across all the cliffs located within the *Prijakt-Polinik Complex*, the results of the analyses have been interpolated so that continuous parameter maps can be generated. A heuristic approach was subsequently used through the application of a reproducible GIS methodology, with the derived parameter maps used as the basis with which to conduct an onset susceptibility assessment across all the cliffs located within *the Prijakt-Polinik Complex* (for further details, see MELZNER, 2011a).

Text-Fig. 5.33 clearly shows the onset susceptibility ranking for the cliffs in the *Prijakt- Polinik Complex*. The potential rockfall source areas have been differentiated according to their susceptibility to the specific failure mechanism (toppling, sliding, wedge failure) through a relative rating system (e.g. quite likely or quite unlikely). (See as well MELZNER et al., 2010d). It would also have been possible to represent the results either in terms of the total number of possible failure mechanisms for each slope unit or in terms of the ratio between the defined number of possible failure mechanisms and the total number of failure mechanisms that could theoretically occur.

It was decided that other methods such as, for example, those of probabilistic design, should not be applied in order to calculate onset susceptibility at the local scale. The parameters required for such methods cannot be acquired in sufficient detail over larger areas (due to time and cost constraints) nor can they be used for interpolation to obtain spatially-continuous parameter maps. Furthermore, techniques such as terrestrial laser scanning could not be used for data collection as the study areas are characterised by a relatively dense vegetation cover.

Area	**Cliff face incline [degrees]**	**Dominant failure mechanism**	
		High susceptibility	**Low susceptibility**
Moertschachberg			
Southwesterly facing cliffs	50	Plane failure	Toppling failure, wedge failure
Southwesterly facing cliffs	50-70	Toppling, plane failure	Wedge failure
Southwesterly facing cliffs	>70	Plane failure	Toppling failure, wedge failure
Southeasterly facing cliffs	50	Wedge failure, plane failure	Toppling failure
Southeasterly facing cliffs	50-70	Plane failure	Toppling, wedge failure
Southeasterly facing cliffs	>70	Plane failure	Toppling failure, wedge failure
Northeast to eastsoutheast facing cliffs	50	Toppling failure	Plane failure
Northeast to eastsoutheast facing cliffs	50-70	Plane failure	Wedge failure, toppling failure
Northeast to eastsoutheast facing cliffs	>70	Plane failure, Toppling failure	Wedge failure
Goschnigkopf			
Southwesterly facing cliffs	50	Toppling, plane failure	Wedge failure
Souteasterly facing cliffs	50-70	Toppling, plane failure	Wedge failure
Souteasterly facing cliffs	>70	Toppling, plane failure	Wedge failure
Steinerwand			
Northwesterly facing cliffs	50	Toppling failure	Plane failure, wedge failure
Northwesterly facing cliffs	50-70	Wedge failure, toppling failure	Plane failure
Northwesterly facing cliffs	>70	Plane failure, wedge failure	Toppling failure,
Southwesterly facing cliffs	50	Toppling failure, plane failure	Wedge failure
Southwesterly facing cliffs	50-70	Plane failure	Toppling failure, wedge failure
Southwesterly facing cliffs	>70	Toppling failure, plane failure	Wedge failure

Table 5.5: An overview of the onset susceptibility in relation to the dominant failure mechanisms for the areas investigated in detail within the Prijakt-Polinik Complex.

5.2.2 Lithology and tectonically predefined structures

In addition to the spatial arrangement of the mass rock structure and its relationship to slope (Chapter 5.2.1), lithological transitions and the occurrence of tectonic structures such as tension cracks also significantly influence rockfall susceptibility within the study area. As detailed in Chapters 2 and 3, within this area the Upper Austroalpine Sub-Unit is represented by a highly competent lithology. The dominant rocks of the *Prijakt-Polinik Complex* are paragneiss and micaschist (see Text-Fig. 5.21). In this unit, these rocks alternate rapidly along with layers of orthogneiss and amphibolite.

Text-Fig. 5.21: The occurrence of coarse-grained micaschist (left) and paragneiss (right) in the Prijakt-Polinik Complex. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

The paragneiss is characterised by a fine to medium texture with a specific concentration of light minerals that form grey-white slates. In contrast to “normal” micaschist, this complex is coarser-grained. Due to the smaller proportion of schist, it is very similar in appearance to the paragneiss. These rock types are both characterised by frequent garnet-inclusions. This rock association appears as a quite compact lithostratigraphic unit in the *Prijakt-Polinik Complex*. The rock masses of this unit are characterised by low persistence discontinuities with low apertures, despite the main foliation and some distinct faults.

In many parts of the *Prijakt-Polinik Complex*, these metasediments are interlayered by massive amphibolite with thicknesses of several tens of meters (Text-Fig. 5.22). The variety of non-persistent discontinuities is responsible for conchoidal fracturing of the amphibolite. Furthermore, within this lithological unit, bands of light minerals and garnet-inclusions are very frequent. In some places, granitic gneiss with partial augen texture is associated with the previously mentioned lithologies.

Within the *Prijakt-Polinik Complex*, these small-scale lithological transitions occur very frequently and cannot be differentiated separately (see also FUCHS & LINNER, 2005).

The limestone micaschist of the *Glockner Nappe System* (Penninic Unit) may vary significantly with regard to its geotechnical behaviour. Depending on its calcium carbonate content, this lithology can form boulders with volumes of several m^3 (Text-Fig. 5.23). These volumes are, for example, frequently associated with micamarble. The competent lithology is pervaded by layers of micaschist. The layers have closely spaced foliation planes, ranging from a few millimetres to several centimetres and this leads to the formation of very small to small rock blocks (Text-Fig. 5.23). This incompetent lithology is often preferred by faults. It is also responsible for the detachment of large rock masses from the adjacent mountain (Chapter 5.2.2.1).

Text-Fig. 5.22: The occurrence of amphibolite (left) and orthogneiss (right) within the *Prijakt-Polinik Complex* (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 5.23: The occurrence of micamarble (left) and micaschist within a fault zone (right) in the *Glockner Nappe System* (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

The following section reviews specific differences in lithology and fracturing, across those areas that have been investigated at the local scale. From the standpoint of rockfall susceptibility, it is very important to recognise deep tension structures as these follow pre-existing tectonic structures.

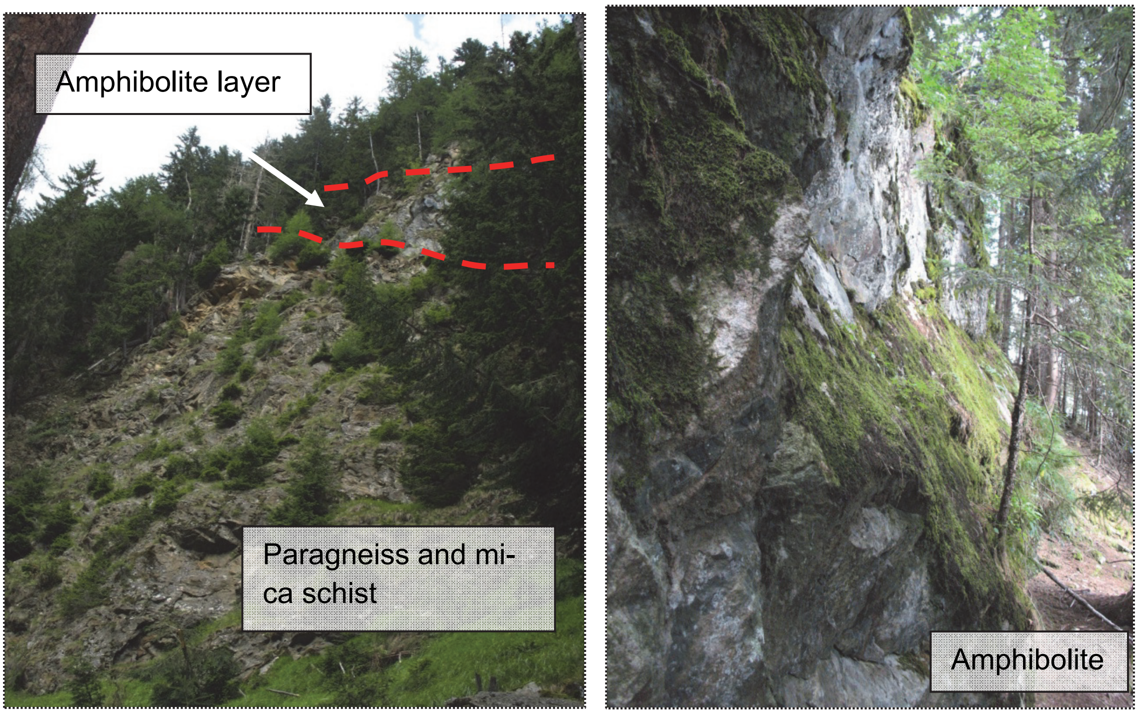
5.2.2.1 Moertschachberg and the Asten Road

The exposed southwestern cliffs of *Moertschachberg* are predominately constructed from micaschist and paragneiss. This lithostratigraphic unit also incorporates massive amphibolite with thicknesses of several tens of meters (Text-Fig. 5.24). The morphological appearance of the cliffs is characteristically step-like, alternating between parts that are vertical or sub-vertical and parts that are horizontal or sub-horizontal. To a certain extent, the scarps associated with previous large volume rockfalls remain readily recognisable.

Text-Fig. 5.24: The southwesterly facing cliffs of Moertschachberg (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

In contrast to the other areas investigated in detail, the gentle NW–NE dipping main foliation (Chapter 5.1) allows the formation of very distinct overhanging rock masses or “ceilings”. The majority of discontinuities have both low persistence and low aperture, with only a few discontinuities attaining apertures of up to ten centimetres. The latter are mainly those discontinuities that strike parallel or sub-parallel to the slope (Text-Fig. 5.25). These are predominately responsible for the detachment of large rock masses.

As an example, a large rock mass of around 10,000 m^3 (20 m x 50 m x 10 m) has almost completely separated from the adjacent mountain near Outcrop 50 on Text-Fig. 5.26. Indicators of recent movement on the discontinuities are provided by the presence of rock flour and gravitationally induced tension and shear joints as well as by the near complete absence of material within the discontinuities. Despite these indicators of movement, significant displacement of the rock mass has not yet occurred. This is indicated by the strong lateral correspondence that exists between the rock mass structure observed in the displaced rocks and the structure observed in the adjacent rock of the mountain (i.e. in the location of gaps and cleavage).



Text-Fig. 5.25: Paragneiss and micaschist in the *Prijakt-Polinik Complex*, intersected by amphibolite bands in the exposed southwestern cliffs of *Moertschachberg*. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 5.26: The step-like cliff morphology that has developed due to differences in rock mass structure and material properties (left). The separation of large rock masses from the adjacent mountain (right). (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

The accessible parts of the cliffs at Moertschachberg have formed in quite a compact lithology with a rock mass structure that is predominantly characterised by widely spaced discontinuity sets. As previously mentioned, the *Prijakt-Polinik Complex* typically includes rocks with a variable content of micaschist. The selective weathering processes and the susceptibility of the area to comparatively large volume rockfalls is likely to result from these small-scale alternations between competent and less competent rock together with the ongoing process of detachment along the discontinuities (Chapter 5.2.2). The dominant morphology of these rock blocks ranges from platy to cubic whilst their volumes range from 0.3 m^3 to 1.0 m^3. The majority of boulders have a volume of around 0.5 m^3.

The southwesterly facing cliffs at *Moertschachberg* present various indicators of high rockfall activity. These include a high number of fresh detachment areas, well-defined talus slopes with a high number of boulders, numerous benchmarks on the ground, the near complete absence of trees within certain corridors (aisles in the woods), and some events (Chapter 6). The benchmarks and aisles in the woods are specifically caused by frequently occurring rockfall events.

Along the *Asten Road*, the majority of the rock slopes that are directly adjacent to the road have already been protected by primary preventive measures (e.g. anchorages, nails, and steelworks). In addition, there are steep morphological forms such as deep crevices that have formed along significant fault lines. Around these forms, secondary preventive measures have been installed (e.g. galleries). This area is also characterised by cliffs, such as those between the first and third gallery ((Text-Fig. 5.32, 5.33); although these cliffs have steep and massive rock faces, there is little evidence for recent rockfall activity as they are presently covered by moss and lichen (Text-Fig. 5.27).

Text-Fig. 5.27: The unprotected potential rockfall source areas above the *Asten Road*. The moss and lichen covered paragneiss cliffs present little evidence for recent rockfall activity (left). Strongly fractured and loosened rockfall source areas composed of amphibolite in the vicinity of a brittle fault (right). (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Conversely, some small-scale potential rockfall source areas are located in deep crevices that have formed perpendicular to the strike of the slope. As a result of their development along brittle faults, these rockfall source areas are highly fractured and loosened. The associated block sizes are far smaller than those recorded in other parts of the study area (Text-Fig. 5.27, right, and Chapter 5.3). However, where it occurs, paragneiss within fault zones is susceptible to generating large volume rockfalls. This area is particularly characterised by deep tension cracks, which dissect the ridges in NE–SW or ENE–WSW directions (Text-Fig. 5.28).

