1661-8726/09/020331-14
DOI 10.1007/s00015-009-1315-3
Birkhäuser Verlag, Basel, 2009

Predisposition and cause of the catastrophic landslides of August 2005 in Brienz (Switzerland)

ROGER MUELLER [1,*] & SIMON LOEW [2]

Key words: landslide, debris flow, Valanginian Marl, Brienz, weathering, colluvium

ABSTRACT

Very intensive rainfall in August 2005 (>300 mm/3 days) triggered moderately deep (2–10 m) landslides of about 50'000 m^3 volume each in two mountain torrent catchments above the village of Brienz (Berner Oberland, Switzerland). These landslides – originating in Trachtbach and Glyssibach catchments – transformed into extremely rapid (>5 m/s) debris flows, which caused significant damage in inhabited areas; two persons lost their lives and about twenty-five families became homeless. The Brienz case was the most damaging one among many landslide disasters occurring during those rainy days in the Swiss Alps. In this paper we study in detail the predisposition and causes of the 2005 landslides in the Brienz area, based on field mapping, analysis of high resolution images and digital terrain models, derived from LIDAR and infrared measurements taken before and after the event. The features of these landslides are compared with past and dormant landslides in the mid-slope portion of the mountain chain north of Brienz, which has been the source of many catastrophic mass wasting events during the last centuries.

Detailed field mapping shows that highly weathered series of strongly overconsolidated Mesozoic marls (Diphyoides Limestone & Vitznau Marls of Valanginian age) and their residual soils form the primary source for the sliding materials. The rupture surfaces of the moderately deep landslides often run at the transition from saprolite to weathered bedrock, with a dip angle of about 40º in the landslide depletion area. These landslides transform into debris flows, where debris slides into strongly convergent hillslopes or directly into headwater channels.

Weathering of the Valanginian Marls is very fast, leading to high frequency landsliding in areas where this formation is exposed or close to ground surface. As not all landslides transform into fast and long runout debris flows, colluvium from older landslides forms a second important material that becomes mobilized by heavy rainstorms.

The depleted volume remaining today in the source areas of the Trachtbach and Glyssibach landslides amounts to about 30'000 m^3 each. These soil masses will be mobilized in future rainstorms. Mitigation actions have been implemented to reduce their damage potential in the Brienz area.

Introduction

An extreme three-day rainstorm in August 2005 triggered two moderately deep landslides in the catchment areas Trachtbach and Glyssibach above the village of Brienz (Switzerland, Central Alps). Both landslides had a volume of about 50'000 m^3 and transformed into extremely rapid debris flows that moved along the headwater channels and reached the villages of Brienz and Schwanden. The debris flows caused significant damage in the inhabited area, two persons lost their lives and about twenty-five families became homeless. The Brienz case was one among many landslide and torrent disasters occurring during those rainy days in the Swiss Alps.

Mapping and historical records show that moderately deep (2–10 m) landslides in soil and weathered rock are common events along the steep (>35°) slopes above the village of Brienz. Already in the past such slides mobilized volumes of some 100 m^3 to several 10'000 m^3 and often transformed into subsequent debris flows that discharged over the headwaters as very rapid, long-runout events to reach the piedmont area and Lake Brienz. Hence they represent a constant hazard to the densely populated area at the lake shore side. Mitigation measures have been implemented for over 100 years.

Facing the catastrophic August 2005 event, a better understanding of the predisposition factors and triggering processes in the source area was needed, including key parameters for hazard assessment and design of efficient mitigation measures, such as landslide volume, potential entrainment and geotechnical material parameters. Discernable features on fresh soil-slides are known to quickly succumb to weathering, erosion

[1] Engineering Geology, Federal Institute of Technology ETH Zuerich, 8093 Zuerich, now at: Dr. Heinrich Jäckli AG, Albulastrasse 55, 8048 Zuerich.
E-mail: mueller@jaeckli.ch
[2] Engineering Geology, Federal Institute of Technology ETH Zuerich, 8093 Zuerich.

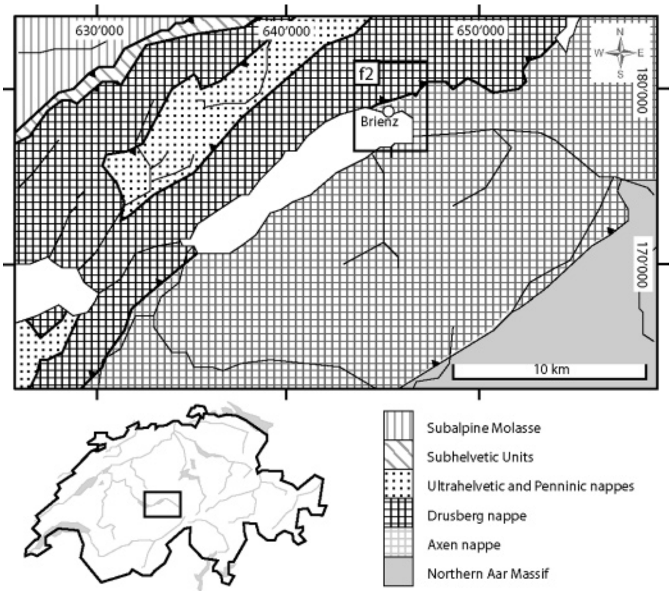

Fig. 1. Simplified tectonic map of the Bernese Oberland. Modified after Hänni & Pfiffner (2001).

and later revegetation (Turner & Schuster 1996). Essential information on the slide may hence be lost within a few years from the event. The genesis and lithology of surficial deposits along with information on bedrock are critical for later engineering measures and may only be preserved on detailed maps of the source area.

In this paper we present in detail the observable landslide features mapped shortly after the event, and discuss the predisposition factors and triggers of the landslides that caused the devastating debris flows of Brienz in August 2005. The findings also help to explain the long history and spatial distribution of landsliding in the study area.

Physiographic and Geological Setting

Physiographic Setting

The study area lies in the Bernese Oberland (Swiss Alps) and extends over approximately 2.5 km^2 (Figures 1 & 2). It includes the August 2005 landslide source areas and headwater systems and is located directly above the village of Brienz. The steep slope of the study area is southward oriented and extends from Undri Urseren (1600 m a.s.l.) below the Brienzer Rothorn (2349 m a.s.l.) down to Lake Brienz (564 m a.s.l.). Debris flows of the August 2005 events occurred in two separate torrent catchments with areas of about 100 hectares each. In total seven torrents run from the crest above Brienz into Lake Brienz.

The slope above Brienz can be geomorphologically divided into upper reaches, mid-slope portion and piedmont region (Figure 2). The August 2005 landslide source areas (700–1400 m a.s.l.) belong to the mid-slope portion, where debris and surface-water discharge occurs mainly over a strongly channelized headwater-system (Figure 4a). Mean slope gradients range between 30 and 45 degrees. Only a few 100 meters downslope from the landslide source-area follows the inhabited piedmont region (564–700 m a.s.l.). The torrents traditionally discharge their load directly across the inhabited area of Brienz and its densly populated surroundings in the piedmont region, like Schwanden (Figure 2). Stone-lined ditches were built already in the late 19th century, which direct the torrents bedload through the villages into Lake Brienz. The national-road and SBB railways also run along the lakeside and cross the respective torrents at their very mouth.

Geologic Setting

The study area is located in the Helvetic domain of the Swiss Alps. Bedrock lithologies exclusively comprise Cretaceous sediments associated to various stacks (imbricates) of the Drusberg nappe (Hänni & Pfiffner 2001). Table 1 presents the lithologies that occur in the mapping area (Ischi 1978, modified after Burger & Strasser, 1981). The Cretaceous series is strongly folded and faulted. In the study area, incompetent shales and marls of the Palfris Formation act as a sliding surface for intense Tertiary thrusting of the Drusberg nappe. Thereby the Drusberg Nappe has become detached from the underlying Cretaceous sediments (Axen Nappe) and experienced a north-directed displacement of up to 10 km (Hänni & Pfiffner 2001).

Along the upper reaches of the slope (>1400–2000 m a.s.l) competent siliceous limestones called Hauterivian Kieselkalk dominate and form steep walls and terraces (Figure 4). Strong erosional processes denudate the steep slopes and colluvial debris only form local thin layers. Snow avalanches (in winter), rock falls and predominantly shallow debris-slides proceed downslope and affect the lower regions.

Below steep limestone walls (<1400 m a.s.l.) follows the well afforested mid-slope portion, characterized by the abundant occurrence of Valanginian Marls (Diphyoides Limestone, Vitznau Marls). Regional mapping at a scale of 1:5000 has been conducted in the area of the 2005 landslides (Figure 4).

