Geo.Alp, Vol. 3, S. 147–166, 2006

SPATIAL FEATURES OF HOLOCENE STURZSTROM-DEPOSITS INFERRED FROM SUBSURFACE INVESTIGATIONS (FERNPASS ROCKSLIDE, TYROL, AUSTRIA)

Christoph Prager[1, 2], Karl Krainer[1], Veronika Seidl[1] & Werner Chwatal[3]

With 11 figures and 2 tables

[1] University of Innsbruck, Institute of Geology and Paleontology, Innrain 52, A-6020 Innsbruck, Austria

[2] alpS Centre for Natural Hazard Management, Grabenweg 3, A- 6020 Innsbruck, Austria

[3] Technical University of Vienna, Institute of Geodesy and Geophysics, Gußhausstrasse 27-29, A-1040 Vienna, Austria

Abstract

A low frequency Ground Penetrating Radar (GPR) system was successfully applied for near subsurface explorations at different accumulation areas of the fossil Fernpass rockslide (Tyrol, Austria), which is one of the largest mass movements in the Alps. Based on detailed field studies and calibrated by drillings down to a depth of 14 m, the reflectors of the processed GPR-data could be well attributed to different depositional units. As a result, the distal rockslide deposits feature intensively varying accumulation geometries and are up to approximately 30 m thick. In addition, the topographically corrected GPR data show that the Toma, i.e. cone-shaped hills composed of rockslide debris, show deeper roots than the topographically less elevated rockslide successions between them. Compiled field-, drilling- and GPR-data indicate that the accumulation pattern and spread of the investigated rockslide deposits was obviously predisposed by the late-glacial valley morphology and that the Sturzstrom surged upon groundwater-saturated, fine-grained lacustrine sediments. Thus we assume that dynamic undrained loading, reducing the effective stresses between the rockslide and its incompetent substrate, enabled the extremely long run-out distance of the sliding mass measuring up to at least 15.5 km. Continuous gravitational spreading, which probably occurred subsequent to the rapid Sturzstrom flow, resulted in a further decomposition of the rockslide deposits and the generation of the present morphology, characterised by the well-known Toma hills and associated funnel- to basin-formed depressions which include several kettle-like lakes. After decomposition, the spreading rockslide deposits have locally been covered by on-lapping fluvial deposits. According to GPR data, these post-rockslide sediments can reach thicknesses of up to at least 20 m.

1. Introduction

"Sturzströme" are rapid moving rock avalanches, commonly greater than 10^6 m^3 in volume and may cover excessive travel distances even on only gently sloped valley floors due to their flow-like behaviour (Heim, 1932; Hsü, 1975). The dynamic disintegration of catastrophic failing rock masses generates unconsolidated attrition breccias of different grain-sizes and with varying contents of fine interstitial material in the pore space. The fracturing and crushing of the sliding mass lower significantly the internal friction coefficient and the shearing resistance, especially when the disintegrating mass and/or its substrate are water-saturated (e.g. Rouse, 1984; Abele, 1997; Erismann & Abele, 2001; Legros, 2002; Hungr and Evans, 2004). Thus, the enhanced mobility of many rockslides may be attributed to lubrication effects that are controlled by grain size reductions and sufficient water supply.

Also one of the largest mass movements in the Alps, the catastrophic Fernpass rockslide in the Northern Calcareous Alps (Tyrol, Austria), shows long run-out distances up to at least 15.5 km in length. Since its complex accumulation path is also characterised by unusually high deflection angles of the sliding debris, some fundamental questions about the processes involved are asked. Detailed field studies show evidence that preferentially in medial to distal accumulation areas the Sturzstrom kinematics could have been favoured by water-saturation of its low permeable fine-grained substrate. Additional questions arise since the distal Fernpass slide deposits are split into numerous isolated outcrops of chain-like arranged, debris-ridges and –hills of unknown thickness and unclear subsurface geometry. Till now the genesis of this hummocky accumulation pattern remained unsolved.

Thus this study aims to present some spatial attributes such as thickness and distribution of distal rockslide deposits, theirs substrate and the groundwater table by testing the applicability of the Ground Penetrating Radar (GPR) system for near-subsurface explorations. In general, this method enables exploration depths in the order of some tens of metres (Davis and Annan, 1989) and was in the Eastern Alps already applied to rock-glaciers and water-unsaturated talus-deposits (Brückl et al., in press; Krainer et al., 2002; Sass and Wollny, 2001). Ideally in the Fernpass region these quick and non-destructive geophysical in-line investigations can also be calibrated by shallow-seated drillings and thus provide spatial information on the varying subsurface geology. Based on the results of the calibrated GPR measurements, we intend to make a contribution to a kinematical model for the accumulation and spread of long run-out Sturzstrom deposits.

2. Location and Geology

The Fernpass is situated in the western part of the Northern Calcareous Alps, approx. 45 km west-northwest of Innsbruck (Tyrol, Austria) and enables an important North-South-passage between the Tyrolean Inn valley in the South and Bavaria (Germany) in the North. Its apex (1332 m a.s.l.) and the valley floors to both sides are covered by at least 16.5 km^2 wide spread rockslide deposits, attributing to one of the largest mass movements in the Alps.

2.1. Scarp area

The source area of the Fernpass rockslide is located within the southernmost Lechtal nappe, a polyphase and heteroaxial folded and faulted major thrust unit of the western Northern Calcareous Alps (Eisbacher & Brandner, 1995). Here the calcareous rockslide debris originated from an exceptional deeply incised, wedge-shaped niche with a present maximum elevation of 2231 m a.s.l., indicating a failure volume of about 1 km^3. The scarp is made up by several hundred metre thick alternations of thin-bedded platy dolomites, limestones and marls belonging to the bituminous Seefeld Fm (Norian, Upper Triassic). These incompetent and low permeable rocks represent an intraplatform-basin succession within the upper Hauptdolomit Group (Norian), one of the main rock units in the Northern Calcareous Alps (Brandner & Poleschinski, 1986, Donofrio et al., 2003). At Fernpass lithological parameters and bedding conditions, but above all, complex intersection of brittle fault systems and fracture zones control the formation of preferred sliding planes and the block size distribution. Crucial slope vulnerabilities result from polyphase faulting along three dominant fault systems, i) E-W-trending normal and reverse faults, ii) NE-trending sinistral and iii) NW-trending dextral faults. Cataclasis induced from brittle faulting along the prominent NE-trending Loisach fault system (Eisbacher & Brandner, 1995) and along a NW-trending fault at Nassereith enabled fluvio-glacial erosion and valley-deepening (Fig. 1). This caused stress redistribution of the valley-slopes and uncovered favourable orientated sliding planes permitting subsequent slope instabilities.

2.2. Accumulation area

Seismic investigations near the Fernpass apex indicate a substantially steepened and undercut slope toe, where the top of the bedrock units is situated in about 700–800 m a.s.l. (Prager et al., in preparation). The overlying 500–600 m thick soft rock units are assumed to originate mainly from the Fernpass rockslide and decrease significantly in thickness laterally. Morphologically the medial to distal accumulation areas are characterised by large-scale transversal debris ridges and trenches, exemplary formed Toma-hills and associated funnel- to basin-formed depressions, some of them filled with kettle-like lakes. According to the morphological definition by Abele (1974:119), the well-known Toma are "isolated, cone- to pyramidal- or roof-shaped elevations, predominately made up by rock-slide debris and characterised by more or less planar hill slopes with constant inclination". Formerly these typical hummocky characteristics of several large rockslides in the Alps, among them also the Fernpass slide, were believed to represent late-glacial dead-ice scenery (Abele, 1964, 1969). In contrast, Abele (1991a, 1997) favoured that the intensively structured rockslide scenery may result from pull-apart mechanisms, generating Horst- and Graben-like transversal debris ridges and depressions, during the rapid rockslides motion on water-saturated substrates. But the internal rockslide kinematics that generated the typical cone-shaped Toma, featuring sub-circular basal planes and occurring often as isolated individuals, is not established till now. However, at Fernpass neither these unsmoothed structures nor the rough scarp shows any signs of glacial overprints and indicates a post-glacial genesis of the hummocky rockslide scenery. This assumption was backed up by the cross-check of three independent and remarkably well coinciding dating methods. Rockslide-dammed torrent deposits, situated close to the scarp-front, yielded a C-14 minimum age of at least 3380-3080 cal. BP, whereby an age of between 3300 and 4600 cal. yrs BP (Mid-Holocene) is assumed for the base of this backwater sequence. This coincides well with two cosmogenic radionuclide Cl-36 exposure ages of large-scale sliding planes at the scarp, which are 3600 $\pm$ 900 and 4800 $\pm$ 1100 yrs old. In addition, small-scale successions of the rockslide deposits are lithified by previously not mentioned carbonate cements. These have been dated by the Th-230/U-234 disequilibrium method and yielded a minimum age of about 4150 $\pm$ 100 yrs for the accumulation of the southward-deflected rockslide deposits. All age data indicate a failure event in the middle Holocene at about 4100–4200 yrs BP (Prager et al., in review).

The internal structure of the Holocene Fernpass rockslide is characterised by chaotic deposits featuring varying block-size separation and fragmentation. Upper parts of the proximal depositional facies contain large angular blocks up to a few metres in diameter and occasionally even slabs of 100´s metres in side length. Due to dynamic disintegration and abrasion of the surging debris, medial to distal areas are built up by subangular to even edge-rounded components of different size (centimetre to several metres) mixed with abundant fine interstitial material. Sieve analyses of 9 gravelly samples yielded approx. 5–30 weight-percent clay- to silt-sized matrix. The basal sliding plane of the Fernpass rockslide, supposed to show fine attrition-breccias, is not exposed. Drilling data show that basal deposits of the adjacent Tschirgant-rockslide are made up by silt- to clay-sized, calcareous deposits with a low hydraulic permeability of about 4.0 - 5.0 x 10^{-9} m/s (Hartleitner, 1993).

2.3. Travel path of the Fernpass rockslide

Due to the oblique impact on its opposite slope, the failing rock masses were proximally piled up to a few hundred metre thick succession and subsequently split into two channelled but diametrically opposed Sturzstrom branches (Fig. 1). The northern Sturzstrom, containing the majority of the debris volume, shows a comparable low deflection angle and surged at least 10.8 km towards northeast on to the aggradation plain of the Lermooser Moos at approx. 970 m a.s.l. This accumulation path is kinematically coherent and thus no further aim of this study.

In contrast, the trajectory flow of the southern Sturzstrom is characterised by unusually high deflection angles. First, the eastward sliding debris was deflected from the proximal accumulation area about 140° to southwest and subsequent, due to channelling in the narrow valley, about perpendicular to southeast. Then, after a travel distance of approx. 11 km from the topmost scar, this Sturzstrom entered at Nassereith an unconfined alluvial plain. But instead of continuing its further run-out path straight on, the debris curiously turned about 90° to southwest and flew another 4 km down the Gurgl valley to its lowermost accumulation point at 790 m a.s.l., covering a total run-out distance of at least 15.5 km. Based on this, both rockslide branches show extremely low angles for their overall slopes, i.e. the ratios of drop height versus run-out length along the channel line (referred to as "Fahrböschung", Heim 1932). This may be used as a geometrical criterion to describe landslides mobility and at Fernpass measures about 6.7° for the northern respectively 5.3° for the highly and curiously deflected southern branch.