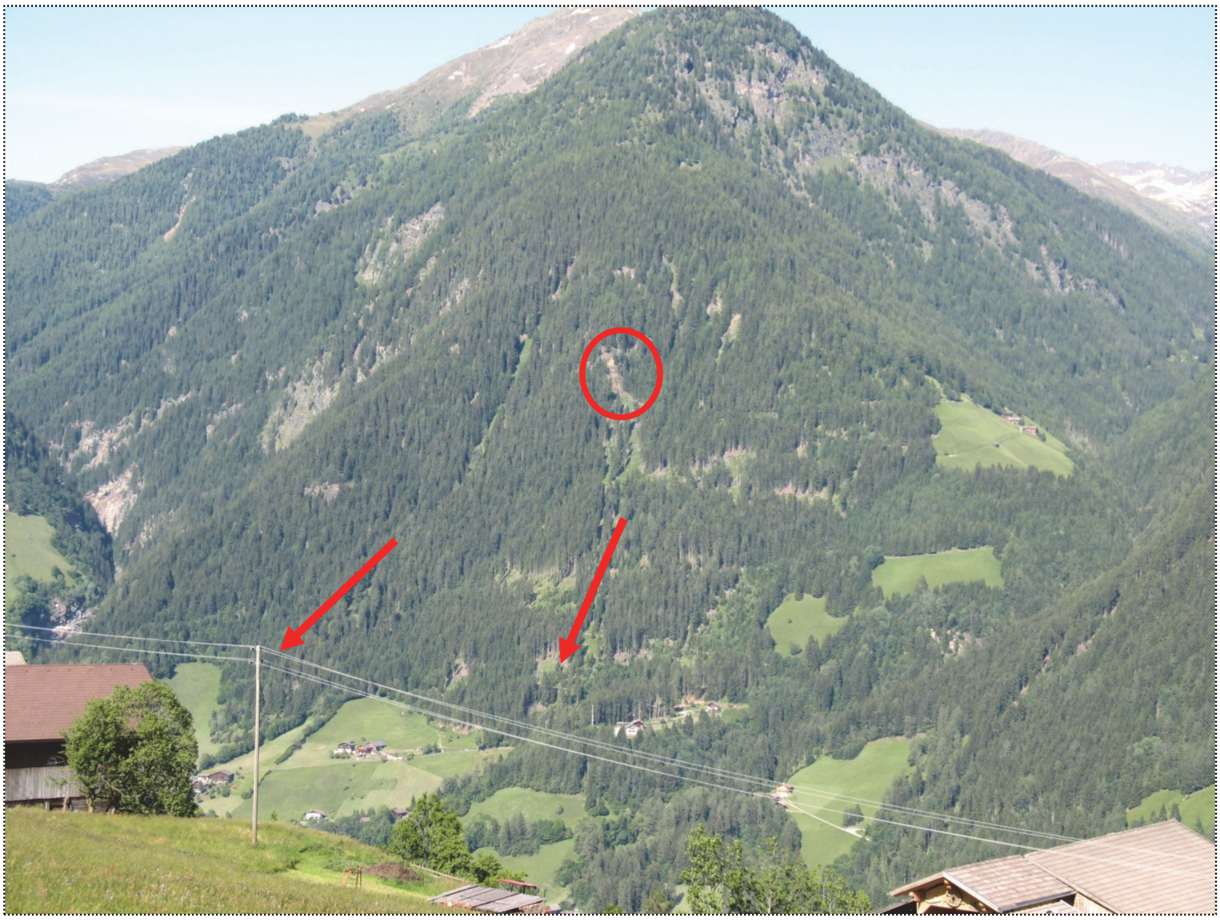
Text-Fig. 5.28: An almost fully detached rock mass (left) and tension cracks in the ridge between *Wetschkenkopf* and *Moertschachberg* (right). (Source: S. MELZNER (left) and I. BARON (right), photographic archive of the Geological Survey of Austria).

5.2.2.2 Goaschnigkopf

In contrast to *Moertschachberg*, the southwesterly facing cliffs at *Goaschnigkopf* (see Text-Fig. 5.29) have fewer small-scale rock associations between paragneiss, micaschist, and amphibolite. In this area, the proportion of orthogneiss is greater and this results in rockfall blocks with average volumes of up to several m^3 (Chapter 5.3.1).

As mentioned in Chapter 4.4.1.2, the characteristic morphological features of the southwestern slopes are scarps and areas of accumulation resulting from two large rockfalls (Text-Fig. 5.30). The southern rockfall area, next to the *Kolmitzen River* (Text-Fig. 5.32), is the far larger of the two. It is likely that its initial failure mechanism was caused by sliding because slide planes can be clearly recognised in the field along a number of discontinuities (see also Chapter 5.2.1). The northern rockfall area has only a few source areas. These are far smaller and follow the direction of a main fault, thus giving a frayed appearance. Furthermore, the narrow transportation area and fan-shaped accumulation area (Text-Fig. 5.32) are characteristically very similar to that which has been observed in the detailed investigation area at *Steinerwand* (Chapter 5.2.2.3).

It is highly probable that these two rockfall areas were subject to a sequence of different events. The field investigations have shown that different block accumulations or different generations of blocks cover or overlap each other. This is particularly true in the southern rockfall area (Text-Fig. 5.30). The cliffs around the scarps are frequently strongly loosened and show some fresh rockfall detachment areas. Within and alongside these scarp areas, there are block accumulations or rock masses with a very loose composition. They may act as future rockfall source areas during secondary rockfall processes.



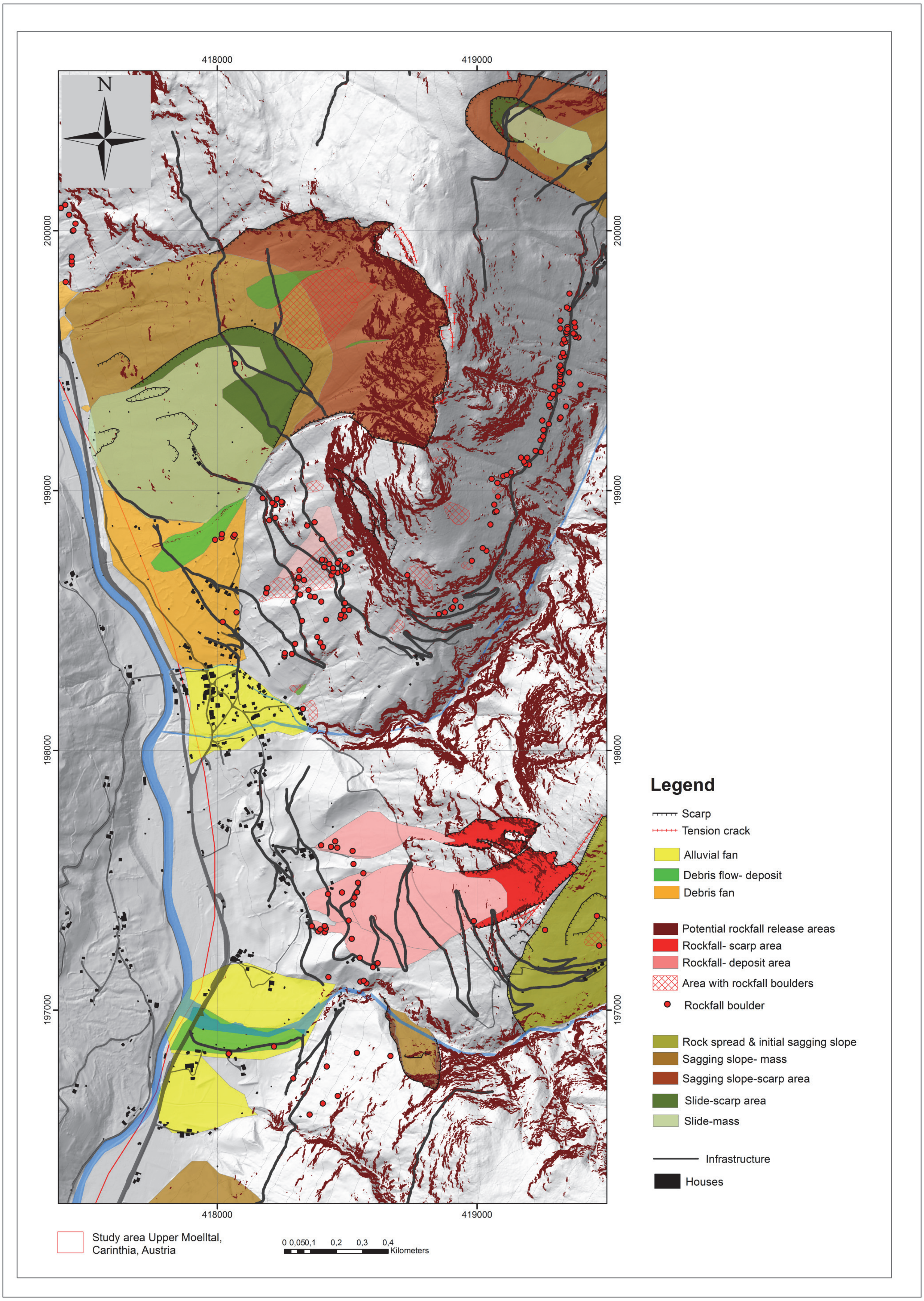
Text-Fig. 5.29: The potential rockfall source areas within the scarps of two previous rockfall events along the southwesterly facing slopes at *Goaschnigkopf*. The red circle indicates the rockfall source area for an event in 2003. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Special mention must be made of the highly significant tension cracks that are oriented NE–SW along the ridge separating the *Kolmitzen Valley* and *Moell Valley* (Text-Fig. 5.31), as well as those perpendicular and parallel to the *Moell Valley*. These tectonically predefined zones of weakness, together with some very steeply dipping faults, are most probably responsible for the high susceptibility to large volume rockfalls.

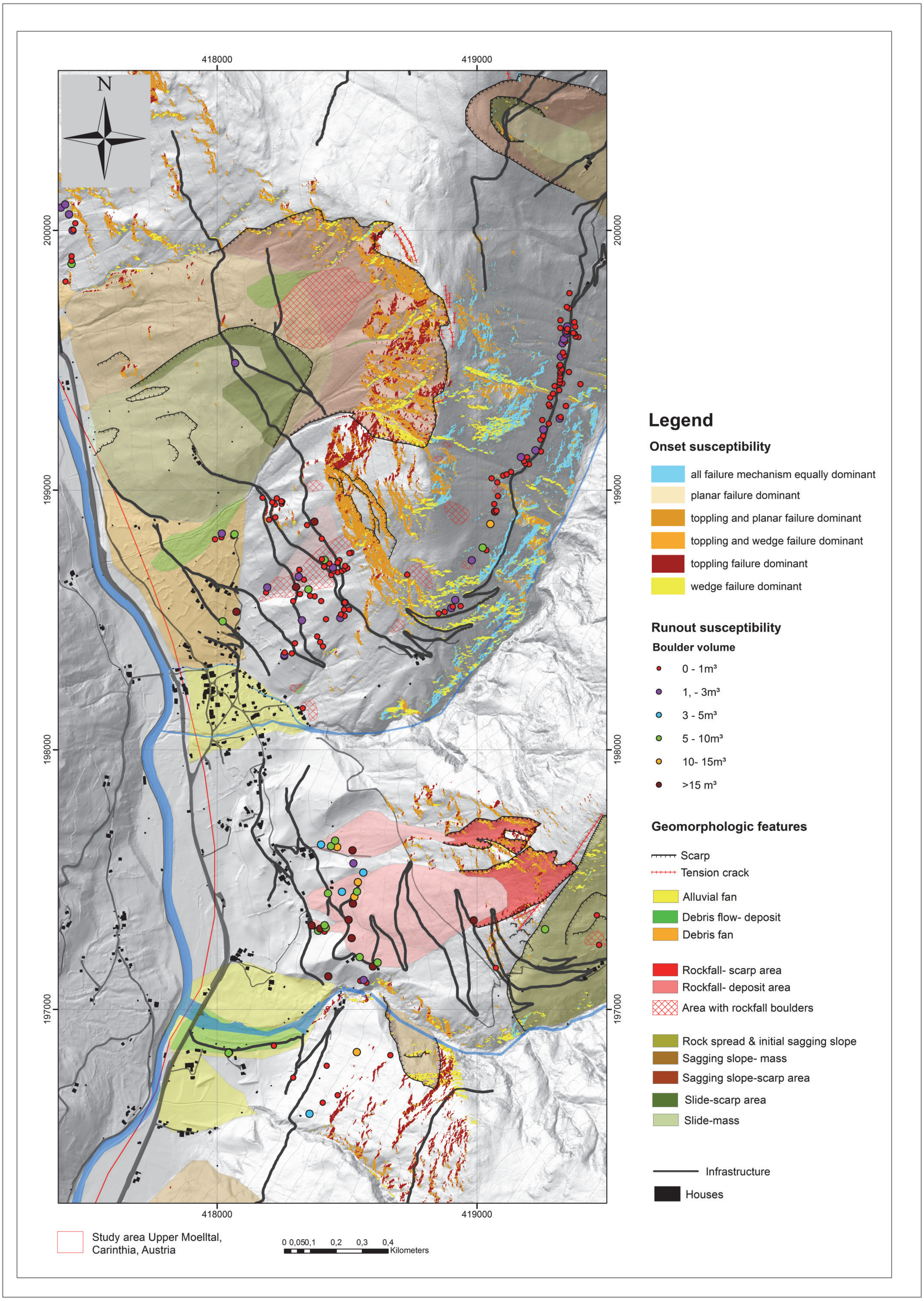
In contrast to *Moertschachberg*, it is not very common to find the overhanging "ceiling" forms ("roof") that characteristically use the main foliation as an upward separation plane for detachment in that area.

