Increased rockslide activity in the middle Holocene? New evidence from the Tyrolean Alps (Austria)

C. Prager & C. Zangerl
AlpS Centre for Natural Hazard Management, Innsbruck, Austria

R. Brandner
Institute of Geology and Paleontology, University of Innsbruck, Austria

G. Patzelt
Former Institute of High Mountain Research, University of Innsbruck, Austria

ABSTRACT: Some of the largest rockslides in the Alps cluster spatially in the Eastern Alps (Tyrol, Austria). A geodatabase was set up to evaluate their timing of failure. Compiled dating data of mass movements show a continuous temporal distribution with accentuations during the early Holocene and, in Tyrol, a significant emphasis of deep-seated rockslides at about 4200-3000 cal BP. Several slopes have been reactivated and show polyphase failure events. However, the majority of dated landslides did not fail immediately after late-Pleistocene glacier-retreat, but clearly a few thousand years later. The middle Holocene rockslide-activity in Tyrol coincides temporally with the progradation of some larger debris flows in the nearby main valleys and, partially, with glacier advances in the Austrian Central Alps. Based on this, deep-seated slope deformations may be induced by complex interactions of lithological, structural and morphological predisposition, fracture propagation, variable seismic activity and climatically controlled water-supply.

1 INTRODUCTION

Several well exposed scarp areas in the Tyrolean Eastern Alps (Austria) provide insights in structures and kinematics of deep-seated mass movements. Based on morphological and lithostratigraphical criteria, the ages of failure were formerly debated controversially. Generally, late-Pleistocene glacier withdrawal, causing an unbalanced relief and thus increasing the stresses within the over-steepened slopes, was assumed to be the most dominant landslides trigger (e.g. Abele 1969, 1974).

But in the majority of cases, radiometric dating of mass movements in the Alps yielded clearly Holocene ages of failure and indicates that slope instabilities are not directly controlled by deglaciation processes. However, in the Western and Southern Alps, a dependency of landslide-activity on climatic fluctuations during the Holocene was assumed already formerly (e.g. Raetzo-Brülhart 1997, Matthews et al. 1997, Dapples et al. 2003, Soldati et al. 2004).

This paper deals with the temporal distribution of dated mass movements in Tyrol (Eastern Alps, Austria) and surroundings, focusing on the Fernpass region. There, several deep-seated rockslides rank among the largest events in the Alps and show a close spatial distribution. One of them, the prominent Fernpass rockslide, was recently dated (Prager et al. 2006a) and forms a temporal cluster with its adjacent rockslides. In view of that, the first comprehensive compilation of dated mass movements in the Eastern Alps was set up and is presented herein. Based on this, several processes that may promote rock strength-degradation and slope failures during the Holocene are discussed.

2 GEOLOGICAL SETTING

The Eastern Alps are made up of complex fold- and thrust-belts of different nappe units, which have been deformed polyphase and heteroaxially. Main geological structures were formed during Cretaceous to Tertiary thrust- and extension-tectonics (Schmid et al. 2004). In Tyrol, the majority of dated mass movements are situated within the polymetamorphic Ötztal basement nappe and within detached Mesozoic cover units of the Northern Calcareous Alps.

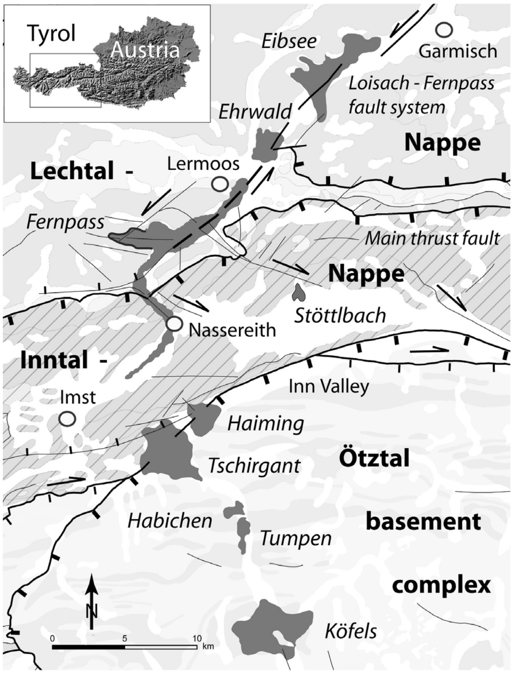

Figure 1. Sketch map of the Fernpass region showing rockslide deposits (shaded dark grey) and main geological structures.

Here detailed field studies at several instable slopes yielded evidence that fault-related valley deepening and coalescence of brittle discontinuities control progressive failure and landslide-kinematics (e.g. Brückl et al. 2004, Prager et al. 2006b, Zangerl et al. 2006). Intensive cataclasis along brittle fracture zones, e. g. the prominent Inntal- and Loisach fault systems (Fig. 1), enabled substantial fluvio-glacial erosion. This morphological change caused stress redistribution of the valley slopes and uncovered favourably oriented sliding planes, permitting subsequent slope instabilities.

3 SEISMICITY

Some major shear systems in Tyrol, e.g. the NE-orientated Inntal- and Engadiner Line, are characterised by recent seismic activity. Compiled earthquake data indicate, that the effective horizontal ground acceleration shows significant maxima of about 1 m/s^2 in the middle Inn valley and the Fernpass region (ÖNORM B 4015 2002). There, several strong earthquakes up to magnitude 5.3 and epicentral intensities I_0 7.5° MSK rank among the most intense ones ever measured in Austria (Drimmel 1980). One of these major events occurred in 1930 in the Fernpass region near the village Namlos. At least 16 main shocks and numerous aftershocks were recorded, whereby this event was subjectively registered even at distances of about 200-400 km. Locally, this earthquake changed the hydraulic flow field by dislocating springs, opened ground clefts and triggered several rockfall events nearby (Klebelsberg 1930).