Table 1. Description of bedrock formations of the study area.

Formation	Age	Lithology
Kieselkalk Limestone	Hauterivian	Silty limestone
Diphyoides Limestone	Valanginian	Deep-water formation of alternating limestones and marls, uppermost 16 m composed of foliated marls („graue Mergelschiefer“)
Vitznaus Marls	Early Valanginian	Alternating beds of limestones and marls, higher limestone content than Palfris-Shales
Palfris-Shales	Berriasian	Alternating beds of limestones and shales

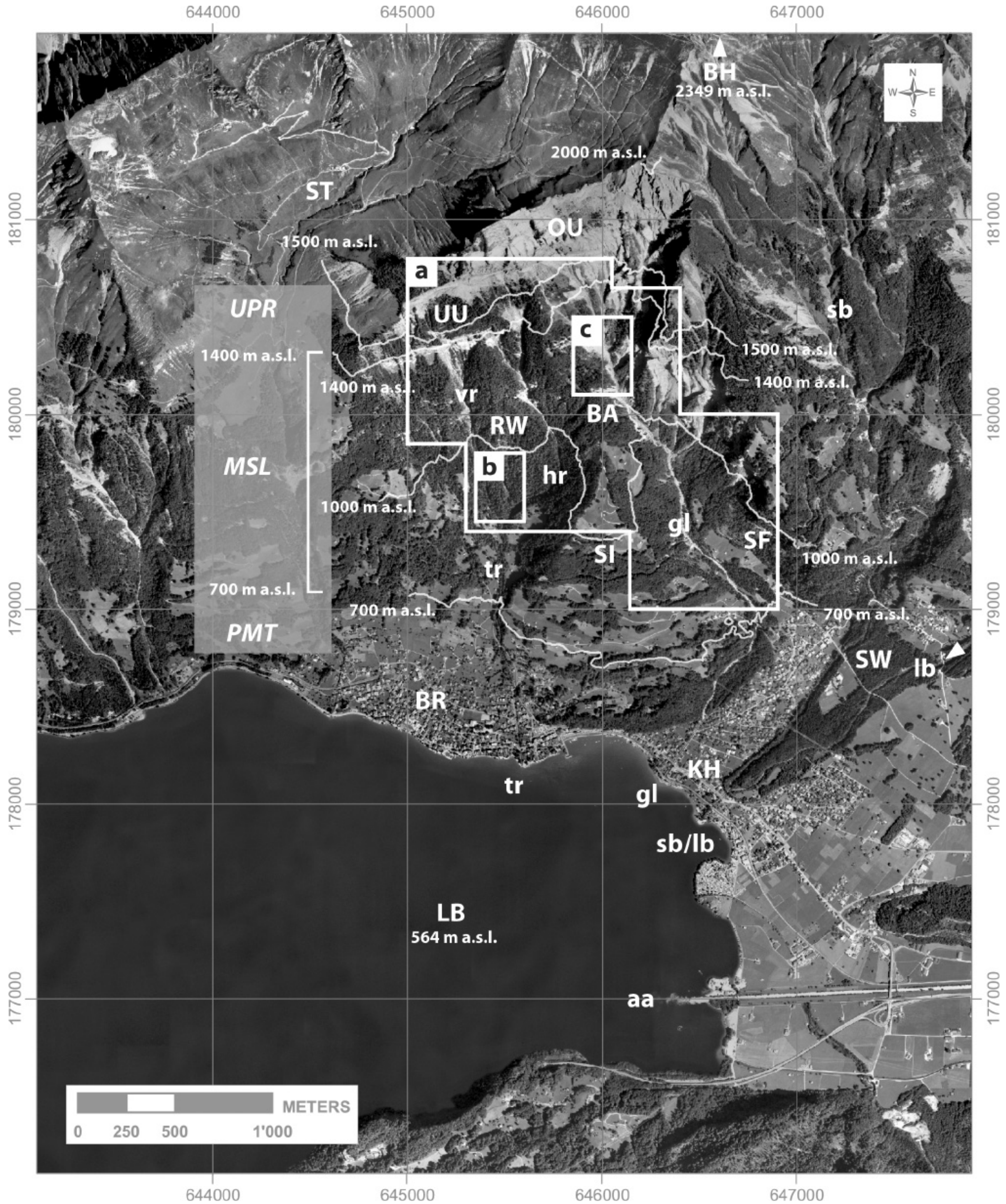

Fig. 2. Geographic Setting. *Geological Maps* a: Regional geological map (Figure 4a), b: August 2005 Trachtbach landslide map (Figure 4b), c: August 2005 Glyssibach landslide map (Figure 4c). *Geomorphological Domains*: MSL: middle reaches (mid-slope portion, 700–1400 m a.s.l.), PMT: lower reaches (piedmont, <700 m a.s.l.), UPR: upper reaches (>1400 m a.s.l.). *Localities:* BA: Baalen, BH: Brienzer Rothorn, BR: Brienz, KH: Kienholz, LB: Lake Brienz, OU: Obere Urseren, RW: Ritzwald, SF: Schwanderflue, SI: Sitschenen, ST: Staffel, SW: Schwanden, UU: Untere Urseren. *Torrents:* aa: Aare, lb: Lammbach, gl: Glyssibach, sb: Schwanderbach, tr: Trachtbach. Orthophotographic base reproduced with the permission of swisstopo (BA 091242).

Fig. 3. Historic painting of the Lammbach catastrophe, at Kienholz from late 19th century.

Mapping has shown that much of this area is composed of a few meters thick soil layer and underlying weathered Valanginian Marls of Cretaceous age (Diphyoides Limestone, Vitznau Marls, Figure 4). The alternating bedding sequence is highly unstable, as relatively hard rocks (limestones) alternate with soft interlayers (marls and shales). Weathering of the strongly tectonized bedrock quickly leads to an altered and presumably permeable residual soil, overlying a low-permeability substrate of bedrock. Most historic, dormant and active landslides occur where the bedding of these marls or the weathering front forms a dipslope oriented plane of weakness, which strongly favours sliding (Figure 5). The predominant form of mass movement within this area is shallow (<2 m) or moderately deep (2–10 m) soil-sliding. These frequent forms of landslides redeposit and discharge their load along the slope or into a headwater system.

The inhabited piedmont area (<700 m a.s.l.) is covered by the debris deposited from the exiting torrents (Trachtbach, Glyssibach) as well as other torrents.

Landslide Phenomena Mapping

The two August 2005 landslides have been mapped at a 1:1000 scale, following the recommendations of the Swiss Federal Office for the Environment (FOEN) published in Kienholz & Krummenacher (1995). High resolution digital terrain models (DTM) from LIDAR measurements carried out before and after the 2005 events, combined with airborne imaging, enabled accurate positioning and geomorphological mapping within the failure zones and the construction of detailed topographic and geologic profiles. The two moderately deep landslides differ in the sliding material, the sliding surface, the slide volume and the landslide-debris flow interactions. The release areas of both landslides are in convergent slopes (Figures 4 & 7).

Landslide and Mitigation History

Historic Damage Records

Landslides in the mid-slope portion and debris flows in the piedmont area of the Brienz area have a long history, covering both geological and historic records. Because the village of Brienz and its surroundings are located directly on the debris fans of active catchments, many hazard studies as well as mitigation plans and actions have been carried since the 19th century. Slope and channel stabilization measures have been implemented for more than 100 years.

