# MASS MOVEMENT PROCESSES IN UNCONSOLIDATED PLEISTOCENE SEDIMENTS – A MULTI-METHOD INVESTIGATION AT THE "HOCHGRABEN" (JENBACH/UPPER BAVARIA)

With 11 figures and 1 table

KARL-FRIEDRICH WETZEL, OLIVER SASS and CAI V. RESTORFF

*Zusammenfassung:* Massenbewegungen in pleistozänen Lockersedimenten – eine Untersuchung mit verschiedenen Methoden am Hochgraben (Jenbach/Oberbayern)

Gravitative Massenbewegungen stellen im Alpenraum ein erhebliches Gefährdungspotential dar. Insbesondere vor dem Hintergrund sich abzeichnender klimatischer Veränderungen ist mit einer Zunahme solcher Prozesse zu rechnen. Die Hochgrabenrutschung im Jenbachtal (Ldkr. Rosenheim/Obb.) vollzieht sich in pleistozänen Lockergesteinen, die in den Bayerischen Alpen erhebliche Flächenanteile aufweisen. Ziel der vorliegenden Untersuchung war es, mit klassischen geomorphologischen Aufnahmetechniken (Kartierung, Sondierungen, Bohrungen) und durch die Anwendung geophysikalischer Erkundungsmethoden (geoelektrische Tomographie, Georadar) Ausdehnung und Tiefgang sowie Ursachen und Beeinflussbarkeit der Hochgrabenrutschung zu erfassen. Darüber hinaus konnte ein Vergleich unterschiedlicher Erkundungsmethoden vorgenommen werden. Als Ergebnisse können festgehalten werden, dass ein breites Spektrum verschiedener Untersuchungsmethoden bei der Untersuchung von gravitativen Hangprozessen anzustreben ist. Erst durch die Ergänzung mit klassischen Aufnahmetechniken sind geophysikalische Methoden verifizierbar. Insbesondere die geoelektrische Tomographie hat sich als ein effizientes Werkzeug für die rasche und weiträumige Erfassung der Untergrundstrukturen erwiesen, während mit dem Georadar aufgrund der hohen Wassergehalte im Untergrund nur geringe Eindringtiefen erzielt werden konnten. Dagegen sind klassische Aufnahmemethoden sehr zeitaufwendig, wobei vor allem die Erkundung des Untergrundes durch den hohen Arbeitsaufwand stichprobenartig erfolgen muss und die Gefahr von Fehlinterpretationen besteht. Für die pleistozänen Lockergesteine im Bereich der Hochgrabenrutschung konnte ein zweiphasiger Aufbau von unverfestigten geschichteten Sedimenten über nagelfluhartig konsolidierten Ablagerungen nachgewiesen werden, an deren Grenzflächen die aktuellen Bewegungen erfolgen. Eine Beteiligung der unterlagernden Gesteine des Flysch kann ausgeschlossen werden. Beeinflussbar ist die Rutschung vor allem durch konsequente Entwässerung auch aus dem Bereich der Forststraßen. Die Verbauung am unteren Ende der Rutschung steht mit den Ursachen der Hangprozesse nur eingeschränkt in Verbindung.