Text-Fig. 5.30: Recent rockfall detachment areas within the scarps of two large relict rockfalls, located on the southwesterly facing slopes at *Goaschnigkopf* (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 5.31: The deep tension cracks and highly loosened rock along the ridge that separates the *Kolmitzen Valley* and *Moell Valley*. These cracks occur alongside the scarps of relict rockfalls (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).



Text-Fig. 5.32: Geomorphological map 1:10,000 – area Moertschachberg and Goaschnigkopf (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia.



Text-Fig. 5.33: Rockfall susceptibility map 1:10,000 – area Moertschachberg and Goaschnigkopf (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia.

5.2.2.3 Steinerwand

The westerly to northwesterly facing cliffs at *Steinerwand* have been constructed by a sequence of scarps that resulted from several large volume rockfall events (Text-Fig. 5.34). These are orientated at a low angle, in the direction of the Moell valley. The cliffs are finely structured with numerous needle-shaped overhanging parts and niches, which are often quite loose and extend deep into the adjacent mountain.
The neighbouring southerly facing cliffs are orientated parallel to the strike of the southwesterly facing cliffs. These are similar to the cliffs at *Moertschachberg*, although the latter cover a far smaller area and are less steep (Text-Fig. 5.35).

Text-Fig. 5.34: The westerly and northwesterly facing rockfall source areas with relict rockfall scarps at *Steinerwand* (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 5.35: The southwesterly facing cliffs at *Steinerwand*, in the vicinity of the restaurant *Grubenbauer*. The main foliation dips gently and this causes the upward detachment of rock blocks. The discontinuities dip steeply towards the slope. Together, these initiate that failure mechanism through the process of sliding (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 5.35 demonstrates that those cliffs which present indicators of recent activity are likely to be, at least partially, unstable in the future. A dominant steep discontinuity set dips towards the slope and this may act as a sliding plane during the detachment of rock blocks (red arrows, Text-Fig. 5.35). Clearly, any sliding may endanger the property located beneath (see chapter 6). As is the case at *Goaschnigkopf*, amphibolite is not common and the orthogneiss generate large rockfall boulders. The mapped rock blocks are usually smaller than those at *Goaschnigkopf* but, as described previously, a certain number will be of far greater volume. The high number of mapped boulders derived from past rockfall events, benchmarks on the trees, and some examples of detachment indicate that rockfalls are frequent in this area.

5.2.2.4 Kulmerkogel

The southwesterly facing slopes beneath *Kulmerkogel* do not form steep cliffs due to the fact that the slopes and lithological units dip parallel to one-another (Text-Fig. 5.1.2 and Chapter 5.1.2.2). The dominant geomorphologic feature in this area is a rockslide in its initial stage. The upper part of the slide has already moved horizontally by about 20 m. In this part, the slide is characterised by highly loosened zones in which caves have formed and tension fissures that strike slopeward (Text-Fig. 5.36). The lower part of the slide is characterised by overturning or folding of rock masses at the toe, with rockfall processes already occurring at the front and along the sides of the slide (Text-Fig. 5.37). These processes are likely to continue in the future.

Text-Fig. 5.36: The initial stage of a rockslide beneath *Kulmerkogel*. This rockslide is characterised in its upper part by highly loosened zones and tension fissures that strike slopeward. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Text-Fig. 5.37: The overturning or folding of rock masses at the toe of the slide (left). The release of very large rock blocks at the front and along the sides of the slide (right). (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

5.2.3 Rock block size and form

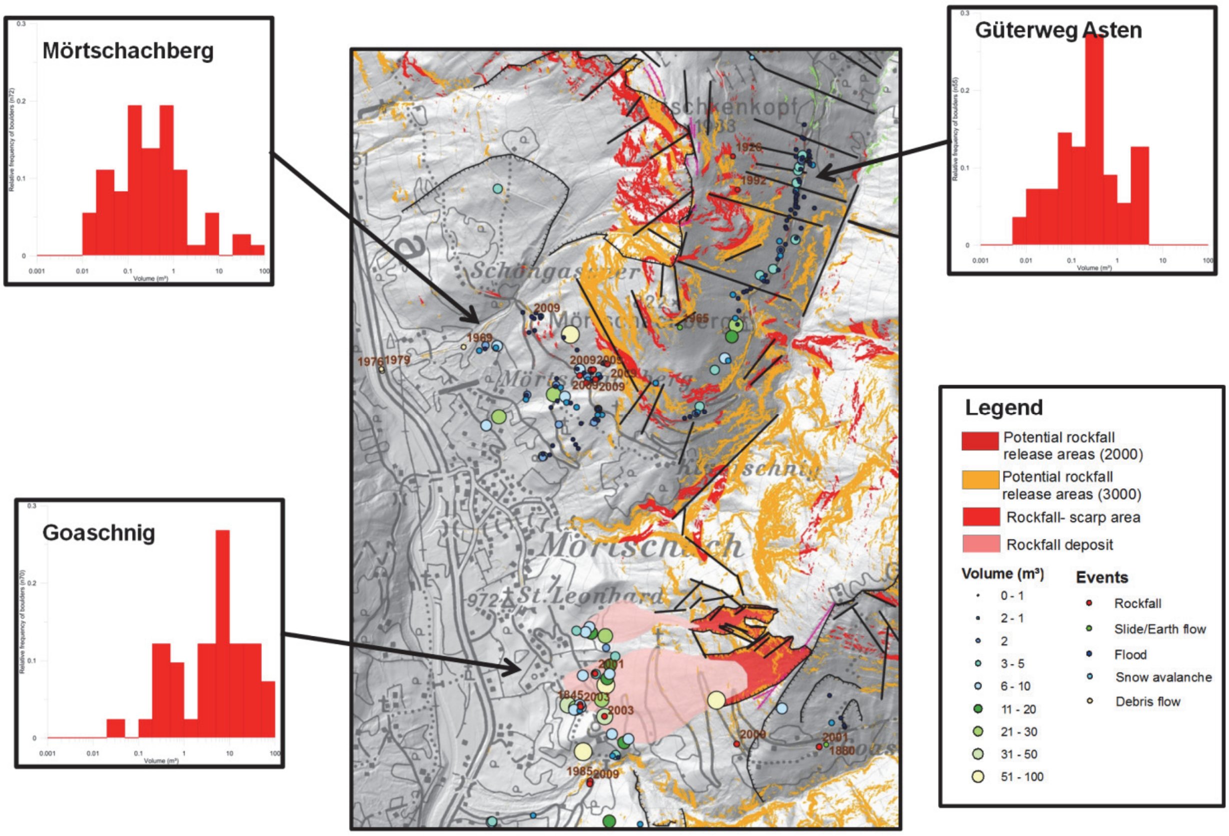
It is particularly important that a rockfall susceptibility assessment evaluates the typical rock block size and form associated with the specific lithological units. This is important as the dominant "block scenario" is a necessary input parameter in some runout models (e.g. *Rockyfor3D*), without which it would not be possible to simulate adequate rockfall trajectory distributions. However, it is not usually possible to define characteristic rock block sizes through investigations of only the rock mass structure. As described in Chapters 5.2.1 and 5.2.2, the rock mass structure of the *Prijakt-Polinik Complex* is characterised by non-persistent discontinuities with only a few persistent fault systems. When combined with rapid small-scale transitions in the degree of fracturing and competence of the lithology, it is clearly very difficult to use the mapped rock mass structure in order to adequately define the rock block size that might be associated with a single cliff. This problem will be exacerbated significantly if a number of cliffs have to be considered.

Text-Fig. 5.38 compares the distribution of rockfall boulder volumes in the area around *Goaschnigkopf*, *Moertschachberg*, and the *Asten Road*. These three areas are all located within the *Prijakt-Polinik Complex* and the distance between them is relatively small. However, there are significant differences in terms of their mapped boulder volumes. These differences generally reflect the previously described rapid small-scale transitions in the degree of fracturing and competence of the lithology. The boulders beneath the southwesterly facing cliffs of *Moertschachberg* are associated with a wide range of boulder volumes; the boulders along the *Asten Road* are associated with smaller volumes, whilst the boulders at *Goaschnigkopf* are associated with larger volumes. Nonetheless, in all three areas the maximum boulder volumes are approximately 1 m^3.

In addition to information regarding boulder volumes across the entire slope, a consideration of these statistics allows future events to be defined in terms of their characteristic block scenarios (Table 5.6).

Area	**Range of expected boulder volumes [m³]**	**Recommended scenarios for simulations**	**Blockform range**	**Recommended scenario for simulation**
Moertschachberg	1-10	3,5,10	All kinds possible	Cubic to ellipsoid
Asten	<0,5	<2	columnar to ellipsoid	columnar
Goaschnigkopf	1-10	5,10	All kinds possible	Cubic to ellipsoid
Steinerwand	1-10	3,5,10	All kinds possible	Cubic to ellipsoid
Kulmerkogel	0,5-50	<2 m³; 20	Rectangle to ellipsoid	Rectangle
Closed forest road	0,2-2,0	<1	columnar	columnar

Table 5.6: The definition of boulder scenarios based on detailed field knowledge.



Text-Fig. 5.38: A comparison of the rockfall boulder volumes in the areas of *Goaschnigkopf*, *Moertschachberg*, and the *Asten Road*. (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).

It is important to also note that the method used to determine the characteristic block scenario may differ depending on the specific aim of the investigation (see also ONR, 2011).

5.3 Runout susceptibility

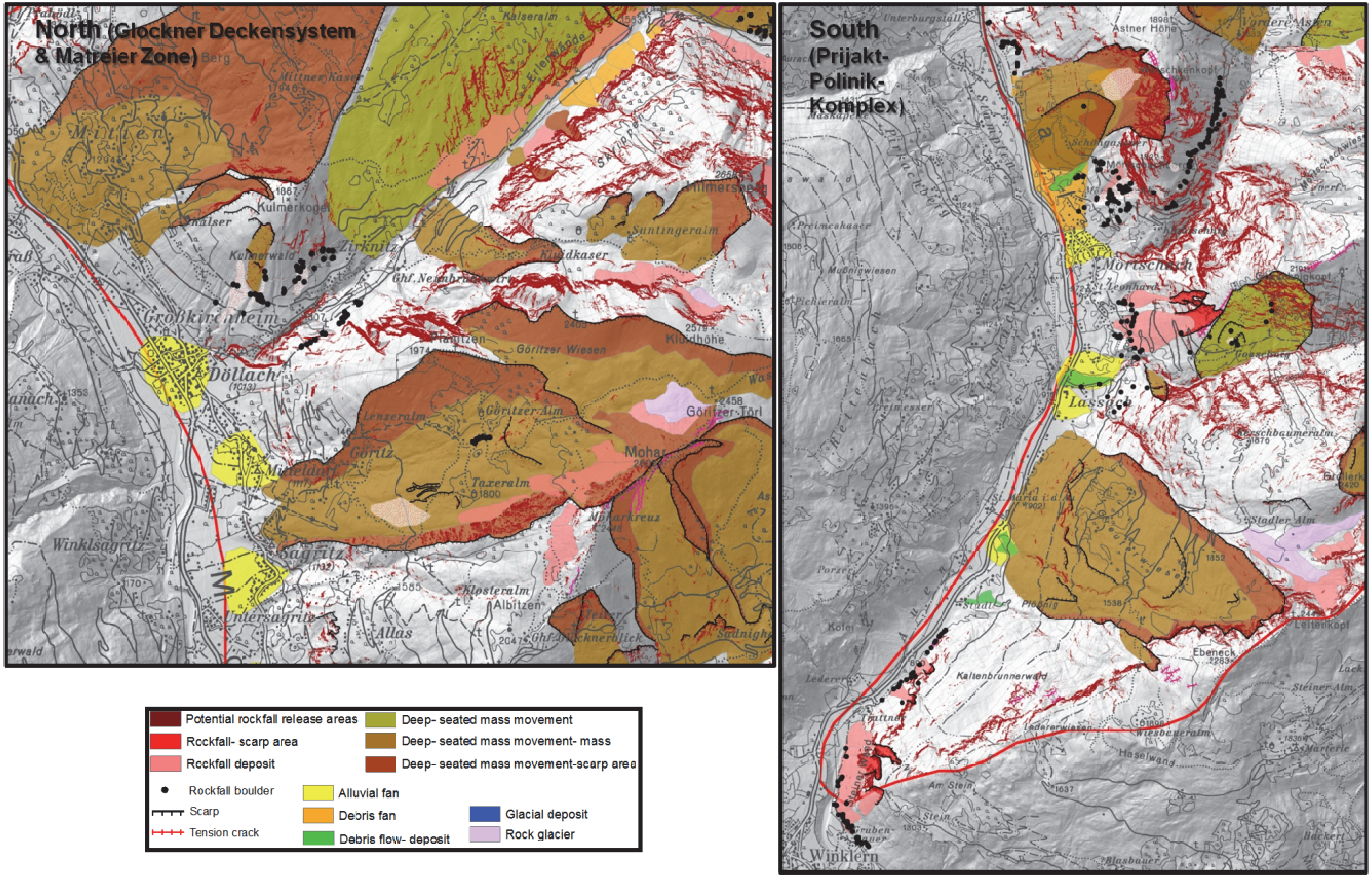
5.3.1 Past rockfall runouts and rockfall volumes

In order to derive information regarding the potential maximum of future rockfall runout zones, blocks associated with recent and historic events were mapped on the lower slopes. During fieldwork, 480 blocks were mapped in total and their dimensions measured. Unfortunately, the fieldwork demonstrated that such mapping is unlikely to be entirely reliable as, especially within settlements, local residents either moved or removed the blocks; clearly, those blocks with small cubature are those most likely to be affected. As a result, larger block classes are likely to be somewhat over-represented in subsequent statistical analyses; this may lead to misleading rockfall block volume distributions.