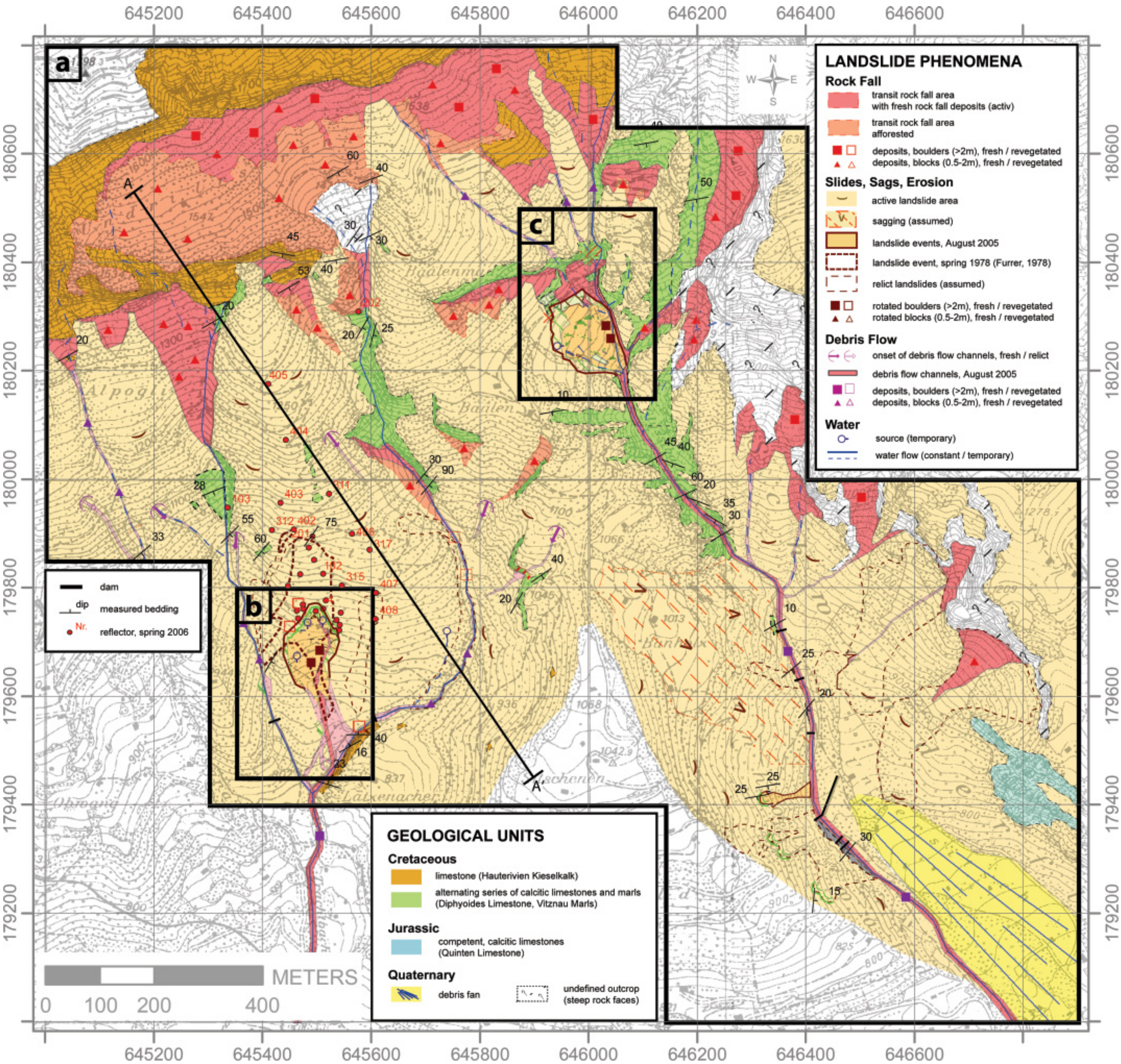

Fig. 4. Regional geological and landslide phenomena map (a) containing information from Furrer (1978); inset b: August 2005 Trachtbach landslide map (Figure 7a); inset c: August 2005 Glyssibach landslide map (Figure 7b); A–A': geological section Ritzwald (Figure 5). Tographic base reproduced with the permission of swisstopo (BA 091242).

Oldest chronicles indirectly allude to landslide events; for example, taxes of the state of Bern were lowered for local landholders due to catastrophic events in 1529, 1535 and 1540 (Dasen 1951). First detailed reports about breakouts and damages caused by the different torrents of the Brienz area date back to 1783 and 1797 (Dasen 1951).

The torrents Trachtbach, Glyssibach, Lammbach and Schwanderbach (Figure 2) have hit the villages of Brienz, Kienholz and Schwanden, one after the other but more often all villages at once. The most dangerous of them crossing through Schwanden and Kienholz are the Lammbach and Schwanderbach. Debris flow records of these torrents date back to 1499, and larger events in the 19th century comprise the years 1804, 1824, 1860, 1867, 1874, 1887, 1894 (twice) & 1896, the latest of which destroyed several houses at Kienholz, along with the federal railway track. The volumes of the last three events have been reported as approximately 300'000 m^3 covering land along a shoreline length of 120 m with an average debris thick-

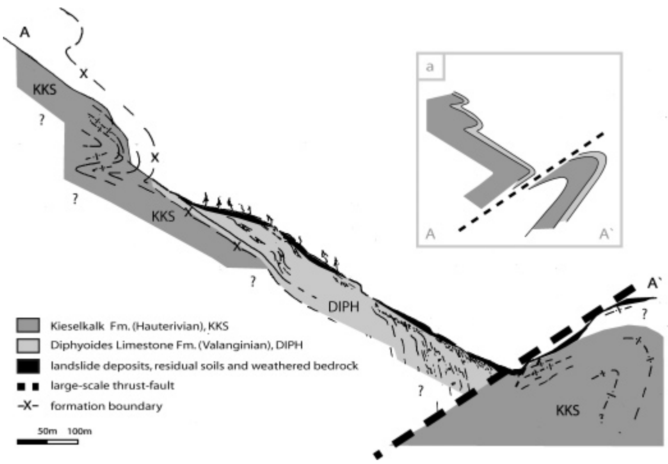

Fig. 5. Geological section Ritzwald (Figure 4, A–A'); inset a: Tectonic interpretation after Hänni and Pfiffner (2001).

ness of 2.5–4.0 m (Dasen 1951), always originating from the Lammbach source area. The most damaging debris flow events of the Glyssibach have been reported for the years 1783, 1797, 1804, 1824, 1894, 1921.

The Trachtbach is another hazardous torrent system, not primarily due to its catchment characteristics, but due to the fact that the major part of the village Brienz is directly positioned on the alluvial fan of its deposits. Major damages from debris flows – often induced by landslides in the Ritzwald area – have been reported for 1796, 1797, 1824, 1846, 1870, 1871 (twice), and 1894. Most these events are clearly related to intensive thunderstorms or long duration rainfalls, occurring in spring, summer or late fall.

After the devastating event of 1896, the State of Berne consulted the geologists A. Heim and E. Kissling for an integrated hazard assessment. Heim predicted future mass movements, involving a potential of 3–6 million cubic meters of mass, which would destroy the village of Schwanden and eventually provoke a flood wave within Lake Brienz to reach the opposite lake shore. Fortunately such events never occurred. Further geological studies, e.g. P. Arbenz in 1919 (Dasen 1951), concluded that afforestation would be the only effective means to stabilize the widely loosened and disrupted geological strata.

Past Reconstruction and Prevention Actions

Some local funds were raised at Schwanden after large debris flows in 1797 and 1804, but they were only used to alleviate the distress of the most affected people. The villages of Brienz and Schwanden started constructional work on deflecting dams in 1850. In early summer of 1871, the local Trachtbach committee paved the lower section of the channel over an approximate distance of 1200 m. This was in direct response to devastating events in 1870 and 1871, when the Trachtbach claimed deaths, destroyed houses and stables with cattle (Dasen 1951). The paving consisted of a stone-lined ditch, capable of directing regular debris flows into the lake. The State of Berne subsidized the overall costs of CHF 48000.–. But already in the same year a debris-flow broke out in the lowermost section of the Trachtbach channel and again loaded the adjacent houses and land with debris. After this event the population became aware that further prevention measures had to be realized and a first afforestation project was carried out between 1883 and 1888 in the Trachtbach catchment area. This project included the planting of 150'000 trees, as well as the construction of avalanche fences in the upper reaches, and 770 m^3 of masonry along the middle reaches.

After the enactment of a federal act on forestry in 1876, a project for the afforestation of the unstable slopes in all catchments was submitted to the Federal Office, which additionally proposed the construction of supportive dams along the upper reaches. A first estimate of the related costs led the community and land-owners to abandon the project at first, but the dramatic events of the late 19th century and their analysis urged the local and state authorities to again request federal subsidies for an extended engineering and afforestation project which finally was accepted by the federal authorities. The main scope of the project was the afforestation of the upper terraces, as further afforestation of the middle reaches could not be realized as long as these were often hit by snow avalanches from above. Therefore solid avalanche barriers were constructed throughout the upper reaches and small bars were placed within the ravines (Dasen 1951). The construction of avalanche barriers and related afforestation were completed in the early 20th century and resulted in intensive vegetation recovery in the upper reaches of the torrents catchment area.