*Summary:* Mass movement processes in the Alps pose enormous hazard. Due to the observed and predicted climatic change the chances are that mass movement processes will increase in future. At the Hochgrabenrutschung in the Jenbachtal near Rosenheim (Upper Bavaria) sliding processes are taking place in Pleistocene loose sediments, consisting of moraines and layered sediments of ice dammed lakes from the Inn-Glacier. Pleistocene loose sediments are a common appearance in the Bavarian Alps. The focus of the current investigation was an examination of the regional extent and the underground structure of the sliding masses, as well as the reasons for sliding and the technical possibilities of influencing the mass movement by use of different methods as classical geomorphological methods (mapping, drilling) and geophysical techniques (Earth Resistivity Tomography – ERT and Ground Penetrating Radar – GPR). Also, a comparison of the different methods of investigation has been conducted. The following results can be summarized. A broad spectrum of different investigation methods can be seen as very useful in producing reliable results in the complex field of mass movement examination. Classical geomorphological methods are very time consuming and the spottiness of drilling results may lead to misinterpretations. In contrast, geophysical methods deliver results quite quickly, but results are reliable only if verification by classic methods has been done. In the Pleistocene loose sediments of the Hochrabenrutschung ERT was very useful in detecting ground structures along different transects. Due to the high water content of the sediments the GPR technique failed and only near surface structures have been detected. The reasons for the sliding processes at the Hochgraben must be seen in the loose sediments, which obviously have been built up in two phases. The unconsolidated sediments of the near surface underground consist of an alteration of sandy pebbles and varvic clays. These sediments are underlain by compacted Pleistocene Sediments (Nagelfluh) acting as a slipping face. The Flysch layers in the deeper underground are not involved in the mass movement processes. Good drainage of the upper part of the sliding masses and by-passing of the overland flow of the forest roads, now entering the sliding mass, seem to be the major technical possibilities to reduce mass movement hazard. A dam built up at the lower part of the sliding mass by the water authority seem to have only a reduced influence on the mass movement processes acting in the upper part.

## *1 Introduction*

Besides avalanches and storm run-off, mass movement processes pose an enormous risk in alpine areas (MOSER 1980; OELTZSCHNER 1997). During the last two decades numerous investigations on the occurrence and triggers of mass movement, as well as on the processes involved, have been carried out. However, knowledge about mass movement processes is still incomplete. Therefore, local studies on the mechanics and the structure of mass movements are still necessary (cf. FISCHER 1999). This issue seems to be very important, taking into consideration the changing climatic conditions. Even if local future climatic scenarios are still uncertain, an increase in extreme precipitation events has been assumed for the Alps (BADER a. KUNZ 1998; WANNER et al. 2000; BENISTON 2002). Because extreme precipitation often triggers mass movement processes (cf. MOSER 1980), a rising number of gravitational slope processes must be expected in future, as well as a degradation of the alpine forests because of changing climatic conditions.

Areas with unconsolidated Pleistocene sediments and slopes within the Flysch zone are particularly vulnerable to mass movement processes (MEISSL et al. 2003). Several factors add to a significantly enhanced probability of mass movement processes in the Bavarian Alps. One major factor is the high rainfall amount as a consequence of orographic precipitation (blocking air flow and forced ascent, FREI a. SCHÄR 1998), which is the reason for extreme floods in the Northern Border Alps (e.g. in August 2002 and 2005). Others are the existence of more than 100 unconsolidated Pleistocene valley fillings (BUNZA 1992) and the widespread occurrence of Flysch in the Bavarian Alps.

The main topic of the current paper is the investigation and quantification of a landslide in unconsolidated Pleistocene sediments by use of a combination of classical geomorphological methods (mapping, core percussion drilling) and geophysical subsurface examination (ERT). The examinations focused on the following issues:

- What is the areal extent and the velocity of the slope movement?
- Which geological and geomorphological preconditions apply to the unstable hillslope?
- How thick are the sliding masses and what are the reasons for the slope failure?
- Is a stabilisation of the mass movement possible by technical efforts?
- Are geophysical sounding methods suitable for improving classical geomorphological examinations?

The investigations at the Hochgraben slide are a regional contribution to improving the knowledge of mass movement processes in areas with Pleistocene loose sediments. The combination of different investigation methods – geomorphological and geological mapping, mapping of hydrological features and geoelectrical tomography (ERT) – should give further information about the performance of each method.

