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On the Connection between Debris Flow Activity and Permafrost Degradation: A Case Study from the Schnalstal, South Tyrolean Alps, Italy

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ABSTRACT

The possible influence of permafrost degradation on the formation of debris flows in an area of the South Tyrolean Alps, Italy, was examined by comparing debris flow activity since 1983 with the modelled contemporary permafrost distribution. The study focused on the spatial congruence of new initiation zones and potentially marginal permafrost, which should be especially sensitive to climatic change and is presumed to be currently degrading. The results show that distinct changes in the spatial position of debris flow initiation areas mainly occurred at elevations above this marginal zone. Consequently, the changes detected in debris flow activity do not appear to have been influenced by atmospheric warming-induced degradation of permafrost. However, a link may exist to the thickening of the active layer caused by the melting of a glacier. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: periglacial debris flows; mapping; permafrost degradation; spatial modelling

INTRODUCTION

Areas of mountain permafrost are expected to be significantly affected by current climate warming (Haeberli and Gruber, 2009). Mountainous areas are also subject to increasingly intense use and development (Haeberli *et al*., 1997). Thus, the possible increase in hazard potential – especially in the European Alps – has generated considerable research on the links between atmospheric warming, permafrost degradation and slope instability (e.g. Schlyter *et al*., 1993; Davies *et al*., 2001; Harris *et al*., 2001; Kneisel *et al*., 2007; Noetzli *et al*., 2007; Allen *et al*., 2010; Keiler *et al*., 2010). The present study focuses on debris flows, which are common mass-wasting processes in the changing alpine environments and thus pose significant hazards to life and infrastructure.

Recent progress in measurement techniques and modelling has improved our knowledge of the relationship between permafrost and rock face stability (e.g. Harris *et al*., 2009), but the possible role of climatically induced permafrost degradation in the initiation of debris flows is not yet well understood. One reason for this is an inadequate comprehension of the evolution of permafrost beneath moderately inclined slopes where debris and snow cover act as complex interfaces between the atmosphere and the subsurface (Luetschg *et al*., 2004; Gruber and Haeberli, 2009). This creates a significant challenge for modelling the thermal condition and spatial distribution of permafrost. Furthermore, permafrost in unconsolidated materials generally has high ice contents, which retard potential thawing by the uptake of latent heat (Noetzli *et al*., 2007). Permafrost soils thus may respond to climate forcing over several decades to centuries (cf. Haeberli, 1992) and the effects of permafrost degradation on debris flows may be difficult to detect within one or two decades. Finally, debris flows themselves are highly complex geomorphic processes. Our understanding of their initiation, resulting from the temporal and spatial concurrence of several highly variable factors including debris availability and the occurrence of transient triggering events, and their overall sensitivity to changes in climatic parameters, is still incomplete (cf. Rebetez *et al*., 1997; Zimmermann *et al*., 1997; Jomelli *et al*., 2004, 2007). Yet, climatically induced thawing of alpine permafrost is expected to significantly affect the hydraulic and geotechnical properties of perennially frozen unconsolidated

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debris and may therefore result in a transient increase in debris flow formation (cf. Zimmermann and Haeberli, 1992; Zimmermann *et al*., 1997).

Permafrost slopes are particularly prone to slips and slides as the permafrost table at depth acts as an aquiclude and hence as a potential failure plane during periods of elevated pore pressure, such as after summer rainfall events or extreme thaw periods (cf. Larsson, 1982). Furthermore, the co-existence of frozen and unfrozen moisture in voids close to the seasonally shifting thawing plane increases the probability of active-layer failure (Nater *et al*., 2008). Active-layer detachment failures are common in arctic fine-grained soils (cf. Harris and Lewkowicz, 2000; Lewkowicz and Harris, 2005) but have been rarely observed on coarse and generally better-drained alpine debris slopes (cf. Zimmermann and Haeberli, 1992; Rist, 2007). However, the progressive lowering of the permafrost table may increase the susceptibility of such slopes for instabilities and thus the occurrence of debris flows. The thickening of the active layer can increase sediment availability in potential debris flow initiation zones. In addition, changes may occur in the frequency of rainfall-related triggering events at high elevations (e.g. due to a rise in the level at which snow falls in the summer and consequently an increase in triggering rainfall events; cf. Beniston, 2006).

Lowering of the thaw front within permafrost soils beyond average active-layer depths may also reduce the shear strength of debris. Rist (2007) found in a laboratory experiment that active-layer instability was not triggered by the oversaturation of material at the base of the active layer but by the release of fine-grained material formerly fixed in the ice matrix. However, the potentially destabilising effect of permafrost degradation is thought to be temporally restricted. As the permafrost table progressively descends, permafrost bodies are also likely to decrease in size due to lateral melting and thermal erosion-related disintegration. The probability of slope instability related to permafrost degradation, therefore, may decrease in the long term as the slope adjusts to new conditions.

During the inferred critical thawing period, instabilities appear most likely to occur in localities near the lower limit of contemporary permafrost distribution, where permafrost bodies are thin and have temperatures close to 0°C (cf. Haeberli, 1992). These are assumed to be especially sensitive in terms of climate warming and therefore may be experiencing slow thaw. High sensitivity of relatively warm permafrost to thermal forcing has been shown in the case of permafrost creep (Kääb *et al*., 2007). Average creep velocities have increased for a large number of rock glaciers in the European Alps since the 1990s, which is believed to be the result of increases in air temperature (Kääb *et al*., 2007; Roer *et al*., 2008). As increased deformation rates equate to higher material transport, accelerated permafrost creep may lead to increased sediment availability in existing debris flow initiation zones or to sediment accumulation in new process-susceptible locations and thus may also enhance debris flow activity in certain locations (cf. Pontresina/Schafberg, Hoelzle *et al*., 1998).