Since this time major damaging events became very rare, and throughout the 20th century heavy damage was only reported once (1921, Glyssibach). This difference to the activity in the 19th century is observed over entire Switzerland. It might not only be related to the afforestation, but also to systematic differences in climatic conditions (long wet periods in the 19th

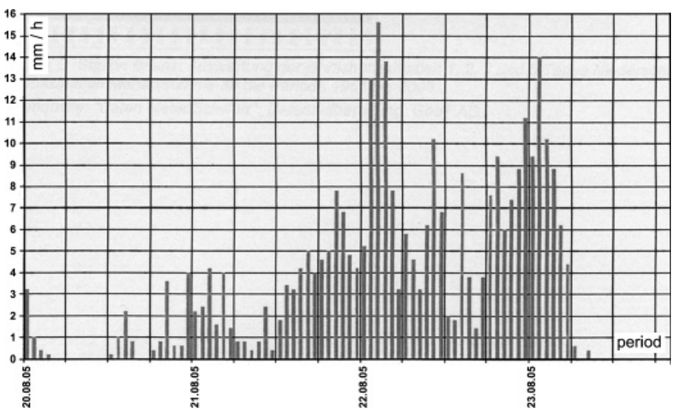

Fig. 6. Hourly rainfall at Gibelegg (1710 m a.s.l., 1 km north-east from the mapping area) from August 20th to August 24th 2005, after Kantonales Amt für Wald, Interlaken.

century). In the 20th century the village of Brienz could develop and become a popular tourist resort, with a current permanent population of 3000 people. In 2003/2005 a hazard map was created for the Brienz area, which assumed partly smaller devastations for the corresponding rainstorm recurrence period than what actually happened in August 2005.

August 2005 Rainstorm Event

On August 18th to 23th 2005, a strong rainstorm event hit Switzerland, resulting in six casualties and causing total property damages of three billion Swiss Francs (Guy Carpenter and Company Ltd., 2005). Flooding, erosion, overbank sedimentation, landslides and debris flow deposition were the dominant

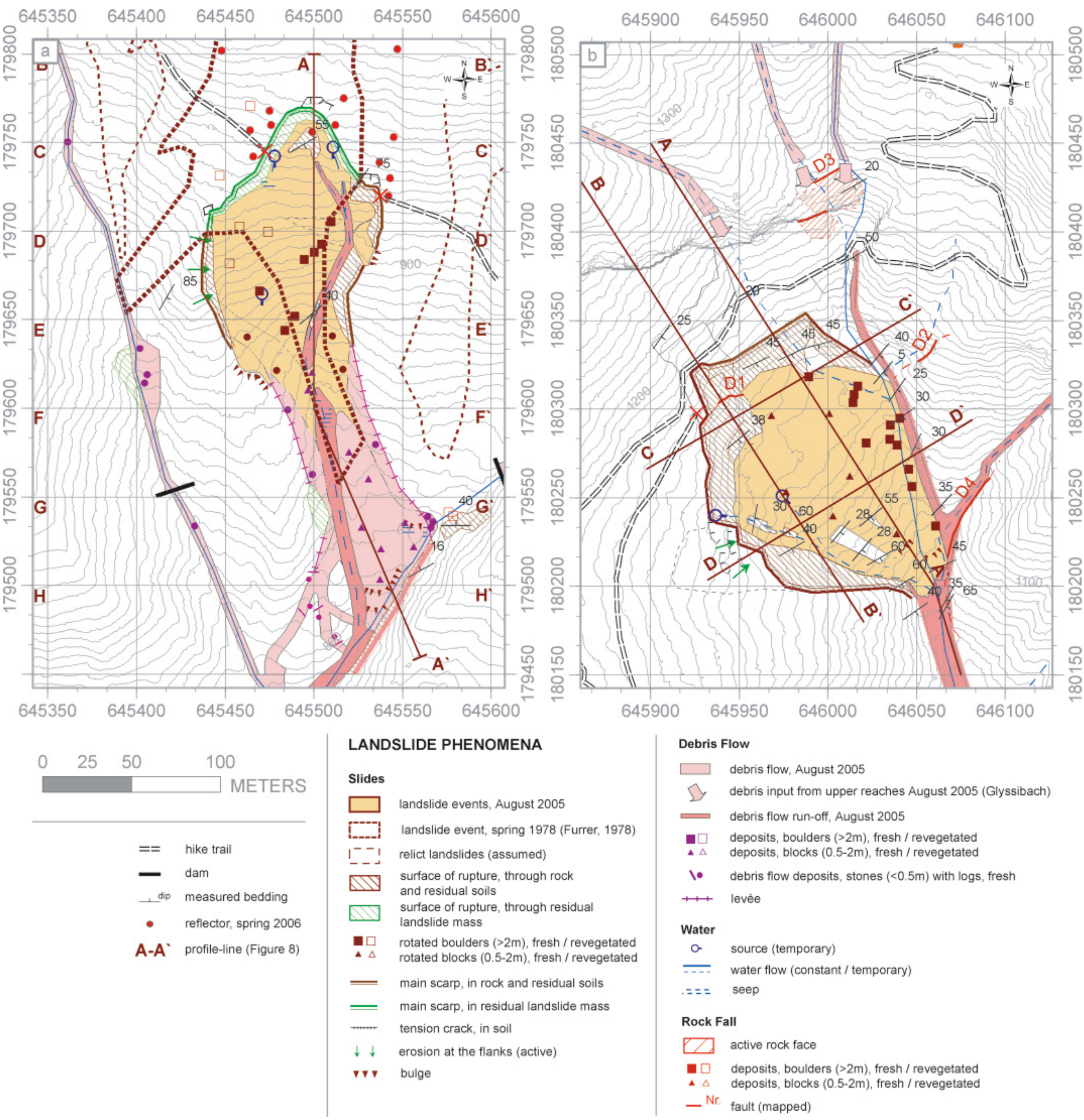

Fig. 7. Detailled August 2005 landslide phenomena maps, a: Trachtbach Landslide, b: Glyssibach Landslide.

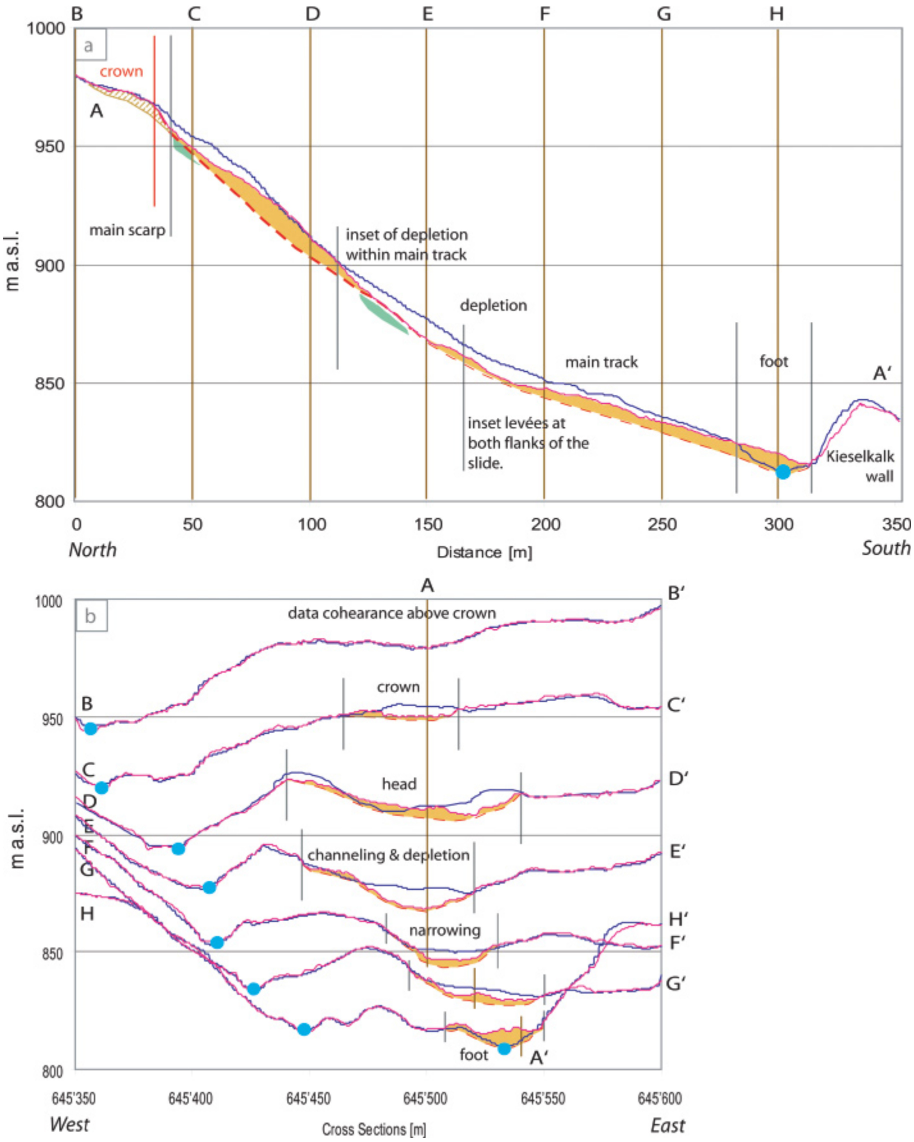

Fig. 8. Detailed terrain sections through August 2005 landslides, derived from airborne LIDAR measurements taken before and after August 2005, a: Trachtbach landslide profile A (Figure 7a), b: Trachtbach landslide profiles B–H (Figure 7a).

damage-causing processes. A total of 5000 landslides of various types and sizes have been registered (Bezzola & Hegg 2007).

