21 Giant “Bergsturz” Landscapes in the Tyrol

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Abstract

The line connecting the Zugspitze and the central Ötz Valley is characterized by a remarkably high density of large prehistoric landslides, with distinctive “Bergsturz” landscapes in their deposition areas. Those events north of the Inn Valley (e.g., Fernpass, Tschirgant) originated in carbonate rock units and those south of the Inn Valley in metamorphic rocks (e.g., Köfels). All events were geologically predisposed by complex fold-, fault- and fracture systems. The failed slopes mobilized substantial rock mass volumes and led to the accumulation of fluvio-lacustrine backwater sediments. Temporally, these early and middle Holocene landslides cluster with other events in the surrounding regions in the Alps. The landslide accumulation areas are characterized by rough debris and rather permeable terrain, and are therefore unfavourable for agricultural use. Distinctive forest ecosystems often dominated by Scots pine (*Pinus sylvestris*) are best adapted to these conditions. Whilst the deposition areas of large landslides were—and are still—obstacles for traffic and unfavourable for many types of land use, they are often perceived as appealing and scenic, and are therefore popular for recreational activities.

Keywords

Landslide • Rock avalanche • Rockslide • Backwater sediments • Land cover

21.1 Introduction

The Ötz Valley represents a major tourist destination in summer and even more so in winter. Many guests approach their holiday resorts straight from the north, crossing the Northern Calcareous Alps to the Inn Valley before entering the Ötz Valley. On busy days, their cars get stuck in traffic jams in a place known as Fernpass where the road is winding through an undulating, forested mass of blocky material. Some lake sites crowded with tourists are passed on the way. Having overcome this nuisance, observant travellers note another hilly mass of blocks spread over the entrance of the Ötz Valley, vegetated by sparsely developed pine forests. Several more rock masses are passed on the way through the Ötz Valley. Most impressive, between Umhausen and Längenfeld—nearby the village of Köfels—the road passes a steep gorge incised hundreds of metres deep into an undulating barrier of crushed rocks.

Travellers and scientists have thought about the origin of these rock masses—mainly the one of Köfels—for almost two centuries. Escher von der Linth (1845) interpreted the Köfels barrier as the result of a gravitational mountain collapse. The presence of fused rocks led to the hypothesis of volcanic activity (Pichler 1863) or a meteorite impact (Stutzer 1936; Suess 1937; Bond and Hempsell 2008). Whilst seismic activity was brought into discussion too (Trientl 1895), more recent studies mainly interpret the phenomenon as the deposit of a prehistoric giant landslide. The other rock masses all the way from the Fernpass to the central Ötz Valley are interpreted in similar ways, and a considerable amount of work has been published with regard to the characteristics, dynamics and timing of these events

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C. Embleton-Hamann (ed.), *Landscapes and Landforms of Austria*, World Geomorphological Landscapes,
https://doi.org/10.1007/978-3-030-92815-5_21

(e.g., Ampferer 1904, 1939; Abele 1974, 1997b; Preuss 1974; Ivy-Ochs et al. 1998; Erismann and Abele 2001; Prager et al. 2006, 2007, 2008, 2009a, b, 2012; Prager 2010; Patzelt 2012a, b, Zangerl et al. 2021; Nicolussi et al. 2015; Ostermann and Prager 2014, 2016; Dufresne et al. 2016a, b, and references therein). Some of these events were characterized by long run-out distances of several kilometres, most likely favoured by the enormous landslide volumes, by dynamic disintegration and, crucially, by interaction with the saturated valley fills.

Compared to other regions in the Alps, the area between the Fernpass and the central Ötz Valley displays spatial clustering of large landslide deposits. Table 21.1 lists the major characteristics of the most notable landslides in this region, whilst Fig. 21.1 provides an overview of their spatial distribution. Other events such as Eibsee or Ehrwald have occurred in the vicinity (Abele 1974; Prager et al. 2008; Prager 2010; Ostermann and Prager 2016), but are not subject of the present chapter.

With this background, one may raise a number of questions. The following ones will be addressed—and as far as possible answered—within the next sections:

1. Why is there a spatial concentration of large prehistoric landslide events in this specific area—i.e., what were the geological and geomorphological factors predisposing the events?
2. What were the temporal patterns of occurrence, and can they be helpful to draw conclusions on the triggers of the mass movements?
3. Which types of habitats do the deposits of the large prehistoric mass movements support?
4. How do those events reflect themselves in the patterns of today's cultural landscape?

Before diving into the issue more deeply, some terms have to be defined. The term "landslide" is used throughout as a general description for all types of gravitational mass movements (Cruden 1991: 27: "*A landslide is the movement of a mass of rock, earth or debris down a slope*"). Concerning this work, reference is made to a practical and useful classification based on the type of material (rock, soil) and type of movement (slides, falls, topples, spreads and flows) of Cruden and Varnes (1996). The term "rock avalanche" describes rapid rockslide and "flow" processes, commonly larger than 1 million m^3 in volume, with a substantial degree of dynamic fragmentation and often displaying long run-out distances, even on only gently inclined valley floors (also referred to as "Sturzstrom"; e.g., Heim 1932; Hsü 1975). The German term "Bergsturz" is commonly applied to a variety of large, rapid rock slope collapses (Abele 1974) and may comprise major rock falls, rockslides and rock avalanches (see, e.g., Erismann and Abele 2001; Hungr and Evans 2004).

Table 21.1 Major characteristics of the landslides considered in the present chapter

Name	Age (ka)	Rock types	Volume (million m^3)	Travel distance (km)	Angle of reach (°)	Selected references
Fernpass	4.1–4.2	Dolostone, marl, limestone	1000[a]	15.5[b]	5.3[b]	Abele (1964, 1997b), Prager (2010), Prager et al. (2006, 2008, 2009a, 2012)
Tschirgant	3.7–3.5[c] 3.0–3.2	Dolostone, breccia, limestone, rauhwacke	100–125[a] 200–250[d]	6.2	12.7	Pagliarini (2008), Patzelt (2012a), Dufresne et al. (2016a; b), Ostermann and Prager (2016)
Haiming	3.7–3.5[c] 3.0–3.2	Dolostone, breccia, limestone	25–60[d]	2.4	13	Abele (1974), Patzelt (2012a)
Habichen	≥ 11.5	Orthogneiss	27[d]	2.9	18.2	Prager et al. (2008), Ostermann and Prager (2016)
Achplatte	≥ 3.6[e]	Orthogneiss	60[d]	2.2	24	Ostermann and Prager (2016)
Tumpen	≥ 3.6[e]	Orthogneiss	Multiple events	Multiple events	Multiple events	Poscher and Patzelt (2000), Ostermann and Prager (2014)
Köfels	9.5	Orthogneiss, subordinary paragneiss	3100[a] 4,000[d]	5.6	11–12	Prager et al. (2009b), Zangerl et al. (2021), Nicolussi et al. (2015)

[a] Release volume (estimation of scarp area)
[b] Complex accumulation path comprising two rock avalanche braches, data given for the longer (southern) branch
[c] According to Patzelt (2012a), the Tschirgant and Haiming rock avalanches comprise at least two events each; according to Ostermann et al. (2016), at Tschirgant only one accumulation event occurred at approx. 3 ka
[d] Deposition volume
[e] Minimum age of the backwater sediments (Poscher and Patzelt 2000)
See Fig. 21.1 for the spatial distribution of the events