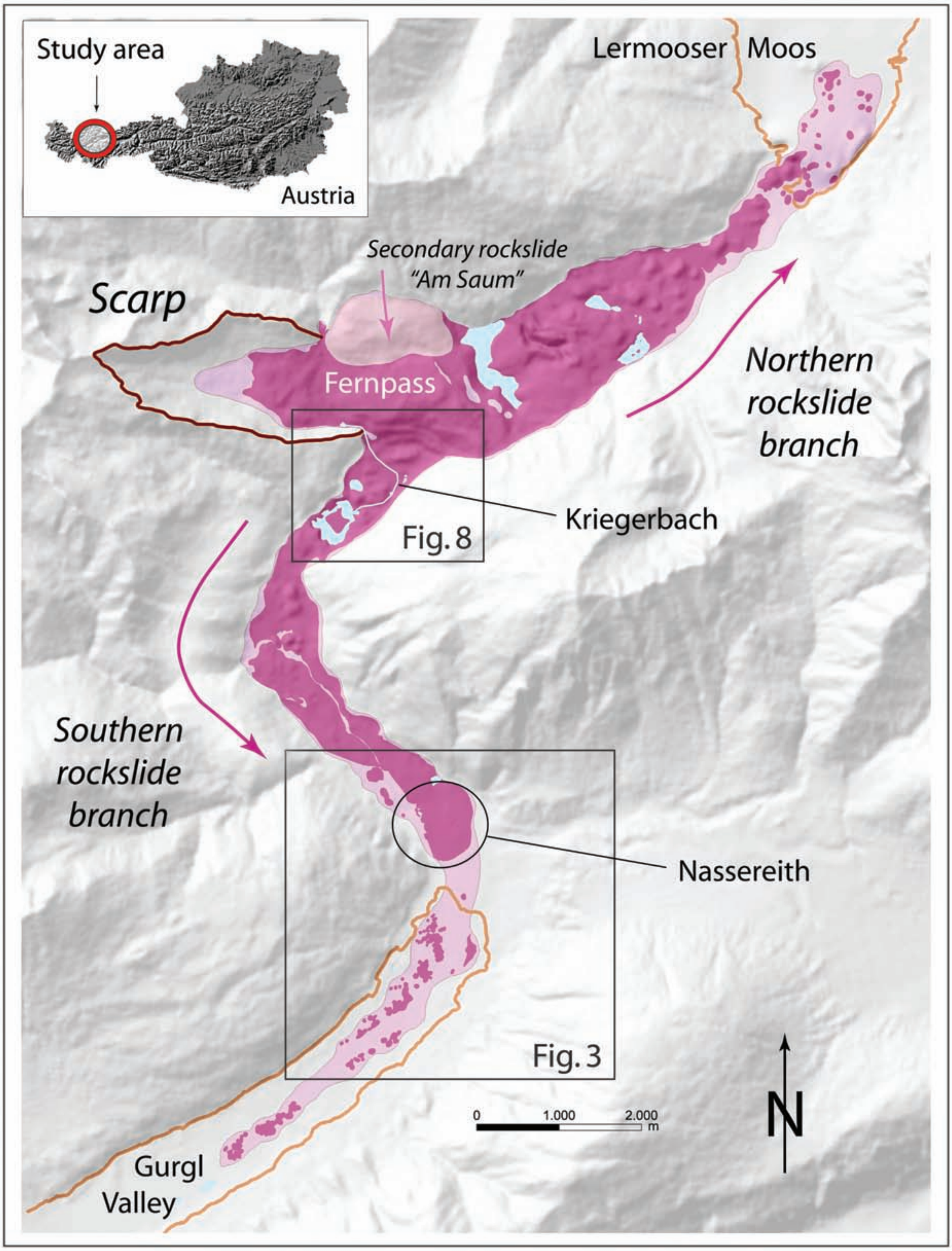

Fig. 1: Digital elevation model of the Fernpass area showing the scarp and the accumulation area of the rockslide deposits (Dark pink: field outcrops of rockslide deposits; light pink: assumed accumulation area; orange line: top of lacustrine deposits, underlying the rockslide debris). Locations of GPR-measurements and drillings are indicated by squares that refer to detail maps (Fig. 3, Fig. 8).

Field investigations (Ampferer 1904, 1924; Ampferer & Ohnesorge, 1924) and drillings (Köhler & Lumasegger, 1992; Poscher, 1993) indicate that the debris of the northern rockslide branch partially rests upon subglacial till, whereas the distal southern Sturzstrom surged upon fine lacustrine sediments. Latter, comprising a thickness of at least 20 m, are interpreted as the bottom set of a late-glacial delta complex covering the Gurgl valley (Bichler, 1995).

Remarkably, based on the absence of field outcrops, the distal accumulation path of the southern rockslide branch seems to be somehow interrupted, as occurring between the southern outskirt of Nassereith and the approx. 10 - 20 m high elevated Toma in the northern Gurgl valley (Fig. 1, Fig. 3). Here this lack is probably due to a post-depositional masking of the rockslide deposits by alluvial debris flows, but may also result from intensive anthropogenic manipulations of the traffic node Nassereith. On the other hand, drilling data show that here only a few metres below surface presumably late-glacial lacustrine deposits are present, containing metamorphic drop-stones in depths below 7–10 m and reaching from the Gurgl valley upstream at least to the Nassereith area (Poscher, 1993). Except for this, here no further subsurface information about the post-glacial valley filling, particularly with regard to the geometry of the Fernpass rockslide deposits, is available. So both, the spatial distribution and the thickness of the apparently disrupted accumulation path of the rockslide deposits as well as the depth of the groundwater-table are relevant research problems for the Sturzstrom kinematics. Based on detailed field studies, the relevant geological discontinuities are assumed in a depth of a few metres (groundwater-table) to maximal a few tens of metres (base of the rockslide deposits). Thus, distinct sections of the Fernpass rockslide are ideal test sites for the applicability of the GPR system as well as for supplementary drilling campaigns to calibrate the geophysical measurements.

3. Methods

Field survey was carried out by a Subsurface Interface Radar (Geophysical Survey Systems Inc., System 2000, Model 3200) equipped with a multiple low frequency antenna. With regard to the best resolution at the intended exploration depth of a few tens of meters, the profiles were measured using a 35 MHz antenna with constant antenna spacing (common-offset profiling) and orientation of the antennae perpendicular to the profile direction. Data were collected by discrete stacking mode. Distance between transmitter and receiver was 4 m, step size, i.e. distance between the data collection points, was 1 m. Detailed descriptions of this method refer to Jol & Bristow (2003) and Milsom (2003). Considering expected water-saturation of the subsurface lithologies, i.e. coarse rockslide deposits upon fine-grained lacustrine deposits, an intermediate dielectric constant of 15 for wet sand (GSSI, 2001) was chosen for the geophysical explorations.

In distal rockslide accumulation areas the measurement campaigns were carried out near the village Nassereith in May 2004 and June 2005 after stable and dry weather- and soil conditions. Special attention was here paid to take field surveys far apart from power supply lines to avoid any electromagnetic interference with the measurement radar signal. A second test site is situated at more proximal deposits southwest of the Fernpass and presumably affected by seasonal varying groundwater-saturation. Thus, to minimize the interfering influence of a high water table, here the field measurements were carried out in winter (February 2005), when also the GPR-antennas could be effectively coupled with the approx. 1 m thick snow pack covering the rough substrate.

Field data were processed by using the software ReflexW version 3.5 and its implemented module 2-D data-analysis (Sandmeier geophysical software, Karlsruhe, Germany). Thereby, to differentiate between geological reflectors and system immanent artefacts, background noises were removed from the raw data by applying following filters: Remove Header Gain, Energy Decay (both amplitudes processing), Background Removal (removal of all horizontal signals deriving from the GPR antennas) and low frequent Bandpass Filter (25–50MHz). Based on this, some vertical elongated and deeper reaching fault signals in the raw data could be attributed to ineffective coupling of the GPR antennas with the substrate and thus were filtered. In contrast, some reflection features such as line- and convex-shaped "air-velocity hyperpoles", come from anthropogenic or natural hindrances (e.g. fences, trees) and are still present in the processed data, but may not be inter-

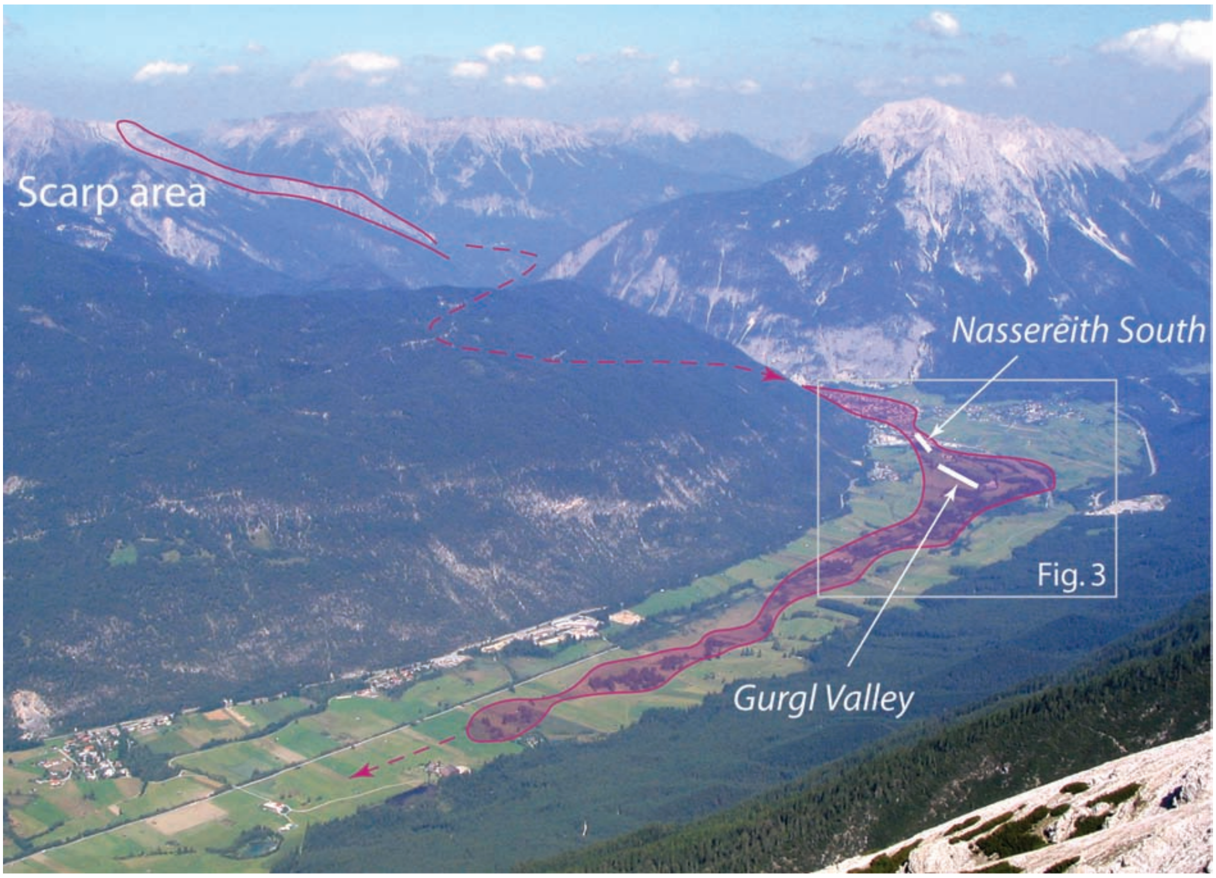

Fig. 2: Oblique view towards northeast to the upper Gurgl valley and the Nassereith area showing the scarp area and the distribution of the Fernpass rockslide deposits. Stippled lines indicate the deflected accumulation path of the southern Sturzstrom branch.

preted as geological discontinuities. Finally, the records were converted to relative depths, with a reliable mean velocity of 0.1 m/ns for the underground, and topographically corrected.