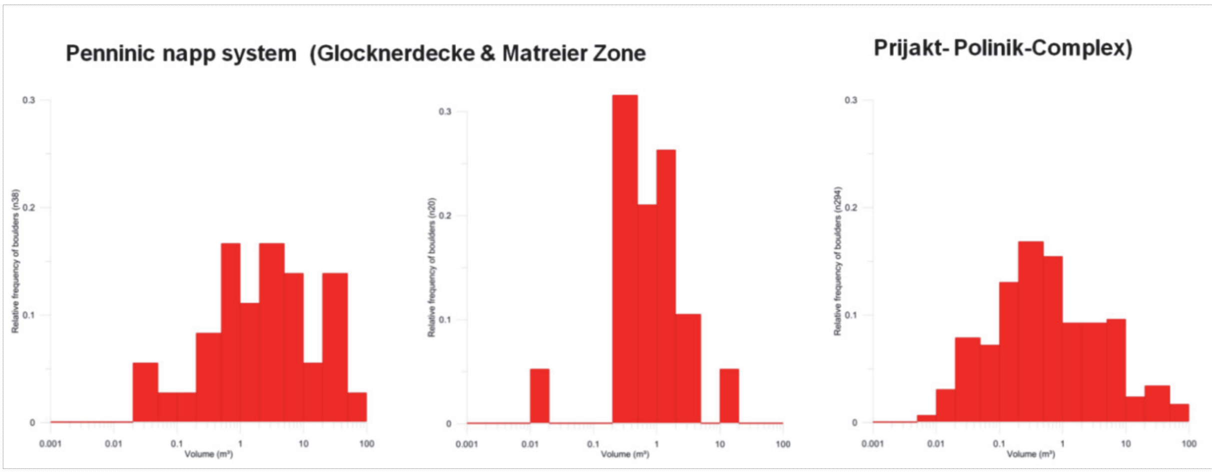
Text-Fig. 5.39 and 5.40 demonstrate that several blocks have reached settlements or major infrastructures. This occurs particularly when the blocks have been derived from the *Prijakt-Polinik Complex*. In addition, several rockfall accumulation zones were recognised around *Goaschnigkopf* and *Steinerwand*. Along the *Asten Road*, it can be assumed that several blocks have been transported as far as the gorge of the *Asten River*; this scenario is particularly likely close to bends in the road and along the first gallery. The same is likely to be true along the locked forest road located on the orographic left slopes of the *Zirknitz River*; here, it is probable that the majority of the transported blocks accumulated directly within the main river gorge.

Text-Fig. 5.39: Rockfall blocks located within settlements. Left: a large block from an old event that has not been removed, probably due to its size. Right: a small block from a recent event that has been subsequently removed. (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

Several blocks were measured along the orographic right slopes of the Zirknitz River (Text-Fig. 5.40). These were originally deposited by rock slides. Text-Fig. 5.40 shows the distribution of mapped rockfall block volumes as a function of lithology. It is remarkable that the largest block volumes are associated with the *Upper Austroalpine Unit* and not the *Penninic or Sub-Penninic Units*. Analysis of the mapping results show that a much greater number of blocks with large volumes (0.5 m^3 to 50 m^3) occur in the vicinity of the initial rock slide, beneath *Kulmerkogel*, and in a zone of slides situated opposite of the property *Zueg*. It is striking that there are a large number of blocks with a cubature of between 20 m^3 and 50 m^3. Along the *locked forest road* (Text-Fig. 4.2.1) on the orographic left slopes of the *Zirknitz River*, the majority of block volumes were found to be between 0.2 m^3 and 2 m^3, whereas smaller and larger blocks were encountered only sporadically. It should be noted that most blocks here were probably transported directly into the river. However, based on the rock mass structure it is concluded that the presented distribution of rock block volumes is representative for this particular area.



Text-Fig. 5.40: Some results of detailed mapping. (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609)..



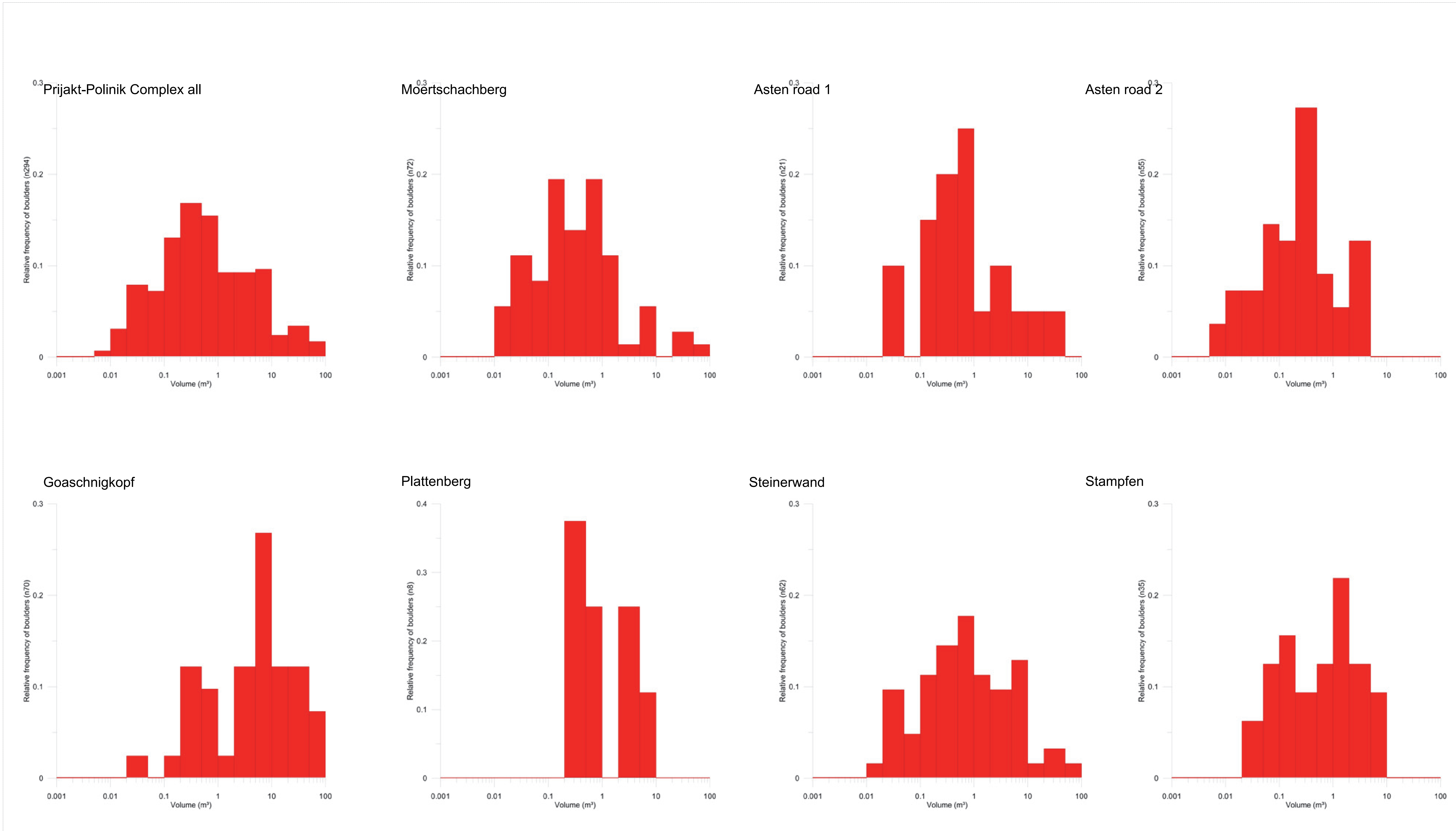
Text-Fig. 5.41: A comparison of rockfall block volumes as a function of lithology. (Fig. by S. MELZNER, Geological Survey of Austria).

Within the *Upper Austroalpine Unit*, the majority of block volumes were found to be below 10 m^3. Most commonly, block volumes occur between 0.1 m^3 and 1 m^3. The number of blocks below (0.02 m^3 to 0.1 m^3) and above (1 m^3 to 10 m^3) this are uniformly distributed.

In the following chapter, the results of those mapping domains within the *Prijakt-Polinik Complex* are described in detail. In these domains, it is possible to examine a classic rockfall scenario and not the secondary rockfall processes that are associated with the deep-seated mass movements within the Penninic and Sub-Penninic Units.

The distribution of block volumes within the sub-domain of *Moertschachberg* (Text-Fig. 5.42) shows that the majority are less than 2 m^3. In fact, the occurrence frequency shows two distinct clusters between 0.02 m^3 and 0.05 m^3 and between 0.2 m^3 and 0.5 m^3. These clusters reflect different source areas and processes. For volumes greater than 2 m^3, a cluster occurs between 5 m^3 and 10 m^3. Although fewer blocks are larger than 2 m^3, the general distribution is similar to that of the whole area.

Along the *Asten Road* (Text-Fig. 5.42), a dominant maximum in the occurrence frequency occurs between 0.2 m^3 and 0.5 m^3 whilst a smaller cluster also occurs between 2 m^3 and 5 m^3. Almost no blocks were found to be greater than 5 m^3. The further breakdown of this area into discrete sub-areas shows that where there is a bend to the first gallery of the forest road, a distinct maximum can be observed between 0.5 m^3 and 1 m^3; the larger block sizes are uniformly distributed. Consequently, a relatively large number of blocks have volumes of between 1 m^3 and 50 m^3 (1 m^3 to 2 m^3 is under-represented). No blocks were found with volumes between 0.05 m^3 and 0.1 m^3. Also on the forest road, between the first and the third galleries, a dominant maximum was found whilst smaller clusters occur between 0.5 m^3 and 1 m^3 and between 2 m^3 and 5 m^3. Almost no blocks were found to be greater than 5 m^3. Again, the general distribution is similar to that of the whole area described previously.



Text-Fig. 5.42: Distributions of block volumes. (Fig. by S. MELZNER, Geological Survey of Austria).

In the *Goaschnikopf* mapping domain, the occurrence frequency shows two distinct clusters at between 0.2 m^3 and 0.5 m^3 and between 5 m^3 and 10 m^3 (Text-Fig. 5.42). In this area, the total number of boulders mapped with large volumes was greater than it was in comparison to the other domains.

In the *Plattenberg* mapping domain, significantly fewer blocks were mapped in comparison to other domains (Text-Fig. 5.42). Of those that were mapped, the volumes ranged widely between 0.2 m^3 and 10 m^3. As a result of this, no significant statistical analysis could be undertaken.

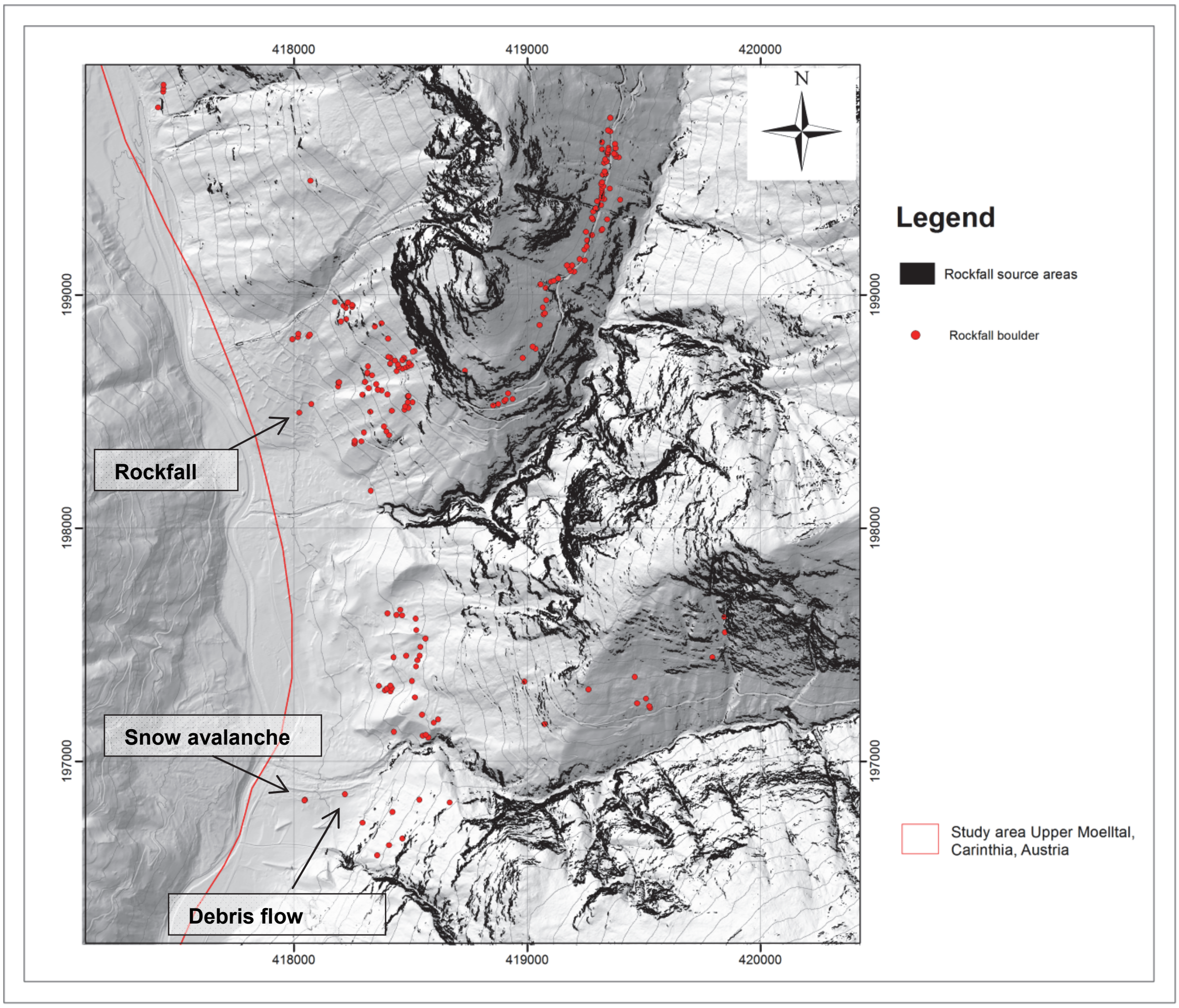
In the *Steinerwand* mapping domain, the majority of boulders have volumes of less than 10 m^3 (Text-Fig. 5.42). Of those boulders of less than 10 m^3, the occurrence frequency is almost uniformly distributed; slight clustering occurs between 0.5 m^3 and 1 m^3 and between 5 m^3 and 10 m^3.