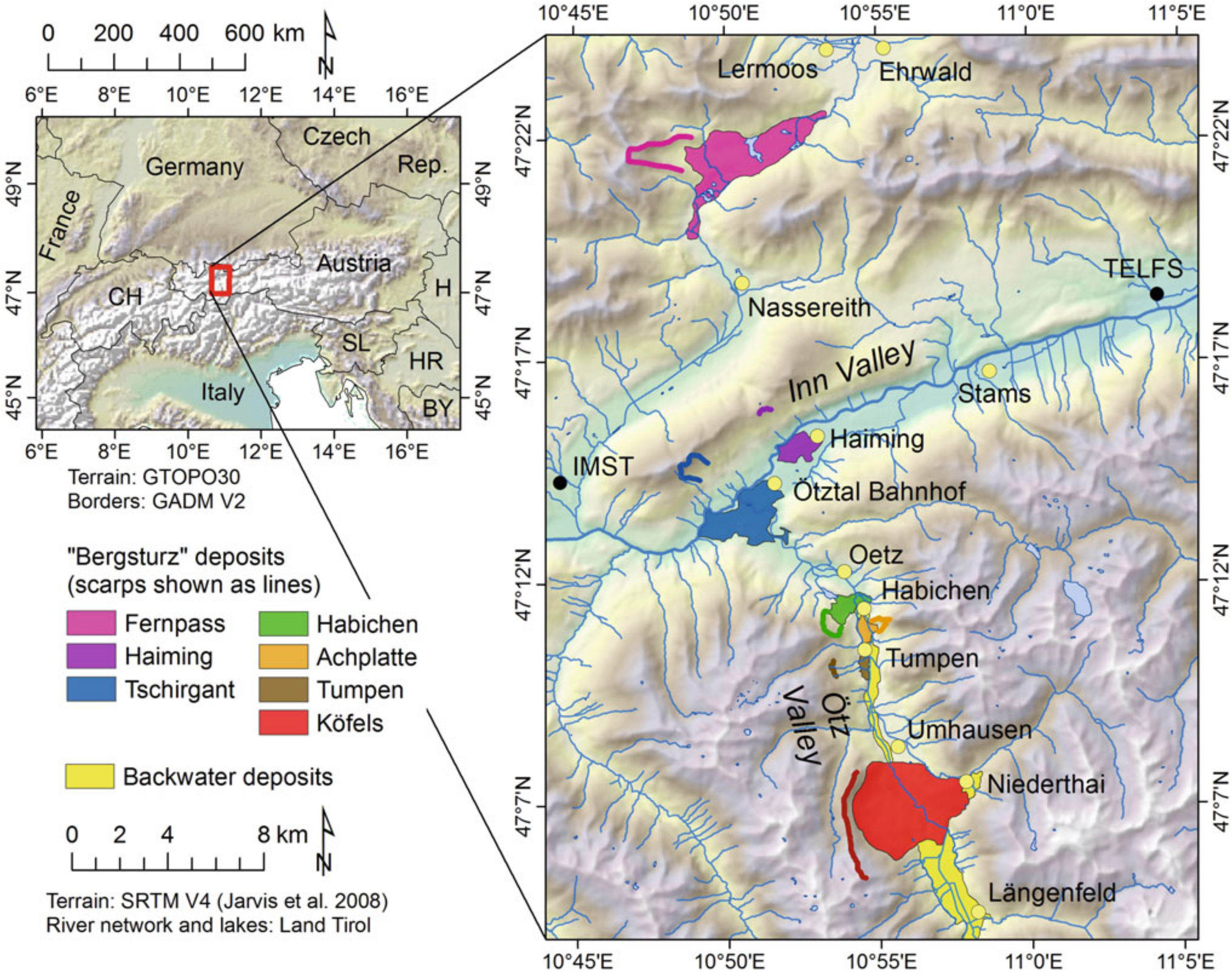

Fig. 21.1 The terrain representation in the right pane is based on Jarvis et al. (2008)

21.2 Geological Setting and Geomorphological Features

The area of interest is composed of Mesozoic sedimentary strata of the Northern Calcareous Alps (north of the Inn Valley) and the Palaeozoic metamorphic Ötztal basement complex (south of the Inn Valley) (Brandner 1980; GBA 2011). The Inn Valley is preconditioned by a major tectonic fault, facilitating glacial and fluvial erosion that shaped the landscape of today. The Ötz Valley, a northward discharging tributary to the W–E-trending Inn Valley, is deeply incised in the Ötztal and Stubai Alps, with a local relief of up to 2500 m.

The Ötztal Alps are made up of poly-metamorphic rocks of plutonic, volcanic and sedimentary origin (orthogneisses, amphibolites, paragneisses and micaschists; see Purtscheller 1978 for a more detailed account). In the medial and lower sections of the Ötz Valley, the landslide masses at Tumpen, Achplatte, Habichen and Köfels (Figs. 21.1 and 21.2c) mainly displaced various types of orthogneisses, embedded in less competent paragneiss units (Purtscheller 1978; GBA 2011; Ostermann and Prager 2016, and references therein). Layering and main foliation mainly trend in W–E direction and are cut by different fault and fracture systems which predisposed the bedrock slope failures. Also the Köfels rockslide, representing the largest known landslide of the Alps in crystalline rocks (Fig. 21.2a, b), was sourced mainly in orthogneisses and structurally predisposed by the coalescence of brittle fracture sets as well as by fault-related valley deepening (Prager et al. 2009b).

In contrast, the Fernpass, Tschirgant and Haiming events occurred in carbonate rocks, which detached from complexly folded and faulted thrust sheets of the Northern Calcareous Alps, the Lechtal nappe in the case of Fernpass and the Inntal nappe in the case of Tschirgant and Haiming