4 DATA COMPILATION

The considerations presented herein base on detailed field studies of selected mass movements in Tyrol and comparative site visits in the adjacency. In order to evaluate the spatial and temporal distribution of mass movements of different types and sizes, a GIS-linked geodatabase has been set up. At present this includes various data of more than 450 different mass movements in Tyrol and surroundings, ranging from late-glacial to modern failure ages. Thereof approx. 230 events feature unknown ages of failures and/or unknown activity. About 130 post-medieval to recent active landslides have been compiled for Tyrol only and were not considered for this study. Dated fossil mass movements were implemented also from adjacent areas such as southern Germany, northern Italy and eastern Switzerland and comprise at present about 110 events, which are mainly rapid events such as rockfalls and rockslides.

Available laboratory dates of ^{14}C-dated mass movements were calibrated to calendar years (cal. BP, quoted 0 BP = 1950 AD) using the software OxCal Version 3.10 (Bronk Ramsey 2005) and its implemented calibration curve IntCal04. The ranges of the arithmetic mean ages are based on the statistical 2-sigma standard deviation (corresponding to 95.4% probability).

5 SELECTED LANDSLIDES

Some of the largest mass movement deposits in the Alps cluster spatially in the Fernpass region, in the western part of the Northern Calcareous Alps. Within an area of less than 40 × 20 km, at least 9 deep-seated failure events occurred and include the prominent rockslides at Eibsee, Fernpass, Tschirgant and Köfels (Fig. 1).

5.1 *Fernpass rockslide*

The Fernpass rockslide is characterised by two channelled Sturzstrom branches, which contain a rock mass volume of about 1 km^3 and cover excess run-out distances up to 12 and 16 km respectively. This large event was followed by a smaller rockslide of unknown age and the development of a deeply fractured slope that has not failed yet (Fig. 2).

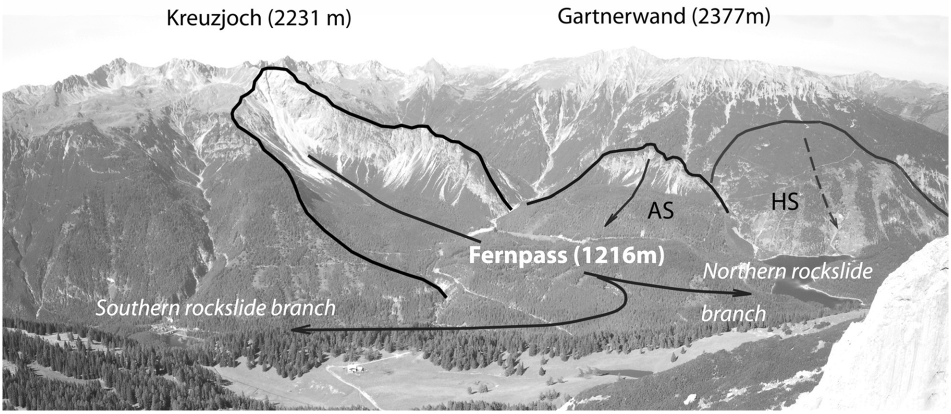

Figure 2. Oblique view to the wedge-shaped scarp of the Fernpass rockslide and its associated mass movements (secondary rockslide "Am Saum" AS, instable slope "Hohler Stein" HS).

The rockslide debris originated from a well exposed and exceptional deeply incised niche, which is made up of platy dolomites, limestones and marls of the several hundred metres thick Seefeld Formation (Norian, Upper Triassic). Polyphase and heteroaxial deformation generated fold- and fracture systems with varying orientation (Eisbacher & Brandner 1995). Thus, the failure zones of the Fernpass rockslide and its juxtaposed slopes evolved by coalescence of brittle discontinuities due to multiple step-path failure mechanisms.

Deep-seated cataclasis along the NE-orientated Loisach-Fernpass fault system (Fig. 1) is here indicated by field data and results of hybrid seismic measurements near the apex of the present Fern-Pass. This clearly revealed a steep pre-failure topography of the valley flanks with a fluvio-glacially undercut slope toe (Prager et al., unpublished data).

Due to an oblique impact of the sliding rock masses against their opposite mountain slope, they were proximally piled up as a remarkably thick debris ridge and split into two Sturzstrom branches. Their run-out was favoured by the large rockslide volume, channelling effects in the narrow valley, dynamic disintegration and, crucially, by undrained dynamic loading of the water-saturated substrate (Prager et al. 2006b).

Formerly, morphological and lithostratigraphical field criteria, e.g. moraine-like debris-ridges, funnel-shaped "dead-ice" sink-holes and the spatial distribution of Pleistocene cover rocks, were used to differentiate between a late-glacial main event and a succeeding postglacial collapse (Abele 1964, 1974). But now detailed field investigations showed that neither the rough scarp nor the intensively structured accumulation area feature any signs of a smooth morphology and argue against glacial overprints.

This was confirmed by the application of three different radiometric dating methods on individual sampling sites (Prager et al., 2006a). Close to the scarp area, rockslide-dammed torrent deposits yielded a ^{14}C minimum-age of 3380–3080 cal. BP. The chronostratigraphic base of this sequence has not been dated yet, but is assumed to date somewhat older into the middle Holocene. This coincides well with two cosmogenic radionuclide ^{36}Cl exposure ages of large-scale sliding planes at the scarp. There the sampled platy dolomites indicate a mean age of 4100 ± 1300 yrs for the failure event. Further data were gained from the curiously and strongly deflected southern rockslide branch. Post-depositional carbonate cements therein have been dated by the $^{230}Th/^{234}U$-disequilibrium method and yielded a minimum age of 4150 ± 100 yrs for the accumulation of the rockslide debris (Ostermann et al., in press).

Based on this, a temporal differentiation between two failure events, one making up the northern rockslide branch, and another, making up the southern branch, is not indicated yet. All dating coincide well and indicate the Fernpass rockslide most likely occurred about 4200–4100 yrs ago. Thus, this event was clearly not in contact with late-glacial ice and not triggered by deglaciation processes.

5.2 *Eibsee rockslide*

The Eibsee rockslide (Fig. 1) is situated 15 km northeast of the Fernpass, on the north-face of the Zugspitze massif (2961 m) the highest mountain in Germany and mobilized about 400–600 mill. m^3 of accumulated debris (Abele 1974, Golas 1996). It originated from a several hundreds metres high and subvertical cliff, built up by mainly well bedded carbonates of the Muschelkalk Group (Anisian) and the thick Wetterstein Formation (Ladinian). Due to Paleogene compression, these Triassic carbonates were thrust over incompetent Jurassic-Cretaceous limestones and marls (Eisbacher & Brandner 1995).