In the surroundings of Brienz the strong rainfall started on August 20, 2005 (Meteodat 2005), and continued uninterruptedly over a period of 72 h (Figure 6). Hourly maxima of 14 mm/h and 16 mm/h were reached around midnight of August 21st–22nd and 22nd–23rd. During the day before the landslide events, which happened in the night of August 22nd–23rd, the mean rainfall intensity was in the order of 6–8 mm/h. The total precipitation between August 20th and August 22nd amounted to 215 mm in the village and 307 mm in the higher altitude hillslope area. From a statistical point of view the local two-, three- and five-day precipitations are all significantly above the 200-year event (NDR Consulting Zimmermann 2006). However, when considering the entire August 2005 rainstorm in Central Europe, the return period for an equivalent local event lies at only 80 years. The extensive rainstorm event can hence be seen as rare, but not exceptional (Bezzola & Hegg 2007). The exceptional local precipitation at Brienz must be seen as one of many storm cells within an extensive, prolonged rainstorm event.

August 2005 Trachtbach Landslide

Landslide type and volume

The Trachtbach slide (Figure 13a–b) follows the exact extent of a geomorphic depression and shows a nearly bi-linear rupture surface along the line of movement (Figures 7 & 8). Based on an orthorectified airborne image from 1987 (Figure 13c), it can be shown that most of the displaced material is a reactivation of an earlier slide, which occurred in 1978 (Furrer 1978). This 1978 slide has its crown 100 m upslope from the 2005 main scarp

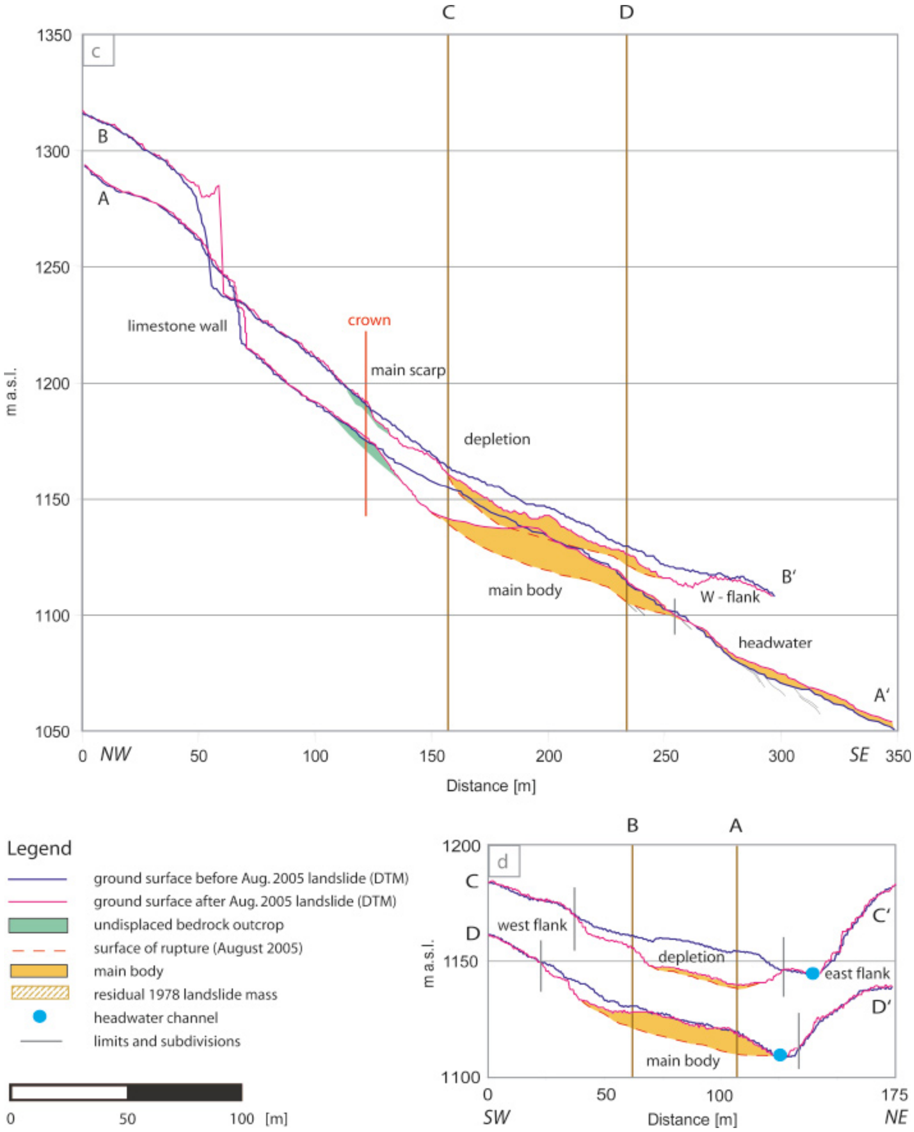

Fig. 8. c: Glyssibach landslide profiles A & B (Figure 7b), d: Glyssibach landslide profiles C & D (Figure 7b).

(Figure 4) and mainly deposited its mass along the slope without reaching the headwater channel of the Hinterer Ritzgraben (Figure 7a). The 1978 colluvium deposits are nicely exposed in the August 2005 main scarp (Figure 13d), which reaches a maximum height of 5 m at the uppermost elevation (965 m a.s.l.) and can be traced along a curved line over about 100 meters.

Between the main scarp and y-coordinate 179625, the depleted mass was initially composed of several large and only slightly backward-rotated "blocks" with preserved original vegetation and soil structure resting on discrete rupture surfaces (Figures 7 & 13b). These can be taken as clear indications for nearly planar sliding as the main failure and transport mechanism north of coordinate 179625. Below y-coordinate 179625 first flow characteristics in the depleted mass have been observed. This is the same location where the main landslide body converges and the landslide base changes its dip angle from 39 to 18 degrees (Figures 7 & 8). Here both flanks rise to >5 m in height and form a distinct channel of 50 m width. Despite steep flanks, the landslide deposited cobbles and stones along with fine-grained material laterally onto afforested ground. These lateral deposits form a sharp line on top of the flanks, interpreted as possible levees, and indicate that the landslide first travelled at an elevated level. Subsequently, the landslide partially eroded its path in the lower section, as it unloaded sediments over the headwater channel of the Hinterer Ritzgraben.

The longitudinal and west-east profiles of the Trachtbach landslide (Figure 8) have been constructed from the LIDAR measurements, and report ground surface elevations (±1 m) before and after the event. An indication of the data accuracy is given in section B, which runs through the crown a few meters above the main scarp. Any net volume change can be read directly from the graphs. Directly after the event the rupture surface remained completely covered and could not be properly located by field-mapping in late autumn of 2005. Erosion after strong rainfall and snow-melt in the following spring and summer 2006 revealed several outcrops of the rupture surface (Figure 13e–f), within the landslide's head and transitional zone, and allowed to fully define the landslide geometry and structure (Figure 8 & 9).

Based on this analysis, the Trachtbach landslide has a depleted volume of 33000 m^3, and an accumulated volume of 9000 m^3 (Figure 8), leading to an initial debris flow solid content of 24'000 m^3 (±500 m^3) without bulking. The estimated volume of displaced material amounts to 57'000 m^3 (±3000 m^3). Landslide erosion (net volume loss) was very effective over most of the source and transit area, and maintains a depth between 6 and 10 meters. The 2005 displaced volume remaining today as new colluvium in the entire depression amounts to 33'000 m^3 (±3000 m^3).

Landslide Rupture Surface and Materials

Below the main scarp the rupture surface is composed of layers of marly clay derived from highly weathered Valanginian Marls, forming a sharp contact to the colluvium (Figure 13e–f). Lab tests of the fine grained clayey matrix in this rupture surface sampled on a rainy day (October 24, 2006), resulted in a shear strength of 70–90 kN/m^2, a relative saturation of about 50%, and a plasticity index of about 10% (17 samples). As the mean dip angle of bedding in the Valanginian Marls is steeper than the slope, and isoclinal folding is very frequent, the rupture surface often runs discordantly to bedding (Figure 9). It can be observed that water runs along this clayey rupture surface or seeps out from the sliding mass above this surface.