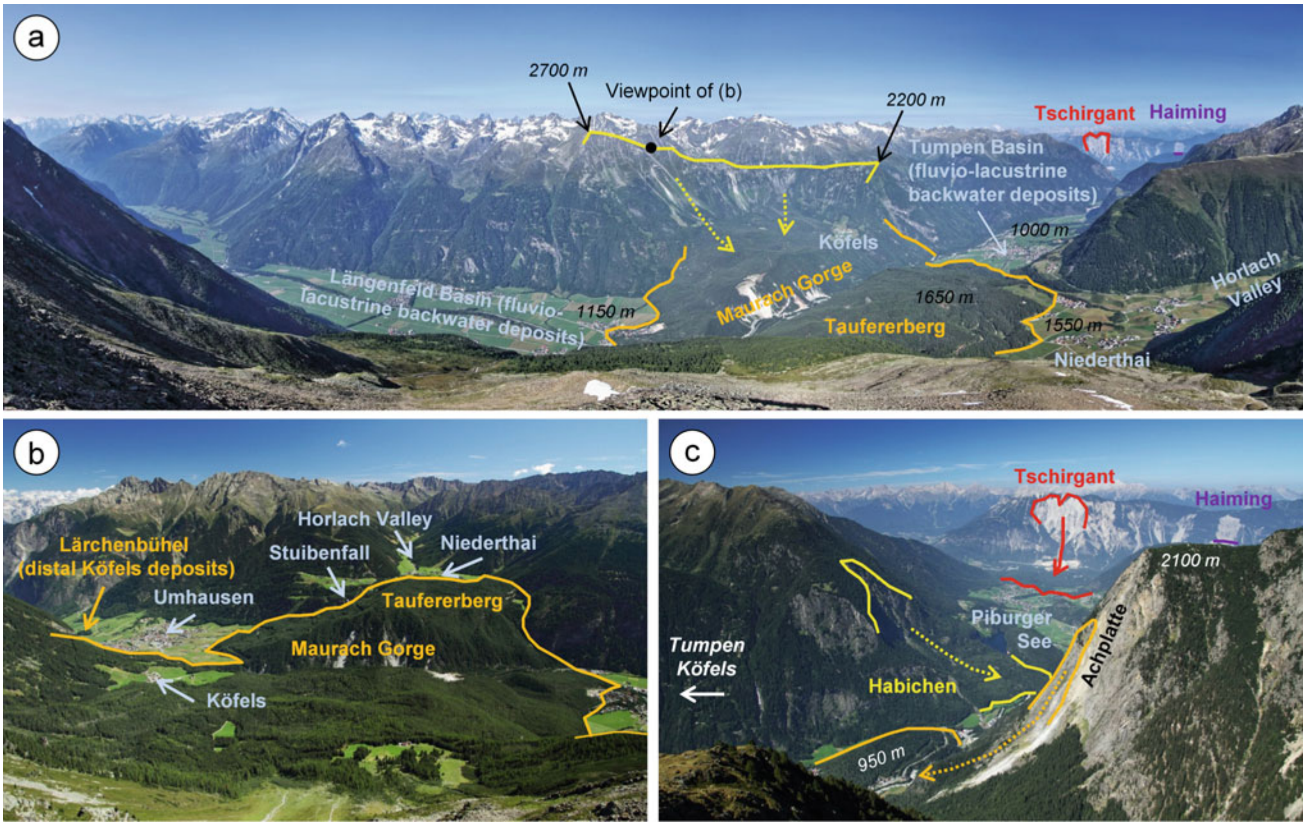

Fig. 21.2 Large landslides of the lower and central Ötz Valley. **a** Panoramic view of the central Ötz Valley with the Köfels rockslide. The left and central background shows the Ötztal Alps (metamorphic rocks), the Northern Calcareous Alps with the headscarps of the Tschirgant and Haiming rock avalanches are seen in the very right background. The river Ötz drains from left to right and the Längenfeld basin represents a backwater area dammed by the deposit of the Köfels rockslide (prior to the incision of the Maurach gorge). The village of Niederthai in the lower right centre of the image is built on a system of terraces of unclear origin. Viewpoint: Hemerkogel; **b** view of the Köfels rockslide from the headscarp; **c** Achplatte and Habichen rock avalanches near the outlet of the Ötz Valley. Lake Piburger See was dammed by the Habichen rock avalanche. The Tschirgant rock avalanche and the headscarp of the Haiming rock avalanche are seen in the background (Northern Calcareous Alps). All line symbols shown are approximate. *Photos* M. Mergili; line symbols modified after Zangerl et al. (2021), Ostermann and Prager (2016)

(Brandner 1980). These events were predisposed by the orientation of bedding planes and fracture systems, dipping out of the slopes and therefore providing preferentially oriented sliding planes (Pagliarini 2008; Prager et al. 2008, 2009a; Ostermann and Prager 2016). The scarp area of the Fernpass rock avalanche consists of dolostones, limestones and marls of the Seefeld Formation (Upper Triassic), several hundreds of metres thick (Prager et al. 2006, 2009a). The scarp area of the Tschirgant rock avalanche is mainly made up by dolostones, breccias and limestones of the Wetterstein Formation (Middle to Upper Triassic), which also represent the main landslide mass. At the lower sections of the failed slope, some weaker units of the lithologically heterogeneous Raibl Group (Upper Triassic) are encountered, including evaporitic strata. Geological field surveys indicate that karst processes may have contributed to the failure (Prager 2010; Prager et al. 2008, Dufresne et al. 2016a). Due to the extremely rugged terrain, the Tschirgant scarp area is still a rockfall-prone site and thus a source of debris flows, indicated also by local site names such as “Breitmure” or “Galgenmure” (the German word “Mure” means debris flow).

The distinctive geometry and topography of the Fernpass rock avalanche deposits indicate an unusual dynamic behaviour and have therefore attracted research for several decades (e.g., Ampferer 1904; Abele 1964, 1975, 1991; Prager et al. 2006, 2009a, 2012; Prager 2010). Figure 21.3 provides panoramic overviews of the scarp and parts of the accumulation area. The initial movement impacted the opposite slope and consequently split into two branches, propagating further in two different directions (Prager et al. 2006, 2012). The northern branch of the rock avalanche—representing the logical continuation of the initial movement—reached a maximum travel distance of at least 10.8 km in the fluvio-lacustrine plain of the Lermooser Moos. More remarkably, the southern part of the rock avalanche was

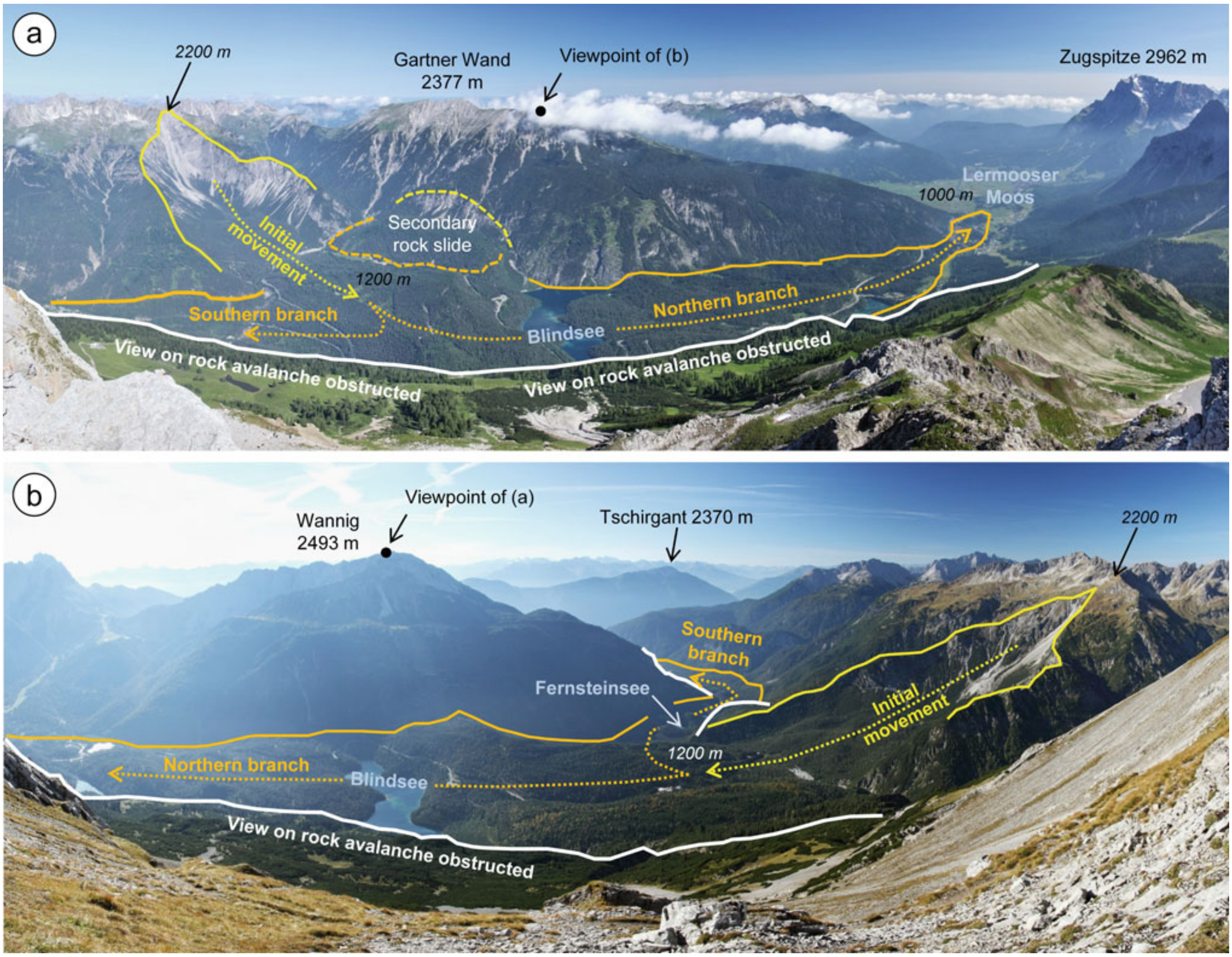

Fig. 21.3 Panoramic views of the Fernpass rock avalanche. **a** Viewpoint: Wannig; **b** viewpoint near Gartner Wand. Note the separation of the rock avalanche into a northern and a southern branch. Only the uppermost section of the southern branch is visible in (**b**). All line symbols shown are approximate. *Photos* M. Mergili; line symbols modified after Prager et al. (2006) and Prager (2010)

deflected by 140° and, after a further curious turn near Nassereith, reached a total travel distance of at least 15.5 km. The angles of reach were extraordinarily low, with 6.7° for the northern and even 5.3° for the southern branch. Prager et al. (2006) inferred that the high mobility of the southern part—despite a comparatively lower volume—was favoured by its propagation over saturated fine valley floor sediments, which were investigated by drillings and geophysical surveys. High pore water pressures could have developed as a response to the undrained loading, due to the inability of the groundwater to escape through the rock avalanche mass (because of the low permeability of the basal sliding zones). The initial rock avalanche deposit was subsequently reshaped by gravitational spreading and creeping, leading to the development of significant extensional structures, e.g., graben with several lakes in the proximal to medial accumulation areas (see also Abele 1972, 1997b), and so-called toma hills in the distal sections of the deposits (Prager 2010; Prager et al. 2012). According to the morphological definition by Abele (1974: 119), toma hills are “isolated, cone- to pyramidal- or roof-shaped elevations, predominately made up by rockslide debris and characterized by more or less planar hill slopes with constant inclination”. The distal portion of the deposition area was also modified by fluvial processes and human activities.