To calibrate the GPR measurements and their interpretations, crucial data concerning lithological parameters and spatial distribution of sediments and groundwater were gained by a shallow-seated drilling campaign. In May 2005 five bore holes up to depths of 14 metres were constructed by using a truck-borne spiral-drill with a diameter of about 15 cm. Fine deposits from clay- to finesand-size were easy to drill and could be well examined, because they stuck on the spirals of the drill, even when water-saturated. In contrast, coarser deposits mostly got lost when pulling out of the drilling hole. In this cases the hardness and duration of the drilling-progress was a criterion for a coarse grain-size classification and recognition of larger boulders. At stable borehole conditions the groundwater table was measured by a light-perpendicular.

4. Field measurements and interpretation

GPR investigations were carried out at three different morphological sites (Fig. 1; Appendix, Table 1): 1. Distal accumulation areas featuring well exposed Toma, 2. Alluvial plain between evident distal rockslide deposits and 3. Alluvial fan between medial rockslide accumulation areas.

4. 1. Toma of distal rockslide deposits

The morphology south of Nassereith is characterised by the confluence of the gently sloped Gurgl valley and a tributary, southwest trending alluvial fan. In the central part of the main valley several well developed, forested Toma rise up to 15 m above the valley floor. There a GRP profile was measured at an elevation of about 810 m a.s.l., trending SSE-NNW almost perpendicular to the run of the valley and running across both lateral slopes of Toma and

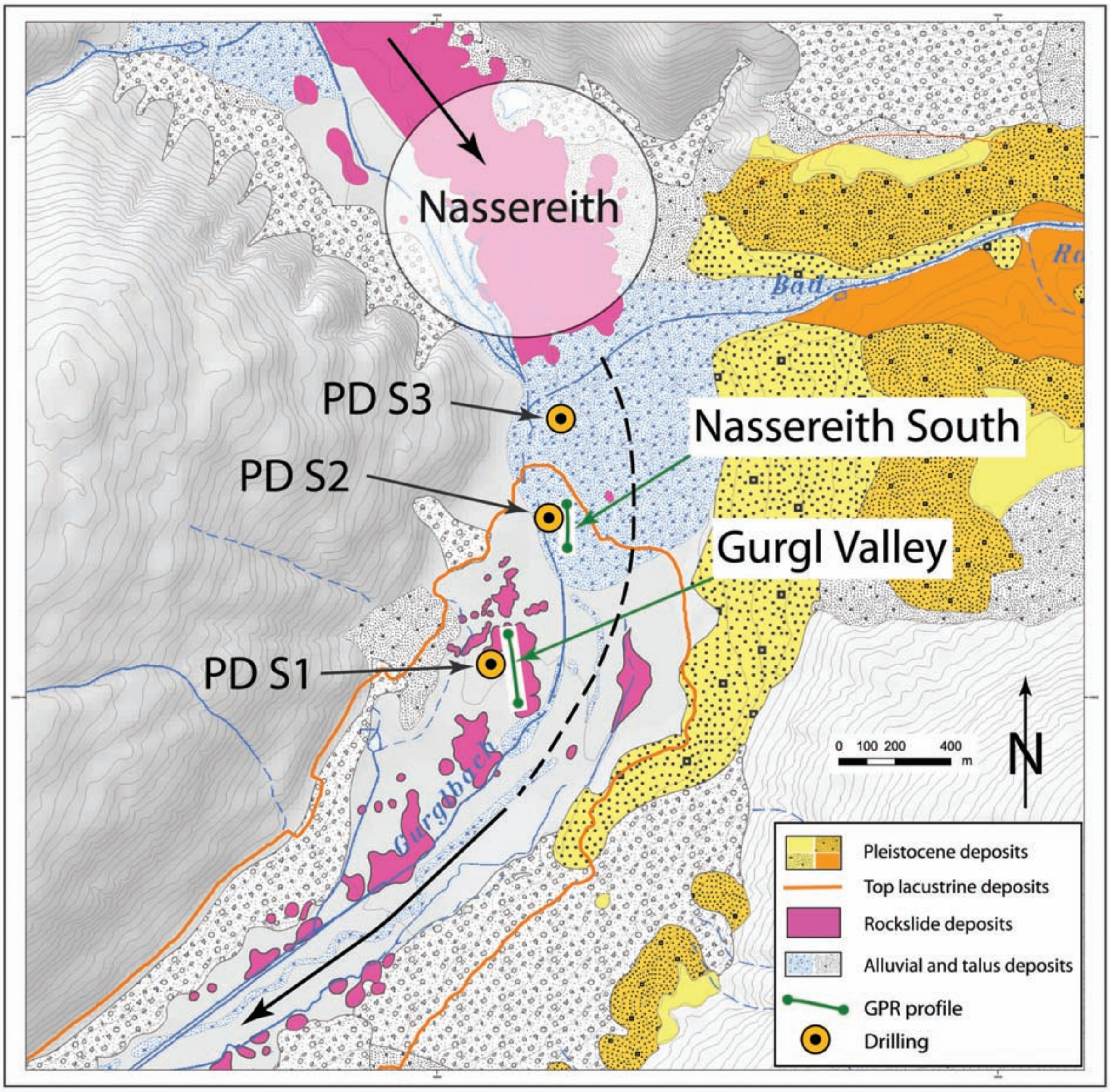

Fig. 3: Geological sketch map of the area Nassereith – upper Gurgl valley showing GPR profiles and drillings. Note the high deflection angle of the rockslide towards SW and lacking field outcrops of rockslide deposits thereat.

flattened to gently inclined alluvial plain between the Toma (Fig. 3, Fig. 4).

This 230 m long radargram is characterised by several densely spaced, subhorizontal discontinuities (Fig. 5). A distinct reflector was recognised at a depth of about 20 m, as best visible within the first 50 profile metres. There it forms a clear concave structure, which is situated straight below a several metres high elevated Toma. Based on the undulating geometry and the geological field situation, we interpret this striking reflector as the base of the Fernpass rockslide deposits that rest on low permeable lacustrine sediments. In central sections of the profile this reflector is superposed by an "air velocity hyperbole", but can be traced further North in about the same depth, i.e. at approx. 790 m a.s.l.. Some accentuated basal reflections, best visible in the raw data between profile-metres 120 - 200 in about 10 m depth, indicate increased lithological contrasts and thus may be attributed to larger and/or less fractured rockslide boulders. However,

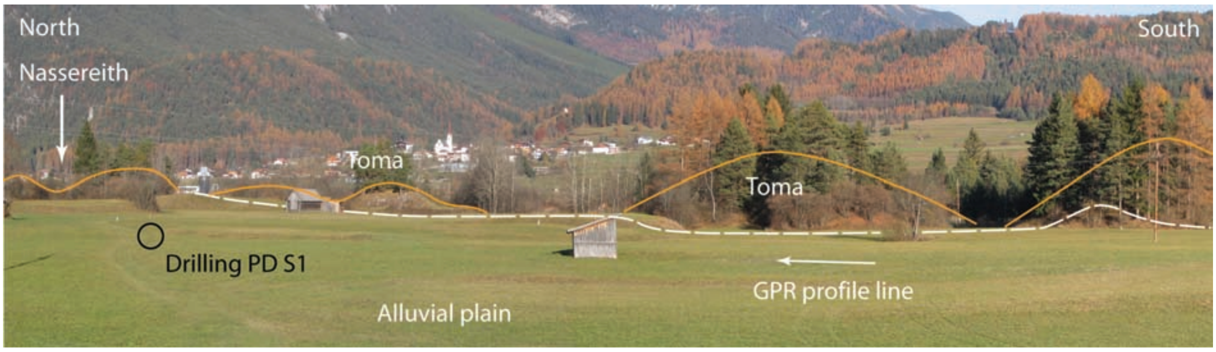

Fig. 4: Typical rockslide morphology of the distal Fernpass rockslide south of Nassereith, featuring the cone-shaped Toma. The location of the GPR profile Gurgl valley is indicated by the stippled white line.