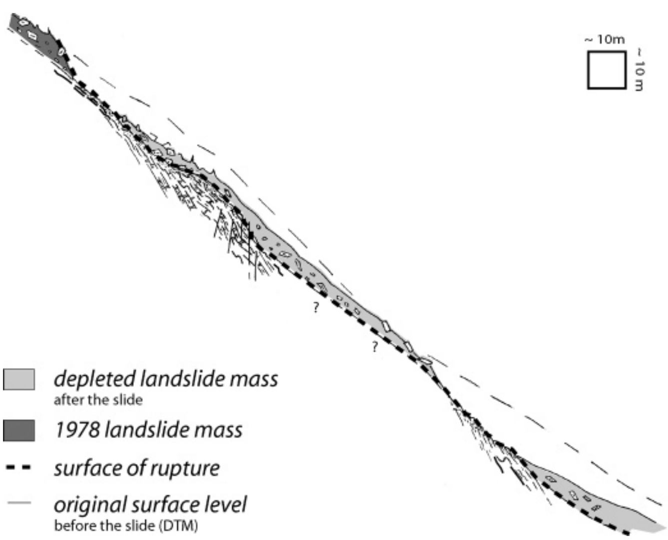

Fig. 9. Detailed geological profile of the Trachtbach landslide (after the 2005 event).

Side scarps in the east, 50 m below the head scarp (y-coordinate 179725), show that the rupture surface downcuts into weathered bedrock with preserved structure. The rupture surface follows 2 sets of fractures, mobilizing large boulders (>1 m^3). In the west and east scarp, between coordinates 179630 and 179710, the rupture surface cuts through saprolites and residual soils, i.e. the August 2005 slide clearly extends beyond the 1978 slide in depth, laterally and downslope.

The dip angle of 39 degrees led to fast erosion of the depleted landslide mass along this steep portion. As of autumn 2006, some blocks of the depleted mass have decayed and eroded in the steep landslide section and several parts of the rupture surface have been uncovered within only one year from the event. The rupture surface disappears below ground where the slide dip angle changes to 18 degrees and the path becomes more channelized.

A composite profile through the landslide has been created based on observations in the main scarp, the side scarps and the visible rupture surfaces (Figure 10). After a thin layer of humus follows colluvium from 1978, composed of large boulders (>1 m^3), stones and gravel, supported by a very fine-grained matrix of clayey silt with a void ratio of about 1 (50% porosity). Grain size distribution analysis of this material resulted in poorly graded clayey gravel with stones and boulders (20–30%) and lack of sand size fraction. The grain size composition of the 2005 landslide deposits is very similar.

Catastrophic Failure and Displacement Monitoring

The actual time of the Trachtbach landslide failure is unknown. According to NDR Consulting Zimmermann (2006) a first, highly viscose debris flow was observed at Rauenhag (750 m a.s.l.) on August 22nd, at 10 p.m. GMT. At 10:15 and 10:20 p.m. two subsequent low-viscosity debris flows reached Lake Brienz without leaving the Trachtbach chanal. The following surges overtopped the dams of the canal and inundated about 76'000 m^2 of land with debris in the central part of the village of Brienz.

A displacement measuring system of 13 geodetic reflectors has been installed on September 4th 2005 for early warning and monitoring of on-going movements. Reflectors have been placed inside the depleted slide mass, in stable bedrock below the rupture surface, around and above the crown. At the end of November an additional seven reflectors have been added to this monitoring network (Figures 4 & 7). In September 2006 the geodetic system was completed for long term monitoring. Displacements along the line of sight have been measured from the school building in the village Brienz.

Results showed fast initial movements and collapse of slide compartments inside the upper depleted mass, as well as secondary failures in the crown during the first months after failure. These movements again showed strong dependence on rainfall intensity. A reflector in bedrock below the rupture surface (No. 19) proved to be stable. Reflectors outside the first few meters of the crown show widespread, het-

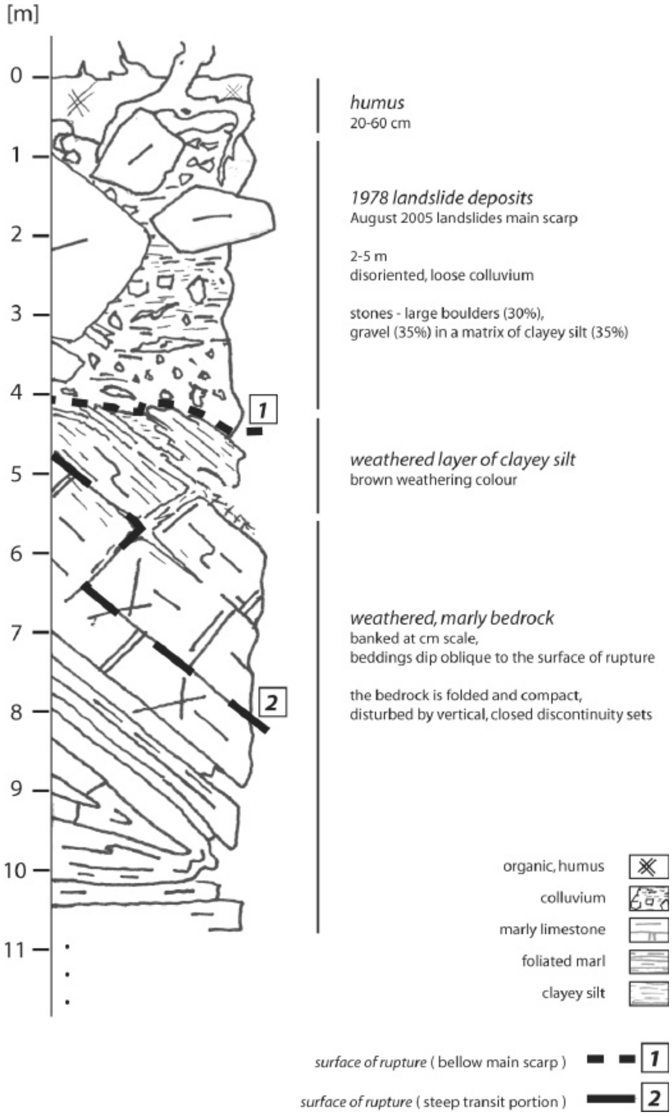

Fig. 10. Reconstructed geological section through the 2005 Trachtbach landslide (head scarp area).

erogeneous and generally slow movements (0.1 to 8 mm per month).

August 2005 Glyssibach Landslide

Landslide Type and Volume

The most destructive landslide of August 2005 initiated within the catchment of the Glyssibach torrent, 1500 m from the inhabited area of Schwanden (Figure 2 & Figure 13g–l). A series of channels, originating from the upper reaches, gather at 1200 m a.s.l. to enter a 500 m long gorge. The location of this convergence coincides with the head scarp area of the Glyssibach landslide (Figure 4 & 7b).

At the head scarp (1175 m a.s.l.) the slide is 130 m wide and failure occurs within weathered rock and residual soils derived from the Valanginian Marls (Figures 11 & 12), composed here of an alternating series of marly limestones, foliated marls and often highly weathered clayey interlayers (Figure 13i–l). Weathering and mechanical weakening of the tectonized marls at this locality is intensified by subvertical faulting and intensive fracturing in the hinge zone of a large isoclinal fold (Figure 11). The mantle of weathered bedrock reaches >10 m thickness and sliding occurs at its very base. The main scarp develops in an area where bedding dip increases from 25 to 45 degrees, along a curved fold hinge. Here sliding has occurred parallel to the bedding and exposed a marly plate over an area of 55 × 20 m (Figure 13i–j). This plate is overlain by a clayey and wet interlayer of about 20 cm thickness (Figure 13k). Section C of Figure 8 is located just below the main scarp and presents a maximal depletion of 15 m.

Based on field mapping and LIDAR measurement, two longitudinal and two transversal sections have been constructed through the Glyssibach landslide (Figure 8). The total landslide volume initially mobilized within the failure zone is roughly estimated to 80'000 m^3 (± 8000 m^3). Initial run-off amounts to 48'500 m^3 (± 500 m^3). Hence, a total of 30'000 m^3 (± 8000 m^3) remained loose within the landslides source area, after a downslope displacement of about 20–30 m. The uncertainty of ±8000 m^3 in the residual volume results from the uncertainty in depth of the sliding surface. Intact beds of Valanginian Marls appear below the disintegrated sliding mass (Figure 13j). The beds appear to belong to actual bedrock, but a deeper seated surface of rupture remains possible.