## 2 *The investigation area*

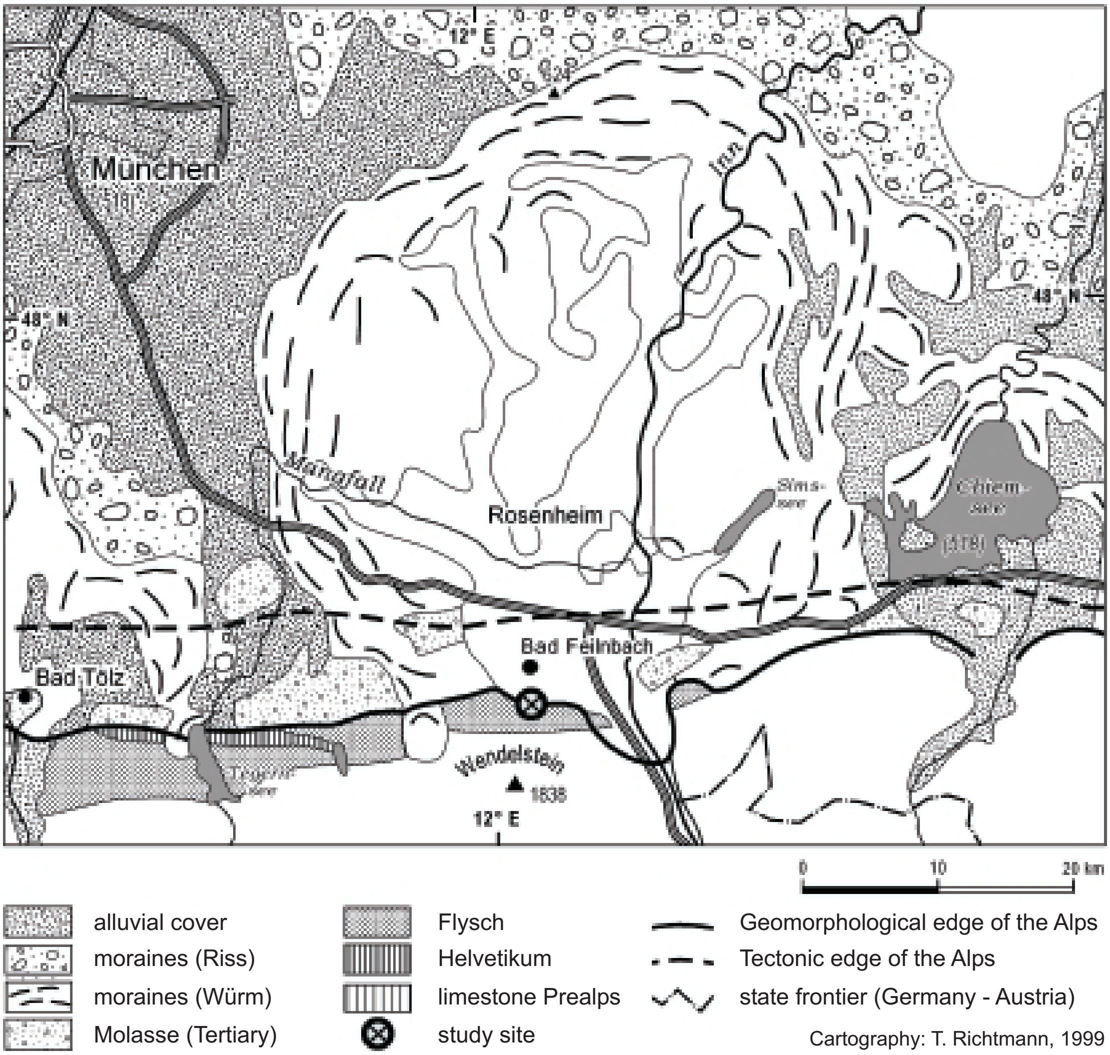
The study site is located at the northern border of the so called “Mangfall Mountains” in the district of Rosenheim (cf. Fig. 1), which are part of the “Chiemgau Flysch Alps” according to the classification of DONGUS (1994). The landslide is situated 3 km south of the village of Bad Feilnbach at the western side of the Jenbach creek. The elevation of the slide extends from about 655 to 750 m a.s.l. For several centuries, the Jenbach has been well known as a dangerous, steep mountain creek. In the medieval records of the monastery of Scheyarn (about 1200 AD), the Jenbach is described as a “creek transporting great stones” and the name “Jenbach” is derived from “jäher Bach”, which may be translated as “sudden creek” (WASSERWIRTSCHAFTSAMT ROSENHEIM 2001). For 130 years people have been trying to reduce sediment transport and the risk of mudflows in the Jenbach basin by the construction of dams. Hence, knowledge about the occurrence and intensity of mass movement processes is essential for calculating risk and planning protection measures.