Field surveys and seismic measurements indicate that the proximal Fernpass rock avalanche deposits are some hundreds of metres thick, and that the gravitational collapses of this thick accumulation ridge released the curiously deflected southern branch of the Fernpass rock avalanche (Prager 2010; Prager et al. 2012). Further local particularities of the Fernpass area include springs featuring very high discharge rates (e.g., the Loisach springs) and springs ranking among the most radioactive ones in North Tyrol. Most likely, the

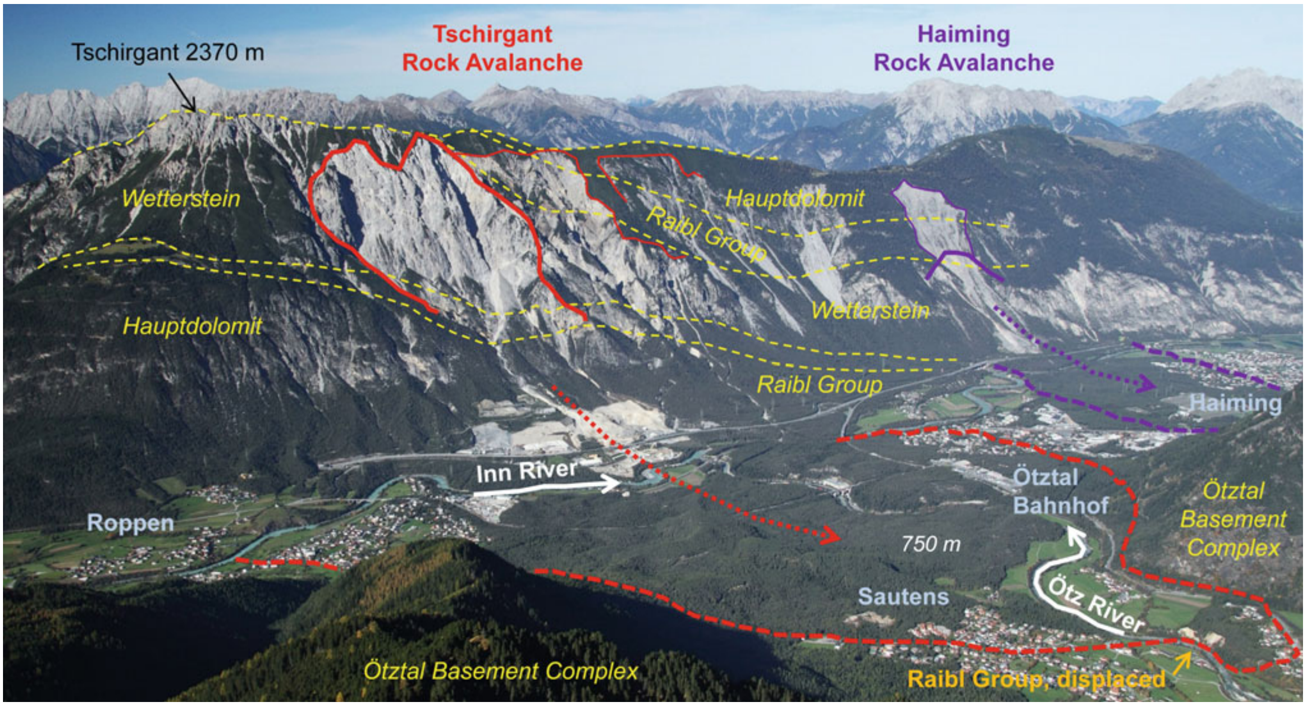

Fig. 21.4 Panoramic view of the Tschirgant and Haiming rock avalanches, with schematic delimitation of lithological units (strata of the Northern Calcareous Alps involved in the events; complex fold- and fault-systems here not depicted). Note that the headscarp of the Haiming rock avalanche is located approximately in the middle of the slope whilst the upward scarp represents an erosional feature. All line symbols shown are approximate. Viewpoint: Blose. *Photo* M. Mergili; line symbols modified after Prager et al. (2008), Patzelt (2012a), Ostermann and Prager (2016), Dufresne et al. (2016a)

known radon emanations in the Fernpass area (Krüse 1937) are to be attributed to intense dynamic fragmentation of the thick landslide rocks, i.e., organically-rich successions of the bituminous Seefeld Formation (for details, see Prager 2010 and references therein).

The Tschirgant rock avalanche (Ampferer 1904, Patzelt 2012a) travelled for a distance of 6.2 km, producing a hummocky landscape with a variety of ridges and depressions (Fig. 21.4). Thereby, the carbonate Wetterstein beds make up the main parts of the accumulation area, with different rocks of the Raibl Group encountered rather at the lateral and distal areas of the deposits (Dufresne et al. 2016a; b). The displaced Raibl beds are well exposed mainly along the banks of the river Ötz (Fig. 21.5, see also Patzelt 2012a). A further very particular feature of the Tschirgant deposit consists in the locally well-exposed basal shear zone. In some places, the substrata (i.e., pre-slide valley deposits) were injected into the landslide debris, and some intermingling took place (Patzelt and Poscher 1993; Prager 2010; Dufresne et al. 2016a, b). Further, the rock avalanche deposit impounded the rivers Ötz and Inn, and thus caused the accumulation of some minor backwater deposits, later eroded to terraces, e.g., in the Roppen and Ambach areas (Ampferer 1904; Ostermann and Prager 2014).

The Habichen, Achplatte and Tumpen rock avalanches (Fig. 21.2c; Heuberger 1975; Poscher and Patzelt 2000; Ostermann and Prager 2014, 2016) disintegrated into relatively coarse blocky masses during motion, resulting in blocks between sub-metre size and >10 m^3, lacking the finer components found in the Fernpass and Tschirgant rock avalanches. The Habichen rock avalanche cut off a drainage channel, and dammed the still existing lake Piburger See. Backwater sediments in the Ötz Valley indicate temporary lakes impounded by all three of the rock avalanches mentioned above.

The prominent Köfels event (Table 21.1 and Figs. 21.1, 21.2a, b) deposited a rather coarse rockslide mass which displays a broad variety of fabrics. The deposits are well exposed in the Maurach gorge, which has been incised by the river Ötz: here, some parts show fractured but rather intact rock slabs; others resemble a fault breccia, with large fragments interspersed in a matrix of crushed material. Other parts are full of fractures, but with lower contents of fine particles. Locally, fused rocks indicate intense shear deformation (frictionites, see below).