Stability relevant discontinuities for the Eibsee rockslide were not the bedding planes, dipping moderately inclined against the slope, but subvertical fault- and fracture systems. Tunnel constructions for the German rack railway up to the Zugspitze ran across such separation planes and cavities, whereat some of them spaced several metres wide open and occasionally showed a contact to the outside world (Knauer 1933). Field evidence of intense brittle faulting can be observed at the NW-face of the Zugspitze, where NE-orientated, subvertical faults and fractures are part of the sinistral Loisach major shear system (Fig. 1). This caused deep seated intensive fragmentation of the folded carbonates and can, within the precipitous rock walls, isolate blocks along wedge-shaped scarps.

Based on morphological field criteria, the Eibsee rockslide deposits were formerly interpreted as a "late-glacial rockslide-moraine" (Vidal 1953), but several wood samples gained in drillings yielded a mean age of around 3700 ^{14}C yrs (Jerz & Poschinger 1995). The six best fitting, presumably not redeposited, samples were calibrated to calendar years and show an arithmetic mean-age at about 4181 ± 627 cal. BP.

5.3 *Ehrwald rockslide*

At the western base of the Zugspitze massif, the Ehrwald rockslide deposits cover an area of about 2 km^2 (Abele 1974). Its lithological and structural predisposition corresponds with those of the adjacent Eibsee rockslide; both failures were clearly controlled by brittle faulting along the NE-orientated Loisach fault system (Fig. 1).

The carbonate Ehrwald deposits make up hilly scenery with several pronounced ridges and were morphologically classified as "late-glacial rockslide moraine" (Abele 1964, 1974). Thus far, radiometric dating has not been carried out here. However, the internal structure is characterised by an unstratified, coarsening-upward facies, wherein several shattered clasts feature a jig-saw-fit of grain-boundaries. These sedimentary features have not been observed in glacially derived deposits and attribute uniquely to dynamically disintegrated rockslide masses. This and the lack of Quaternary cover rocks and missing glacial smoothing of the topography clearly suggest a Holocene age for the Ehrwald rockslide.

5.4 *Tschirgant – Haiming rockslides*

About 10 km south of the Fernpass, the Tschirgant massif (2370 m) forms a steep rugged NE-SW-trending slope and released two well known, deep seated rockslides down to the river Inn: the smaller Haiming event (25–34 mill. m^3) in the northeast and the prominent Tschirgant rockslide (180–240 mill. m^3, Abele 1974) in the southwest (Fig. 1).

The scarp areas are situated at the southern margin of the Northern Calcareous Alps, which were here obliquely cut off by the NE-SW-striking Inntal fault system and separated from the metamorphic Ötztal basement complex (Eisbacher & Brandner 1995). Slope deformation was clearly structurally controlled by the complex cross-linking of medium inclined bedding planes and subvertical brittle fracture systems. Due to these densely spaced discontinuities, the deeply incised source area of the Haiming rockslide exhibits an unusually rough, stepped scarp. Lithologically this comprises dolomites of the Wetterstein Formation (Ladinian), the carbonate-siliciclastic Raibl Group (Carnian) and the Hauptdolomit Formation (Norian). At the base of the Haiming scarp, a drilling penetrated ca. 670 m subhorizontally into the slope and proved the existence of an effective water-table. Dammed to the South by low permeable siliciclastics, here high pore pressures up to 43 bar came across within the intensively fractured and thus highly permeable dolomites of the Raibl Group (Intergeo Consultants, pers. comm. 2005).

Adjacent southwest, poorly bedded dolomites of the Wetterstein Formation make up the huge Tschirgant scarp. At downslope sections, these competent and dolomites border tectonically to an incompetent succession of the Raibl Group, containing dolomites, limestones, marls and evaporates. Especially the significant carbonate-evaporitic breccias (Rauhwacken), here some decametres in thickness, make up a zone of structural weakness at the slope toe. However, the intensively fractured Tschirgant scarp exhibits several large-scale bedding- and fault planes, dipping desk-like out of the slope and enabling the translational slide of a larger rock mass volume.

The failing debris entrapped fluvio-glacial sediments from the slope toe and valley floors and penetrated into the mouth of the Ötz valley (Fig. 3). Outcrops at the riverside show here polymict fluviatile gravels overridden by carbonate rockslide-debris. Along subvertical pull-apart structures the mobilized valley fill was injected into the rockslide debris, indicating water-saturation of the substrate (Abele 1997).

Based on morphological criteria, Heuberger (1975) assumed an interaction of the Tschirgant rockslide with Late-glacial Ötztal ice. But radiometric dating indicate a Holocene age at about 2900 ^{14}C yrs (ca. 3000 cal. BP, Patzelt & Poscher 1993) for the main event. Further investigations showed that both slopes, Tschirgant and Haiming, did not release only one single event, but are characterised by multiple failures. Patzelt (2004a) differentiated here at least four significant rockslides, all occurring between 3753 ± 191 cal. BP and 3065 ± 145 cal. BP.

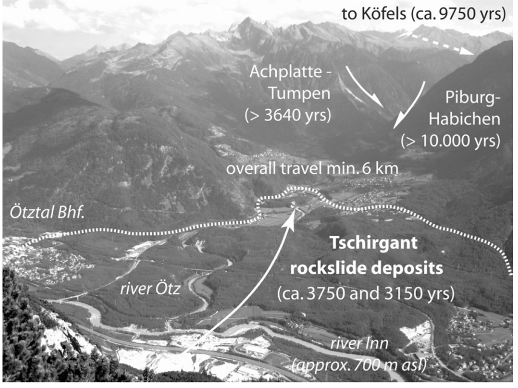

Figure 3. View from the Tschirgant massif towards Southeast to the rockslide deposits and adjacent scarp areas in the northern Ötz valley.

About 10 km to the NE of the Haiming scarp, the Stöttlbach mass movement deposits (Fig. 1) have been dated recently. There, preliminary ^{36}Cl exposure ages of accumulated limestone-boulders indicate a failure event at about 4000–3600 yrs (Kerschner & Ivy-Ochs, pers. comm. 2006).