From the geological point of view, the area is situated within the Flysch-Zone – locally called the Wendelstein-Foreland-Flysch (WOLF 1973). The Rhenodanubic Flysch trough is subdivided into sedimentary units stretching parallel to the axis of folding (FREUDENBERGER a. SCHWERD 1996). In the investigation area, the outcropping “Oberstdorfer” facies type forms part of the southern trough. The layers were deposited during the Barêmmian up to Palaeocene (WOLF 1973) and consist of typical uniformly repetitive strata, changing between thin beds of clays and series of breccias, sandstone and limestone. This series is typically sedimented by turbidity currents in a deep marine miogeosyclinal trough (cf. HESSE 1972). In the deeper part of the investigation area (645–690 m a.s.l.) the older parts, called “Reiselberger Sandstein” and “Upper Coloured Marl” outcrop in an anticline structure.

The Pleistocene history of the investigation area is closely connected with the advance of the Inn-Chiemsee-Glacier into the alpine foreland (Fig. 1). The foreland glacier dammed numerous north draining valleys in the Flysch Mountains. As a consequence, ice-dammed sedimentary basins were built up. Related to the glacier surface in front of the mountain range, the level of the ice-dammed lake in the Jenbach valley was situated at an elevation of about 800 to 900 m a.s.l. In the basin, sedimentation of allochthonic and autochthonic materials took place by glaciofluvial and glaciolimnic processes. The mass movement processes at the Hochgraben slide are taking place in these unconsolidated sediments.

The pine and fir forests surrounding the landslide are subject to forestry use. Above the Wirtsalm road, which crosses the landslide at an altitude of 740 m a.s.l. (cf. Fig. 3), the age of the forest is about 80 to 100 years, pointing to a plantation at the beginning of the 20th century. Aerial photographs of the years 1973, 1983, 1994 and 2000 show the effects of forest management. In 1973, 36% of the forest was cleared. Later on, alder trees were planted for stabilization within the sliding masses. In the upper part of the landslide, 13 year-old pines and some 50 year-old beeches are growing, some of which are inclined due to slope movement.

The Wirtsalm road, crossing the landslide, is often used for timber transport by heavy trucks. During the summer months, the road is free for public traffic. At the bottom of the landslide, another forest road was built alongside the Jenbach by the water authority. Directly above this road a massive dam was constructed for stabilizing the landslide and protecting the road. Former efforts to stop or slow down the slope movement are witnessed by several artificial trenches. The trenches have been dug to drain the landslide. An adjacent hillslope receives the bypass water and as a consequence a young erosion scar has developed. Directly



Cartography: T. Richtmann, 1999

*Fig. 1:* Location and geomorphological situation in the surroundings of the investigation area

Die Lage des Untersuchungsgebietes und die geomorphologischen Verhältnisse der Umgebung above the massive dam at the bottom of the landslide, the water is entering the original creek again (cf. Fig. 3). The exact date of the construction of the trenches is unknown.

## 3 Methodology

The slope movement processes at the Hochgraben landslide were investigated using a bundle of different methods. Detailed geomorphological, geological and hydrological mapping of the landslide was carried out, aided by pre-existing maps (geological map 1:25 000, hydrologic-morphological map 1:25 000) and their written comments (Wolf 1973; Bunza a. Karl 1975). In the field, mapping was carried out according to the geomorphological mapping instruction of Leser and Stäblein (1975). Enlarged aerial photographs and the Bavarian contour map 1:5 000 proved very helpful. In the course of the hydrological mapping, all the fluvial channels (even if dry), catch pits, water holes and springlets were recorded. Additionally, run-off was measured at each incoming and outgoing channel by use of the salt dilution method (Käss 1992) on different key-days.