In the *Stampfen* mapping domain to the north of *Talzuschub Wetschenkopf*, the majority of boulders again have volumes of less than 10 m^3; almost no blocks were found to be greater than 10 m^3 (Text-Fig. 5.42). Of those boulders of less than 10 m^3, the occurrence frequency is almost uniformly distributed; slight clustering occurs between 0.1 m^3 and 0.2 m^3 and between 1 m^3 and 2 m^3.

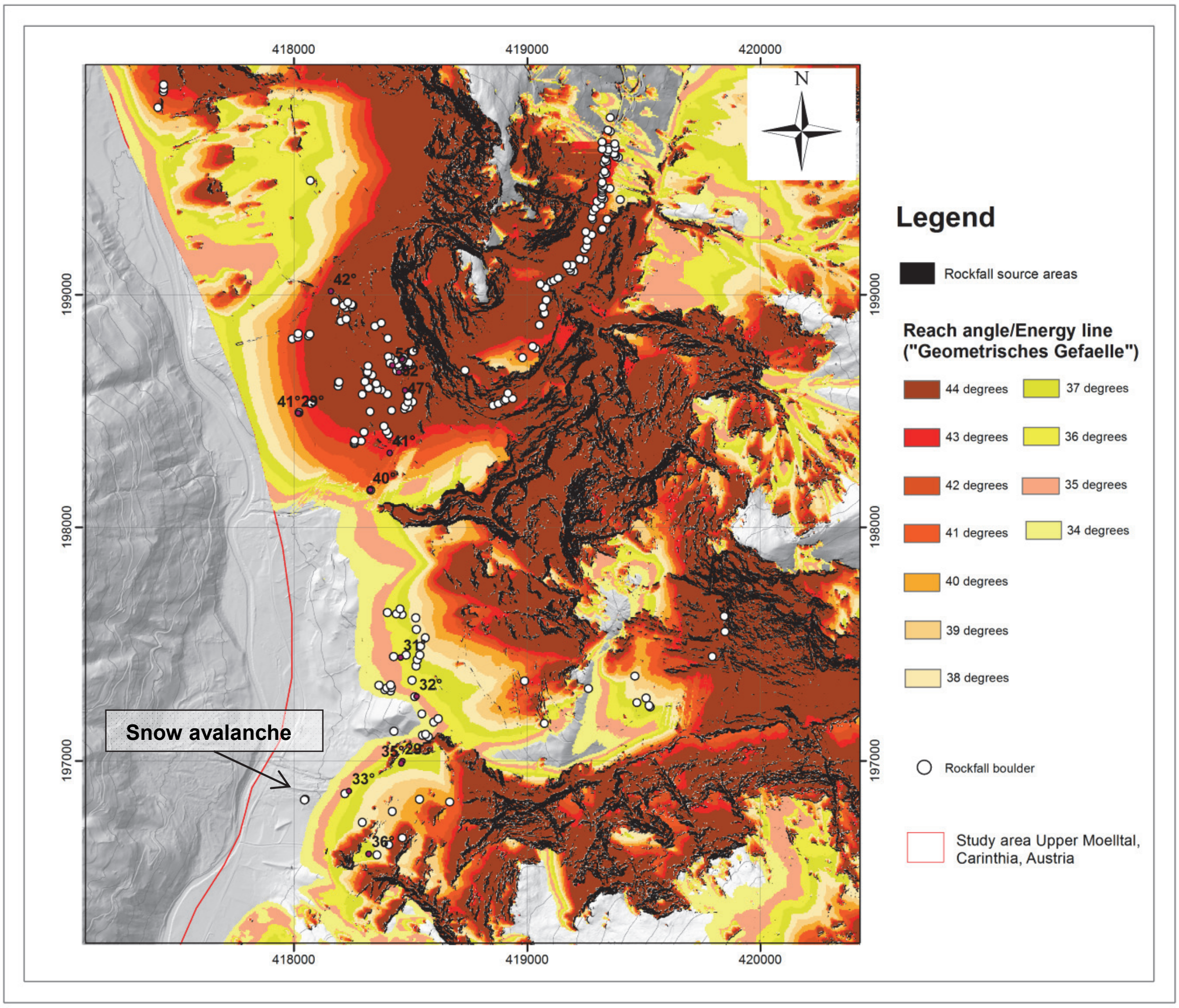
5.3.2 The definition of rockfall susceptibility zones

The potential runout zones associated with future rockfall events can be determined from mapping the spatial distribution of boulders derived from past rockfall events (Text-Fig. 5.43). As described in Chapter 5.3.1, these boulders are frequently moved or removed by the inhabitants within or close to settlements. As a result, this type of analysis does not always provide accurate information with regard to the maximum reach of past rockfall events. Furthermore, areas that have not thus far been affected by rockfall events cannot be incorporated into the defined susceptibility and/or hazard zones because no boulder can be used to categorise these areas. It is, therefore, necessary to apply methods based on detailed knowledge so that the results may be extrapolated over larger areas.

Within the framework of the MassMove Project, two approaches have been applied in order to construct runout susceptibility maps at the regional scale (for details, see Chapter 4.4). The Department of Engineering Geology (GBA) applied a reach angle approach (German: *Geometrisches Gefaelle*) to identify runout susceptibility zones. DORREN et al. (2011) undertook a three-dimensional simulation of the entire study area using the software *Rockyfor3D*, based on highly generalised input parameter maps. The results of these two approaches have been compared with the spatial distribution of recorded events and mapped boulders. In the vicinity of *Moertschachberg*, all the mapped boulders within the maximum reach are captured by reach angles varying between 39°, in the worst case, and 42°, in the best case (see table 5.7). The model outputs also show a good accordance with the reach angles measured in the field using an inclinometer. The boulder with the maximum reach (see Text-Fig. 5.44) is associated with measured angles of 38° (apex of the main cliff) and 41° (apex of the highest cliff). It was also possible to measure the shadow angle of 29° at this location. This suggests that boulders will reach this point again in the future, if a shadow angle of 27.5° (HUNGR & EVANS, 1988) is applied. In the vicinity of the houses close to the *Asten River*, reach angles in the field were observed to be between 40° and 41°. In contrast, most of the mapped boulders beneath the southwest facing cliffs of the *Goaschnigkopf* are represented by a much lower reach angle of about 34°. This is predominately due to the fact that this area is more susceptible to large volume rockfalls and rock avalanches, which have far greater runouts due to the different process mechanism. In the vicinity of the *Steinerwand*, most of the rockfall blocks are represented by the model at angles ranging from 39° to 43°. As previously described in Chapter 5.3.1, it is highly probable that a considerable number of past rockfall boulders fell directly into the *Moell River*. Therefore, lower reach angles may occur than that of the measured minimum value of 39°.



Text-Fig. 5.43: The delineation of susceptibility zones based on the spatial distribution of boulders derived from past rockfall events. (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia.



Text-Fig. 5.44: A comparison of the boulders mapped and reach angles measured in the vicinity of *Moertschachberg* and *Goaschnigkopf* with the results of the empirical runout model (*Geometrisches Gefaelle*). (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia.

The three-dimensional simulation model constructed using Rockyfor3D generates a variety of different output files (DORREN et al., 2011). These may then be used for susceptibility and/or hazard zonation (for further details, see MELZNER et al., 2011a,b,c and MELZNER, 2011b). For the model comparison, it was decided that the output file "nr_passages" should be used. This file depicts the number of blocks that have passed through each cell. It also reflects the maximum reach of the rockfall boulders. In Text-Fig. 5.45, the results of four block scenarios (0.125 m^3, 1 m^3, 8 m^3, and 64 m^3) are displayed without the effects of a forest cover. A comparison of the boulders mapped in the vicinity of *Moertschachberg* and *Goaschnigkopf* with the results of the three-dimensional model shows that the trajectories of the small volume block scenarios (orange and pink) fail to represent all mapped blocks. In contrast, the larger block scenarios (green and blue) most probably overestimate the potential maximum reach of future rockfall processes and, as a result, too large an area may theoretically be endangered by rockfall processes (up to the *Moell River*).

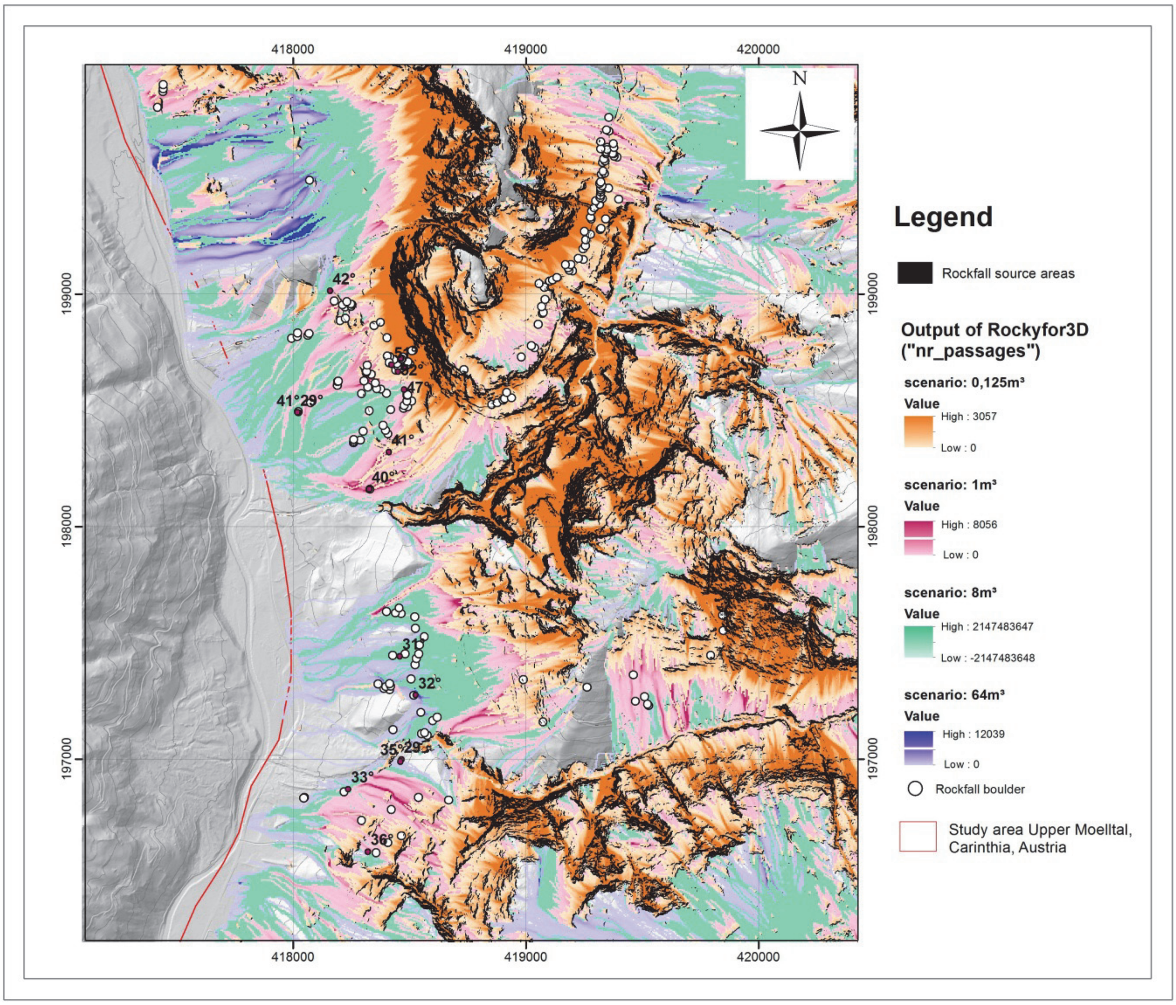
The model parameters applied to three-dimensional simulation were based upon highly generalised maps (for a detailed description regarding the quality of the underlying geological data, see Chapter 2.3). As a consequence, it is difficult to define reproducible criteria relating to the "appropriate" trajectories required to delineate the susceptibility zones. Using a line to connect the end points of the various trajectories would produce a comparable result to that of the before mentioned reach angle approach.