5.5 *Northern Ötz valley*

The Ötz valley, a N-trending main tributary to the river Inn, is deeply incised in the metamorphic Ötztal basement complex. Its Quaternary valley filling is characterised by the polyphase interplay of different rockfalls, rockslides and their backwater deposits.

The Habichen rockslide deposits (Fig. 1), situated close to the distal deposits of the Tschirgant rockslide, dammed the south bay of Lake Piburg towards the valley floor beneath. Pollen analyses of aggradated lakefronts yielded a minimum age of about 10,000 yrs (Oeggl, pers. comm. 2005) and indicate a similar age for the rockslide barrier.

Adjacent to the southeast, the Tumpen plain exhibits several rockslides and rockfalls, originating from both valley slopes. Based on drillings, the several decametres thick rockslide-dammed backwater deposits show an at least two-phase fluvio-lacustrine sequence. The younger succession provided a minimum age of about 3380 ± 80 ^{14}C yrs (Poscher & Patzelt 2000), i.e. 3640 ± 200 cal. BP, for the damming rockslide. Depth-extrapolations of the existing dating data suggest the older sequence and its damming rockslide barrier date at about 6000 cal. BP (Patzelt 2001).

To the south, the Tumpen backwater deposits border to the largest crystalline mass movements in the Alps, the famous Köfels rockslide. This event features a well established early Holocene age at about 9800 cal. BP (Ivy-Ochs et al. 1998) and dammed the several decametres thick fluvio-lacustrine deposits of the Längenfeld basin.

6 TEMPORAL AND SPATIAL DISTRIBUTION OF DATED EVENTS IN THE EASTERN ALPS

Compiled dating data show a rather continuous temporal distribution of landslides and debris flows during the Holocene, without longer time-gaps (Fig. 4). However, there is no evidence for increased activity due to deglaciation processes during the late-Glacial and early Holocene. In Austria, late-glacial ages have been established for a few landslides only, e.g. an event at Pletzachkogel (Tyrol, Patzelt 2004b) and the prominent Almtal rockslide (Upper Austria, Ivy-Ochs et al. 2005a).

At about 10,000–9000 cal. BP some of the largest rockslides in the Alps failed, e.g. Flims, Kandertal (both Switzerland), Köfels and parts of the slope Gepatsch-Hochmais (both Tyrol). Between approx. 9000 to 5000 cal. BP, only a few and smaller events, with the exception of the large Wildalpen rockslide (Styria, Austria), have occurred.

In contrast, numerous deep-seated events cumulate in the middle to early Holocene, with significant emphasis in the Subboreal at about 4200–3000 cal. BP (Fig. 4). This temporal cluster comprises some of the largest rockslides in Tyrol, which, remarkably, also cluster spatially (Figs 1, 5).

Some radiometric data prove polyphase reactivations of predisposed vulnerabilities and repeated slope failures, e.g. at Tschirgant-Haiming and Pletzachkogel (Inn valley, Patzelt 2004a, b), Köfels and Tumpen (Ötz valley, Ivy-Ochs et al. 1998, Poscher & Patzelt 2000). Several modern landslides show fossil and/or historically documented precursory events, e.g. the catastrophic events at Vajont 1963 (Kilburn & Petley 2003), Val Pola 1987 (Azzoni et al 1992) and Randa 1991 (Santori et al. 2003).

Also dated debris flows show periods of fluctuating activity. Concerning the Tyrolean Inn valley and its tributaries, Patzelt (1987) established phases of raised accumulation at about 9400 ^{14}C yrs (ca. 10,630 cal. BP), between 7500–6000 (ca. 8350–6840 cal. BP) and a third at about 3500 ^{14}C yrs (ca. 3780 cal. BP). According to this, some of the largest alluvial fans in Tyrol and Northern Italy, e.g. the rivers Gadria and Weissenbach, show significant activity at about 7900–7100 cal. BP (Fig. 4). Others, e.g. the rivers Sill and Melach, show raised debris accumulation in the middle Holocene at about 3700–3600 cal. BP. In between these periods, at about 6000–4500 ^{14}C yrs (ca. 6840–5170 cal. BP), the Inn valley was affected by a distinctive phase of fluvial erosion (Patzelt 1987).

Increased fluvial dynamics and debris flow progradation in the Subboreal were established at several sites

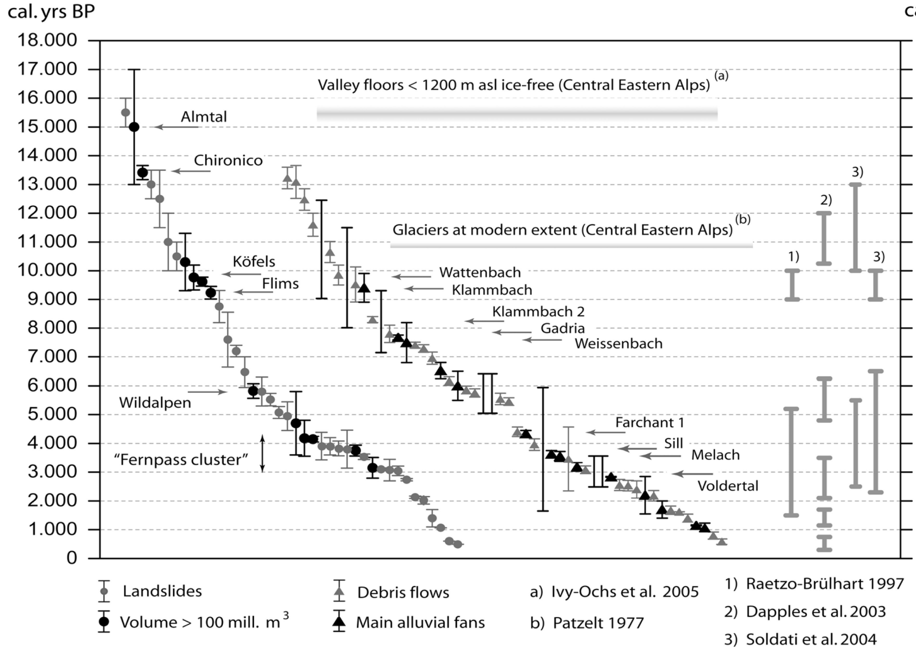

Figure 4. Temporal distribution of Late-glacial to Holocene mass movements in Tyrol and surrondings (vertical axes: calibrated years BP, horizontal axes: dimensionless sequence of dated events; vertical range bars to the right: periods of increased landslide acitivty, according to the references).