The Köfels slide blocked the Ötz Valley—and the outlet of the tributary Horlach Valley—with a dam height of several hundreds of metres. The resulting backwater deposits in the Längenfeld basin upstream reached a depth of up to

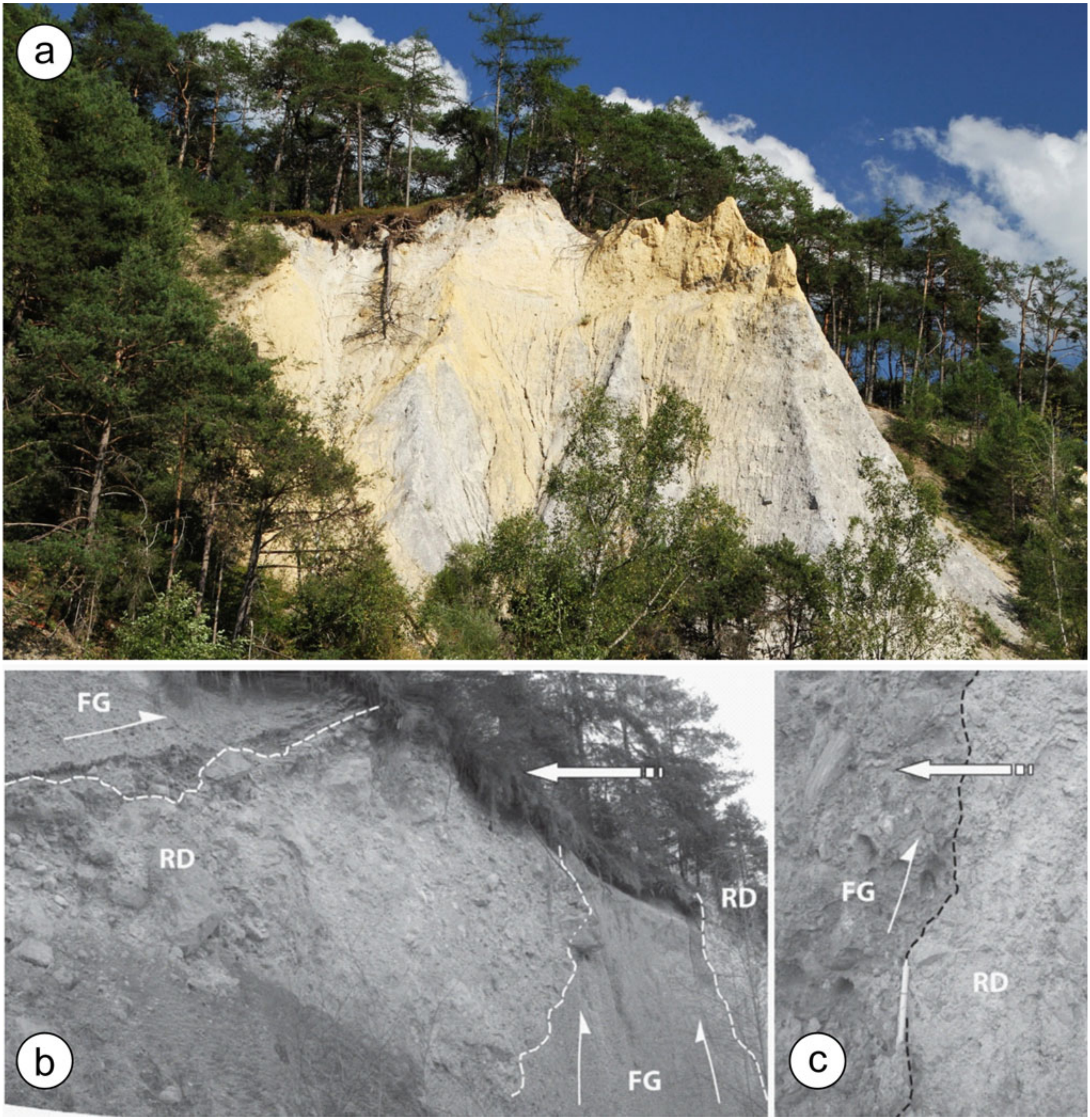

Fig. 21.5 Depositional area of the Tschirgant rock avalanche. **a** Fragmented dolostones and rauhwacken of the Raibl Group, accumulated in the distal part of the deposit of the Tschirgant rock avalanche (see Fig. 21.4 for the location; *Photo*: M. Mergili); **b** and **c** dynamic interaction of rock avalanche debris (RD) and fluvial gravels (FG). Bold arrows indicate the direction of rock avalanche propagation and thin arrows the direction of injection and back-thrusting (Prager 2010; Prager et al. 2012)

100 m (Ampferer 1939; Klebelsberg 1951; Heuberger 1966, 1975). Most likely, the surface of the backwater deposits did not exceed the present-day surface of the Längenfeld basin due to a sufficiently high hydraulic permeability of the Köfels deposits to allow a subsurface drainage (Ampferer 1939; Klebelsberg 1951). The origin of the terraced sediments at Niederthai (in the lower Horlach Valley; Fig. 21.6a) is not yet clear. Presumably a few tens of metres thick, they may relate to a pre-slide (possibly periglacial) origin and/or to the Köfels event (either as displaced valley fill and/or backwater sediments; Geitner 1999; Prager et al. 2009b and references therein; Jarman 2011). Temporary exposures in local construction pits show coarse rockslide material next to fine-grained sediments (Fig. 21.6b and c).

Fig. 21.6 Terraces of Niederthai are developed in a depositional mass of unknown origin, representing either displaced sediments from the Ötz Valley floor and/or backwater sediments (see Fig. 21.2 for the location). **a** Overview. Photo M. Mergili; **b** excavation pit at Niederthai, exposing coarse rockslide deposits (angular gneiss debris with clast- and matrix-supported fabric). Photo C. Prager; **c** fine terrace deposits in the same pit as shown in (**b**), adjacent to the east (poorly stratified sands with fining-upward trend). *Photo* C. Prager

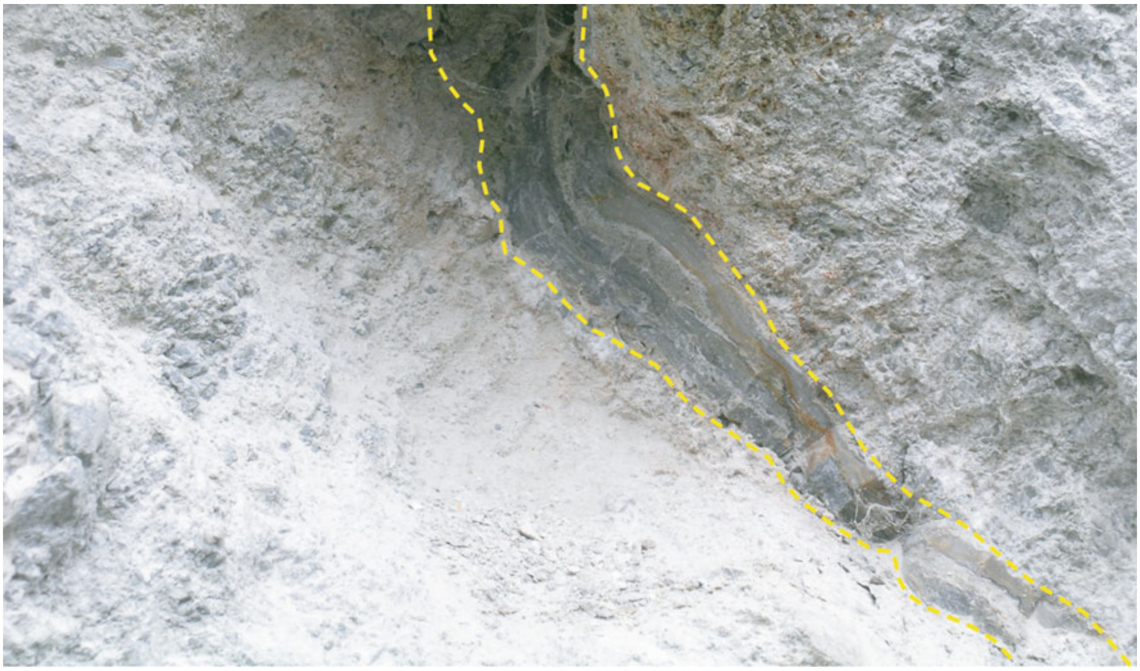

Fig. 21.7 Frictionite (fused hyalomylonite) locally encountered at the Köfels rockslide. The photo was taken in the Maurach gorge, and the thickness of the frictionite in the photo is up to 3 cm. *Photo* C. Prager (Prager et al. 2007)

Formerly, in an abandoned gravel pit, un-stratified gravels and sands with an obscure fining-upward trend were locally exposed. Presumably, they represent sediments displaced/liquefied by the Köfels event.