The hypothesised connection between permafrost degradation in non-creeping slope material and enhanced debris flow activity has not yet been proven. Field studies of debris flow-triggering mechanisms on thawing slopes remain a challenge given the difficulties to predict where and when slope instabilities will occur (Harris, 2005). Observations of large numbers of debris flows originating in areas presumed to be at the margin of contemporary permafrost distribution lend support to the hypothesis (e.g. Zimmermann and Haeberli, 1992; Stötter, 1994; Damm and Felderer, 2008), but these are typically made following an exceptional heavy rainfall event or refer to a specific year of geomorphological mapping. The goal of the present paper is to examine debris flow activity through time in a periglacial area, which might allow for a better-informed evaluation of the influence of permafrost degradation on the initiation of debris flows.

STUDY AREA

The study area is located on the southern flank of the main divide of the European Alps and comprises the head area of the Schnalstal (Val Senales) in the northwestern part of the Autonomous Province Bozen - South Tyrol, Italy (Figure 1). The lithology is dominated by the old crystalline schistose gneiss of the Ötztaler Alps (Purtscheller, 1971) and the topography is steep with a relative relief of up to 1000 m. Some sites have only recently been deglaciated and rates of geomorphic activity are high throughout the area.

The climate is continental with an annual monthly temperature range of 16.5°C and low precipitation due to rain shadow effects (cf. Fliri, 1975). The mean annual precipitation at the Kurzras climate station (2012 m a.s.l., records since 1990; Figure 1c) is 711 mm (Autonomous Province Bozen - South Tyrol, Department of Hydrology, 2007). Mean maximum snow depth for the month of March is 90 cm at the Lazauner Alm (2427 m a.s.l., records since 1987; Autonomous Province Bozen - South Tyrol, Department of Hydrology, 2008).

The climatic conditions and the steep relief that is unsuitable for widespread glaciation favour the development and preservation of alpine permafrost, as indicated by the presence of numerous rock glaciers and protalus ramparts in the valley head area. Measurements of the basal temperature of the snow cover (BTS) indicate that the Lazaun rock glacier (Figures 1 and 5) is active and temperatures measured within a borehole drilled recently through the summit of the Grawand also show the presence of permafrost (Mair *et al*., in preparation).

Debris flow activity in the last two decades was examined in three sub-areas (Figure 1c; Tables 1 and 2):

1. The Langgrub sub-area (Figure 2A) is in the south of the Langgrub Valley in the western part of the study area. According to a historical topographic map of the Italian Military Cartography Institute, the slope was covered by a glacier as recently as the 1960s. The glacier is no longer present and a large part of the area is mantled by

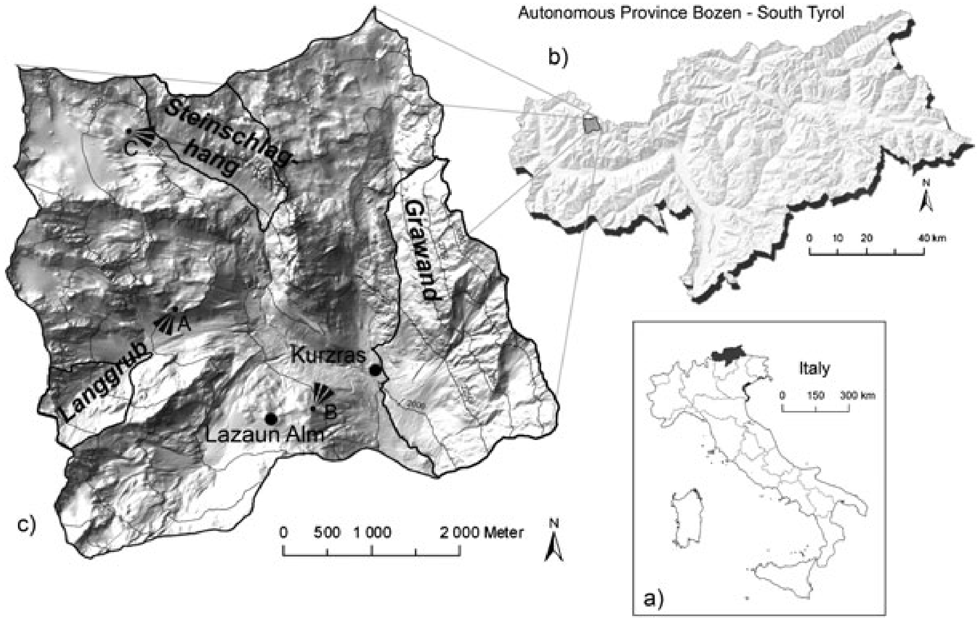

Figure 1 (a, b) Location of the study area; (c) hill shade of the study area showing sub-areas under further investigation regarding the development of debris flow activity since 1983 (outlined using a solid line), location of climate stations referred to in the text and viewpoints of photographs shown in Figure 2. (Cartographic basemap: LIDAR DEM, Autonomous Province Bozen - South Tyrol, Department of Regional Planning, 2008.)

Table 1 Basic characteristics of the investigated sub-areas.