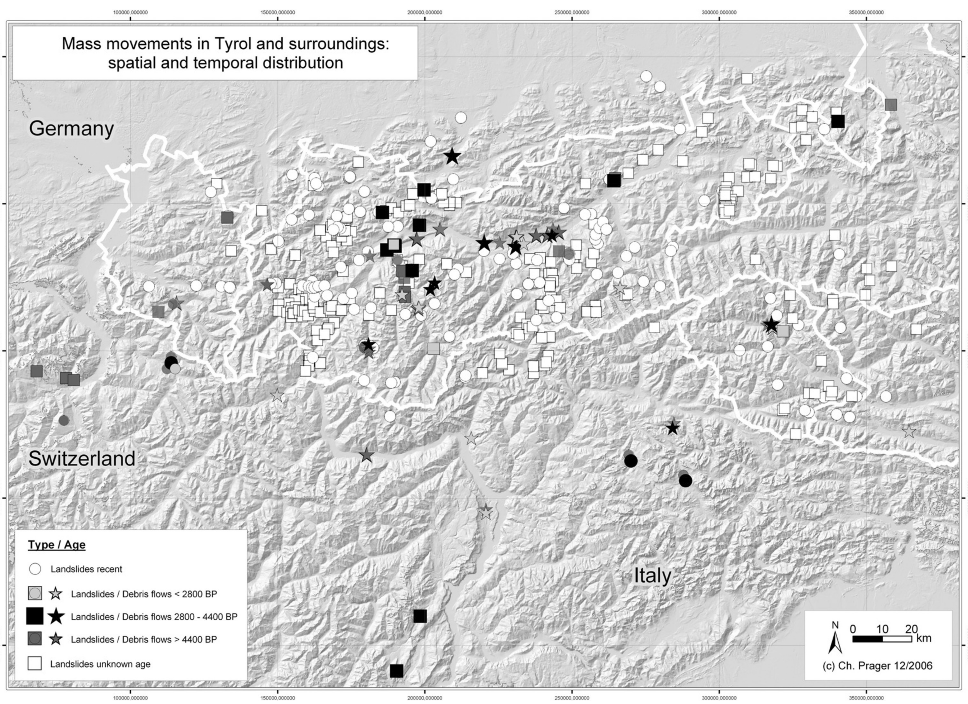

Figure 5. Spatial and temporal distribution of Lateglacial to Holocene mass movements in Tyrol and surroundings.

in Tyrol and have now been compiled in a geodatabase for the first time.

7 DISCUSSION

Detailed field surveys and compiled data indicate that rock strength degradation and slope deformation are controlled by a complex and polyphase interaction of variable processes, which may superpose each other.

7.1 *Deglaciation and decompression*

In the Eastern Alps, stability conditions within the polyphase and heteroaxially fractured rock units were fundamentally influenced by morphological changes during the Quaternary. Late-glacial Gschnitz valley-glaciers advanced, at the type locality in the central Eastern Alps, down to lowermost altitudes of about 1200 m asl not later than 15,400 ± 1400 yrs ago (Ivy-Ochs et al. 2005b). This indicates that the toes of several instable slopes, especially when East- and Southward exposed, such as e.g. at Köfels, Fernpass and Tschirgant, bordered on thin dead-ice or even ice-free valley-floors and however, were not glacial buttressed at least since the Younger Dryas. Subsequently, late-Pleistocene glaciers rapidly melted down till they reached at about 9500 ^{14}C yrs (ca. 10,850 cal. BP) for the first time modern extents (Patzelt 1972, 1977).

Fluvio-glacial erosion, valley-deepening and post-glacial debuttressing uncovered favourable oriented sliding planes and caused substantial stress redistribution within the undercut and oversteepened slopes. Therefore, the high and unbalanced relief since the early Postglacial is certainly a dominant factor for any Alpine mass movement. Subsequently some slopes, characterised by critical fracture density and thus close to their stability limit equilibrium, failed.

7.2 *Progressive failure*

Glacier retreat left oversteepened valley flanks with characteristic unloading fractures, where slope stability was continuously lowered by long-term processes due to stress redistribution. Further rock strength development has been intensively affected by stepwise interactions of pre-existing brittle discontinuities and subcritical fracture propagation (e.g. Eberhardt et al. 2004).

Thereby, complex processes of subcritical crack growth depend on the interaction of several parameters, e.g. in-situ stresses, bedrock mineralogy, fracture geometries and pore-water-characteristics. Being significantly favoured by high pore pressures, a lower bound of fracture propagation velocities ranks at about several centimetres per 1000 years (Atkinson & Meredith 1987).

7.3 *Dynamic loading*

Regional seismic data show that earthquakes close to the Fernpass feature epicentral intensities up to 7.5° and rank among the strongest ones ever measured in Austria. That some of these triggered rockfalls and changed locally the hydraulic flow field (Klebelsberg 1930) suggests, here also the release of fossil rock-slides with similar ages could have been essentially favoured by seismic shaking.

But with the exception of the prominent 1348-release of the Dobratsch rockslide in Carinthia, Austria (Eisbacher & Clague 1984) and some events triggered by the 1998-earthquake in NW-Slovenia (Vidrih et al. 2001), documented case studies of seismically induced slope failures in central Europe are commonly of small dimensions. However, active fault systems can not only trigger mass movements, but do produce intensely fractured and uncemented rock masses to substantial depths, inclusive potential sliding planes.

Moreover, even less energetic earthquakes may accelerate progressive fracture propagation within the shook rock units. Comparable load tests show that component parts with discontinuities show no further fracture propagation under static loading conditions below its critical collapse load. In contrast, dynamic loading initiates fracture propagation far below the critical load (Gross 1996). Such fatigue crack growth can step-wise weaken intact rock bridges and raise the effective joint porosity. Thus, repeated seismic loading can effectively favour and prepare landslides.