Area	Model output [°] representing the mapped boulders	Reach angle measured in the field [°]	Remarks
Moertschachberg	39-42	40-41	2009 event: 51-52° (on road)
Goaschnigkopf	34-38	31-32	2003 event: 32° (next to embankment: boulder was stopped by another accumulated boulder)
Steinerwand	39-43	36-42	2000 event: 37° (on road)
Plattenberg	38-40	35-36	Two blocks transported by snow avalanche next to houses: <33°
Asten	43-44	Not possible	Most of the blocks stopped due to the road or vegetation

Table 5.7: A summary of the characteristic reach angles for different parts of the study area. The reach angles have been both automatically generated and measured in the field.

As previously stated by MELZNER et al. (2010c), DORREN et al. (2011), and MELZNER et al. (2011b), susceptibility maps produced at the regional scale serve as a first indication of potentially endangered areas. They should, therefore, only be used as a basis with which to plan more detailed assessments at local scale. To avoid the misuse of these output data, its resolution could be altered so that the grid size is coarser. Alternatively, the resolution of the digital terrain model (ALS data) could be altered at the outset of the simulations so that it is consistent with the quality of the other available input data (mainly at the scale of 1:50,000).

More accurate simulations are required if the results are to be applied to specific landuse planning issues, such as defining so-called "brown indication areas" within the concept of hazard zoning in Austria. For a two-dimensional model, this requires the construction of a sequence of representative slope profiles for each predefined homogeneous sub-unit. For a three-dimensional model, this requires spatially continuous mapping of the required input parameters (for further details, see MELZNER et al., 2011b).



Text-Fig. 5.45: A comparison of the boulders mapped in the vicinity of *Moertschachberg* and *Goaschnigkopf* with the results of the three-dimensional model constructed using Rockyfor3D by DORREN et al. (2011). (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM: BEV and Federal State Government of Carinthia. Source of situation data: © BEV 2011, reproduced with the permission of the BEV (Bundesamt für Eich- und Vermessungswesen, T2011/80609).

6. Potentially endangered areas and the need for site-specific assessments at the slope scale

As described in the previous chapters, rockfalls within this region are commonly associated with **deep-seated slope deformations**. These slope deformations have come to fundamentally shape the landscape hereabouts. The specific characteristics of the slope deformation (e.g. location and mechanism) are defined by the varying lithological and structural anisotropy of rock. For a specific deformation, rockfall may occur within the scarp area, along/within the main body, or along the oversteepened frontal part. This depends on the type of mass movement (e.g. rock slides, sagging slopes etc.) and its stage of development (initial, developed, or final stage).

Within the study area, most of the slopes are covered by **scree** or **moraine deposits** due to the glacial and post-glacial development of the landscape. The mobilisation or remobilisation of boulders is a common phenomenon that may be caused by erosion processes, mass movements, or windthrow. Such "secondary" rockfalls are liable to be triggered throughout the study area and it is, therefore, impossible to sufficiently constrain the source areas for this type of rockfall.

Typically, **steep cliffs** close to settlements occur within the Upper Austroalpine *Prijakt-Polinik Complex.* The lithological properties of this complex and the orientation of its rock mass structure (gently dipping from the NW to NE) favour the development of significant rockfall source areas. Field investigations demonstrated that these **cliffs** are generally **very susceptible** to rockfalls due to the heterogeneous anisotropy of this lithological unit. The heterogeneous anisotropy may result in a range of failure mechanisms as well as considerable diversity in block size and shape. As described in Chapter 5, those areas subject to detailed field investigations (e.g. *Moertschachberg*, *Asten Road*, *Goaschnigkopf* and *Steinerwand*) show slight differences with regard to their **onset susceptibility**:

- The cliffs at *Moertschachberg* are characterised by small-scale transitions in lithology and the degree of fracturing. These small-scaled transitions between competent and less competent rock together with the ongoing process of detachment along a few widely spaced discontinuities sets are likely to cause selective weathering and subsequent susceptibility to comparatively large volume rockfalls.
- In contrast, the southwestern slopes of *Goaschnigkopf* are characterised by two large rockfalls. The lithology is more homogeneous due to the greater proportion of very competent and hard orthogneiss and paragneiss. Within and adjacent to the old scarp areas are block accumulations or rock masses with a very loose composition.
- The lower part of the cliffs along the *Asten Road* is characterised by steep and massive rock faces. The number of brittle faults increases from the *Prijakt-Polinik Complex* towards the *Melenkopf Complex*. This results in rockfall source areas that are very small but highly fractured and loosened.
- The westerly to northwesterly facing cliffs at *Steinerwand* have been constructed from a sequence of scarps generated by several large volume rockfall events. It is striking that the scarps follow the same orientation as some of the dominant fault planes, which occur with a high degree of separation.

Within the *Moell Valley*, the almost entirely preserved glacial and post-glacial relief ensures that slope inclinations range from 35° to 50°. It is unsurprising that a high number of rockfall boulders reach houses and infrastructure along the valley floor given the high slope inclination and competent nature of the lithology.

Smaller boulders, in particular, are frequently moved or removed by local residents close to or within settlements. This creates a specific challenge with regard to **mapping the maximum reach of past rockfall events**. Along the Asten Road and in the area of Steinerwand, it can be assumed that several blocks have been transported directly into the Asten or Moell Rivers respectively. As a result, the maximum reach of past rockfall events is likely to be underestimated. This is important to recognise as the maximum reach is required in order to validate the runout models. It is also possible to use the maximum reach in order to define **runout susceptibility zones**.

However, this technique is somewhat unreliable and cannot be applied in areas without rockfalls. It is, therefore, necessary to apply two-dimensional or three-dimensional runout models in order to delineate the susceptibility of hazard zones at the **local scale**.

Evidence for past **rockfall activity** is necessarily collected in order to determine the extent to which an area is "hazardous". Nearly all the cliffs within the Prijakt-Polinik Complex show numerous fresh detachments relating to past events. During the course of the detailed field mapping, information relating to a number of rockfall events was collected. Table 6.1 shows that several reoccurring rockfall events have taken place within those areas investigated in detail.

It is probable, and in some cases known, that residents do not report events if no damage occurred or if there is no tangible need to (e.g. for the purpose of gaining compensation). It is, therefore, very seldom that a complete rockfall inventory can be established. Indeed, at present, most of the event databases only include information when an exact date is known. The authors wish to stress that qualitative information regarding event frequency within an area should also be included in such databases, perhaps using terms such as "frequent rockfall problems" or "occasional rockfall events". This type of information can usually be obtained from discussions with local residents. It would significantly increase the amount of information known about rockfall occurrence frequency (see map).

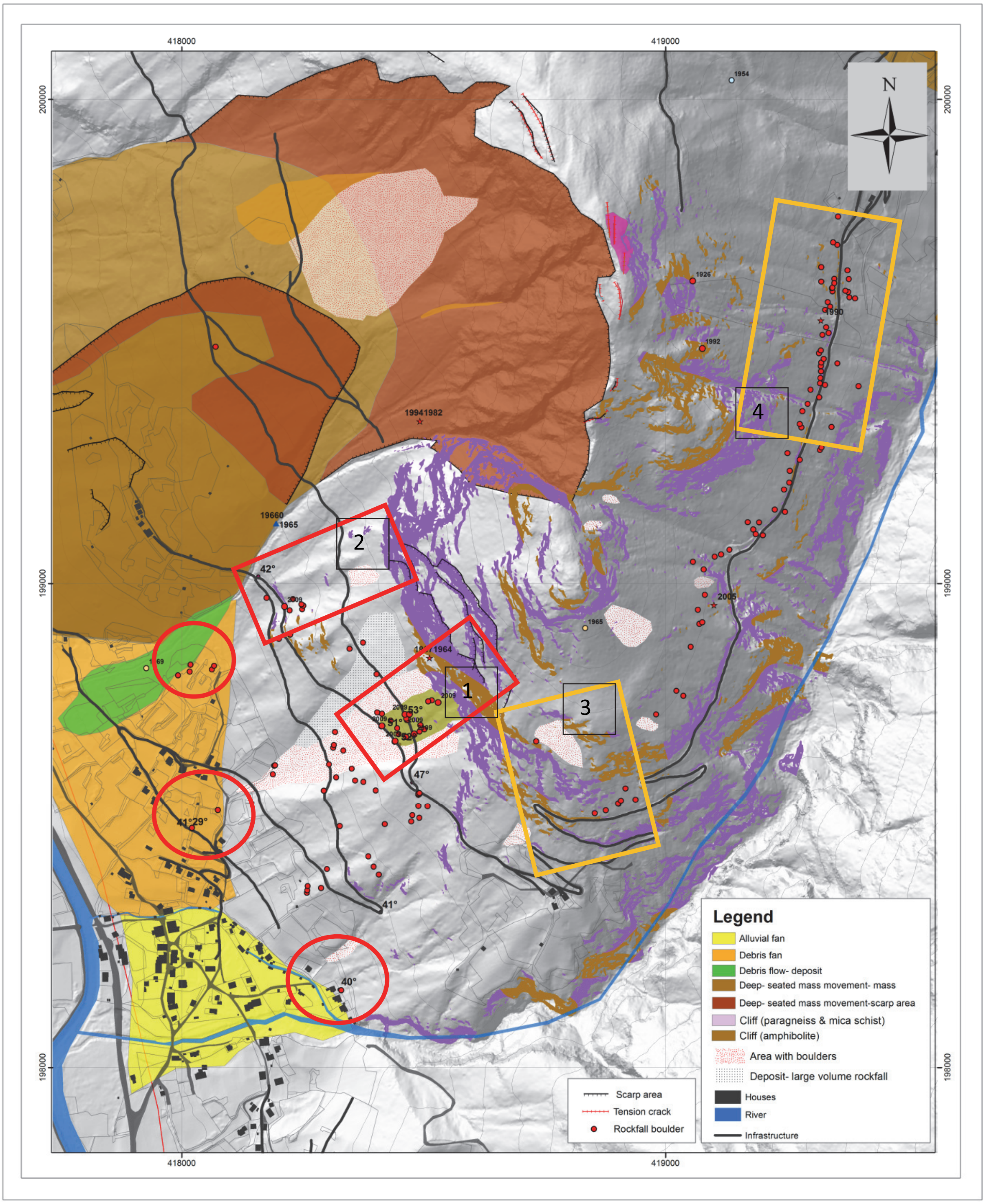
In addition, further evidence for rockfall activity may be found from indicators such as benchmarks on the ground or on trees. By combining all the results obtained at the local scale, it is possible to accurately define those areas that should be subject to further investigations at the local or slope scales.

The southwesterly slopes of *Moertschachberg* are associated with numerous indicators, and these suggest there is a need for a detailed assessment hereabouts. In the upper slope along the *Asten Road*, two events were recorded during fieldwork by the GBA. An event was recorded between 12.00–13.00 on 7th August 2009. This triggered the movement of rock with a total volume of ~7 m^3 (Red box No. 1, Text-Fig. 6.1) and affected both the forest road and the Asten Road (Text-Fig. 5.37). The area above the forest road is characterised by a high number of recent and relict boulders as well as numerous fresh benchmarks on the ground and on trees. Furthermore, the forest is interspersed by corridors in which there is no vegetation. These "aisles in the woods" indicate that the rockfall events occur with high frequency. In addition, the cliffs here also incorporate instable rock masses that may fall in the future (for details, see Chapter 5.2.2.1).

Location	Date of event	Volume (m³)	Type of process	Remarks
Moertschachberg	1964	3	Rockfall	
	1967	3	Rockfall	
	2009	0,1	Mobilization of scree	10.7.2007 (morning), heavy rains the night before, road affected
	2009	7	Rockfall	7.8.2009 (12.00.13.00), road and forest road affected
Asten road				
	1926	1500	Large volume RF (Felssturz)	Asten road affected
	1990	>100	Large volume RF (Felssturz)	
	1992	unknown	Rockfall	Asten road affected
	2005	0,5	Rockfall	
Goaschnig				
	1845	50, prob. even more	Rockfall	
	1992	200-400	Large volume RF (Felssturz)	
	2001	5	Rockfall	Block removed
	2003	70	Large volume RF (Felssturz)	
	2009	0,2	Mobilization of scree	8.7.2009 (morning), heavy rains the night before
Steinerwand				
	1921	unknown	Large volume RF (Felssturz)	Visible in the field
	2000	5	Rockfall	
	2008	small	Rockfall	
	2009	<1m³	Rockfall	16.7.2009 (midday), rain during the day
Kulmerkogel				
	1976	>100	Large volume RF (Felssturz)	Road affected
	1997	40	Rockfall	
	2004	0,1	Rockfall	Property affected
	2004	0,2	Rockfall	Property affected
	2005	unknown	Rockfall	Road affected
	2007	0,2	Rockfall	House affected

Table 6.1: A summary of rockfall event frequency for those areas investigated in detail.

A second rockfall event was observed along the Asten Road by a researcher from the GBA on 10th July 2009. This event moved a boulder with a volume of 0.1 m³ (Red box No. 2, Text-Fig. 6.2). Due to its rounded form, it is probable that the boulder was remobilised from the scree or kames material of the slope. The Federal State Government database lists two further events that occurred in 1964 and 1967. There are also boulders derived from past events lying by the side of the Asten Road.