Area	Size (ha)	Altitudinal range (m a.s.l.)	Predominate aspect	Debris-covered area (% of total area)
Langgrub	73	2504 – 3194	N – NE	75
Grawand	410	1898 – 3251	W – SW	54
Steinschlaghang	127	2434 – 3227	S – SW	50

Table 2 Characteristics of debris flow activity in the investigated sub-areas (as of 2006).

Area	Number of initiation zones	Type of debris flows (% of total number)		Material in source areas (% of total number)		
		Landslide type	Mobilised type	Rockfall debris	Morainic material	Rock glacier
Langgrub	67	36	64	22	78	—
Grawand	272	9	91	94	5	1
Steinschlaghang	125	6	94	80	20	—

morainic material, which can be easily remobilised by debris flows. Initiation zones are mainly located beneath prominent rock convexities. The debris flows are therefore predominantly of the 'mobilised' type, where the local concentration of water drainage is the decisive initiating factor (see Takahashi, 1981). Given the abundance of glaciogenic sediment, it is assumed that the occurrence of suitable rainfall events is the primary factor controlling their frequency. The generally long runout distances (> 500 m) observed in the sub-area support this assumption.

2. The Grawand sub-area (Figure 2B) lies in the east of the study area and comprises the whole slope-rock face complex from the Hochjoch glacier lake in the north to the Korbeck peak in the south. Initiation zones are mainly located at the mouths of steep rock channels where they meet talus slopes and are also of the mobilised type. Talus slopes below active rock walls, representing recent debris storages, are mainly of moderate size and the availability or re-accumulation of rockfall debris is hence an important factor for process initiation. The magnitude of these events is

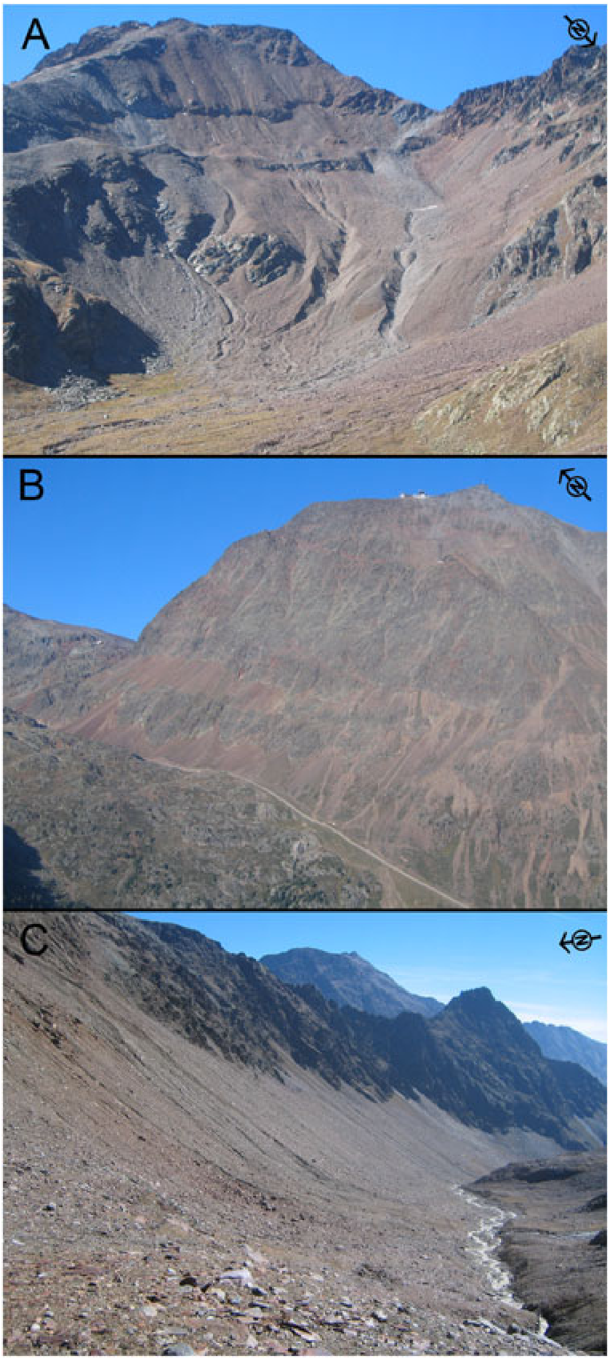

Figure 2 Photographs of the sub-areas, taken September 2006, showing different debris flow environments: (A) Langgrub, (B) Grawand and (C) Steinschlaghang. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

smaller than in the Langgrub sub-area, and source areas, travel paths and depositional areas of the debris flows are generally limited to the talus slopes (runout distances mainly < 200 m). Debris flows originating from a fossil rock glacier at the exit of the southernmost gully system are notable exceptions as this old debris storage provides abundant material for the rainfall-dependent debris flows and slides emanating from the frontal lobe.

3. The Steinschlaghang sub-area (Figure 2C) is located in the northwest of the study area in the Steinschlag Valley. The lower part was covered by a valley glacier during the Little Ice Age, which reached its last maximum extent around 1850 AD (cf. Grove, 1988; Stötter, 1994) as evidenced by well-preserved left lateral and terminal moraines and a highly consolidated ground moraine. Debris flow initiation zones are predominantly located at the mouths of steep rock channels. The talus accumulations beneath, however, are small compared to those in the Grawand sub-area and their volume is thought to be only due to the blocking effect of the lateral moraine. Given their small size, it is assumed that the formation of debris flows in this sub-area is particularly supply dependent. Process magnitudes are small and runout distances are short (~ 250 m).