7.4 *Climatic aspects*

After the Younger Dryas cold period, glaciers in the Central Eastern Alps rapidly melted down to modern extents. Subsequent glacier- and forest-line fluctuations indicate considerable changes of Holocene climate, whereat glaciers varied about modern sizes and had limited extents over longer periods in the middle and early Holocene (Patzelt 1977, 2001). During the glacial unfavourable period between ca. 10,450–3650 cal. BP both Austrian largest glaciers, Pasterze and Gepatschferner, were repeatedly and even for longer phases smaller than at present, but show from 3650 cal. BP till waning Roman age several smaller and fluctuating advances up to modern dimensions (Nicolussi & Patzelt 2001). Based on this, long periods in the Holocene showed favourable climatic conditions with average summer temperatures predominantly slightly higher than at present. Repeatedly these were interrupted by pronounced but relative short-termed deteriorations with multiple glacier advances (Fig. 6), e.g. the Löbben advance at about 3750–3250 cal. BP (Patzelt & Bortenschlager 1973).

Unstable Holocene climatic conditions are also indicated by glacier fluctuations in the Central Swiss

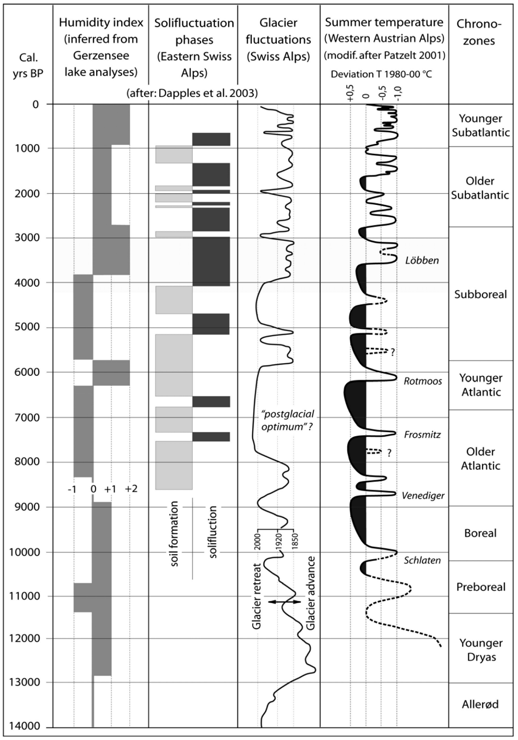

Figure 6. Late-glacial to Holocene paleoclimatic indicators of Lake Gerzensee (−1: dry, 0: normal, +1: wet, +2: very wet), solifluctuation activity and glacier fluctuations (Dapples et al. 2003) with combined glacier- and forest-line data from the Austrian Central Alps (modified after Patzelt 2001).

Alps, featuring at least eight phases of significant glacier recession with several cold-wet periods in between (Hormes et al. 2001).

Compiled dating data of mass movements in Tyrol and surroundings show a continuous temporal distribution of events during the Holocene. At least two age-clusters of enhanced slope instability are characterised by the occurrence of several deep-seated failure events: firstly in the early Postglacial and secondly in the Middle Holocene, with lower landslide activity in between (Fig. 4).

Early Holocene rockslide activity, at about 10,000-9000 cal. BP, comprises some of the largest alpine rockslides, e.g. Köfels, Kandertal and Flims, and is generally assumed to attribute to postglacial warming. This coincides well with an early phase of precipitation-controlled, raised debris accumulation of tributaries to the Tyrolean Inn valley, occurring at about 9400 ^{14}C yrs (Patzelt 1987, i.e. approx. 10,630 cal. BP). Remarkably, compiled data also indicate a significant emphasised landslide activity during the Subboreal about approx. 4200–3000 cal. BP (Fig. 4). This includes some of the largest rockslides in Tyrol, which even cluster spatially in the region Fernpass – Northern Ötz valley (Figs 1, 5). Since theirs releases were clearly not directly linked with deglaciation processes, a striking environmental change was likely to occur during this period.

The Fernpass landslide cluster correlates temporally with the activity of several debris flows in the nearby main valleys (Fig 4). At about 3500 ^{14}C yrs (approx. 3780 cal. BP), a phase of raised alluvial accumulation in the Tyrolean Inn valley was established (Patzelt 1987). This and the activity of several local torrents and debris flows nearby indicate periods of raised water supply in the catchments areas.

Similar groupings of early post-glacial and middle to young Holocene landslides, but with a phase of relative inactivity in between, were established also in the surroundings. In Switzerland, Raetzo-Brülhart (1997) attributes two distinct cluster of raised landslide activity, at about 10,000–9000 and 5200–1500 cal. BP, to warmer and/or more humid paleoclimatic conditions. Dapples et al. (2003) correlate five Lateglacial to Holocene pulses of raised landslide dynamics with climatic deteriorations, indicated by glacier advances, solifluctuation and lacustrine stratigraphical records (Fig. 6).

In the Italian dolomites, Soldati et al. (2004) differentiate also two striking age-clusters of landslides: one early postglacial at about 13,000–9000 cal. BP, which is due to deglaciation processes and was probably favoured by increased precipitation and/or permafrost meltdown, and a younger one, at about 6500–2300 cal. BP in the Subboreal, which is assumed to correlate with an increase of precipitation.

Thus, high groundwater levels, due to increased precipitation, might have climatically controlled Holocene rockslide activity. Raised pore pressures increase the velocity of subcritical crack growth (Atkinson & Meredith 1987) and lower the friction angle of weathered and water-saturated rock surfaces, which is generally lower than those of dry and unweathered ones. Coupled hydro-mechanical destabilising processes are also indicated by drilling-results from the basal Tschirgant massif (Tyrol, Austria), which is characterised by polyphase rockslide events. Here remarkably high pore pressures suggest, deep seated slope deformations could have been favoured by water-saturation of the fractured rock masses. In coincidence, also historical case studies point out that rainstorm is a dominant trigger (Eisbacher & Clague 1984) and pore pressure changes drive slope movements respectively (e.g. Weidner 2000).