The most distinctive feature of the Köfels rockslide, however, is the occurrence of fused rocks, i.e., “pumice” and glassy frictionites (Fig. 21.7) that led researchers to theories of volcanic activity (Pichler 1863) and a meteorite impact (Stutzer 1936; Suess 1937; Bond and Hempsell 2008). However, according to current knowledge, these frictionites originated from partial melting in the sliding zone (Preuss 1974, 1986; Erismann et al. 1977; Erismann and Abele 2001). Such frictionites are up to now known from a few sites worldwide (Weidinger and Korup 2009; Weidinger et al. 2014). Related to the intense rock mass fragmentation, radioactive springs discharge locally and very high radon gas concentrations are emitted from the deposits (Purtscheller et al. 1995).

21.3 Temporal Patterns and Possible Triggers

The previous decades have brought a dramatic increase of knowledge with regard to the timing of large landslides in the Alps. The ages summarized in Table 21.1 were derived by means of radiocarbon, surface exposure and/or U/Th dating (e.g., Ivy-Ochs et al. 1998; Prager et al. 2009a; Patzelt 2012a, Nicolussi et al. 2015; Ostermann et al. 2016).

In the Alps, several major rock slope failures occurred throughout the Holocene. However, compiled age determinations indicate two clusters in the temporal distribution: one around 10.5–9.4 ka BP and another one around 4.2–3.0 ka BP (Fig. 21.8; Prager et al. 2008). The first, early Holocene cluster includes the Köfels rockslide (±9.5 ka, Nicolussi et al. 2015) as well as other very large events such as Flims (±9.4 ka, Deplazes et al. 2007) and Kandertal (±8.6 ka, Tinner et al. 2005), along with others, e.g., the two Rinderhorn rock avalanches (±9.8 ka, Gräminger et al. 2016). For the Köfels rockslide, Nicolussi et al. (2015) constrained the age to 9527–9498 years (earlier radiocarbon dating of this wood fragment and exposure dating campaigns had indicated slightly higher ages; e.g., Ivy-Ochs et al. 1998). This age of the Köfels failure possibly overlaps with the range of the largest Alpine landslide, the Flims rockslide 130 km farther west and ranges close to the timing of some other major events cited above. The second temporal cluster, addressed as “Fernpass cluster” (Prager et al. 2008), includes the rock avalanches at Fernpass, Tschirgant and Haiming, as well as at Eibsee, Stöttlbach, Pletzachkogel and others (Fig. 21.8 and Table 21.1).

However, ideas about a possible common trigger, e.g., climate change and/or seismic loading, remain hypothetic so

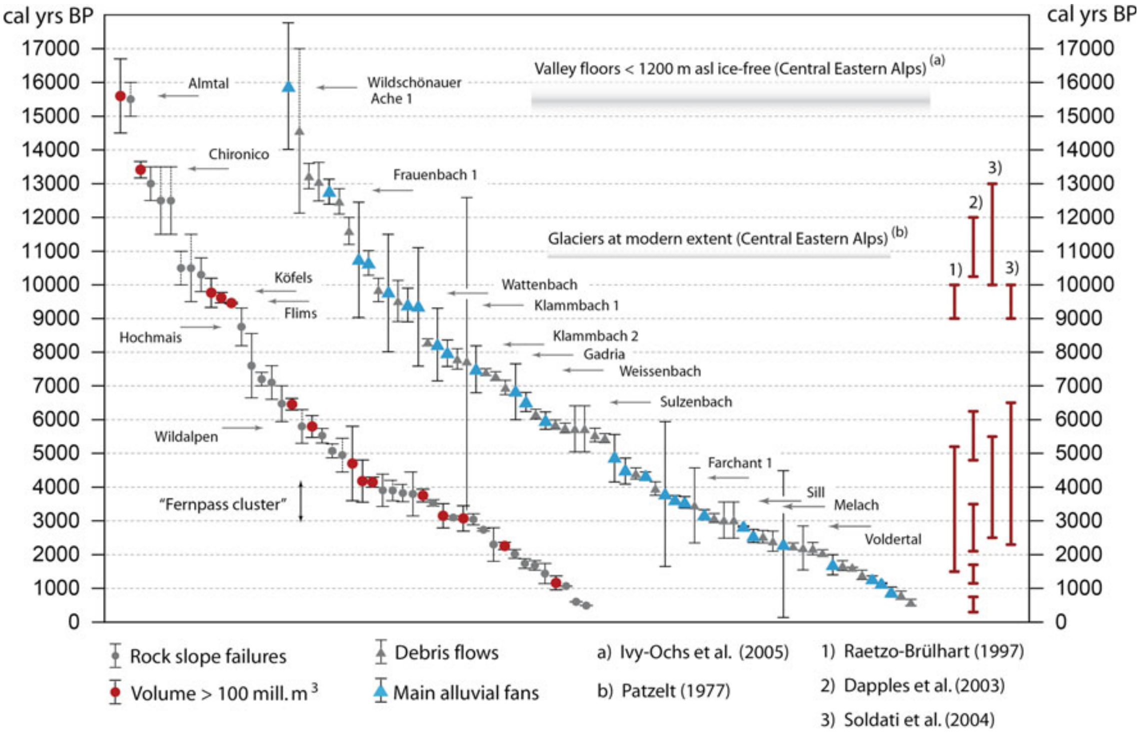

Fig. 21.8 Temporal distribution of fossil landslides in the Tyrol and its surrounding areas. Vertical axes: calibrated years BP, horizontal axes: dimensionless sequence of dated events (see Prager et al. 2008; Prager 2010 for details)

far, but represent an interesting field for further research. In general, the observed temporal distribution has led to various hypotheses with regard to the disposition (causes) and triggering of the events. Disregarding exotic and yet not validated theories such as a meteorite impact, the following factors (or a combination of them) may have been involved (Prager et al. 2008, and references therein):

- Slope dis-equilibrium resulting from glacial debuttressing, exposure of potential sliding planes and stress redistribution due to glacial erosion, the associated valley-deepening and subsequent retreat of the Pleistocene glaciers may have either directly triggered landslides, or at least reduced the stability of slopes (longer termed rock mass weakening and progressive failure).
- Dynamic loading induced by earthquakes may either have directly triggered events or led to progressive weakening and destabilization of the rock masses.
- A climatically humid period may have led to high groundwater levels and may have increased the pore water pressures, thereby fostering the growth of cracks and triggering hydromechanically coupled destabilization processes.

In the older literature, large Holocene landslides have often been attributed to glacier retreat, debuttressing and associated slope destabilization effects (e.g., Heuberger 1966, 1975; Abele 1969, 1972, 1997a). However, compiled age determinations indicate a time lag of several thousands of years between deglaciation and the actual occurrence of many of the landslides (Prager et al. 2008). In the long term, the propagation and coalescence of fractures may have triggered landsliding by reaching a stability threshold or by reducing the equilibrium far enough to facilitate landslide initiation even through a small trigger of different kind.