METHODS AND DATA

Geomorphological Mapping

The geomorphology of the valley head area was first mapped using analogue colour aerial photographs taken in 2004. These were examined stereoscopically and information was digitised in a GIS using a standardised group of symbols for mapping natural hazards (Bundesamt für Wasser und Geologie, 2002; see Sattler *et al.*, 2007, and Sattler, 2008). Digital orthophotographs from 1997 and 1999 and an extended field survey in September 2006 allowed for verification and updating of the digitally mapped geomorphology.

Multi-temporal Analysis of Debris Flow Activity

The geomorphological mapping and a distinct spatial concentration of debris flows led to differentiation of the three investigated sub-areas (Figure 1c). Since the absolute age of debris flow deposits and the resultant frequency of individual debris flow events are not known, a spatial clustering of process traces was taken to be indicative of a high level of debris flow activity. In the following, the term 'activity' mainly refers to the spatial occurrence of debris flows and not to magnitude-frequency relations.

The three sub-areas were analysed for changes in debris flow activity from 1983 (the earliest aerial photographs available) to 1997 and on to 2006 (including field survey observations). The low quality of the oldest aerial photographs, arising from their small scale and photographic overexposure of the slopes of interest, prevented a detailed evaluation of antecedent geomorphic situations in the sub-areas. Hence, the multi-temporal analysis involved only a visual assessment of changes in the spatial position of debris flow initiation zones such as spatial enlargement of existing initiation zones, or the development of new initiation zones at higher elevations and/or on previously stable slopes.

Estimation of Contemporary Permafrost Distribution

Contemporary permafrost distribution in the study area was modelled using an empirical-statistical approach based on 'the rules of thumb for potential permafrost distribution in the Alps' (Haeberli, 1996). These guidelines include a list of numeric threshold values for the lower boundary, differentiating between zones of probable and possible permafrost occurrence (Table 3). The values incorporate aspect-dependent radiation effects, elevation-dependent changes in air temperature and influences of relief-controlled snow cover variation (Haeberli, 1975). Although the values were regionally calibrated in the Swiss Alps, they are thought to be applicable to the study area owing to comparable climatic conditions.

Areas bounded by the threshold values were demarcated within a GIS (ArcGIS 9.2) using a Digital Elevation Model (DEM) (2.5-m high-resolution LIDAR (light detection and ranging) DEM, Autonomous Province Bozen - South Tyrol, Department of Regional Planning, 2008) following the approach of the programs PERMAKART for slopes ≥ 11° (Keller, 1992) and PERM (Imhof, 1996) for less-inclined areas. Gentle slopes where avalanche deposits might accumulate were omitted from the distribution predictions

Table 3 Threshold values (m a.s.l.) used for modelling the potential contemporary distribution of alpine permafrost in the study area, slightly modified after Haeberli (1996).

	Permafrost	
	Possible	Probable
Steep areas (≥ 11°)		
N	2400	2600
NE	2450	2600
E	2600	3000[a]
SE	2850	3000[a]
S	3000	3175[b]
SW	2700	2900
W	2500	2600
NW	2350	2400
Flat areas (< 11°)		
Wind exposed	2600	2700
Wind sheltered	2650	3000[a]

Note: Additional to probable and possible permafrost occurrence, steep areas where local permafrost distribution is primarily determined by radiation and thus aspect and flat areas where next to air temperature the existence of snow cover has significant influence are distinguished. The limit value of 11° was taken from Haeberli *et al*. (1999).
[a]Haeberli (1996) indicates these values with higher uncertainty (see text).
[b]Value derived from the averaged differences of adjacent orientation classes to the 'possible permafrost' threshold value.

as preliminary identification of foot-slope areas showed that they do not accumulate deep snow. Furthermore, the focus of this study is on potential debris flow initiation zones, which excludes these gently sloping sites.

Occurrences of permafrost are assumed to be extensive in the zone of 'probable permafrost' and sporadic in the 'possible permafrost' zone where they are linked to specific topo-climatic conditions (Keller and Hoelzle, 1996). Predictions in this latter category are presumed to be only 50 per cent accurate and therefore considerable spatial uncertainty exists (Haeberli, 1975). Furthermore, it is inferred that ground temperatures in the zone of 'possible permafrost' as well as areas close to the lower boundary of the 'probable permafrost' zone are close to 0°C and therefore are especially sensitive in terms of climatic change. Consequently, for this study, the zone of 'possible permafrost' and the lower 50 m of the 'probable permafrost' elevational zone were grouped as 'sensitive permafrost'.

RESULTS

Debris Flow Activity Since 1983

Distinctive shifts in the spatial position of debris flow initiation zones within the last two decades were only observed in the Langgrub sub-area where almost half of the initiation zones mapped in 2006 developed after 1983 (Table 4). Numbers of initiation zones particularly increased above 2850 m a.s.l. (Figure 3) and three out of the seven elevation classes showed disproportionately high spatial concentrations. Approximately three-quarters of the new initiation zones developed between 1983 and 1997 (Figure 4) with almost all of these located in formerly glaciated, till-covered areas. The number of initiation zones doubled above 2900 m a.s.l. from 1983 to 1997 and those that developed between 1997 and 2006 also formed predominantly in this upper slope area. No trends were observed in the type of debris flow initiation zones for the two periods.