Landslide Rupture Surface and Materials

Mapping within the failure zone revealed that the sliding surface geometry is also strongly controlled by the rock mass

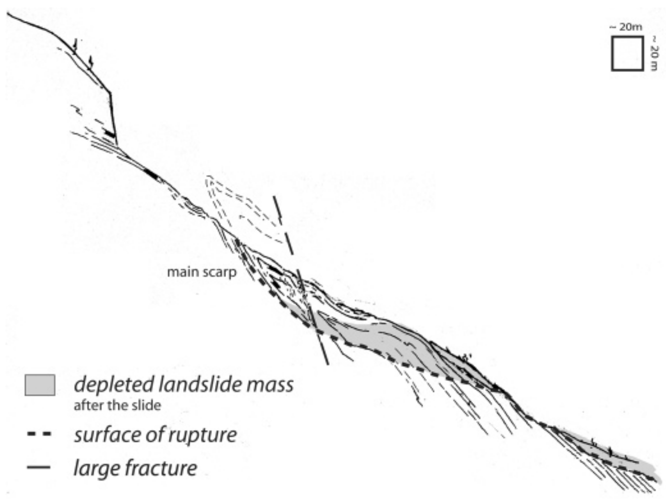

Fig. 11. Detailed geological profile of the Glyssibach landslide (before the 2005 event).

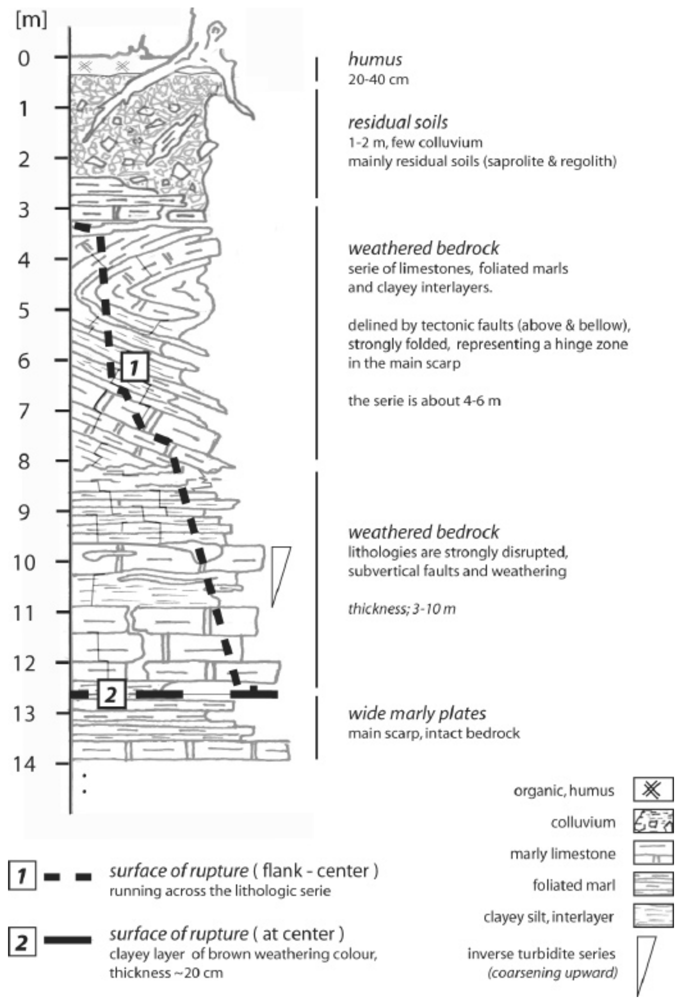

Fig. 12. Reconstructed geological section through 2005 Glyssibach landslide (head scarp area).

structure: The nearly isoclinal fold of the main scarp has secondary folds and an axial plane which is refolded in open, low amplitude and large wavelength folds (Figure 11). The curved rupture surface in the upper part of the landslide follows bedding and cuts through bedding in the lower section, resulting in a slightly rotational failure surface (Figure 11).

The Glyssibach landslide occurs where the slope dips locally towards SE–SSE, i.e. in exactly the same direction as bedding, and where the slope strikes parallel to bedding and the isoclinal fold axes orientations (dip azimuth 60°, dip angle 18º, mean values from 35 measurements). Bedding orientations are placed on the map (Figure 7b) and labelled with dip angle and altitude (m a.s.l.). The NE-dipping inclination of the fold axis is reflected in a vertical shift of longitudinal profiles A and B (Figure 8c) respectively.

The three-dimensional internal structure of the Gyssibach landslide is complex and controlled by SE-dipping folds and two dominant steeply dipping fault sets, striking NNW–SSE and NE–SW. The thickness or original depth of the mobilized mass increases towards NE up to 15 m in height and abruptly terminates at the Glyssibach on the NE flank (Section C & D of Figure 8d). At the NE lateral boundary fluvial erosion in the headwater possibly eroded the landslide foot down to rupture surface level.

A composite section through the landslide has been created based on outcrops below the crown (Figure 12): A thin humus cover of 20–40 cm is followed by a coarse grained soil layer composed mainly of saprolite. The poorly graded gravel is grain supported, containing a considerable percentage of fines, along with interbedded stones and larger, platy boulders. The structure of the original bedrock is visible within the saprolite as aligned blocks of limestones follow bedding layers. The transition from saprolite to weathered bedrock is sharp, but its vertical position varies strongly within different profiles due to the uneven weathering, rock mass structure and tectonic overprint. As seen on airborne images from 2002 (Swisstopo) surficial erosion before the catastrophic failure was already strong in the center of the future slide, where vegetation and substantial soil cover were missing.

Catastrophic Failure

The Glyssibach landslide directly slid into the headwater channel. Transition from rock slide to debris flow possibly occurred where the displaced mass was taken up by the headwater channel. Mud-marks from sweeps on the east-flank indicate flow. The only net volume increase of a few 100 m^3 is visible at the bottle-neck to the gorge (Section A in Figure 8c). Significant entrainment has occurred in the channel as this debris flow ran through lower reaches (<930 m a.s.l.). Here the erosion depth within the riverbed amounts to 2–6 m (NDR Consulting Zimmermann, 2006). An approximate volume of 70'000 m^3 of debris and large boulders (>4 m) of the very rapid debris flow (6–10 m/s) hit the village of Brienz at approximately 2:00 a.m. GMT on August 23rd 2005, causing major damage.

Summary and Discussion

Many analogies exist between the two August 2005 landslides and numerous past landslides in the mid-slope portion above Brienz (Figure 4). In all cases we find a mantle of colluvium and/or residual soil along with weathered bedrocks of intermediate thickness (2–15 m) derived from the Valanginian Marls. Hence, the August 2005 landslide events can be seen as model examples for typical landslides in this geomorphic and geologic setting. A complex interplay of several geological factors with the slope morphology controls the predisposition of the Brienz landslides, which are triggered by strong but not uncommon rainstorm events.

The Trachtbach and Glyssibach landslides highlight that convergent slopes are especially susceptible to strong and prolonged infiltration, as this slope plan form tends to