Increased earthquake activity, compared to other regions nearby, is measured in the surroundings of the area investigated (Inn Valley and Engadin Line), with some of the strongest earthquakes ever recorded in Austria (up to magnitudes 5.3; Drimmel 1980; Reiter et al. 2003). Long-term seismic weakening of fractured bedrock slopes may also trigger large failure events as proposed, e.g., for the Tschirgant and Haiming rock avalanches (Patzelt 2012a). On the other hand, historical records of large earthquake-triggered landslides are rare. The recorded seismic activity is limited at least in the Ötz Valley (ÖNORM B 4015: 2007), so that the occurrence of a sufficiently strong seismic event here is not indicated yet. Evidence of earthquake-triggered landslides in the past may be given, e.g., by systematic analyses and dating of disturbed lake sediments and speleothems (Becker et al. 2006; Strasser et al. 2013).

Similar ages of dated alluvial fans and debris flow deposits may indicate periods of increased water and/or debris supply in the catchment areas, possibly resulting in temporally increased mass displacements (Prager et al. 2008). Since such periods in the Holocene coincide with several dated landslides (Fig. 21.8), there might be a relationship between the large landslides in the investigation area and climatic conditions, even though this issue is disputed. Climate change might be an issue for slope stability since increased groundwater levels (and related pore water pressures) would lower the rock mass strength, especially in terms of weakened potential failure planes. For the Köfels rockslide, for example, Zangerl et al. (2021) proposed that an increased groundwater level and an internal friction angle of the basal shear zone of <27–30° would be necessary to enable failure. These assumptions are in accord with geotechnical data on fault and shear zone materials comparable to the Köfels rocks (e.g., Engl et al. 2008). However, although at Köfels several major sliding planes are well exposed (see, e.g., Prager et al. 2009a), the question in which way a rather continuous shear zone required for such a massive rock slope failure can have developed remains open. It has to be emphasized that simple, i.e., mono-causal explanations for the release of the large landslides are probably inappropriate. More likely, the long-term effects of crack growth and fracture propagation due to stress redistribution (post-glacial debuttressing), seismic activities and/or climate changes (varying groundwater/pore water pressure conditions) might control processes of slope destabilization. Thus, even minor triggers below significant thresholds may shift the equilibrium of a fractured bedrock slope far enough to promote failure and release even major landslides (Prager et al. 2008).

21.4 Ecological Implications

Whilst vegetation is largely able to cope with slow moving landslides (“creeping slopes”), large, rapid landslides leave behind pristine environments which have to be newly colonized. Therefore, such events may give ecologists the chance to study the succession of ecosystems. Thousands of years of succession have already taken place on the prehistoric landslides in the Tyrol. However, the land cover of large “Bergsturz” deposits still differs markedly from the surroundings. This phenomenon may be attributed to two closely connected reasons: the highly distinctive topography and substrate created by the sometimes turbulent motion, and, as a consequence, the unfavourableness of these environments for agricultural use. Whilst the floors of the Inn and Ötz valleys have almost completely been converted to agricultural or built-up areas, some of the large landslide deposits have remained in a near-natural state.

On the other hand, landslide deposits often consist of highly porous material, so that the habitats are dry due to the soil-related conditions, even when there is plenty of precipitation. This effect increases in limestone, where very slow soil formation and local karst effects further facilitate the drainage of water. The Scots pine (*Pinus sylvestris*) is well adapted to this type of condition. Whilst it is weak in competition with other tree species at more favourable sites, it can reasonably well survive in dry habitats. Kral (1989) underlines the relict character of the pine forests in the "Bergsturz" landscapes: in the Lateglacial and early Holocene, before immigration of more competitive tree species such as spruce, pines were equally important in various habitats, but later could only persist in unfavourable sites. On the deposits of the Fernpass (Starlinger 1992), Tschirgant (Mair 1997) and Haiming rock avalanches, *Pinus sylvestris* forms characteristic plant communities together with the heather *Erica carnea* in the undergrowth. These sparse stands of pine with an undergrowth of variable density are known as *Erico-Pinetum*, which also grows on sunny southerly exposed slopes in other parts of the Inn Valley and can shelter a high variety of species. The Fernpass deposit also hosts one of the easternmost populations of *Pinus mugo* ssp. *uncinata* ("Spirke"; Starlinger 1992), rare elsewhere in North Tyrol.

From an ecological point of view, the best studied site is the deposit of the Tschirgant rock avalanche (Fig. 21.9; Knoflach and Thaler 1994; Mair 1997; Oberhuber and Mayr 1998). The mean annual precipitation in that area is less than 800 mm. Oberhuber and Mayr (1998) emphasize the poor growth of *Pinus sylvestris* in years of reduced spring precipitation, when the water stress induced by the shallow soils with a high content of coarse material is accentuated. This phenomenon was observed for different types of habitats within the rockslide deposit. Besides the drought, the poor growth of the pines also points to the infertile soils, only weakly developed and often with thick acidic organic layers, on the nutrient-poor and weathering-resistant carbonates of the Wetterstein Formation (dolostones, breccias, limestones). The undergrowth is strongly differentiated according to the topographic position within the rockslide mass, with a very sparse cover on steep, southerly exposed slopes and a dense cover of mosses and *Vaccinium myrtillus*, remarkably an acidity indicator on carbonates, in sinks (Oberhuber and Mayr 1998). Only the most favourable places are suitable for spruce (*Picea abies*).

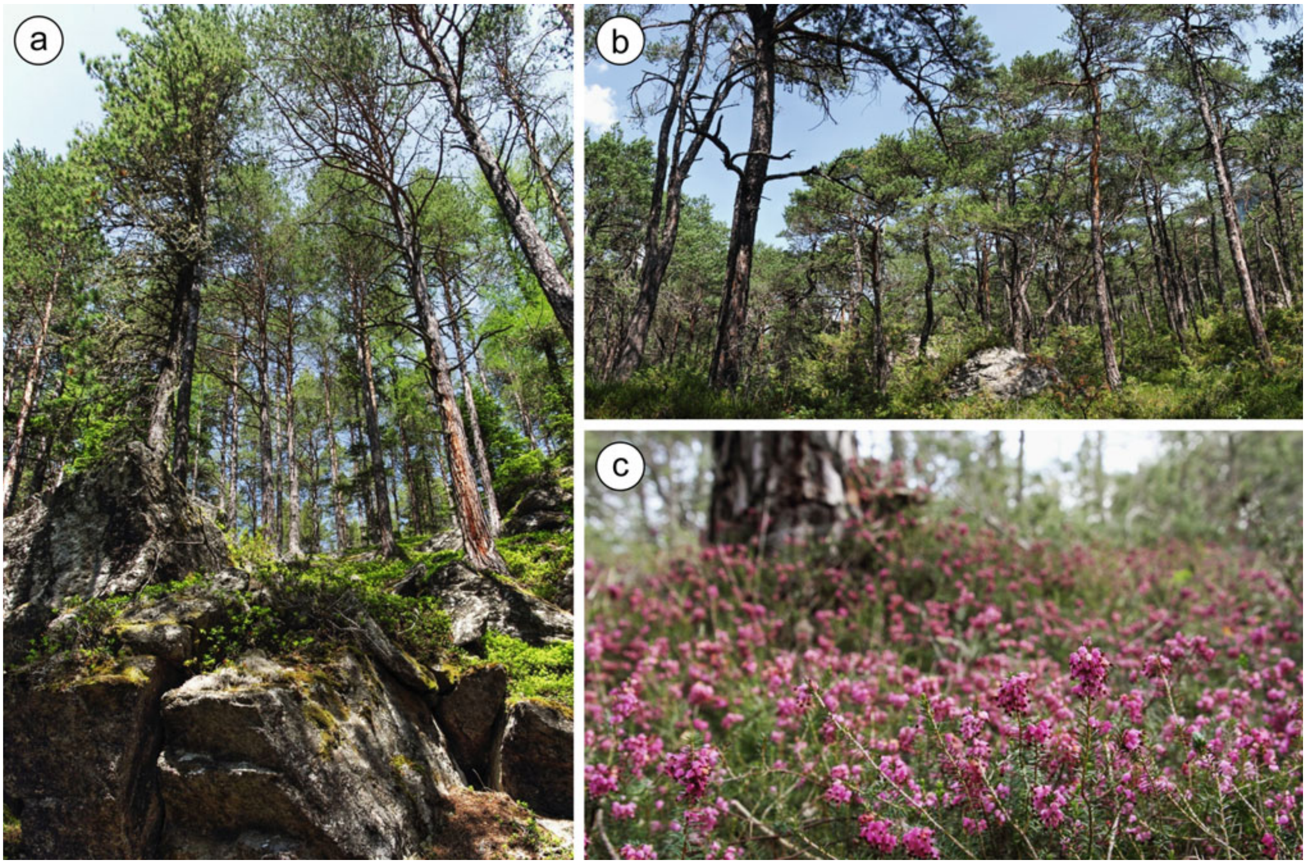

Fig. 21.9 Scots pine (*Pinus sylvestris*) forests on the deposits of the large landslides. **a** Stand of *Pinus sylvestris* on blocky material deposited by the Köfels rockslide; **b** *Erico-Pinetum* on the carbonate deposit of the Tschirgant rock avalanche; **c** *Erica carnea* in the undergrowth of an *Erico-Pinetum* on the same deposit. *Photos* M. Mergili