Only minor changes in debris flow activity were observed within the Grawand sub-area. A mere 3 per cent of the debris flow initiation zones mapped in 2006 developed after 1983 (Table 4). These were predominantly in rock-debris contact zones and slightly more new initiation zones developed between 1983 and 1997 than in the subsequent period. However, in view of the limited number of changes, no conclusions can be reached regarding their spatial occurrence and type.

Changes in the spatial position of the debris flow initiation zones could not be evaluated for the Steinschlaghang sub-area owing to the poor quality of the 1983 aerial photographs.

Estimation of Contemporary Permafrost Distribution

A validation of the model output using the distribution of rock glaciers and perennial snow patches as direct and

Table 4 Number and location of new initiation zones in the sub-areas since 1983 (% of total in 2006).

	1983–97				1997–2006			
	% new initiation zones	Probable permafrost	Sensitive permafrost	Improbable permafrost	% new initiation zones	Probable permafrost	Sensitive permafrost	Improbable permafrost
Langgrub	34	31	3	0	12	11	1	0
Grawand	2	0	0	2	1	0	0	1
Steinschlaghang	—	—	—	—	—	—	—	—

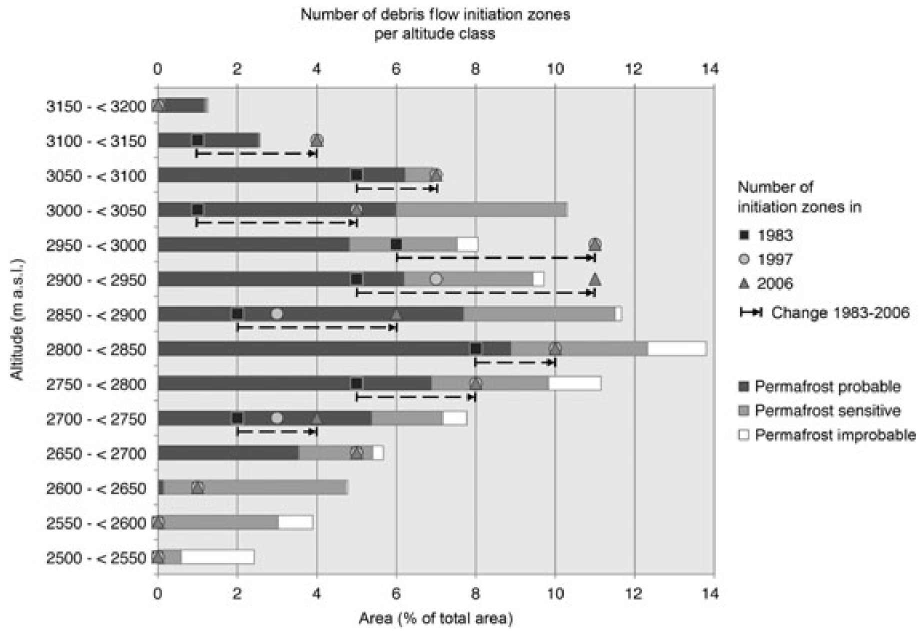

Figure 3 Changes in the number of debris flow initiation zones through time in the Langgrub sub-area in relation to observed altitude. Bars show the area of each altitudinal class and the proportional extent of modelled classes of contemporary permafrost distribution. (Numbers of debris flow initiation zones in 1997 resp. 2006 are cumulative, i.e. initiation zones that were e.g. visible in the 1983 photograph but not identifiable in the 1997 photograph (e.g. due to refilling by rockfall debris or upward shift) were also included in the 1997 count in order to illustrate the observed changes.)

indirect permafrost indicators, respectively, showed that the empirical threshold values of Haeberli (1996) produced reasonable results (Figure 5). All of the active rock glaciers inventoried lie within the modelled permafrost extent. The distribution of perennial snow patches, however, which were mapped by Zischg (2006) from orthophotographs and which comprises a synthesis of observations from 1996, 1999 and 2003, shows less accordance with the modelled permafrost distribution, especially on south-facing slopes. This may indicate an incorrect choice of threshold value for this aspect category, supporting the uncertainty originally indicated by Haeberli (1996) (Table 3). Alternatively, it relates to particularly extensive snow in 1999, perhaps due to summer snowfall or other exceptional meteorological conditions. As a result, the accuracy of permafrost modelling for south-facing slopes cannot be evaluated. However, as the modelled permafrost distribution is otherwise in good agreement with the permafrost indicators, the model is thought to be reasonable.

According to the model, approximately half of the head area of the Schnalstal has possibly permafrost and about one-third probably permafrost (Figure 5). The latter includes steep rock faces at high elevations as well as large areas of debris accumulations on north- and northeast-facing slopes in the western tributary valleys, where the permafrost extends to lower elevations. Sensitive permafrost, which may be experiencing significant degradation due to ongoing climate warming, occupies 23 per cent of the area. Information on potential permafrost distribution in the sub-areas is listed in Table 5.