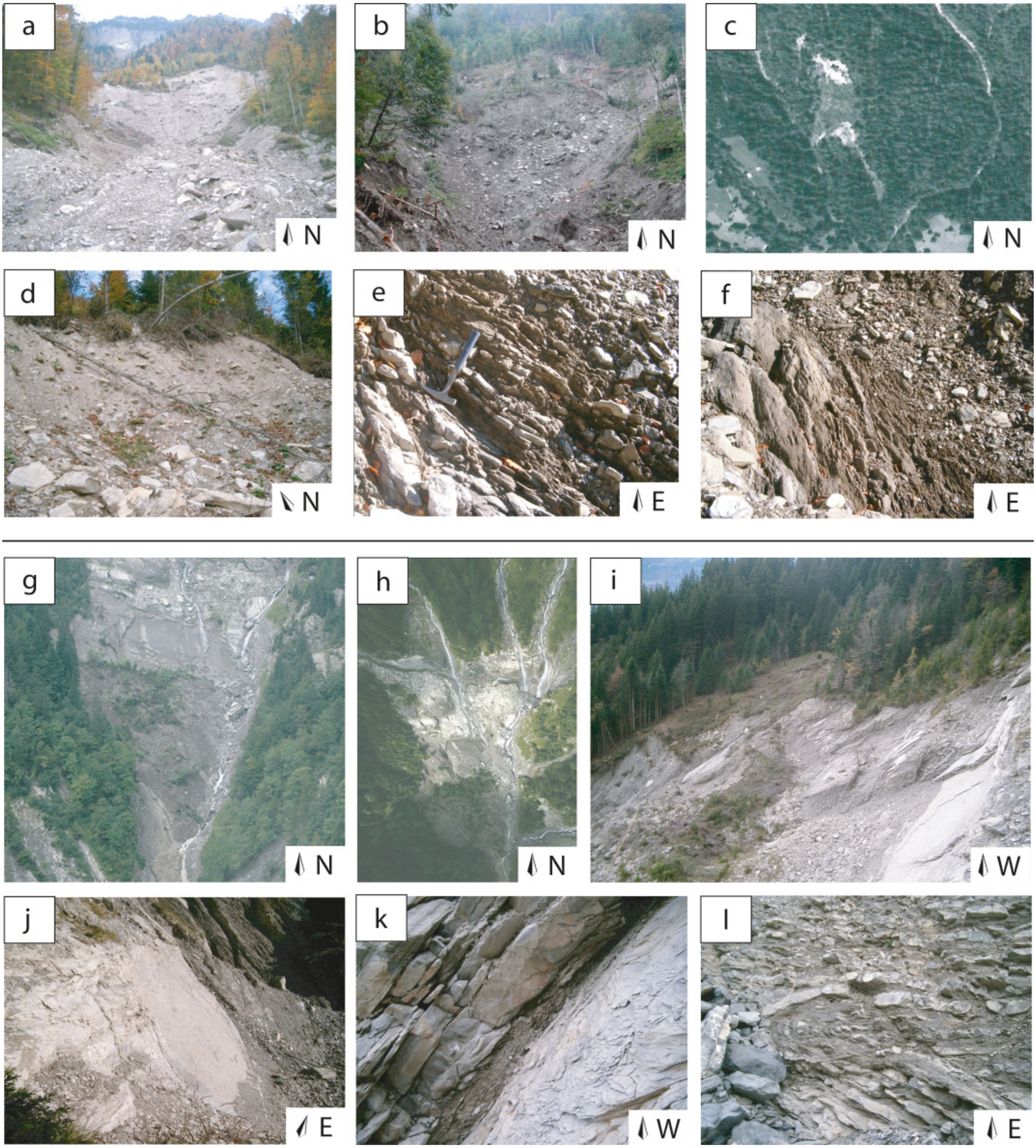

Fig. 13. Photo plate, a–f: August 2005 Trachtbach landslide, a: view from toe area towards head, b: rotated "blocks" with preserved vegetation in head scarp area, c: 1978 Trachtbach landslide (airborne image 1987), d: 2005 main scarp exposing the 1978 landslide body, e–f: weathered bedrock exposures at rupture surface, g–l: August 2005 Glyssibach landslide, g-h: airborne images of 2005 slide (airborne image 2005), i–j: 2005 main scarp following bedding of marly plate (55 × 20 m) dipping at 45° SSE, k: rupture surface at marly layer, overlain by 20 cm thick clayey interlayer and fractured limestone beds, exposed at west-end of the marly plate (i), l: isoclinal fold in weathered bedrock at the east-flank.

concentrate surface and subsurface water into small areas of the slope, generating rapid pore water pressure increases (Onda 1992; Sidle and Ochiai 2007). Whereas rock mass structure plays a minor role for the mobilized colluvium at the Trachtbach landslide, the Glyssibach landslide demonstrates the important role of bedding, fault and fold orientations when the mobilized material only consists of weathered bedrock.

In both cases, new discrete rupture surfaces have evolved, which remain partially covered by depleted landslide mass. The ground surfaces before and after failure as well as the rupture surfaces have been reconstructed in great detail from high resolution LIDAR measurements and detailed field mapping. The rupture surface of the Trachtbach landslide locally cuts through bedding of the Valanginian marls and has a bi-linear geometry in a longitudinal profile, with a dip angle of 39º in the upper section and 18º in the lower section. The rupture surface of the Glyssibach landslide is strongly influenced by bedding, which is intensively folded and faulted, creating a stepped and curved sliding surface with dip angles ranging from 18º to 45º.

Weathering of the Valanginian Marls is a relatively fast ongoing geological process within the mid-slope portion above Brienz. Afforestation stabilized weathered materials in the 20th century, but does not stop the weathering process. Small marly blocks exposed by the 2005 Trachtbach landslide decay into clayey soil within a few years. Also, as shown in the Glyssibach landslide, the production of weathered material in the subsurface reaches up to 15 m depth along open fractures and faults, especially in areas where surface layers have been eroded. It has to be assumed that several other locations exist where thick weathering products have accumulated in the past. Systematic geomorphic analysis and geophysical mapping of the thickness of saprolite and colluvium could assist in the development of hazard index maps for the entire midslope area above the villages of Brienz and Schwanden.

The August 2005 landslides each redeposited approximately 30'000 m^3 of debris within the failure zones. Though the net mass balance is negative, this mass is now forming a loose colluvium which could be remobilized quickly by future rainstorms. Currently installed monitoring systems keep these source areas under observation.

A more practical value of this publication lies in the metric (1:1000) documentation of the August 2005 Trachtbach and Glyssibach landslides and the phenomena mapping in the surrounding area. The various maps and figures will allow quick identification of new landslide features along the afforested slope.

Acknowledgements

The authors would like to thank Markus Zimmermann, Hugo Raetzo and Jörg Häberli for making this study possible, and providing substantial scientific and technical inputs. We also acknowledge the fruitful discussions with Frank Lemy, Helmut Weissert, Peter Haldimann, Ueli Gruner and Hans Kienholz, as well as the support from Raquel Martinez Scheiwiler, Jonas von Rütte, Margrit Arnold and Gregory de Souza.

REFERENCES

Bezzola, G. R. & Hegg, C. (Ed.) 2007: Ereignisanalyse Hochwasser 2005, Teil 1 – Prozesse, Schäden und erste Einordnung – Bundesamt für Umwelt BAFU, Eidgenössische Forschungsanstalt WSL, Umwelt Wissen Nr. 0707, 215 pp.

Burger, H. & Strasser, A. 1981: Lithostratigraphische Einheiten der untersten Helvetischen Kreide in der Zentral- und Ostschweiz – Eclogae Geologicae Helvetiae 74/2, 529–560.

Dasen, E. 1951: Verbauung und Aufforstung der Brienzer Wildbäche – Eidgenössisches Departement des Innern, Inspektion für Forstwesen, Jagd und Fischerei, 59 pp.

Furrer, H. 1978: Geologischer Bericht betreffend Rutschung Ritzwald – Unpublished report.

Guy Carpenter and Company Ltd. 2005: European Flood Report 2005 – Central and Eastern Europe – Marsh & McLennan Companies, 18 pp.

Hänni, R. & Pfiffner, A. 2001: Evolution and internal structure of the Helvetic nappes in the Bernese Oberland – Eclogae Geologicae Helvetiae 94, 161–171.

Ischi, H. 1978: Das Berriasien-Valanginien in der Wildhorn-Drusberg-Decke zwischen Thuner- und Vierwaldstättersee – Inauguraldissertation der Philosophisch-Naturwissenschaftlichen Fakultät der Universität Bern.

Kienholz, H. & Krummenacher, B. 1995, Symbolbaukasten zur Kartierung der Phänomene – Federal Office of the Environment (FOEN)

Meteodat 2005: Meteorologische Daten aus dem Jahr 2005 – http://www.meteoschweiz.ch/de.

NDR Consulting Zimmermann, Niederer und Pozzi Umwelt AG 2006a: Lokale Lösungsorientierte Ereignisanalyse Trachtbach – Tiefbauamt des Kantons Bern, Oberingenieurkreis I, Thun, 51 pp.

NDR Consulting Zimmermann, Niederer and Pozzi Umwelt AG 2006b: Lokale Lösungsorientierte Ereignisanalyse Glyssibach – Tiefbauamt des Kantons Bern, Oberingenieurkreis I, Thun, 36 pp.

Onda, Y. 1992: Influence of water storage capacity in the regolith zone on hydrologic characteristics, slope processes, and slope form – Zeitschrift für Geomorphologie, Neue Folge 36, 165–178.

Sidle, R.C. & Ochiai, H. 2006: Landsildes – American Geophysical Union, Water Resources Monograph 18, 312 pp.

Turner, A.K., & Schuster, R.L. 1996: Landslides – National Research Council (U.S.) Transportation Research Board, Special Report 247, 673 pp.

Manuscript received September 9, 2008
Revision accepted December 12, 2008
Published Online first May 7, 2009
Editorial Handling: Pierre Perrochet, Stefan Bucher