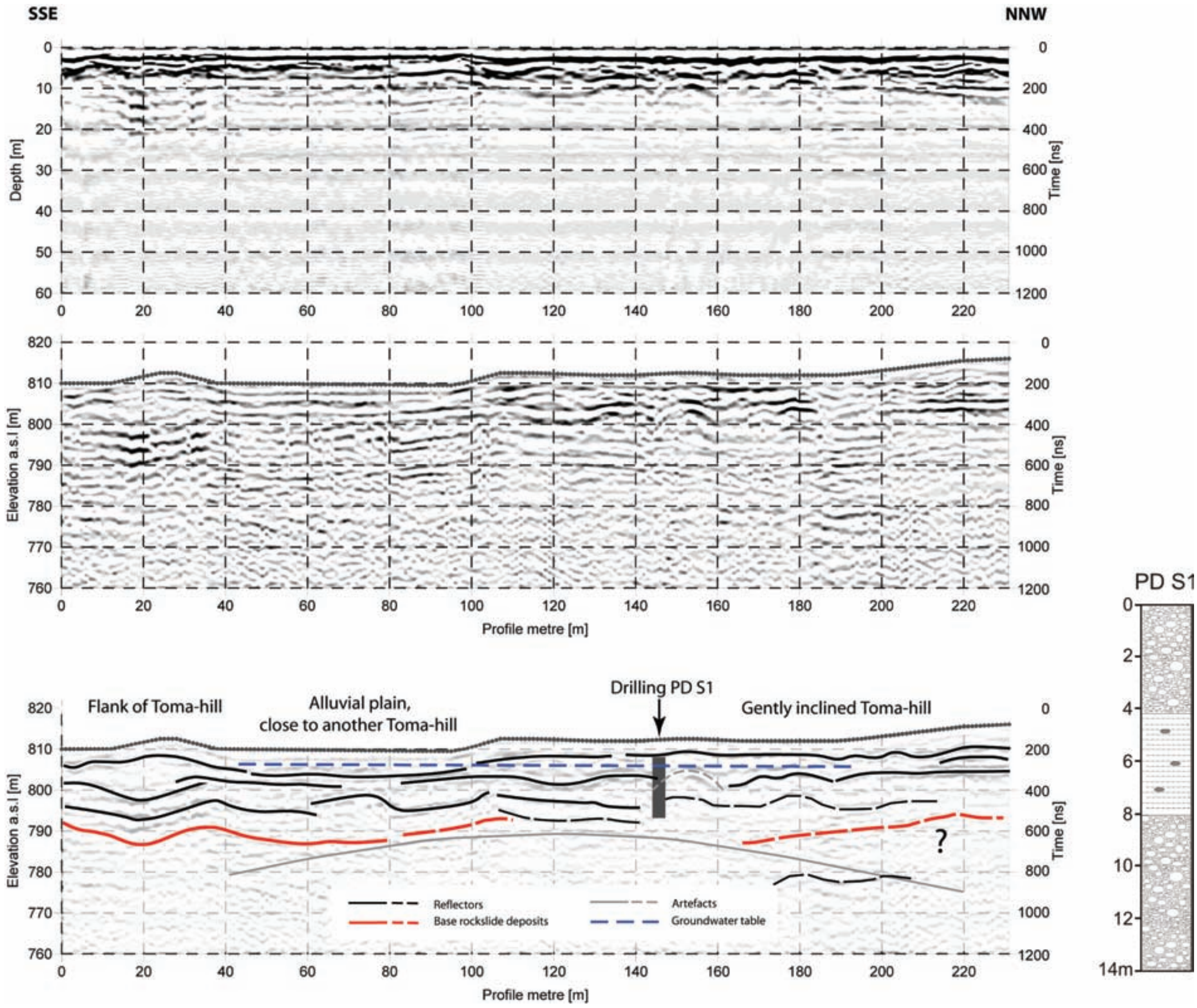

Fig. 5: GPR profile Gurgl valley, from top to bottom: radargram, processed and topographically corrected data, geological interpretation with therein projected drilling PD S1 (c. at profile metre 145) and its lithological succession to the right (for the legend see Appendix, Table 2).

the radargram provides clear evidence that Toma have obviously more pronounced roots than the successions between these debris cones. This indicates substantial subsidence of the rockslide mass into its fine-grained substrate, i.e. glacio-lacustrine silts and clays, due to loading and therefore disables the detection of a primary subplanar basal sliding plane. According to these data (5–15 m high Toma with 15–20 m deep roots), the distal deposits of the Fernpass rockslide show here a total maximum thickness of about 20–30 m.

Another striking reflector was detected at an altitude of about 805 m a.s.l., situated within the uppermost rockslide deposits. The interpretation of this curvilinear reflector is based on subsurface data provided by the adjacent drilling PD S 1 situated about 100 m west of this GPR profile. Surprisingly this borehole, which is bounded to the North, East and South by a chain of Toma at a distance of a few tens of meters, yielded an entirely fluvial-lacustrine succession of alternating fine- to medium-sized clastic deposits, but lacking evidence of larger boulders down to a depth of 14 m. Since the GPR data clearly point to the presence of a basal plane of the rockslide deposits at depths of about 20 m, we assume that the drilled fluvial-lacustrine sediments are, at least partially, younger than the deeper rooting rockslide deposits. These fluvio-lacustrine sediments lap on and fill up the depressions between the individual Toma. In the drilling PD S1 the groundwater table was detected 3.5 m below the surface, i.e. at an altitude of approx. 806.5 m a.s.l. (Fig. 5; Appendix, Table 2). This groundwater table may cause the shallow subsurface GPR reflector detected at about the same depth.

4. 2. Distal rockslide deposits buried by alluvial debris flows

Some distal accumulation areas of the rockslide deposits are poorly exposed due to decreasing thickness, post-depositional burial by fluvial deposits and anthropogenic influences near the surface of the valley-floor. All this may be the case at the southern outskirt of Nassereith, where the field situation provides only little information about shallow subsurface structures. However, no field outcrops of the Fernpass rockslide deposits occur between Nassereith and the nearest Toma approx. 600 m further downstream (Fig. 1, Fig. 3). Moreover, right there the trajectory flow of this Sturzstrom shows a high deflection angle of about 90° and turned towards the upper Gurgl valley. Thus the subsurface geology of the area next to Nassereith is of special interest concerning this curious accumulation path and its causal kinematics.

In the commercial zone of Nassereith a GPR profile was recorded from N to S at an altitude about 815 m a.s.l. (Fig. 3). This profile shows numerous distinct and densely spaced reflectors, and can geophysically be subdivided into three units (Fig. 6). The upper succession of the valley fill is characterised by reflectors that dip about 5–15° relative towards the south. At a depth of about 6 m, i.e. at an altitude of approx. 807 m a.s.l., these planes lap down onto a slightly undulating main discontinuity and its associated reflectors. Below this, several second order reflectors can be traced to another main reflector at a depth of approx. 15 m. Further down, the radar signals are less clear and also superposed by a hyperbolic air reflection.

A calibration drilling, situated approx. 15 m west of this GPR profile, yielded a fluvial succession overlying fine-grained lacustrine deposits, but did not supply material between 7.5–12.5 m (PD S2, Appendix, Table 2). As this depth was almost not to drill, we assume the presence of coarse material, probably larger (rockslide-) boulders, in this section. Thus, the GPR-reflectors, detected at depths of approx. 6 m and less distinct about 15 m, however, may be correlated with the top and with the obviously undulating base of the Fernpass rockslide deposits. The uppermost, clearly inclined reflectors indicate distinct stratification, due to changes in grain size of the prograding fluvial debris flow deposits. The groundwater table was well-defined at a depth of 3.2 m, i.e. at an altitude of about 812 m a.s.l. within the inclined bedded fluvial deposits. These subsurface conditions were backed up by another drilling about 300 m north of the profile (PD S 3). In this borehole water-saturated coarse-grained deposits, which were extremely hard to drill, were recognized at a depth of about 7.5–9.0 m. But it remained unclear whether these sediments all belong to a tributary, Holocene alluvial fan, which progrades here towards south-west into the Gurgl valley (Fig. 3). However, both drillings did not exceed depths of 14 m, but penetrated fine-grained, probably peri-lacustrine deposits below the blocky successions (Appendix, Table 2).

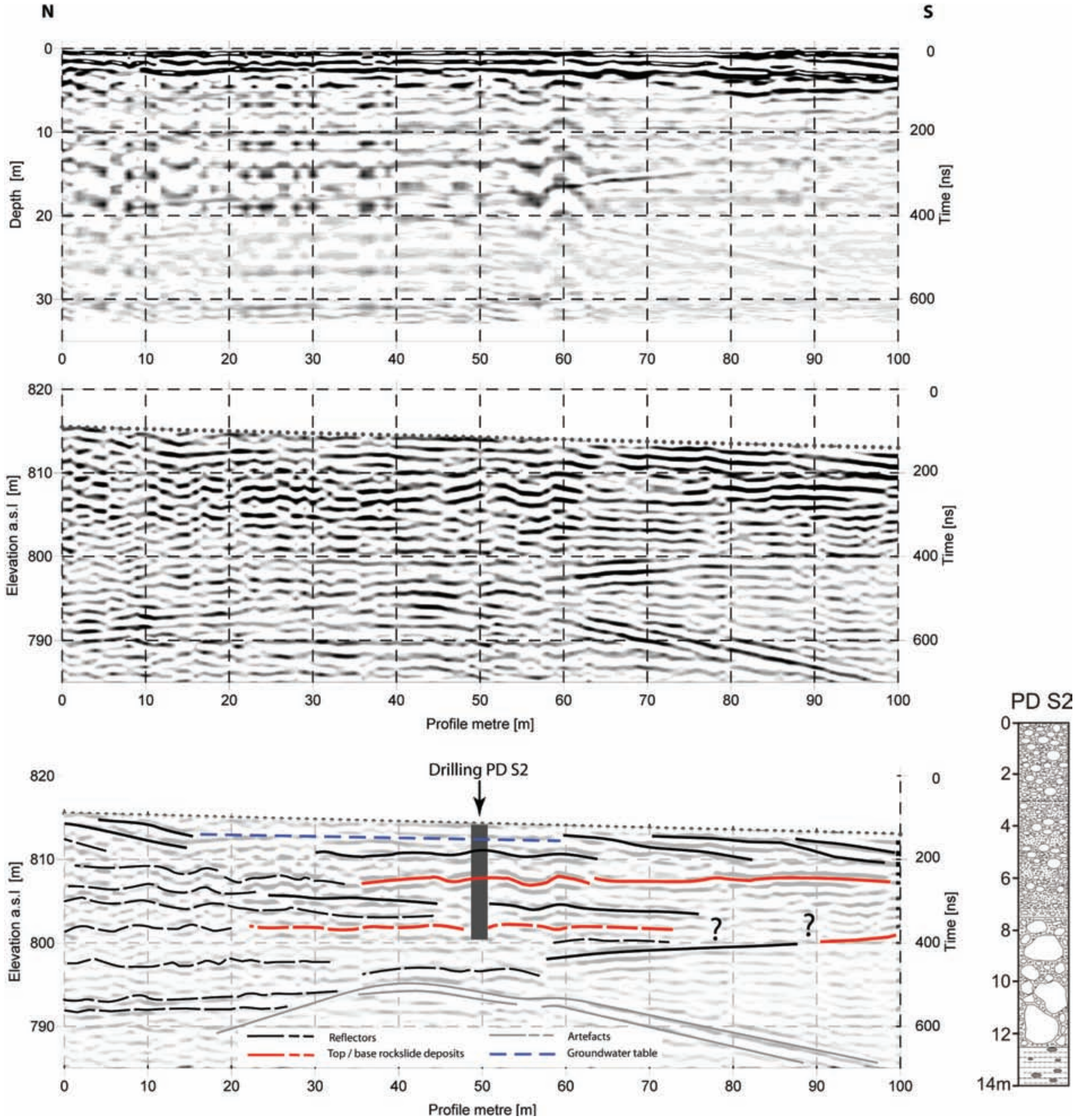

Fig. 6: GPR profile Nassereith South, from top to bottom: radargram, processed and topographically corrected data and interpretation with therein projected drilling S2 (at profile-metre 50.00).

Further information concerning the subsurface lithology is derived from an excavation pit in the commercial area of Nassereith (April 2004). There the uppermost 2.5 m of the valley fill were exposed, composed of dry, polymict fluvial gravels, characterised by mean diameters of less than 20 cm, with thin intercalations of silty layers at its base. Remarkably, the well-rounded clasts of metamorphic and carbonate composition contained a few metre-sized angular boulders of dark grey dolomite. These exotic boulders can clearly be interpreted as rockslide deposits floating in the valley fill.