Spatial Correlation of Process Initiation Zones and Permafrost Occurrence

All but one of the debris flow initiation zones mapped in 2006 for the Langgrub sub-area are situated in areas where permafrost is currently probable or possible (Table 6). This is not surprising given that these zones cover 93 per cent of

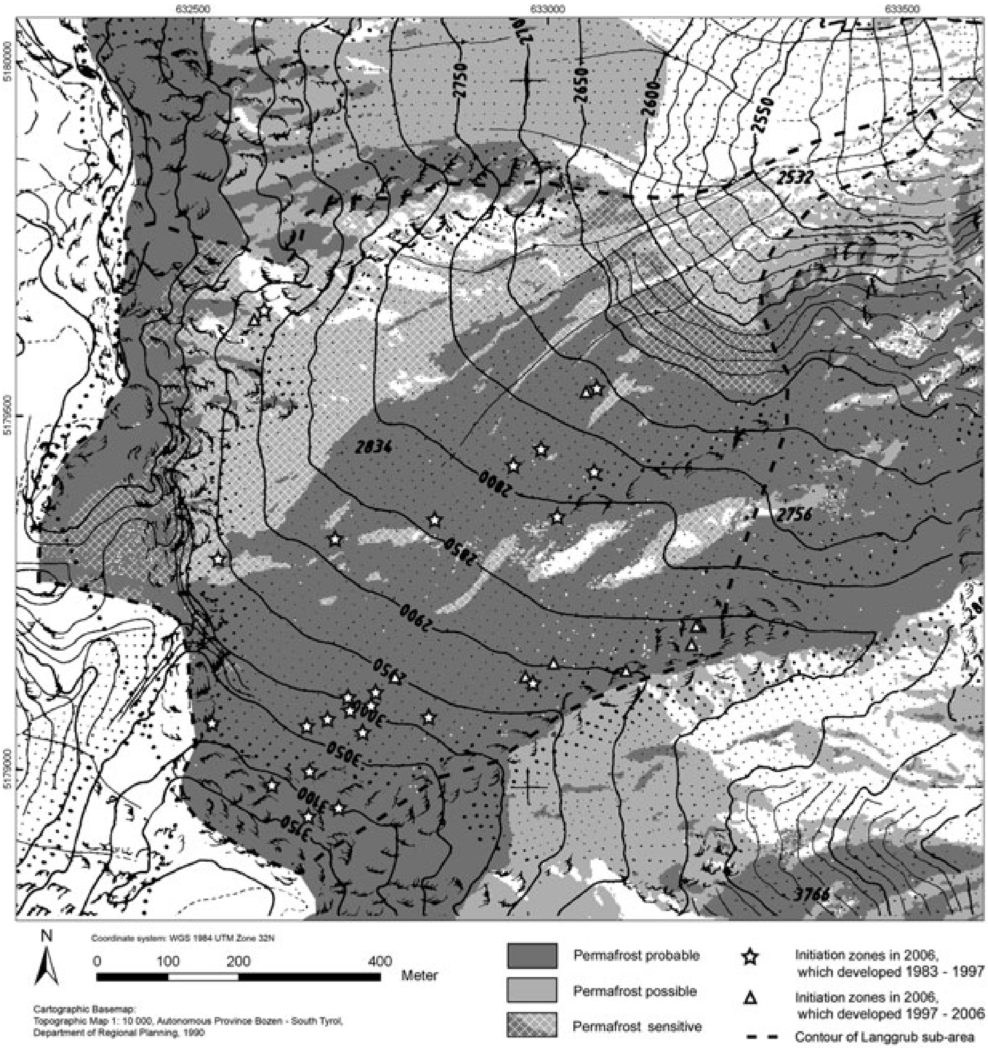

Figure 4 Location of debris flow initiation zones that developed after 1983 in the Langgrub sub-area in relation to modelled permafrost distribution.

the area. Approximately one-fifth of the initiation zones are located in areas with sensitive permafrost, predominantly at the contact zone of the western rock faces and their debris slopes. Almost all (90%) of the initiation zones that developed after 1983, however, formed in areas of probable permafrost (Figure 4).

In the Grawand sub-area, slightly more than one-third of the initiation zones observed in 2006 lie in areas of probable or possible permafrost occurrence. Three-quarters of these are in areas categorised as sensitive permafrost, predominantly at rock-debris contact zones. However, all but one of the initiation zones that developed after 1983 were below the assumed lower boundary of contemporary permafrost.

Approximately 80 per cent of the process initiation zones mapped in 2006 in the Steinschlaghang sub-area are in areas where permafrost occurrences are currently probable or possible, and here also nearly three-quarters of these are in areas of sensitive permafrost. Two-thirds of debris flows mapped as comparatively recent, owing to the light colour of the deposits and the distinctiveness of the process traces, originated in these areas.

As none of the investigated sub-areas showed any indications of active permafrost creep, the possible influence of accelerated creep processes on debris flow activity is not regarded as significant.

DISCUSSION

Distinct changes in debris flow activity over the last two decades could be detected only in the Langgrub sub-area. Nearly half the initiation zones mapped in 2006 developed after 1983, with many of these in the upper slope area. However, almost all of these formed in areas where the probability of extensive permafrost occurrence is assessed as high and which are therefore considered to be well above the