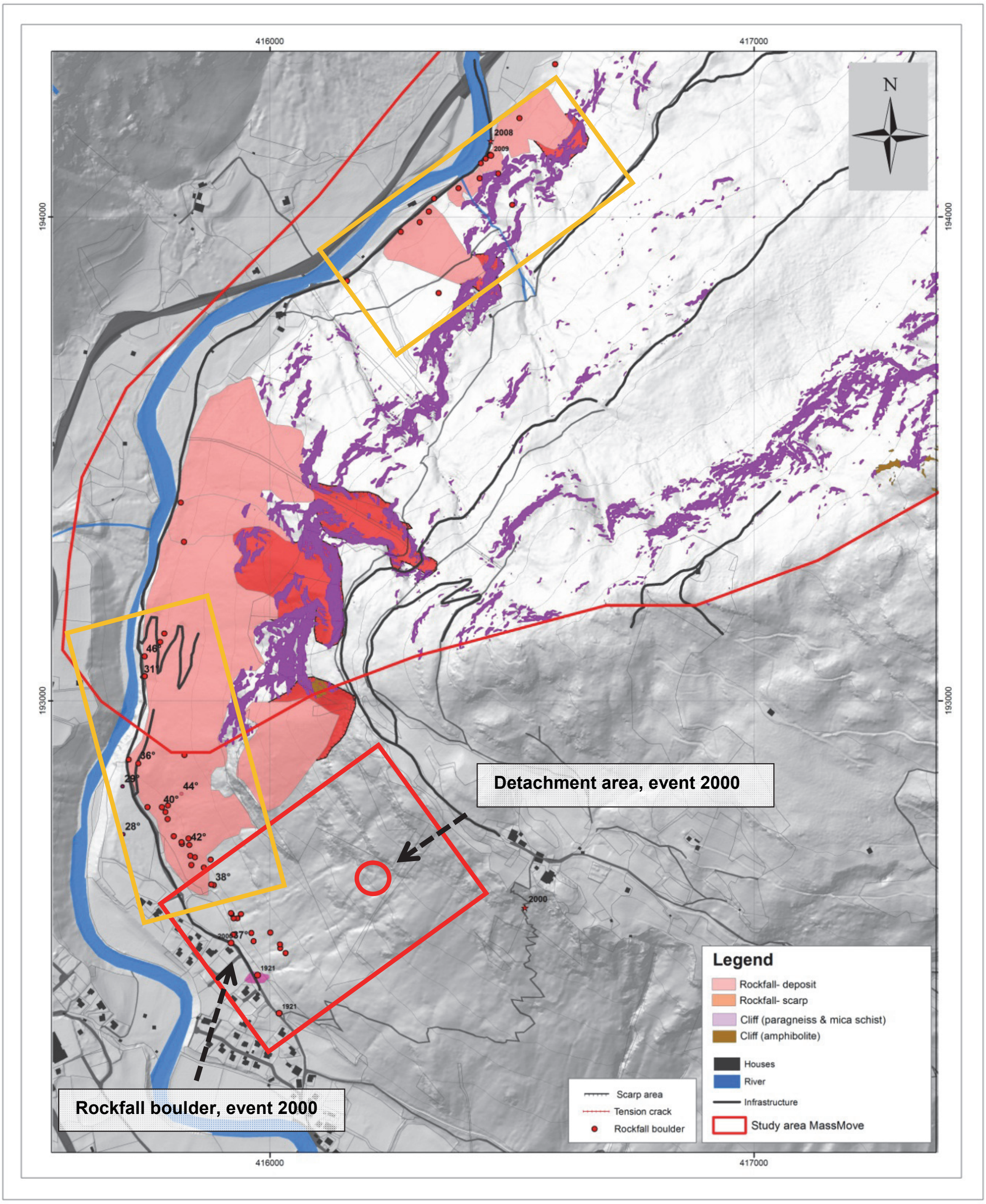
Text-Fig. 6.1: The investigated area of *Moertschachberg* and the *Asten Road*. The red boxes indicate those areas in which site-specific studies are highly recommended. The orange boxes indicate those areas in which the residents described reoccurring rockfall events or where a large number of boulders and fresh benchmarks are visible. The red circles indicate the maximum reach of the mapped boulders. (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM and Digital Land Use Map: BEV and Federal State Government of Carinthia.

It is likely that local residents moved these to their present position. The local residents also report that boulders often reach the road close to where the serpentine occurs (Orange box No. 3, Text-Fig. 6.3). Towards the settlement of Asten, there are numerous boulders and benchmarks on trees (Orange box No. 4, Text-Fig. 6.1).

It is important to note that the *Asten Road* is frequently used by both local residents and tourists. Although warning signs already indicate the potential rockfall hazard, the authors highly recommend that site-specific studies are conducted in relation to the planning of preventive measures (e.g. rockfall fences). In addition, future assessments should include runout simulation at the local scale. Within the *Moell Valley*, mapped boulders indicate that future events are also likely to reach residential areas. Indeed, it is probable that future events will surpass the mapped maximum reach of past rockfall events given the measured shadow angle of ~29° and reach angle of ~41°.

Text-Fig. 6.2: The southwesterly slopes of the investigated area of Moertschachberg. These slopes are associated with numerous rockfall benchmarks on the ground and on trees (left) and corridors in which there is no vegetation (right) due to reoccurring rockfall processes (Source: S. MELZNER, photographic archive of the Geological Survey of Austria).

In addition to the area around *Moertschach*, some parts of *Steinerwand* should also be subject to detailed assessments at the slope scale (Text-Fig. 6.3). It has to be noted that the road beneath the cliffs is not frequently used by vehicles, but is often used by cyclists. In 2000, a boulder with a volume of ~5 m^3 reached this road within the residential area. The maximum reach of past events indicates that this has occurred previously.



Text-Fig. 6.3: The investigated area of *Steinerwand*. The red boxes indicate those areas in which site-specific studies are highly recommended. The orange boxes indicate those areas in which further assessments at local and/or slope scale could be performed. (Fig. by S. MELZNER, Geological Survey of Austria). Source DTM and Digital Land Use Map: BEV and Federal State Government of Carinthia.

In the vicinity is one property, above which are cliffs with a very susceptible rock mass structure that is characterised by steeply dipping discontinuity sets in the direction of the slope. These discontinuity sets may cause plane failure (Text-Fig. 5.33). It is clear that some blocks are already very close to separating completely from the adjacent rock.

7. Conclusions

In Austria, little work has thus far focused on generating spatially-continuous susceptibility or hazard maps. This is in marked contrast to the situation in Italy. The only exceptions are a few regional studies conducted by the Austrian Torrent and Avalanche Control in Tirol and Vorarlberg. An initial attempt to conduct a spatially-continuous rockfall assessment for Carinthia was performed in 2005 (LETOUZÉ et al., 2005). The aim of this assessment was to generate an onset susceptibility map at the national scale using the location of cliffs extracted from topographic maps and the interpretation of existing lithological maps. It has already been shown that rockfall assessments at the national scale are associated with a variety of challenges. These challenges are even greater at the regional scale as there are higher expectations with regard to the quality of the results.

The rockfall assessment presented here faced a range of challenges due to the complex geomorphological, lithological, and tectonic history of the study area. At the beginning of the project, the basic data were of low quality and little information existed with regard to the rockfall susceptibility of that area. It was, therefore, decided that the susceptibility assessment should follow an efficient multi-scale strategy. This integrated a range of spatial scales (regional, local, slope scale) and incorporated different methods, data types, and data qualities. It was specifically designed to maximise the available resources and generate as much information as possible with regard to rockfall susceptibility over a large area.

The **regional scale assessment** focused on identifying potentially endangered areas. This assessment scale is important as it allows a **sustainable and preventative land use planning strategy** to be developed for those areas that are not yet inhabited. The resulting onset and runout susceptibility maps have a scale of 1:50,000. These are **indication maps** to be used for the planning of more detailed assessments at the local scale. Due to the accuracy of the geological base map and the simple algorithms of the reach angle approach, these maps **cannot** be used for **more detailed interpretations** (“zooming-in”) of rockfall susceptibility. In contrast, the rockfall source area map and the geomorphological map may be used at the local and slope scales as these were generated through the analysis of the high resolution laser scan data (ALS). It should be noted, however, that the rockfall source area map contains an automatically generated GIS-layer (48°–50°, depending on the lithological unit) that may depict potential rockfall source areas which do not exist in reality (e.g. anthropogenic cuttings). However, this layer was deliberately included at the regional scale and only modified for those areas investigated in detail. The modifications were only undertaken when the necessary changes could be verified in the field.

The **local scale assessment** focused on specifying rockfall susceptibility around those areas that were defined as potentially endangered in the regional scale assessment. Field mapping was conducted at a scale of 1:10,000 concentrated on rockfall source areas and rockfall accumulation zones. Although the work undertaking during this stage is necessarily much more detailed than it is during the regional assessment, spatially-continuous mapping of the cliffs was often not possible. Thus, the discontinuous nature of this mapping meant that the recorded parameters had to be interpolated based on expert knowledge in order to generate spatially-continuous parameter maps for further susceptibility analysis. As a result, the field data and analysis of results are of high quality whist the interpolated parameter maps and derived onset susceptibility maps have a slightly lower quality. These results can be used for land use planning issues as they provide important information for the planning of runout simulations at the local scale and further site specific studies at slope scale.

In the future, it will be critical to make the step from a **susceptibility assessment** to a **hazard assessment** (for definitions, see the MassMove Glossary). Within the study area, information relating to the age of past events is generally very limited. It is, therefore, impossible to calculate the probability of events occurring in the future. In addition, in contrast to fluvial processes, rockfalls and other gravitational mass movements do not necessarily reoccur at the same location. It is also possible that the initiating and predispositional conditions will change over time and, therefore, so too will the underlying process mechanism. Nonetheless, even if further information relating to the age of past events is available, the number of events deemed to be representative in order to calculate the probability of events occurrence in the future would still need to be determined.

In respect to **future rockfall studies**, the chosen assessment strategy should consider following aspects:

- Irrespective of the scale of the rockfall assessment, it is necessary that the surveyor has a profound field knowledge of the study area.
- The collection of project-relevant data and goal-orientated analysis is time-consuming. It is, however, cost-effective within the context of preventive land-use planning when set against the cost of damage.
- Without a reliable project-relevant set of process data and parameter maps, no realistic rockfall susceptibility or hazard assessment can be conducted.
- An important part of any assessment is the validation of the modelling results with reference to the obtained field data. At present, few techniques are able to validate the methods used in rockfall susceptibility analysis. It is generally done using the location of boulders mapped in the field. However, this technique cannot be applied where no rockfall events have yet occurred or where the boulders have been moved or removed by inhabitants.
- Different runout models require different input parameters (MELZNER et al., 2011b). The required slope surface parameters (e.g. Rn, Rt) needed for some models (e.g. *STONE, HY-STONE*) are very difficult to obtain from field mapping and are therefore often based on values determined from the literature. It

is, therefore, difficult to validate and calibrate these model results in a reproducible way.

- Different runout models produce different outputs in terms of number and content (MELZNER et al., 2011b). It is important to define the required output parameters (e.g. energy or number of accumulated boulders) that can then be used for the runout susceptibility and hazard zoning.
- The application of three-dimensional runout models over large areas (national and regional scale) is only possible using highly generalised parameter maps. It is also, at least with some models (e.g. *Rockyfor3D*), a very time-consuming procedure (mostly in terms of computing). This makes it nearly impossible to validate and calibrate the model results in a reproducible and efficient manner. Thus, the authors emphasise that an empirical approach is better suited to such regional assessments because this method requires only two inputs. The results are similar to those generated by three-dimensional simulation based upon highly generalised parameter maps.
- At the slope scale, more quantitative methods than those presented in this study have to be applied in order to ensure reliable planning of site-specific issues as preventive measures.

The definition of minimum requirements for the generation of susceptibility and hazard maps within the MassMove project were founded on the need to satisfy the requirements of both partner countries (see MassMove Guidelines). In the opinion of the authors, ALS data should be the minimum requirement at all scales of investigation. In many parts of Austria, these data are already available or will be in the next few years.

8. References

BRAUNSTINGL, R., PESTAL, G., HEJL, E., EGGER, H., VAN HUSEN, D., LINNER, M., MANDL, G., REITNER, J., RUPP, C. & SCHUSTER, R. (2005): Geologische Karte von Salzburg 1:200.000. – Geol. B.-A., Wien.

DORREN, L., LIENER, S. & HOESLE, B. (2011): Producing susceptibility maps using 3D rock fall simulations and shallow landslide modelling in the Moelltal and Auental (Carinthia, Austria). – Final report Project MassMove (http://www.massmove.at/fileadmin/downloads/01_MassMove_Endbericht.pdf). (Retrieved 29.11.2011).

EXNER, C. (1962): Geologische Karte der Sonnblickgruppe 1:50.000. – Geol. B.-A., Wien.

EXNER, C. (1964): Erläuterungen zur Geologischen Karte der Sonnenblickgruppe. –170 S., Geol. B.-A., Wien.

FRISCH, W. (1976): Ein Modell zur alpidischen Evolution und Ororgonese des Tauernfensters. – Geol. Rundschau, **65**/2, 375–393, Stuttgart.

FRISCH, W. (1977): Der alpidische Internbau der Venedigerdecke im westlichen Tauernfenster. – N. Jb. Geol. Paläont. Mh., **11**, 675–696, Stuttgart.

FROITZHEIM, F., DERKS, J.F., WALTER, J.M & SCIUNNACH, D. (2008): Evolution of an Early Permian extensional detachment fault from synintrusive, mylonitic flow to brittle faulting (Grassi Detachment Fault, Orobic Anticline, Southern Alps, Italy). – In: SIEGESMUND, S., FÜGENSCHUH, B. & FROITZHEIM, N. (Hrsg.): Tectonic aspects of the Alpine-Dinaride-Carpathian system. – Geol. Soc. Spec. Publ., **298**, 69–82.