Compiled field- and subsurface data indicate that near Nassereith the fine-grained lacustrine sediments are overlain by a thin fluvial succession, which covers the coarse rockslide deposits and locally even intermingles. According to both GPR- and drilling-data, in the area next to Nassereith the rockslide deposits are extremely thin with varying

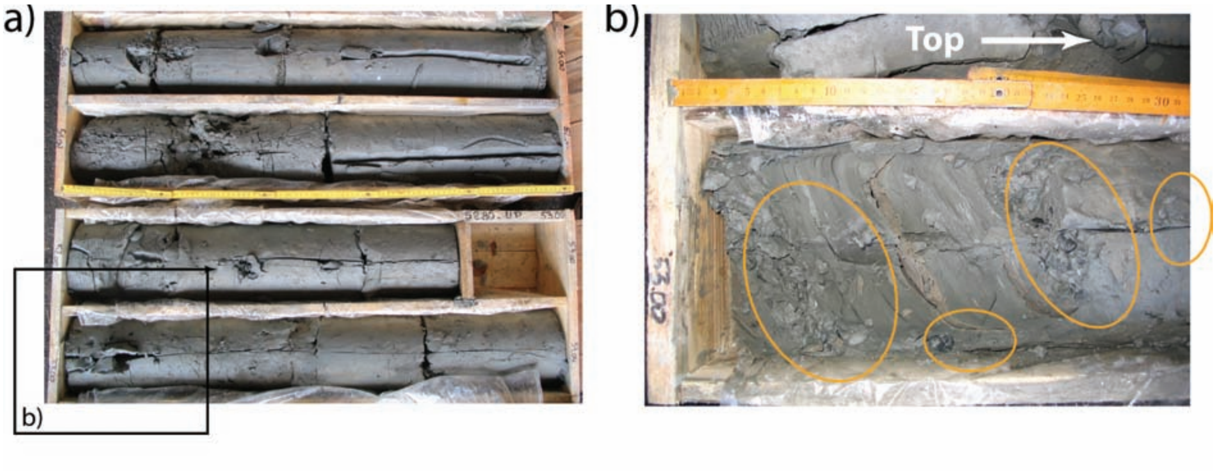

Fig. 7: Substrate of the distal Fernpass rockslide near Nassereith: lacustrine fine deposits ("varved clays") containing several subspherical pebbles ("dropstones", indicated by circles)
(Drilling core Tschirgant KB 9, 858 m a.s.l.; a) section metres 50–54 and b) metre 53.10 in detail).

thicknesses ranging from presumably 1.5 m (PD S3), to 5 m (PD S2) and 9 m (GPR profile Nassereith South). This contrasts clearly with the increased thickness up to 20–30 m further downstream (Fig. 5).

Considering these complex relationships, the underlying substrate of the Fernpass rockslide deposits is of special interest. Borehole data in the course of terrain explorations for the by-pass of Nassereith show that fine-grained lacustrine sediments contain metamorphic dropstones at depths below 7–10 m, i.e. approx. 800 to 810 m a.s.l., pointing to an ice-marginal facies (Poscher, 1993). Also the adjacent drillings PD S1 and PD S2 yielded fine-grained deposits that are similar to lacustrine "varved clays" (Appendix, Table 2). Embedded in the fine-grained matrix are numerous spherical, predominantly carbonate, locally densely packed pebbles with polished grain-surfaces. We interpret these sediments as peri-lacustrine deposits, which were also mined on the southern flank of the uppermost Gurgl valley. There several drillings exposed polymict Pleistocene gravels with tens of meters thick intercalations of lacustrine clays and silts (unpubl. reports by Ilbau, 1996; Asfinag Austria, 2005). These fine-grained deposits commonly show high contents of re-deposited pebbles such as well rounded and sub-spherical polished clasts (Fig. 7), predominantly of carbonate and less common of metamorphic composition. According to Bichler (1995), these mud-supported gravity flows may be part of a delta-complex, where debris from the terrace-slopes interfinger with the proximal bottom set of a presumably late-glacial lake.

However, both the field outcrops and these corresponding subsurface data exhibit a top of lacustrine sediments, i.e. the varved clays of the bottom set, at an altitude of 800 to 810 m a.s.l. Where these fine deposits interfinger with the coarser grained delta forests, the top of the peri-lacustrine facies extends to an altitude of at least 822 m a.s.l. (e.g. KB 9; Asfinag, 2005).

4. 3. Medial rockslide accumulation areas

Medial depositional areas of the Fernpass rockslide show several tens of meters high debris ridges, Toma and corresponding depressions, orientated transversal to the direction of the rockslide propagation, between. At the base of the proximal accumulation area of the thick Fernpass ridge, the rockslide deposits feature a significant, since deeply incised trench-structure at an altitude of about 950 m a.s.l. Therein an approx. 300 m wide, NW-SE-trending alluvial fan of the creek Krieger-Bach is arranged approx. perpendicular to the direction of the former rockslide. On this accumulation plain, which is gently inclined (5°) towards SE, the GPR profiles were measured both parallel to the discharge from NW to SE (profile Kriegerbach 1) and

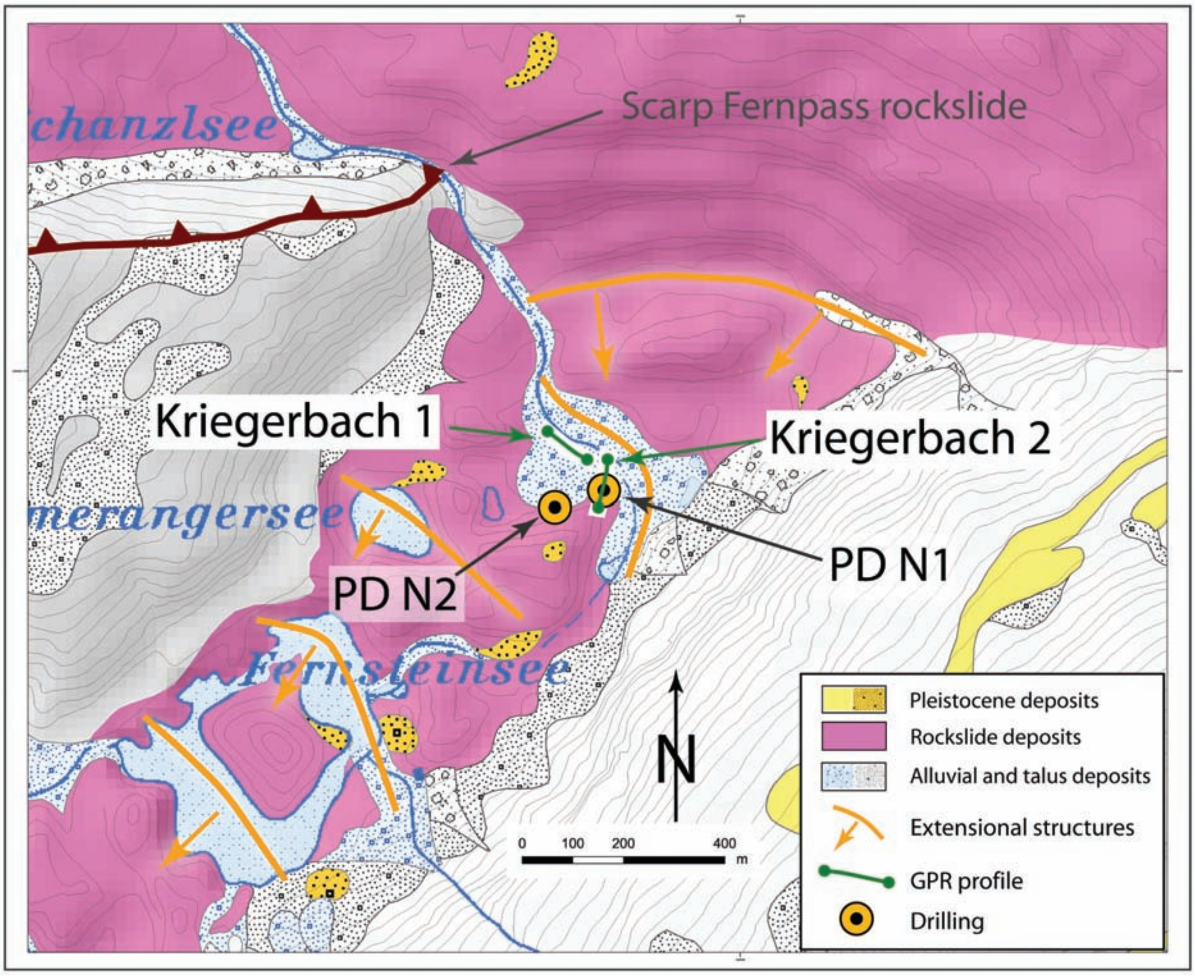

Fig. 8: Geological sketch map of the medial accumulation area of the southern branch of the Fernpass rockslide, showing GPR profiles and drillings on the alluvial accumulation plain of the river Kriegerbach. Note extensional structures within the rockslide deposits, approx. perpendicular to the direction of the Sturzstrom motion; some of these depressions are filled with lakes or fluvial discharge systems such as the river Kriegerbach.

obliquely across the debris fan from N to S, ending near the base of an approx. 30 m high Toma (profile Kriegerbach 2; Fig. 8, Fig. 9).

GPR profile Kriegerbach 1 (Fig. 10) was measured downstream along the orographic right bank of the present torrent channel. The subsurface geometry is characterised by numerous reflectors, which are arranged mainly subhorizontally. In coincidence to field- and drilling-data (PD N1, PD N2; Appedix Table 2), this indicates repeated grain size changes of the stratified debris flow deposits. This radargram shows at least two main unconformities at intermediate depths: an upper one dipping from about 5 m downstream to about 15 m below the surface; and a distinct lower one situated at a depth of about 15-20 m. These main reflectors display a wedge-shaped set of numerous planes that clearly dip subparallel at an angle of approx. 10 - 15° downstream relative towards SE. The thickness of this wedge decreases downstream, where several less inclined on-lapping reflectors discordantly overlie it. Based on the field geometry of the rockslide deposits, we interpret the subhorizontal GPR basal discontinuity at a depth of about 20 m as the top of the Fernpass rockslide deposits. These deposits are buried by down-lapping plane-sets of the prograding fluvial debris flows, which are clearly stratified due to grain-sizes changes. Their lithological composition equals those of the carbonate rockslide deposits. Probably due to channel shift, this sedimentary accumulation wedge is truncated and overlain by less inclined fluvial deposits. Thus, upper sections of this radargram are characterised by the internal