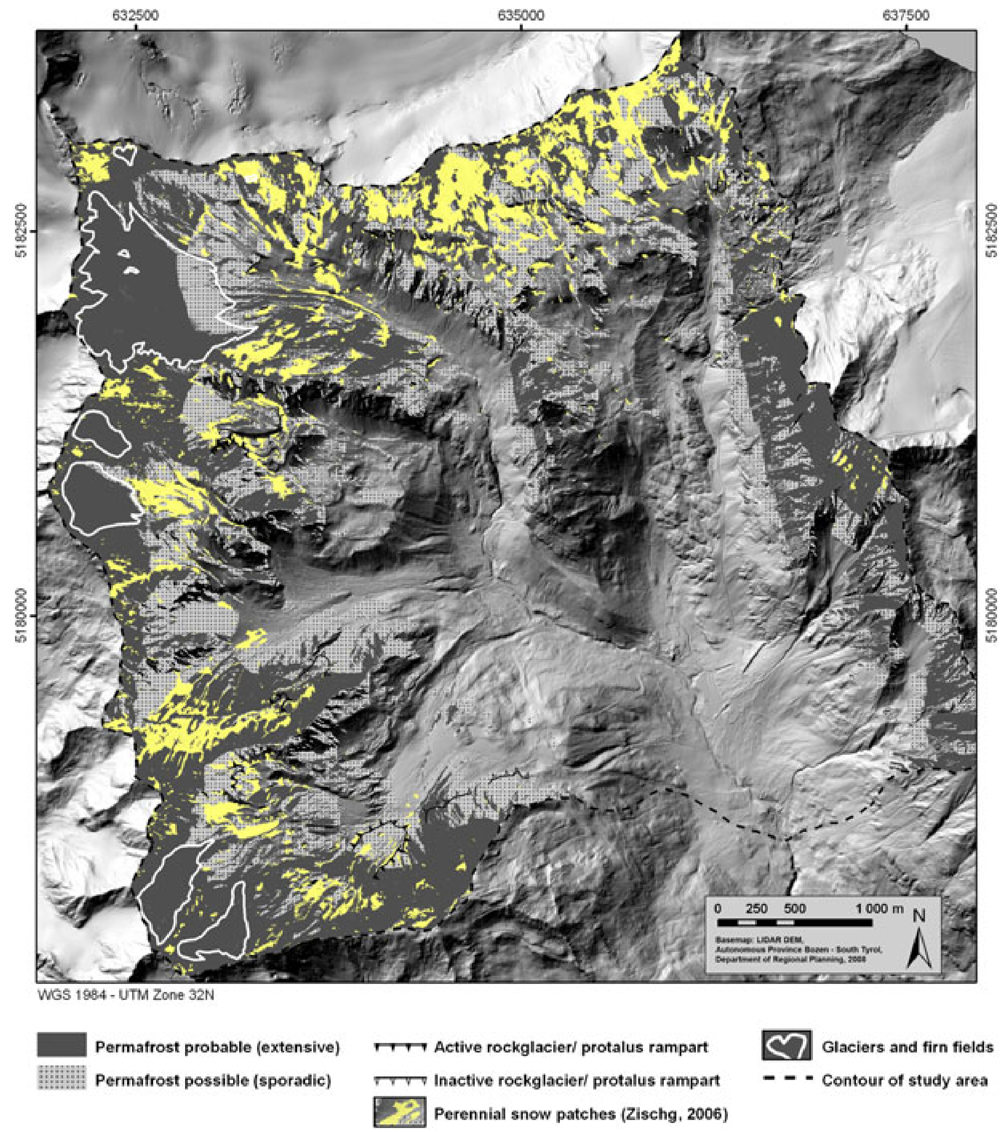

Figure 5 Map showing potential contemporary permafrost distribution in the study area as modelled according to the empirical threshold values of Haeberli (1996), as well as the distribution of permafrost indicators used for model validation. Today's extent of glaciers and firn fields are included to indicate those areas that may be only partly underlain by permafrost due to the polythermal character of ice bodies in permafrost environments (cf. Suter *et al*., 2001; Etzelmueller and Hagen, 2005). This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

Table 5 Potential contemporary permafrost distribution in the investigated sub-areas according to the modelling categories (% of total sub-area).

Area	Probable permafrost	Possible permafrost	Improbable permafrost	Sensitive permafrost
Langgrub	67	26	7	33
Grawand	25	12	63	15
Steinschlaghang	25	24	51	29

margin of contemporary permafrost distribution. Based on the theoretical framework outlined above, a correlation between the development of the new initiation zones and climate change-induced degradation of permafrost is thus unlikely.

Given that most of the recent debris flows formed in areas that were formerly covered by ice, they may be connected to the melting of the eastern Langgrub glacier. A possible explanation is the paraglacial adaption of over-

Table 6 Location of debris flow initiation zones in the sub-areas within the modelled potential permafrost distribution (% of total number).

Area	Location of debris flow initiation zones		
	Probable permafrost	Possible permafrost	Sensitive permafrost
Langgrub	81	18	21
Grawand	21	17	27
Steinschlaghang	34	47	58

steepened morainic material to unglaciated conditions (cf. Ballantyne, 2002). These sediments may have been in a geomorphodynamic unstable or metastable state and were especially susceptible to erosion and hence debris flow formation. However, increased debris flow activity was only observed for 1983–97. This tends to invalidate the concept of increased geomorphic activity after deglaciation, since this normally commences shortly after ice retreat. Furthermore, in the course of the multi-temporal mapping a progressive increase in debris cover was noted in the analysed aerial photographs. These observations suggest another possible explanation connected to permafrost degradation: Slope gradient and elevation suggest that the Langgrub Glacier was polythermal (cf. Suter *et al*., 2001; Etzelmueller and Hagen, 2005) or at least to some extent frozen to the rock, especially in the higher, steep slope areas close to the bergschrund. Temperatures at the glacier base in these localities may have been below 0°C and the permafrost table hence directly at the surface. The loss of ice cover, which is thought to have occurred in the late 1960s or 1970s, triggered thawing of the permafrost. As an active layer developed and *in-situ* weathering occurred, loose material became available which was easily mobilised by erosive processes given the steep slope gradient. The marked development of debris flow initiation zones can thus also be interpreted as a sign of the paraglacial adaption of near-surface permafrost to modern unglaciated conditions. A possible increase in debris flow activity due to exceptional rainfall events could not be clarified owing to a lack in climate data.