FUCHS, G. & LINNER, M. (2005): Die Geologische Karte der Sadnig-Gruppe: Ostalpines Kristallin in Beziehung zur Matreier Zone. – Jb. Geol. B.-A., **145**, 293–301, Wien.

FUCHS, G., LINNER, M. & HEINISCH, H. (1996): Geologische Karte der Sadnig-Gruppe, 1:25.000. – In: FUCHS, G. & LINNER, M. (2005): Die Geologische Karte der Sadnig-Gruppe: Ostalpines Kristallin in Beziehung zur Matreier Zone. – Jb. Geol. B.-A., **145**/3+4, 293–301, Wien.

GOODMANN, R.E. & BRAY, J.W. (1976) Toppling of rock slopes. – Proceedings, Speciality Conference on Rock Engineering for Foundations and Slopes, American Society of Civil Engineers, Boulder, **2**, 201–234.

GOODMANN, R.E. (1980): Introduction to Rock Mechanics. – John Wiley and Sons, New York.

HEIM A. (1932): Bergsturz und Menschenleben. – Beiblatt zur Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich, **77**, 20, 218 S., Zürich.

HOCKING, G. (1976): A method for distinguishing between single and double plane sliding of tetrahedral wedges. – Int. J. Rock Mech. Mining Sci., **13**, 225–226.

HUNGR, O. & EVANS, S.G. (1988): Engineering evaluation of fragmental rockfall hazards. – Proc. 5th Int. Symp. Landslides, Lausanne, **1**, 685–690, Rotterdam.

JABOYEDOFF, M. (2003): Preliminary assessment of rockfall hazard based on GIS data. – In: Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy.

KOÇIU, A., LETOUZÉ-ZEZULA, G., TILCH, N. & GRÖSEL, K. (2006): Gefährdungskarte (KC-29 „Georisiko-Potenzial Kärnten"). – Unveröff. Endbericht, 88 S., Geol. B.-A., Wien.

LETOUZÉ-ZEZULA, G., ATZENHOFER, B., BERKA, R., HEINRICH, M., HELLERSCHMIDT-ALBER, J., LIPIARSKA, I., LIPIARSKI, P., MOSHAMMER, B., POLTNIG, W., POSCH-TRÖTZMÜLLER, G., SCHUSTER, R. & UNTERSWEG, T. (2005): GIS-Generierung einer geologischen Arbeitskarte von Kärnten als Basis weiterführender rohstoff- und angewandt-geologischer Bearbeitungen – Digitale geologische Karte Kärnten. – Unveröff. Endbericht Bund-Bundesländer-Proj. K-C-025/04, Bibl. Geol. B.-A. / Wiss. Archiv, 29 S., Wien.

LINNER, M. & HEJL, E. (2009): Das Unterostalpin. – In: PESTAL, G., HEJL, E., BRAUNSTINGL, R. & SCHUSTER, R. (Ed., 2009): Erläuterungen zur Geologischen Karte von Salzburg 1:200.000. – Geol. B.-A., Wien.

LINNER, M. & FUCHS, G. (2005): Das Ostalpine Kristallin der Sadnig-Gruppe – mit einem Fragment einer unterostalpinen Decke am Südrand des Tauernfensters. – Arbeitstagung Geol. B.-A. Gmünd 2005, 155–158, Wien.

LINNER, M., HABLER, G. & GRASEMANN, B. (2009): Switch of kinematics in the Austroalpine basement between the Defereggen-Antholz-Vals (DAV) and the Pustertal-Gailtal fault. – 9th Workshop on Alpine Geological Studies Cogne/Italy 16.–18.September 2009: Abstract Volume, 53 S., Cogne.

LOTTER, M., MELZNER, S. & KOÇIU, A. (2010): Geotechnisch-lithologische Bewertung der geologischen Einheiten im Bereich des Untersuchungsgebietes „Oberes Mölltal". – Unveröff. Bericht, Geol. B.-A., Wien.

MARKLAND, J.T. (1972): A useful technique for estimating the stability of rock slopes when the rigid wedge sliding type of failure is expected. – Imperial College Rock Mechanics Research Report No. **19**, 10 pp.

MEIßL, G. (1998): Modellierung der Reichweite von Felsstürzen. Fallbeispiele zur GIS-gestützten Gefahrenbeurteilung aus dem Bayerischen und Tiroler Alpenraum. – Innsbrucker Geographische Studien, **28**, Innsbruck.

MELZNER, S. & KOÇIU, A. (2010): Ausweisung potentieller Herkunftsbereiche (Klippen) für Sturzprozesse. – Unveröff. Bericht, Geol. B.-A., Wien.

MELZNER, S., DORREN, L., KOÇIU, A. & BÄK, R. (2010a): Regionale Ausweisung potentieller Ablöse- und Wirkungsbereiche von Sturzprozessen im Oberen Mölltal/Kärnten. – Poster im Rahmen des 12. Geoforum Umhausen 14.–15.10.10, Niederthai.

MELZNER, S., MÖLK, M., DORREN, L. & BÄK, R. (2010b): Comparing empirical models, 2D- and 3D process based models for delineating maximum runout distances. – EGU General Assembly 2010, Session GM8.5/NH3.14 „Rockfall I & II: Detachment, trajectory modelling, deposition and mitigation strategies", 07.05.2010, Wien.

MELZNER, S., TILCH, N., LOTTER, M. & KOÇIU, A. (2010c): Rock fall susceptibility assessment using structural geological indicators for detaching processes such as sliding or toppling. – EGU General Assembly 2010, Session GM8.5/NH3.14„Rockfall I&II: Detachment, trajectory modelling, deposition and mitigation strategies“, 07.05.2010, Wien.

MELZNER, S. (2011a): Geländeerhebungen und Dispositionsanalyse im Oberen Moelltal, Kärnten, Österreich. – Unveröff. Bericht Geol. B.-A., Wien.

MELZNER, S. (2011b): 3D Simulation mittels Rockyfor3d auf der lokalen Hangskala. – Unveröff. Bericht Geol. B.-A., Wien.

MELZNER, S., DORREN, L., KOÇIU, A. & BAEK, R. (2011a): Rockfall susceptibility assessment in the Upper Moelltal, Carinthia, Austria. – EGU, poster session, Vienna.

MELZNER, S., MOELK, M., DORREN, L., REICHENBACH, R. & GUZZETTI, F. (2011b): Rockfall runout modelling for susceptibility evaluation: a multi-scale comparison at different sites. – talk and extended abstract at the "Interdisciplinary Rockfall Workshop 2011", Innsbruck, abstract (http://www.rocexs2011.at/Alle Final Versions/Session 3/Melzner1.pdf), presentation (http://www.rocexs2011.at/Vorträge/Vorträge/Rockfall runout.pdf). (Retrieved 29.11.2011).

MELZNER, S., DORREN, L. & BAEK, R. (2011c): The Interreg IV project – MassMove – Rockfall susceptibility assessment in the Upper Moelltal (Carinthia, Austria). – Interreg IV Italien Österreich. Informationsveranstaltung CYCLORAMA, am 20.10.2011, Monastier di Treviso, Italien.

ONR 24810 Technischer Steinschlagschutz: Begriffe, Einwirkungen, Bemessung und konstruktive Durchbildung, Überwachung und Instandhaltung. Entwurf. – Austrian Standards Institute, 2011.

PESTAL, G., HEJL, E., BRAUNSTINGL, R. & SCHUSTER, R. (Ed.) (2009): Erläuterungen zur Geologischen Karte von Salzburg 1:200.000. – Geol. B.-A., 162 S., Wien.

PREY (1964): Die Matreier Zone in der Sadniggruppe. – In: EXNER, C. (1964): Erläuterungen zur Geologischen Karte der Sonnenblickgruppe. – Geol. B.-A., 131–151, Wien.

SCHMID, S.M., FUEGENSCHUH, B., KISSLING, E. & SCHUSTER, R. (2004): Tectonic map and overall architecture of the Alpine orogen. – Eclogae geol. Helv., **97**, p. 93–117, Basel.

STAUB, R. (1924): Der Bau der Alpen. – Beitr. Geolog. Kt. Schweiz, **52** (N.F. **82**), 272 S., Bern.

TILCH, N. & KOÇIU, A. (2007): Digitale Ingenieurgeologische Karte von Blatt 47 Ried im Innkreis. – Poster Arbeitstagung der Geol. B.-A., 7.–11. Mai 2007 in Linz, (http://www.geologie.ac.at/pdf/Poster/poster_2007_ata2007_tilch_kociu.pdf). (Retrieved 29.11.2011).

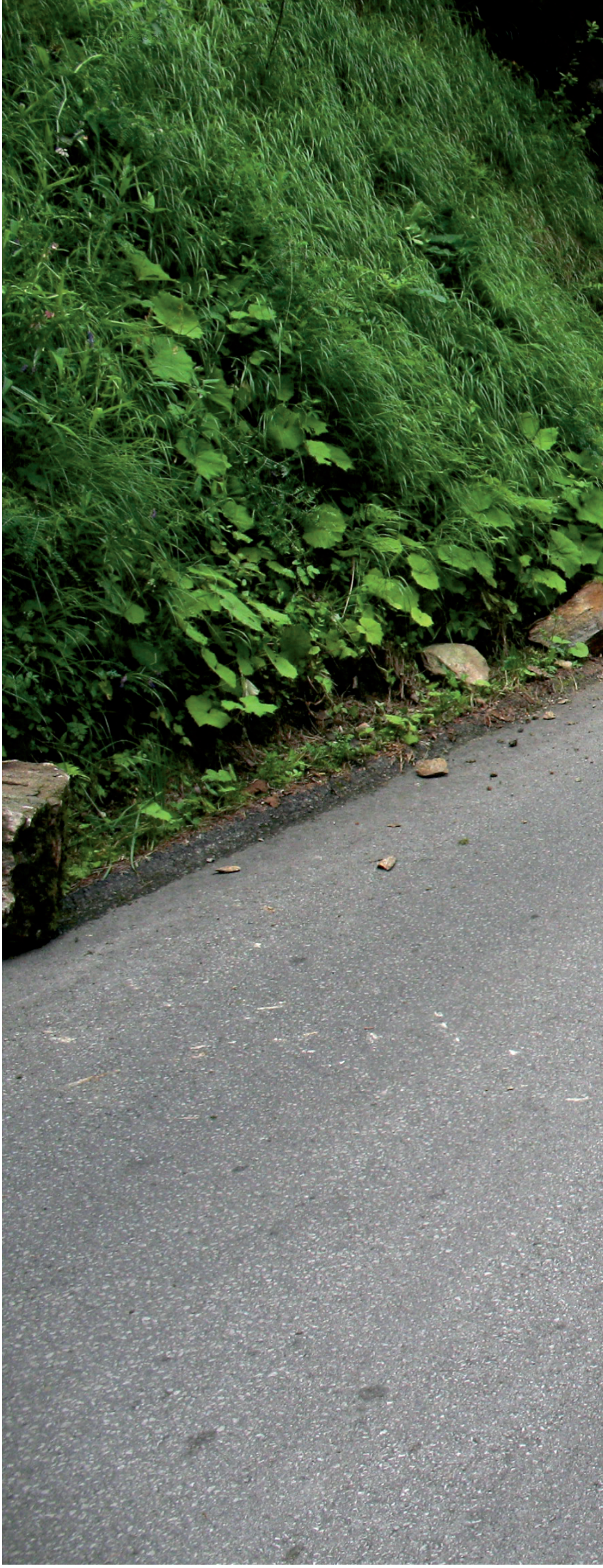
TILCH, N. & SCHWARZ, L. (2010): Erstellung von Dispositionskarten für Massenbewegungen – Herausforderungen, Methoden, Chancen, Limitierungen. – Vortrag Innsbrucker Hofburggespräche 26.05.2010, Innsbruck, (http://bfw.ac.at/050/pdf/IHG260510_Tilch_Schwarz.pdf). (Date of link: 29.11.2011).

TILCH, N., KOÇIU, A., HABERLER, A., MELZNER, S., SCHWARZ, L & LOTTER, M. (2011a): The Data Management System GEORIOS of the Geological Survey of Austria (GBA). – Poster im Rahmen "Interdisciplinary Rockfall Workshop 17.–19.05.2011", Postersession am 18.05.2011, Innsbruck, (http://www.geologie.ac.at/pdf/Poster/poster_2011_tilch_georios.pdf). (Retrieved 29.11.2011).

TILCH, N., SCHWARZ, L. & WINKLER, E. (2011b): Einfluss der Prozessdatenqualität auf die mittels Neuronaler Netze, Logistischer Regression und heuristischer GBA-Methode erstellten Dispositionskarten hinsichtlich spontaner gravitativer Massenbewegungen im Lockergestein und die Ergebnisvalidierung. – Poster 13. Geoforum Umhausen, 20.–21. Oktober 2011, (http://www.geologie.ac.at/pdf/Poster/poster_2011_geoforum_umhausen_tilch_etal.pdf). (Retrieved 29.11.2011).

WYLLIE, D.C. & MAH, W. (2004): Rock Slope Engineering – civil and mining. – 4th ed., 431 S., New York.

"Minimal requirements for
compilation of danger maps
like landslides and rock fall
as a tool for disaster prevention"
(Acronym MassMove)



www.geologie.ac.at