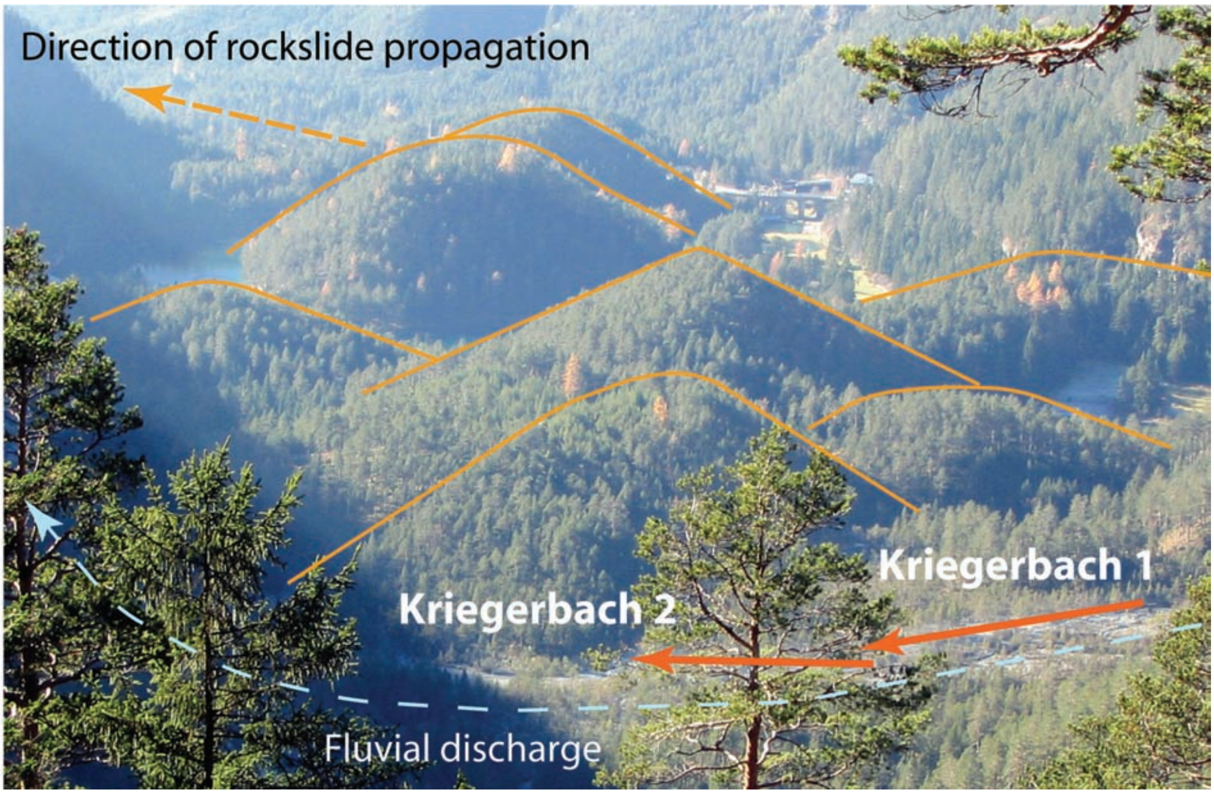

Fig. 9: Morphology of the alluvial plain of the river Kriegerbach (foreground, with thereat measured GPR profiles), surrounded by well exhibited Toma up to 50 m elevation (background).

interplay of fluvial erosion and sedimentation. Reflectors below 25 m are difficult to interpret.

A distinct basal reflector was also detected in the adjacent GPR profile Kriegerbach 2 (Fig. 11). There a main unconformity plunges within the last 30 profile-metres from a depth of 6 m in the S down to a depth of approx. 16–20 m in the N, resulting in a dip angle of about 20°. Based on this geometry, the corresponding field outcrops further south and data from the adjacent drilling PD N1, indicating very coarse material at this position and depth, the basal reflector is interpreted as the top of the Fernpass rockslide deposits. According to the GPR data, the rockslide deposits are discordantly overlain by on-lapping fluvial sediments. Numerous parallel reflectors indicate corresponding sedimentary stratification due to grain size changes, i.e. a sub-horizontal alternation of coarse- and fine-grained torrential debris layers. Sections around profile-meter 10 and at depths between 15–20 m indicate a buried channel situated straight beneath the present torrent (not shown on the radargram; situated just a few metres north of the starting point of this profile).

Remarkably both high-resolving GPR profiles at the locality Kriegerbach, show significant attenuated radar signals below depths of approx. 10 m and further downwards a progressive fading away, as is best indicated by the unprocessed field data. Radar signals vanished along the entire profile length and cut even across the basal main reflector of the buried Toma. Thus we attribute this attenuation not to an increasing amount of fine-grained clastic sediments but more likely to an increased humidity of the debris. The adjacent drillings PD N1 (near the end point of radargram Kriegerbach 2) and PD S2 (approx. 100 m west of PD N1; Fig. 8) reached a depth of 7.5 respectively 14 m, but did not provide stable borehole conditions to measure the water-level. However, clearly wet gravel was drilled at depths of approx. 5 and 7 m respectively below the ground, indicating a close-by groundwater-table within this highly permeable debris (Appendix, Table 2).

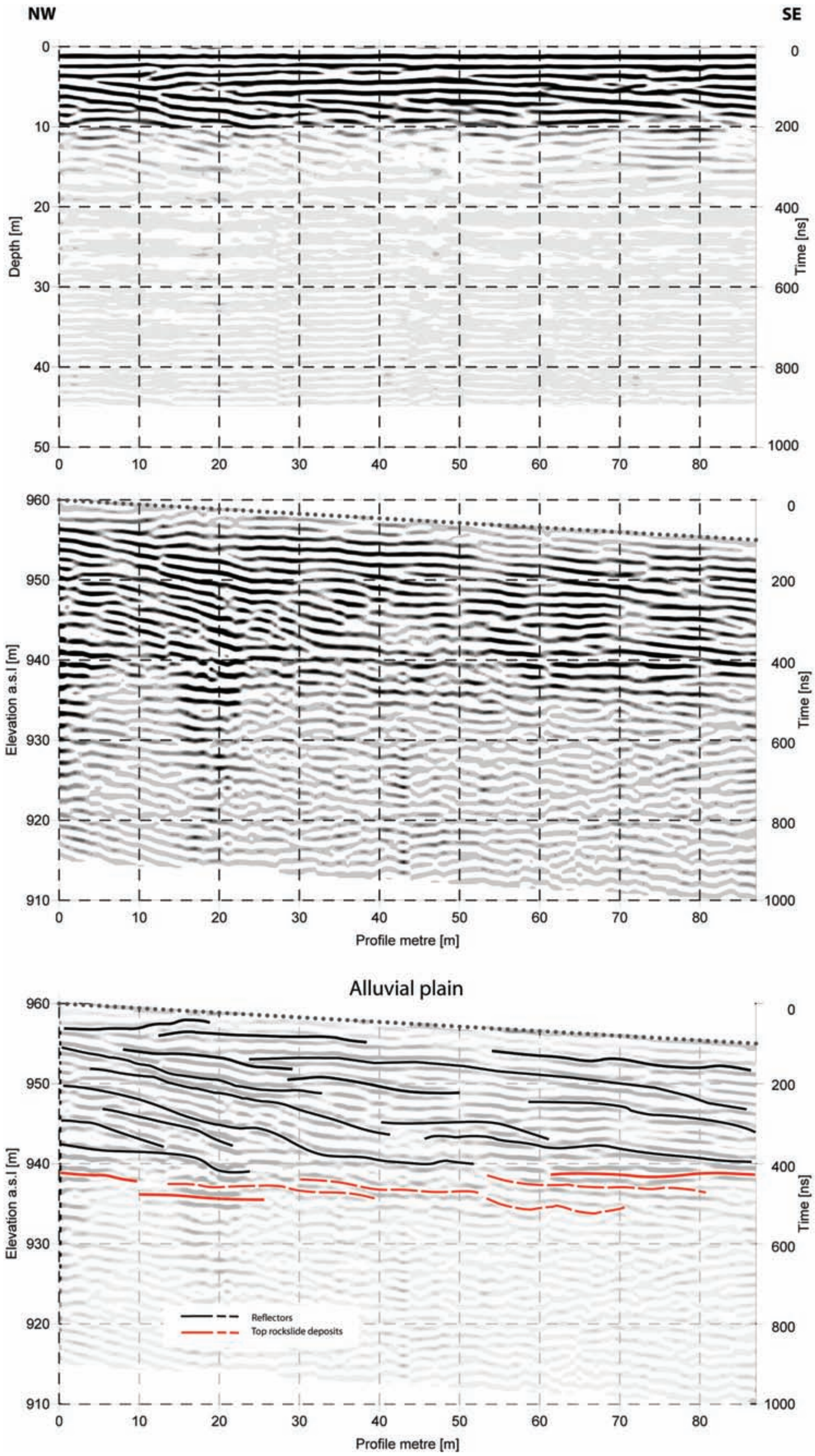

Fig. 10: GPR profile Kriegerbach 1, from top to bottom: radargram, processed and topographically corrected data and interpretation.

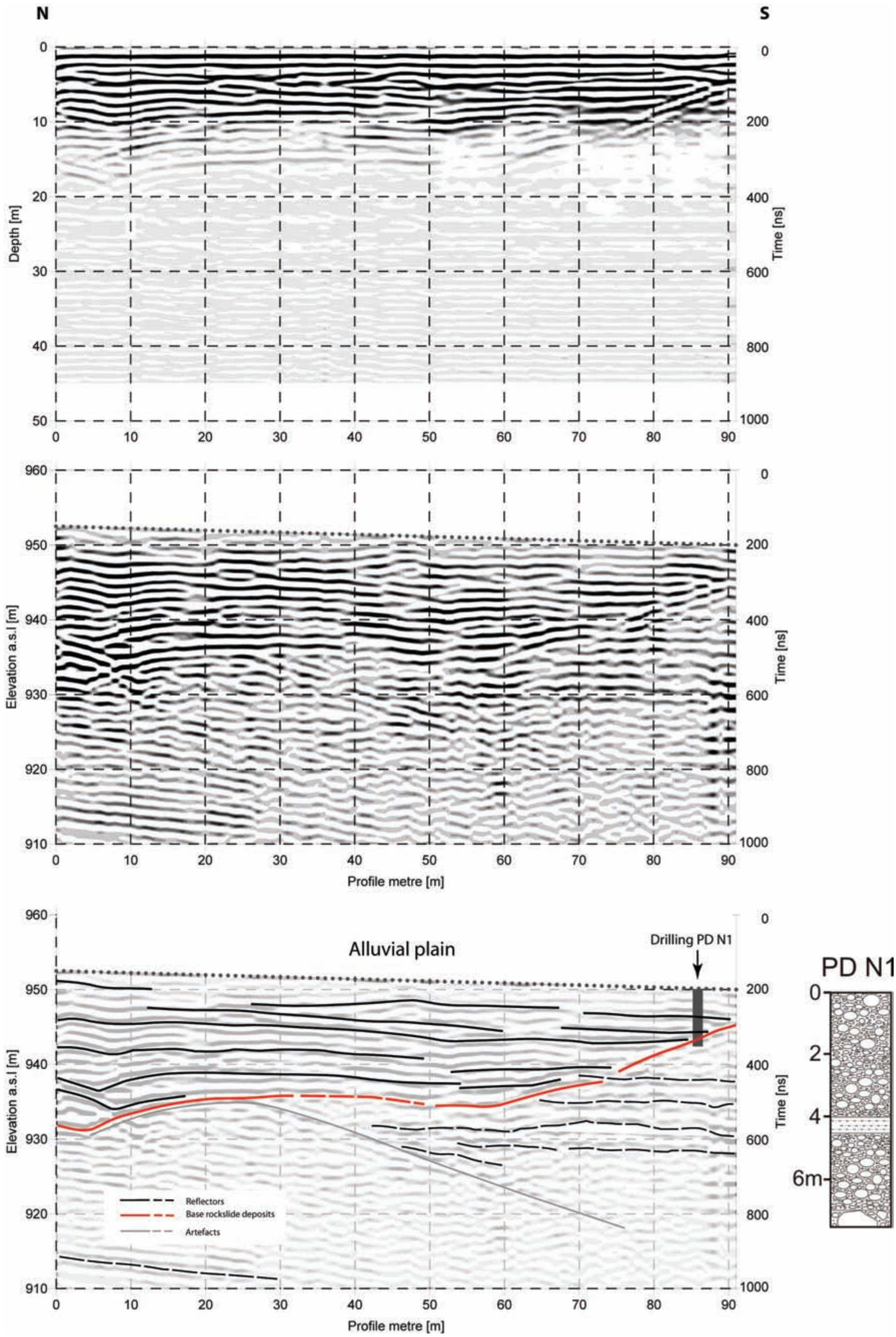

Fig. 11: GPR profile Kriegerbach 2, from top to bottom: radargram, processed and topographically corrected data and interpretation with therein projected drilling N1 (approx. at m 4.00).