8 CONCLUSIONS

Dated mass movements in Tyrol and surroundings have been compiled for the first time and show a rather continuous temporal distribution of events in the Holocene. However, there is no evidence for increased activity due to deglaciation processes during the late-Glacial and early Holocene, but at least for two phases of increased landslide-activity. One at about 10,000–9000 cal. BP and another, spatially clustered, in the middle Holocene at about 4200–3000 cal. BP. Latter comprises the prominent Fernpass rockslide and several large events nearby and coincides temporally with periods of increased debris flows activity in the nearby main valleys. All data indicate, the majority of slope collapses were not directly triggered by late Pleistocene deglaciation processes, but occurred clearly later after a preparing lag-time of several 1000 years.

Well-exposed scarp areas show that slope failures were clearly structurally controlled by fracture propagation and coalescence of brittle discontinuities. Regional earthquake data suggest a considerable neotectonical influence on slope instabilities. Active faulting can directly trigger mass movements, but above all, effectively prepare these by increasing fracture density to substantial depths.

Debris flow activity, glacier fluctuations and case studies from adjacent landslide areas are proxy of paleoclimatic conditions and indicate periods of raised precipitation and groundwater flows. These control pore pressure within the fractured rock masses and favour progressive failure.

Thus, structurally and morphologically predisposed mass movements were prepared and triggered by the complex and polyphase interaction of several rock strength degrading processes. Deep-seated slope deformations may be attributed to initiation, propagation and coalescence of brittle discontinuities, favoured by seismic activity and climatically controlled pore pressure changes. Any of these destabilising processes, even if only at subcritical thresholds, can trigger a failure event if slope stability is already close to its limit equilibrium.

ACKNOWLEDGEMENT

Discussions with Ch. Spötl and H. Kerschner (both University of Innsbruck) and financial support from ILF Consulting Engineers Ltd., TIWAG Tyrolean Hydroelectric Power Company Ltd., p+w Baugrund + Wasser Geo-ZT Ltd. and AlpECON Oeg. (all Tyrol, Austria) are gratefully acknowledged.

REFERENCES

Abele, G. 1964. Die Fernpaßtalung und ihre morphologischen Probleme. *Tübinger Geograph. Studien* 12: 1–123.

Abele, G. 1969. Vom Eis geformte Bergsturzlandschaften. *Zs. f. Geomorph. N. F.* Suppl. 8: 119–147.

Abele, G. 1974. Bergstürze in den Alpen. Ihre Verbreitung, Morphologie und Folgeerscheinungen. *Wiss. Alpenvereinshefte* 25: 1–230. München.

Abele, G. 1997. Rockslide movement supported by the mobilization of groundwater-saturated valley floor sediments. *Zs. f. Geomorph. N. F.* 41(1): 1–20.

Atkinson, B.K. & Meredith, P.G. 1987. The theory of subcritical crack growth with applications to minerals and rocks. In B.K. Atkinson (ed.), *Fracture mechanics of rock*: 111–166. London: Academic Press.

Azzoni, A., Chiesa, S., Frassoni, A. & Govi, M. 1992. The Val Pola landslide. *Eng. Geology* 33 (1): 59–70.

Bronk Ramsey, C. 2005. OxCal Version 3.10. *Computer software*. Online at: www.rlaha.ox.ac.uk/orau/oxcal.html.

Brückl, E., Zangerl, C. & Tentschert, E. 2004. Geometry and deformation mechanisms of a deep seated gravitational creep in cyrstalline rocks. In W. Schubert (ed.), *ISRM Regional Symposium Eurock 2004*: 227–230. Essen: Glückauf.

Dapples, F., Oswald, D., Raetzo, H., Lardelli, T. & Zwahlen, P. 2003. New records of Holocene landslide activity in the Western and Eastern Swiss Alps: Implication of climate and vegetation changes. *Ecl. Geol. Helv*. 96: 1–9.

Drimmel, J. 1980. Rezente Seismizität und Seismotektonik des Ostalpenraumes. In R. Oberhauser (ed.), *Der geologische Aufbau Österreichs*: 507–527. Wien: Springer.

Eberhardt, E., Stead, D. & Coggan, J.S. 2004. Numerical analysis of initiation and progressive failure in natural rock slopes – the 1991 Randa rockslide. *Int. J. Rock Mechanics Mining Sc.* 41: 69–87.

Eisbacher, G. & Clague, J. J. 1984. Destructive mass movements in high mountain: hazard and management. *Geol. Surv. Canada Paper* 84 (16): 1–230.

Eisbacher, G.H. & Brandner, R. 1995. Role of high-angle faults during heteroaxial contraction, Inntal Thrust Sheet, Northern Calcareous Alps, Western Austria. *Geol. Paläont. Mitt. Innsbruck* 20: 389–406.

Golas, B. 1996. Der Eibseebergsturz, Eine geomorphologische Studie. *Dipl. Thesis*: 1–96. Univ. Innsbruck.

Gross, D. 1996. Bruchmechanik: 1-218. Berlin: Springer.

Heuberger, H. 1975. Das Ötztal. Bergstürze und alte Gletscherstände, kulturgeographische Gliederung. *Innsbrucker Geograph. Stud.* 2: 213–249.

Hormes, A., Müller, B.U. & Schlüchter, C. 2001. The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. *The Holocene* 11 (3): 255–265.

Ivy-Ochs, S., Heuberger, H., Kubik, P.W., Kerschner, H., Bonani, G., Frank, M. & Schlüchter, C. 1998. The age of the Köfels event. Relative, 14C and cosmogenic isotope dating of an early Holocene landslide in the Central Alps (Tyrol, Austria). *Zs. Gletscherkd. Glazialgeol.* 34 (1): 57–68.

Ivy-Ochs, S., Van Husen, D. & Synal, H.-A., 2005a. Exposure dating large landslides in the Alps: Almtal. 10th *Int. Conf. Accel. Mass Spectrometry*: Poster session II. Berkeley, CA.

Ivy-Ochs, S., Kerschner, H., Kubik, P.W. & Schlüchter, C. 2005b. Glacier response in the European Alps to Heinrich event 1 cooling: the Gschnitz stadial. *J. Quatern. Sc.* 21: 115–130.