Also the crystalline “Bergsturz” deposits in the Ötz Valley—particularly the deposit of the Köfels rockslide—are partly covered by *Pinus sylvestris* forest, along with a species-poorer undergrowth adapted to the gneissic substrate (Mair 1997). Those areas where the soils can retain enough water are covered by spruce or larch forests broadly common in that area.

The large landslide-dammed backwater plains, e.g., the Tumpen and Längenfeld basins (Klebelsberg 1951; Heuberger 1975; Poscher and Patzelt 2000), are integral parts of the “Bergsturz” landscapes. However, they differ substantially from the actual rockslide or rock avalanche deposits not only in terms of their flat terrain surface, but also in terms of hydrology and ecology. The often fine-grained fluvio-lacustrine deposits have a varying but generally low hydraulic permeability (i.e., a comparatively higher capacity to retain water). Thus, they were originally swampy but are rather fertile due to replenishment of nutrients by the effects of flooding. Therefore, by means of water management measures such as river regulation and drainage, such areas have been converted into cultural landscapes used for agriculture and settlements and contrast sharply with the topographically rugged, forested “Bergsturz” deposits (Fig. 21.2a).

21.5 Implications for the Cultural Landscape and Society

The giant “Bergsturz” landslides have modified the landscapes of the affected areas. Mountain ridges were displaced, slopes completely reshaped, valleys blocked and fluvio-lacustrine backwater areas created upstream. Those landscapes were populated at least at the time of the Tschirgant rock avalanche (see Table 21.1), as indicated by a fire place at the base of the deposit (Patzelt 2012a), so that this event may have been observed by humans and may even have badly affected the society. It may be inferred that the Tschirgant rock avalanche induced logistic problems due to the interruption of old traffic lines. In general, the deposits of large landslides were and still are major obstacles for traffic and communication and as such even led to the development of certain types of borders: the Fernpass rock avalanche represents the border between the Bajuvarian and Alemannic language domains.

Comparable ramifications are observed in other cases such as the multi-phase Pletzachkogel rock avalanches (Patzelt 2012b) in the lower Inn Valley (former border between Tyrol and Bavaria, and maybe former border between Noricum and Raetia), or the Sierre landslide and the debris cone of Pfyn in Switzerland (German and French language border) (pers. comm. Gernot Patzelt). Whilst the Fernpass still represents some kind of obstacle for traffic, this is not so much the case for the “Bergsturz” landscapes at the entrance of and within the Ötz Valley. However, thick landslide debris can be relevant for the integrity of infrastructure facilities and make protection works necessary. In the steep Maurach gorge (Fig. 21.2), the Ötztal road B186 was sporadically affected by secondary rock falls originating from the thick Köfels deposits, and thus requiring some technical mitigation measures (retention walls). Not only traffic, but also other types of use are complicated. For example, coarse boulders and mega-blocks can hardly be excavated but may require drill and blast works to enable construction of foundations for roads and buildings.

Possible indirect negative effects of large prehistoric landslides may include less obvious health risks: the radon emissions from the Köfels deposit (Purtscheller et al. 1995) have led to increased rates of lung cancer in the surroundings, compared to the average for the province of Tyrol (Ennemoser et al. 1994). In this context, also the radioactive spring “Pseirer-Brünnl” leaking from the Köfels deposit has to be mentioned. Its emanation rate of 400 Bq/l and more (Krüse 1940) is the second highest among all springs in Northern Tyrol. Also, the emanation from the “Radiumquelle” (Krüse 1937), most likely leaking from the Fernpass deposits and/or the adjacent Seefeld beds, may be related to the intensive degree of rock fragmentation (Prager 2010).

In general, the “Bergsturz” deposits are potential pore aquifers and some are used for the extraction of groundwater (e.g., Loisach-Quellen and others; Prager 2010). They are also used for the commercial exploitation of mineral resources such as gravel at the Tschirgant, Haiming and Köfels deposits. With respect to the morphological setting, i.e., several 100-m-thick rockslide debris blocking the Ötz Valley and surface discharge occurring only through the fluvial Maurach gorge (Fig. 21.2a, b), the Längenfeld basin and the damming rockslide barrier were formerly investigated for a hydropower project (Ampferer 1939; Klebelsberg 1951). In a related investigation adit, surveying the pre-rockslide mouth of the Horlach Valley, a larch wood fragment was encountered between the rockslide debris and the bedrock underneath. The wood samples thus obtained enabled a quite early application of ^{14}C dating of the Köfels event (Heuberger 1966; Ivy-Ochs et al. 1998; Nicolussi et al. 2015).

As outlined above, the backwater plains are highly favourable for agricultural land use and for settlement areas due to their flat terrain surfaces and fine sediments. In contrast, the landslide deposits are highly unfavourable for these types of use. Nevertheless, the hummocky landscapes with the prevailing near-natural ecosystems—a kind of remaining wilderness—are often perceived as scenic and appealing, and therefore are of high recreational value. The deposits of the Köfels rockslide and the Tschirgant rock avalanche offer networks of hiking paths. Furthermore, the deposit of the Fernpass rock avalanche hosts a number of scenic lakes (Fig. 21.10a), one of which is used to generate income through

Fig. 21.10 Elements of “Bergsturz” landscapes appropriate to generate income through tourism: **a** Lake Fernsteinsee, privately owned with a hotel nearby (Fernpass rock avalanche); **b** Stuibenfall Waterfall (area of Köfels rockslide). *Photos* M. Mergili

tourism (adjacent view point, kiosk and hotel). Lake Piburger See (Habichen rock avalanche) represents a popular spot of recreation especially during summer time. The Stuibenfall Waterfall (Fig. 21.10b), having formed due to reshaping of the landscape by the Köfels rockslide, is the highest waterfall in the province of Tyrol. It provides the basis for local tourism, especially for a nearby restaurant and a snack station, and represents the perfect ambience for the “Ötzi village”, a hiking trail and the spectacular Stuibenfall climbing path.

21.6 Conclusions

Several Holocene giant rockslides and rock avalanches, often referred to as “Bergsturz” landslides, have shaped the landscapes between the Fernpass and the central Ötz Valley. Some of the events occurred in carbonate rock, others in metamorphic crystalline rock. Ideas concerning the causal factors of the spatial—and, to some extent, also temporal—clustering of events still remain hypothetic. A sound geological and geotechnical understanding of the predisposing and triggering factors, and of the mechanisms involved in these “Bergsturz” landslides is essential, not only for reconstructing the past but also for anticipating possible hazards and risks. Due to the dimensions, the implications for society and the recreational importance of the “Bergsturz” deposits, these landscapes display a high (yet only partly deployed) potential for environmental education. They may serve as “field laboratories” for enhancing the awareness and understanding of geomorphological processes in mountain areas, but also of the implications of such processes for ecosystems and society at various spatial scales.

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