5. Results

Different accumulation sites of the fossil Fernpass rockslide (Northern Calcareous Alps) were successfully explored by a low frequency GPR system down to a depth of at least 20–30 m. Some fault signals, e.g. coming from ineffective coupling of the antennas with the substrate or from superficial reflections, were effectively filtered from the raw data. All processed radargrams show several distinct reflectors with varying intensities and geometries.

Based on detailed field studies and calibrated by drillings, these geophysical discontinuities were attributed to different depositional units and also to varying groundwater-saturation of the substrate. As a result, the distal Fernpass rockslide deposits rest upon fine-grained peri-lacustrine sediments and show strong variations in thickness. Measurements taken at the flanks of Toma-hills, at a distance of approx. 11 km from the uppermost scarp area, clearly point to a maximum thickness of the distal slide debris of about 20–30 m. There the undulating basal reflectors indicate a differential subsidence of the rockslide debris into its fine-grained substrate due to loading. Thus, a distinct subplanar sliding plane is not detectable.

Another test site, a few hundred metres upstream, does not show any field outcrops of rockslide deposits along a length of approx. 600 m along the streamline. The assumption, that the accumulation path of the Sturzstrom could have been somehow interrupted was backed up by the GPR explorations and drilling-data. Both show an extremely reduced thickness of the rockslide material, ranging between approximately 2 and 9 m. Locally these coarse but extremely thinned out deposits even intermingle with the uppermost fluviatil valley filling. Drilling campaigns in the distal rockslide accumulation area, down to depths of 14 m, established a shallow groundwater-table only at between 3–6 m below surface. According to this, the present groundwater flow in the quaternary valley fill is inclined approx. 0.5° downstream. However, the GPR signals were not effectively shielded by this shallow water-table but penetrated down into deeper successions of the water-saturated rockslide deposits and its fine substrate.

Further GPR measurements, carried out at medial accumulation areas, could not penetrate the several decametre thick rockslide deposits, but show clearly an on-lapping of prograding debris flows onto the hummocky rockslide relief. Also the internal stratification of the 5 - 20 m thick fluviatile debris is best recognisable in the radargrams and demonstrates the high resolution of the applied GPR system.

6. Discussion and Conclusions

Due to an oblique impact at its opposite slope, the Fernpass rockslide was split into two diametrically opposed Sturzströme. Regardless of the resulting loss of kinetic energy, both cover long travel distances up to 15.5 km. Compiled data of rockslides in the Alps indicate, that increased mobility correlates well with the rockslides volume, whereas lengths of 10 km were only exceeded by events containing a volume of about 1 km^3 and above (Heim, 1932; Scheidegger, 1973; Abele, 1974). But at Fernpass the moderately deflected northern rockslide branch, which clearly contains the majority of the debris, shows a shorter travel path than the less thick southern rockslide branch. In addition, latter is also characterised by remarkable high deflection angles of its curiously curved accumulation path. This field data point out, that here the run-out of the slide debris cannot be attributed mono-causal to size-effects.

Since many landslides cover larger travel distances than might be expected from their morphological settings and their material properties, several kinematical models have been established to explain enhanced landslide mobility, all of them somehow dealing with reducing the dynamic coefficient of friction. Among these are frictional melting and acoustic fluidization due to internal vibrations, the dynamic disintegration of the rock masses and attempts of adopting granular flow models. But most models concentrate on lubrification mechanisms and the presence of fluidising media such as air, water and/or vapour (e.g. Rousse, 1984; Erismann & Abele, 2001; Legros, 2002; Hungr & Evans, 2004). Based on field studies, interactions of descending rockslides with water-saturated valley-fillings are common features of several large rockslides and have already been observed at Flims/Switzerland (Pavoni, 1968; Poschinger et al., in press), in Austria at Wildalpen (Fritsch, 1993), Almtal (Abele, 1991b; Van Husen, 1995) and Tschirgant (Abele 1991a, 1997; Patzelt & Poscher, 1993). However, the spread of rockslides on water-saturated substrates is believed to be the most favourable parameter enabling excess run-out distances. According to the geotechnical basic principle of undrained dynamic loading (Hutchinson & Bhandari, 1971), rapid mass movements may abruptly load water-saturated deposits and cause a sudden increase of both the pore-pressure and the total vertical stress therein. This, in turn, increases the shear stress within the zone of principal displacement and thus substantially facilitates the further landslide propagation, even along low-angle slopes and valley-floors. Fine and low permeable attrition breccias at the base of large catastrophic rockslides, as drilled at the Tschirgant rockslide deposits (Hartleitner, 1993) adjacent to the Fernpass region, may prevent the vertical escape of confined pore-water from the water-saturated sliding zone up into the permeable rockslide debris and thus hold up an excess pore-pressure.

At Fernpass, the long run-out of the southern rockslide branch was certainly favoured by the dynamic disintegration of the failing rock masses and a substantial channelling in the narrow valley. But above all, the mobility of the distal Fernpass rockslide was favoured by two aspects: 1) the water-saturation of the uppermost valley fill and 2) the Sturzstrom discharged, at least from the Nassereith area on, onto low permeable, lacustrine deposits. Both field studies and drilling data show that fine lacustrine sediments, underlying the distal rockslide deposits, are present upstream at least to Nassereith and extend at the valley flanks up to elevations of 810–820 m a.s.l. In contrast to this, here the central valley floor exhibits distal rockslide deposits that show a bottom surface at elevations of about 790 m a.s.l. Subsurface data inferred from GPR measurements show that adjacent rockslide deposits root at a depth of about 15–20 m. Thus, the top of the lacustrine deposits does not form a horizontal plane, but a smooth concave-curved depression towards the middle of the valley. This geometrical implication suggests that the spatial distribution of the distal rockslide deposits was substantially controlled by the late-glacial valley morphology. Movements on an incompetent fine substrate with a trenched and confining topography may explain the curious rockslide deflection at Nassereith: instead of continuing its straight accumulation path towards SE, the sliding debris turned here approx. perpendicular towards SW. Obviously the distal rockslide was not able to override a predisposed channel-like topography, but forced to accumulate as chain-like arranged Toma in the middle of the valley floor.

In addition, straight within this zone of deflection, the accumulation path of the slide debris was somehow interrupted. Between well-exposed Toma further up- and downstream, here evident field outcrops of rockslide deposits are absent for several hundred metres along the channel line. Both GPR- and drilling data backed up, that south of Nassereith the rockslide deposits are extremely reduced in thickness and accumulated within an only 2–9 m thick layer. Remarkably the very front of the rockslide, which travelled from this zone of disintegration more than 4 km further downstream, maintained as a more coherent debris mass with a thickness up to approx. 20–30 m. These geometrical relations suggest the distal Fernpass rockslide was obviously affected by differential accelerations, which caused a pulling-apart and splitting into several individual slide-units. Once preferential water supply from the substratum must have somehow favoured the dynamic undrained loading and thus the mobility of the frontal rockslide and left the main debris mass behind. Drilling campaigns showed a shallow groundwater-table, close below the present surface at between -3 to -6 m, and thus an effective water-saturation of both, the subsurface rockslide deposits and its fine lacustrine substrate. Whether the southern branch of the Fernpass rockslide discharged into a relict reservoir of a late-glacial lake or, more likely, just surged onto water-saturated lacustrine deposits, cannot be reconstructed yet.

Based on field observations, already Abele (1991a, 1997) suggested that catastrophic rockslide masses may disintegrate by being stretched and pulled-apart, especially when moving along water-saturated valley fills. Such distensive movements may generate debris ridges and associated depressions in between, both being striking morphological features of several large landslides. However, we do not assume that these pull-apart mechanisms attribute exclusively to rapid moving, high-energy Sturzströme. This cannot satisfyingly explain both the observed intensively varying thickness of the rockslide deposits along the channel line and also the in-line configuration of the cone-shaped Toma. Also one of the most significant extensional structures, containing the alluvial plain of the creek Kriegerbach where two GPR profiles were measured, is genetically certainly not only due to the rapid Sturzstrom flow.

Rather all these features indicate that the semi-coherent rockslide-debris, and presumably also the uppermost parts of the incompetent substrate included, were affected by creeping processes and gravitational spreading. These distensive movements along water-saturated, basal sliding planes probably occurred at lower kinetic energy levels, however subsequent to the rapid Sturzstrom surge (Prager & Zangerl, 2005). This resulted in a further decomposition of the rockslide deposits and the generation of the present morphology, which is characterised by the well-known Toma and associated funnel- to basin-formed depressions including several kettle-like lakes. Cohesion, which is needed to form the cone-shaped Toma from the collapsing debris mass, was provided by the jig-saw-fitting of several shattered clasts and by the considerable amount of fine interstitial matrix. Since then, the spreading rockslide deposits have locally been covered by on-lapping fluvial clastics. According to GPR data, these post-rockslide sediments can reach thicknesses up to at least 20 m.

Acknowledgement

We gratefully acknowledge Wolfram Mostler (Univ. Innsbruck, Austria) for his help during the GPR field measurements and for providing insights in to unpublished drilling data (Ilbau, 1996) of the gravel-pit near Nassereith. Also Intergeo Consultants (Salzburg, Austria) kindly provided insights into drilling cores (Asfinag Austria, 2005) from Quaternary deposits at the southern flank of the Gurgl valley. Christian Zangerl (alpS, Innsbruck, Austria) is gratefully acknowledged for fruitful discussions and his input to the development of some ideas, concerning the rockslide kinematics, presented herein. Financially this study was supported by the ILF Consulting Engineers Ltd. and the TIWAG Tyrolean Hydroelectric Power Company Ltd. (both Innsbruck, Austria).

References

Abele, G. (1964): Die Fernpaßtalung und ihre morphologischen Probleme. - Tübinger Geograph. Stud., 12: 1-123.

Abele, G. (1969): Vom Eis geformte Bergsturzlandschaften. - Zs. f. Geomorph. N. F., Suppl. 8: 119-147.

Abele, G. (1970): Der Bergsturz im Almtal im Toten Gebirge. - Mitt. Österr. Geograph. Ges., 122: 120-124.

Abele, G. (1974): Bergstürze in den Alpen. Ihre Verbreitung, Morphologie und Folgeerscheinungen. - Wiss. Alpenvereinsh., 25: 1-230, München.

Abele, G. (1991a): Der Fernpaßbergsturz. Eine differentielle Felsgleitung. - Österr. Geograph. Ges., Zweigver. Innsbruck Jhrber. 1989/1990: 22-32.

Abele, G. (1991b): Durch Bergstürze mobilisierte Muren und durch Muren transportierte Bergsturzmassen. - Österr. Geograph. Ges., Zweigver. Innsbruck, Jhrber. 1989/1990: 32-39.

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

Ampferer, O. (1904): Die Bergstürze am Eingang des Ötztales und am Fernpaß. - Verh. Geol. R.-A., 1904: 73-87.