It is doubtful that even the few debris flow initiation zones that developed in the Langgrub sub-area after 1983 in areas of sensitive permafrost relate to its recent degradation. They are mainly located at the rock-debris contact zone and the debris flows themselves are of the ‘mobilised’ type. Process initiation in these cases is highly dependent on the rocky topography above, which can be considered to be stable and thus process-triggering concentrated flow within rock channels is likely to have occurred repeatedly in the past. The *ab-initio* development of these initiation zones in recent years is therefore improbable. More likely is the refilling of existing initiation zones prior to 1983 by rockfall debris from the active rock walls above so that their existence was hidden on the 1983 aerial photographs but was revealed by subsequent reactivation. It is possible that the degradation of permafrost within the debris slopes promoted their recurrence through an increased supply of loose material with a thaw plane providing a sliding surface, but this cannot be demonstrated. Even if magnitude-frequency data were available, correlation between process activity and permafrost degradation would remain challenging as a wide range of interacting factors, such as the natural variability of debris flows, unknown lag and reaction times of alpine permafrost to climate change, and the re-accumulation time of debris storage under stable as well as changing climatic conditions, would have to be considered.

The findings for the Langgrub sub-area demonstrate the limitations of the study’s methodological approach not only in terms of the interpretability of results but also regarding its significance. For example, the dependence of observed changes in debris flow activity on the type of initiation zones is apparent. As a consequence of restricting the multi-temporal analysis to an assessment of spatial displacement in the formation of initiation zones, changes regarding debris flows originating at rock-debris contact zones were generally not registered. Since the location of these initiation zones is primarily controlled by topography, the formation of new zones or a change in position is unlikely. Changes in process activity at these sites would be better revealed by changes in the magnitude and frequency of events rather than by the formation of new initiation zones. However, only a few new initiation zones could be observed in the Grawand sub-area where ‘mobilised’ debris flows represent the prevailing process type. In view of the low number and uncertainties associated with their identification as described above, an interpretation of the results of the multi-temporal analysis is not justified in this case. Results for the Steinschlaghang sub-area may have been similar, given the similarity in debris flow characteristics.

Comparing the location of debris flow initiation zones and the potential distribution of permafrost, it is notable that a high proportion of initiation zones in the Grawand and Steinschlag sub-areas are situated in the sensitive permafrost zone (Tables 5 and 6). There may be a connection between process activity and permafrost degradation, especially given that two-thirds of the debris flows mapped as comparatively recent events in the Steinschlaghang sub-area originated in these areas. A coincidental juxtaposition of the topographically determined, most active zones and the potential marginal occurrences of contemporary permafrost distribution is, however, a more likely explanation. Furthermore, an interpretation of the spatial concurrence of debris flow initiation zones and the potential permafrost distribution has to consider uncertainties in the permafrost modelling approach. The ‘rules of thumb’ were originally designed for a scale of 1: 25 000 and a spatial resolution of 50–100 m (Haeberli *et al*., 1996). The lower limits of particular zones therefore represent a fringe rather than a sharp line, and especially in the case of the lower boundary of the possible permafrost zone mark only the presumed border between potential permafrost areas and likely permafrost-free areas. Permafrost occurrences developed due to particular micro-climatic conditions (such as extremely shadowed locations) can also exist below this elevation.

The use of a high-resolution elevation model as data input implies an unjustified degree of spatial accuracy, as shown by the highly fragmented model output on some slopes due to localised changes in aspect. An interpretation of the concurrence of debris flow initiation zones and permafrost areas is thereby impeded or leads to outliers such as the one in the Langgrub sub-area. To counteract this fragmentation effect and reduce uncertainties, debris flow initiation zones were treated as polygons with a 10-m diameter rather than as points.

Furthermore, the permafrost model's uncertainties differed with aspect. Haeberli (1996) marked probable permafrost thresholds for eastern and south-eastern aspects as doubtful and did not develop thresholds for south-facing slopes (Table 3). The southern value was therefore derived mathematically from the adjacent orientation classes. As these values and the model predictions have not been verified in the field using geophysics, conclusions regarding a possible correlation between process activity and permafrost degradation can only be made with caution.

CONCLUDING REMARKS

Observed changes in the spatial distribution of debris flow activity over the past two decades are not thought to have been influenced by atmospheric warming-induced thawing of perennially frozen debris in the process source areas. Although situated at high enough elevations, debris flows predominantly started at sites that are not predicted to be at the margin of contemporary permafrost distribution, and thaw of permafrost at these locations in reaction to current changes in climatic conditions is therefore unlikely. However, a connection between the development of new initiation zones in the Langgrub sub-area and the thickening of the active layer as a reaction to the melting of a former glacier is thought to be possible.

In assessing the links between permafrost degradation and debris flow initiation, attention has to be paid to the type of initiation zones analysed, as permafrost thawing-related changes may manifest themselves differently depending on the initiation type. The nature of the source area (old vs recent debris storage) and the triggering mechanism (rainfall dependent vs sediment-supply dependent) may also be decisive factors in the response of debris flows to permafrost-related changes in the spatial distribution of initiation zones. Straightforward research approaches, such as the one used, help clarify associations among contributing factors and can identify suitable study sites for more intensive geophysical research at the slope scale.

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