Jerz, H. & Poschinger, A. 1995. Neueste Ergebnisse zum Bergsturz Eibsee-Grainau. *Geol. Bavarica* 99: 383–398.

Kilburn, R. J. & Petley, D. N. 2003. Forecasting giant, catastrophic slope collapse: lessons from Vajont, Northern Italy. *Geomorphology* 54: 21–32.

Klebelsberg, R. 1930. Das Nordalpenbeben vom 8. Oktober 1930. *Mitt. Dt. u. Österr. Alpenverein* 12: 251–254.

Knauer, J. 1933. Die geologischen Ergebnisse beim Bau der Bayerischen Zugspitz-Bahn. *Abh. Geolog. Landesunters. Bayer. Oberbergamt* 10: 23–50.

Matthews, J.A., Brunsden, B., Frenzel, B., Gläser, B. & Weiß, M.M. (eds) 1997. Rapid mass movement as a source of climatic evidence for the Holocene. *Paläoklimaforschung Spec. Iss*. 19 (1-6):1–444. Stuttgart: Fischer.

Nicolussi, K. & Patzelt, G. 2001. Untersuchungen zur Holozänen Gletscherentwicklung von Pasterze und Gepatschferner (Ostalpen). *Zs. Gletscherkde. Glazialgeol*. 36 (2000): 1–87.

ÖNORM B 4015 2002. Belastungsannahmen im Bauwesen – Außergewöhnliche Einwirkungen – Erdbebeneinwirkungen. *ÖNORM B 4015, Ausgabe 2002-06-01*: 1–59. Wien: Österreichisches Normungsinstitut.

Ostermann, M., Sanders D., Kramers, J. & Prager, C. in press. Aragonite and calcite cement "boulder-controlled" meteoric environments on the Fern Pass rockslide (Austria): implications for radiometric age-dating of catastrophic mass movements. *Facies*, in press.

Patzelt, G. 1972. Die spätglazialen Stadien und postglazialen Schwanklungen von Ostalpengletschern. *Ber. Dt. Bot. Ges.* 85: 47–57.

Patzelt, G. 1977. Der zeitliche Ablauf und das Ausmass postglazialer Klimaschwankungen in den Alpen. In B. Frenzel (ed.), *Dendrochronologie und postglaziale Klimaschwankungen in Europa*: 248–259. Wiesbaden: Steiner.

Patzelt, G. 1987. Untersuchungen zur nacheiszeitlichen Schwemmkegel- und Talentwicklung in Tirol. *Veröff. Mus. Ferdinandeum* 1987 (67): 93–123.

Patzelt, G. 2001. Natur und Mensch im Ötztaler Gebirgsraum der Nacheiszeit. *Manuscript, Inst. f. Hochgebirgsforschung*. Univ. Innsbruck.

Patzelt, G. 2004a. Tschirgant-Haiming-Pletzachkogel. Datierte Bergsturzereignisse im Inntal und ihre talgeschichtlichen Folgen. *Presentation.* alpS Symposium 13.10.2004. Galtür.

Patzelt, G. 2004b. Die Bergstürze vom Pletzachkogel bei Kramsach und ihre talgeschichtlichen Folgen. *Presentation*. Geokolloquium 11.03.2004. Univ. Innsbruck.

Patzelt, G. & Bortenschlager, S. 1973. Die postglazialen Gletscher- und Klimaschwankungen in der Venedigergruppe (Hohe Tauern, Ostalpen). *Zs. Geomorph. N. F.* Suppl. 16: 25–72.

Patzelt, G. & Poscher, G. 1993. Der Tschirgant-Bergsturz. *Arbeitstagung 1993 Geol. B.-A., Geologie des Oberinntaler Raumes:* 206–213.

Poscher, G. & Patzelt, G. 2000. Sink-hole Collapses in Soft Rocks. *Felsbau, Rock and Soil Engineering* 18 (1): 36–40.

Prager, C., Patzelt, G., Ostermann, M., Ivy-Ochs, S., Duma, G., Brandner, R. & Zangerl, C. 2006a. The age of the Fernpass rockslide (Tyrol, Austria) and its relation to dated mass movements in the surroundings. *Pangeo Austria 2006*: 258–259. Innsbruck: University Press.

Prager, C, Krainer K., Seidl V. & Chwatal, W. 2006b. Spatial features of Holocene Sturzstrom-deposits inferred from subsurface investigations (Fernpass rockslide, Tyrol, Austria). Geo.Alp 3: 147–166.

Raetzo-Brülhart, H. 1997. Massenbewegungen im Gurnigelflysch und Einfluss der Klimaänderung. *Arb.-Ber. NFP 31*: 1–256. Zürich: Hochsch.-Verl. ETH Zürich.

Sartori, M., Baillifard, F., Jaboyedoff, M. & Rouille, J.-D. 2003. Kinematics of the 1991 Randa rockslides (Valais, Switzerland). *Natural Hazards Earth System Sc*. 2003 (3): 423–433.

Schmid, S., Fügenschuh, B., Kissling, E. & Schuster, R. 2004. Tectonic map and overall architecture of the Alpine orogen. *Ecl. Geol. Helv*. 97 (1): 93–117.

Soldati, M., Corsini, A. & Pasuto, A. 2004. Landslides and climate change in the Italian Dolomites since the Late glacial. *Catena* 55: 141–161.

Vidal, H. 1953. Neue Ergebnisse zur Stratigraphie und Tektonik des nordwestlichen Wettersteingebirges und seines nördlichen Vorlandes. *Geol. Bavarica* 17: 56–88

Vidrih, R., Ribicic, M. & Suhadolc, P. 2001. Seismogeological effects on rocks during the 12 April 1998 upper Soca Territory earthquake (NW Slovenia). *Tectonophysics* 330 (3-4): 153–175.

Weidner, S. 2000. Kinematik und Mechanismus tiefgreifender alpiner Hangdeformationen unter besonderer Berücksichtigung der hydrogeologischen Verhältnisse. Ph.D. Thesis: 1–257. Univ. Erlangen-Nürnberg.

Zangerl, C., Prager, C., Volani, M. & Brandner, R. 2006. Structurally controlled failure initiation of deep seated mass movements. *Geophys. Res. Abstr.* 8: 03516.