Ampferer, O. (1924): Erläuterungen zur Geologischen Spezial-Karte der Republik Österreich Blatt Lechtal (5045). - 55 pp., Geol. B.-A,. Wien.

Ampferer, O. & Ohnesorge, T. (1924): Erläuterungen zur Geologischen Spezial-Karte der Republik Österreich Blatt Zirl-Nassereith (5046). - 68 pp., Geol. B.-A., Wien.

Bichler, B. (1995): Quartärgeologie im Gurgltal unter besonderer Berücksichtigung der Pitztalmündung (Bezirk Imst/Tirol). - Ph.D. thesis, 77 pp., Univ. Innsbruck.

Brandner, R. & Poleschinski, W. (1986): Stratigraphie und Tektonik am Kalkalpensüdrand zwischen Zirl und Seefeld in Tirol (Exkursion D am 3. April 1986). - Jber. Mitt. oberrhein. Geol. Ver. N.F., 68: 67-92, Stuttgart.

Brückl, E., Hausmann, H., Krainer, K. & Mostler, W. (in press): Internal structure, composition and dynamics of Reichenkar rock glacier (western Stubai Alps, Austria). – Permafrost and Periglacial Processes.

Davis, J.L. & Annan, A.P. (1989): Ground penetrating radar for high-resolution mapping of soil and rock stratigraphy. - Geophysical Prospecting, 37: 531–551.

Donofrio, D. A., Brandner, R. & Poleschinski, W. (2003): Conodonten der Seefeld-Formation: Ein Beitrag zur Bio- und Lithostratigraphie der Hauptdolomit-Plattform (Obertrias, Westliche Nördliche Kalkalpen, Tirol). - Geol. Paläont. Mitt. Innsbruck, 26: 91-107.

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

Erismann, T. H. & Abele, G. (2001): Dynamics of rockslides and rockfalls. - 316 pp., Springer.

GSSI (2001): Operation Manual, SIR-System 2000, Model 3200. - Geophysical Survey Systems Inc., North Salem, 2001.

Fritsch, A. (1993). Das Quartär der westlichen Hochschwab-Nordabdachung unter Berück-sichtigung des Bergsturzes von Wildalpen.- Ph.D. thesis, 122 pp., Univ. Vienna.

Hartleitner, K. (1993): Die Planung der 'Neuen Bahn' im Abschnitt Ötztal-Landeck: Geologische Ergebnisse. - In: Hauser, C. & Nowotny, A. (Eds.): Arbeitstagung 1993 Geol. B.-A., Geologie des Oberinntaler Raumes, Schwerpunkt Blatt 144 Landeck: 139-140.

Heim, A. (1932): Bergsturz und Menschenleben. - 218 pp., Wasmuth, Zürich.

Hsü, K. (1975): Catastrophic Debris Streams (Sturzstroms) generated by Rockfalls. - GSA Bull., 86: 129-140.

Hungr, O. & Evans, S. G. (2004): Entrainment of debris in rock avalanches: An analysis of a long run-out mechanism. - GSA Bull., 116: 1240-1252.

Hutchinson, J. N. & Bhandari, R. K. (1971): Undrained loading; a fundamental mechanism of mudflows and other mass movements. - Geotechnique, 21: 353-358.

Jol, H.M. & Bristow, C.S. (2003): GPR in sediments: advice on data collection, basic processing and interpretation, a good practice guide. - In: Bristow, C.S. & Jol, H.M. (Eds), Ground Penetrating Radar in Sediments. Geological Society, London, Spec. Publ., 211: 9-27.

Köhler, M. & Lumasegger, M. (1992): Hydrogeologische Untersuchung des Fernpassgebietes. - 239 pp., Unpubl. Report, ILF Consulting Engineers Ltd, on behalf of Amt der Tiroler Landesregierung, Abt. IIIg - Kulturbauamt, Innsbruck.

Krainer, K.; Mostler, W. & Span, N. (2002): A glacier-derived, ice-cored rock glacier in the western Stubai Alps (Austria): evidence from ice exposures and Ground Penetrating Radar investigation. – Zs. f. Gletscherkunde u. Glazialgeologie, 38/1: 21-34, Innsbruck.

Legros, F. (2001): The Mobility of long-runout landslides. - Eng. Geol., 63: 301-331.

Milsom, J. (2003): Field Geophysics (3rd Ed.). – 232 pp., John Wiley, Chichester (The Geological Field Guide Series).

Patzelt, G. & Poscher, G. (1993): Der Tschirgant-Bergsturz. – In: Hauser, C. & Nowotny, A. (Eds.): Arbeitstagung 1993 Geol. B.-A., Geologie des Oberinntaler Raumes, Schwerpunkt Blatt 144 Landeck, Exkursion D: Bemerkenswerte Geologische und Quartärgeologische Punkte im Oberinntal und aus dem äußerem Ötztal: 206-213.

Pavoni, N. (1968): Über die Entstehung der Kiesmassen im Bergsturzgebiet von Bonaduz-Reichenau (Graubünden). - Ecl. Geol. Helv., 61: 494-500.

Poscher, G. (1993): Neuergebnisse der Quartärforschung in Tirol. – In: Hauser, C. & Nowotny, A. (Eds.): Arbeitstagung 1993 Geol. B.-A., Geologie des Oberinntaler Raumes, Schwerpunkt Blatt 144 Landeck: 7-27.

Poschinger, A. v.; Wassmer, P. & Maisch M. (in press): The Flims Rockslide: History of Interpretation and new Insights. in: Evans, S.G., Scarascia-Mugnozza, G., Strom, A., Hermanns, R.L. (eds.), Massive rock Slope Failures, 341-369, Kluwer Academic Publ., Dordrecht.

Prager, C. & Zangerl, C. (2005): Kinematics of a long run-out rockslide: a case study from the Fernpass-region (Northern Calcareous Alps, Tyrol, Austria). - Geophys. Res. Abstr. 7: 02737, EGU 2005, Vienna.

Prager, C.; Ivy-Ochs, S.; Ostermann, M.; Synal, H.-A. & Patzelt, G. (in review): Geology and age of the catastrophic Fernpass rockslide (Tyrol, Austria). - Geomorphology, Spec. Iss., Large slope instabilities: from dating, triggering and evolution modelling to hazard assessment.

Rouse, W.C. (1984): Flowslides. - In: Brunsden, D. & Prior, D.B. (Eds.): Slope instability, 491-522, Wiley.

Sass, O. & Wollny, K. (2001): Investigations regarding alpine talus slopes using ground-penetrating radar (GPR) in the Bavarian Alps, Germany. - Earth Surf. Process. Landforms, 26: 1071–1086.

Scheidegger, A. (1973): On the prediction of the reach and velocity of catastrophic landslides. – Rock Mechanics and Rock Engeneering, 5/4: 231-236.

Van Husen, D. (1995): Bericht 1994 über geologische Aufnahmen im Quartär auf Blatt 67 Grünau/Almtal. – Jb. Geol. B.-A., 138/3: 490-491, Wien.

Appendix: Basic data of GPR profiles and drillings cited in this study.

Profile	Date of measurement	Start	End	Length	Main reflectors	Interpretation	Relevant Drilling
Gurgl valley	11.05.2004	188290 239980	188255 240210	230	4 - 6 20	Groundwater -3,5 m Base rockslide / Top lacustrine deposits	PD S1
Nassereith South	29.07.2005	188420 240700	188415 240605	100	6 15	Base fluvial deposits / Top rockslide Base rockslide / Top lacustrine deposits	PD S2 (PD S3)
Kriegerbach 1	04.02.2005	187675 245870	187725 245800	91	5 - 15 15 - 20	Debris flows (prograding) Top Rockslide	PD N1, PD N2
Kriegerbach 2	04.02.2005	187740 245850	187725 245760	96	6 - 20	Base debris flows / Top Rockslide	PD N1, PD N2

Remarks: Geographic Information (National Austrian Grid Bundesmeldenetz, Meridian M 28) measured by GPS and controlled by ortho-corrected images. Length of profiles quoted in metres, depth of reflectors in metres below ground surface. Interpretation of the reflectors implies their depth (quoted in below ground surface) as observed in probe drillings (Tab. 2).

Tab. 1 – Basic data of measured GPR profiles.

Drilling	Locality	Long. (E)	Lat. (N)	Elevation	Depth	Lithology	Interpretation	Groundwater
PD S1	Nassereith, field track	188195	240130	ca. 810	0 - 4.2	Polymict gravel (carbonatic and crystalline) with varying content of sand and silt	Fluviatil deposits (debris flows)	- 3.50 (806.5)
					4.2 - 8.0	Clayish silt with little content of sand and several polished (drop-?)stones	Stillwater deposits (“varved clay”)	
					8.0 - 14.0	Polymict gravel (coarse from 10.0 - 12.5) with clayish - sandy matrix	Fluviatil deposits (debris flows)	
PD S2	Nassereith, industrial area	188405	240640	ca. 815	0 - 3	Polymict gravel	Fluviatil deposits, anthropogenic affected	- 3.20 (811.8)
					3 - 7.5	Polymict gravel (carbonatic and crystalline) with varying content of sand and silt	Fluviatil deposits (debris flows)	
					7.5 - 12.5	Boulders (very hard to drill) in sandy - silty matrix	Rockslide (mingled with fluviatil deposits ?)	
					12.5 - 14.0	Clayish silt with numerous polished (drop-?)stones	Lacustrine deposits (“varved clay”)	
PD S3	Nassereith, communal road	188440	240995	ca. 820	0 - 13.2	Polymict gravel with varying content of sand and silt, therein loose layers of silty clays and occasional (7.5 - 9.0 m) occurrence of boulders	Fluviatil deposits (debris flows) with overbank deposits and boulders (rockslide ?)	- 6.00 (814.0)
					13.2 - 14.0	Clayish silt with sandy gravel (polymict, but crystalline-dominated)	Distal debris flows / proximal lacustrine deposits	
PD N1	Kriegerbach, forest track	187745	245760	ca. 950	0 - 4.0	Carbonatic gravel (fine) and sand with varying content of silt	Torrential deposits (debris flows)	clearly wet gravel underneath - 7.00 (*)
					4 - 4.5	Sand with clayish-silty matrix		
					4.5 - 7	Carbonatic gravel (coarse) and sand with varying content of silt (hard to drill)		
					7.0 - 7.5	Boulders (not to drill)	Rockslide ?	
PD N2	Kriegerbach, forest track	187635	245725	ca. 950	0 - 8.0	Alternation of fine and coarse carbonatic gravel and sand, both with varying content of silts (easy to drill)	Torrential deposits (debris flows)	clearly wet gravel/sand underneath - 5.00 (*)
					8.0 - 12.5	Carbonatic gravel (coarse) and sand (hard to drill)	Debris flows ?	
					12.5 - 14.0	Boulders (not to drill)	Rockslide ?	

Longitude and Latitude (based on National Austrian Grid Bundesmeldenetz, Meridian M 28) measured by GPS and controlled by ortho-corrected images, Elevation from Austrian Map. Depth of lithological changes quoted in metres below ground surface. Ditto groundwater level, this additionally also quoted in metres above sea level.

(*) SB-N N1-2: Drilling hole unstable, no water table measurable.