A detailed survey of the landslide was undertaken in collaboration with the Institute of Photogrammetry and Cartography at the Bundeswehr-Universität Neubiberg (Prof. Brunner) with a Leica TC 600. In the field, a closed 16-step polygon was measured precisely (cf. Lermann a. Teubner 2002). After correction of the raw data by use of the PANDA software tool (GeoTec), a standard deviation of the location of $s_y = s_x < 2$ mm and of the elevation of $s_z < 3$ mm (cf. Lermann a. Teubner 2002) was achieved. The ring-polygon was marked in the field using iron tubes (50 cm long) to allow a repeated survey of the sliding masses. A detailed topographic survey of the landslide at a scale of 1:500 was achieved by measuring 2,085 single points from the ring polygon with a medium point distance of about 3 m. Because of the deeply incised, north-facing valley the GPS signal is poor. Thus, a relation to the official German grid could not be established with a reasonable effort and a local grid was used. On the base of the survey data a digital terrain model was computed by a GIS software (AutoDesk LDT). Each cross section and all elevation plots were calculated by use of the DTM.

Additionally to the geological mapping, drillings with the Pürkhauer auger and several percussion core drillings (35 mm diameter cores) were conducted. Percussion core drillings in the Pleistocene loose sediments reached a depth of penetration of more than 8 m. The grain size distribution of the cores as well as moisture content, stability and colour (Munsell soil colour chart) were examined using basic field methods. Each 20 cm

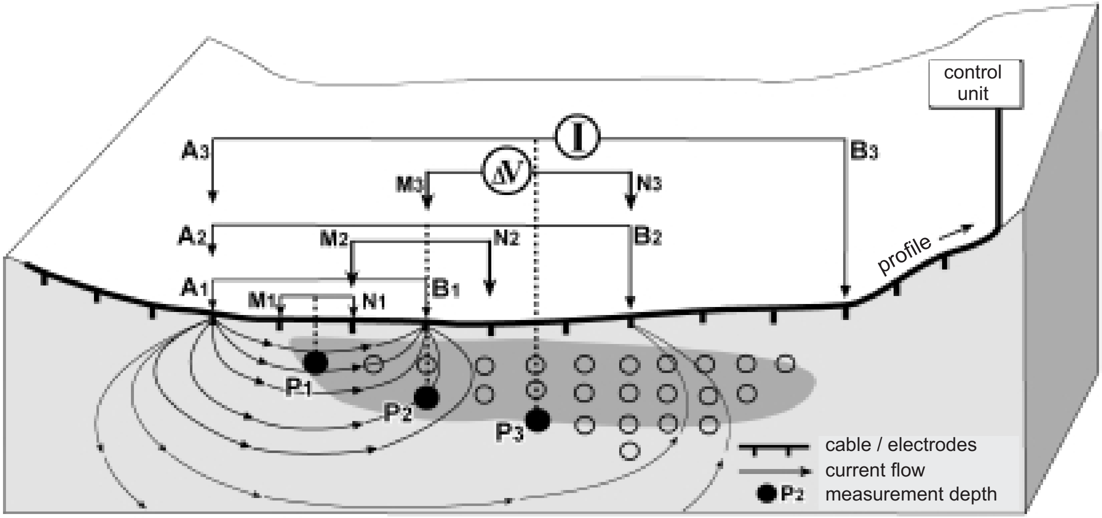


*Fig. 2:* The principle of earth resistivity measurement with the four-point-array and different electrode spacing (after Knödel et al. 1997, 123, modified)

Das Prinzip der Widerstandsmessung mit einer Vier-Punkt-Anordnung und verschiedenen Sondenabständen (nach Knödel et al. 1997, 123, verändert) a sample was taken for gravitational moisture determination in the laboratory. The drilling progress was exactly recorded to create a simple percussion drill profile.

In the current investigation, 2D-geoelectrics (earth resistivity tomography, ERT) was the main tool for the subsurface examinations. The principle of ERT is based on a constant current which is applied at two current electrodes C1 and C2 (cf. Fig. 2). An artificial potential field is created which is influenced by different conductivity of the strata. The resulting voltage difference is measured at a second pair of electrodes (P1 and P2). According to Ohm's law the electrical resistivity can be calculated by the potential difference between the pairs of electrodes C and P (cf. KNÖDEL et al. 1997).

Linear electrode arrangements with different electrode spacing for different examination depths are often used in geophysics. The so-called "Wenner array" realizes an increasing penetration depth by stepwise increasing the electrode spacing. In figure 2, this procedure is demonstrated schematically by an arrangement

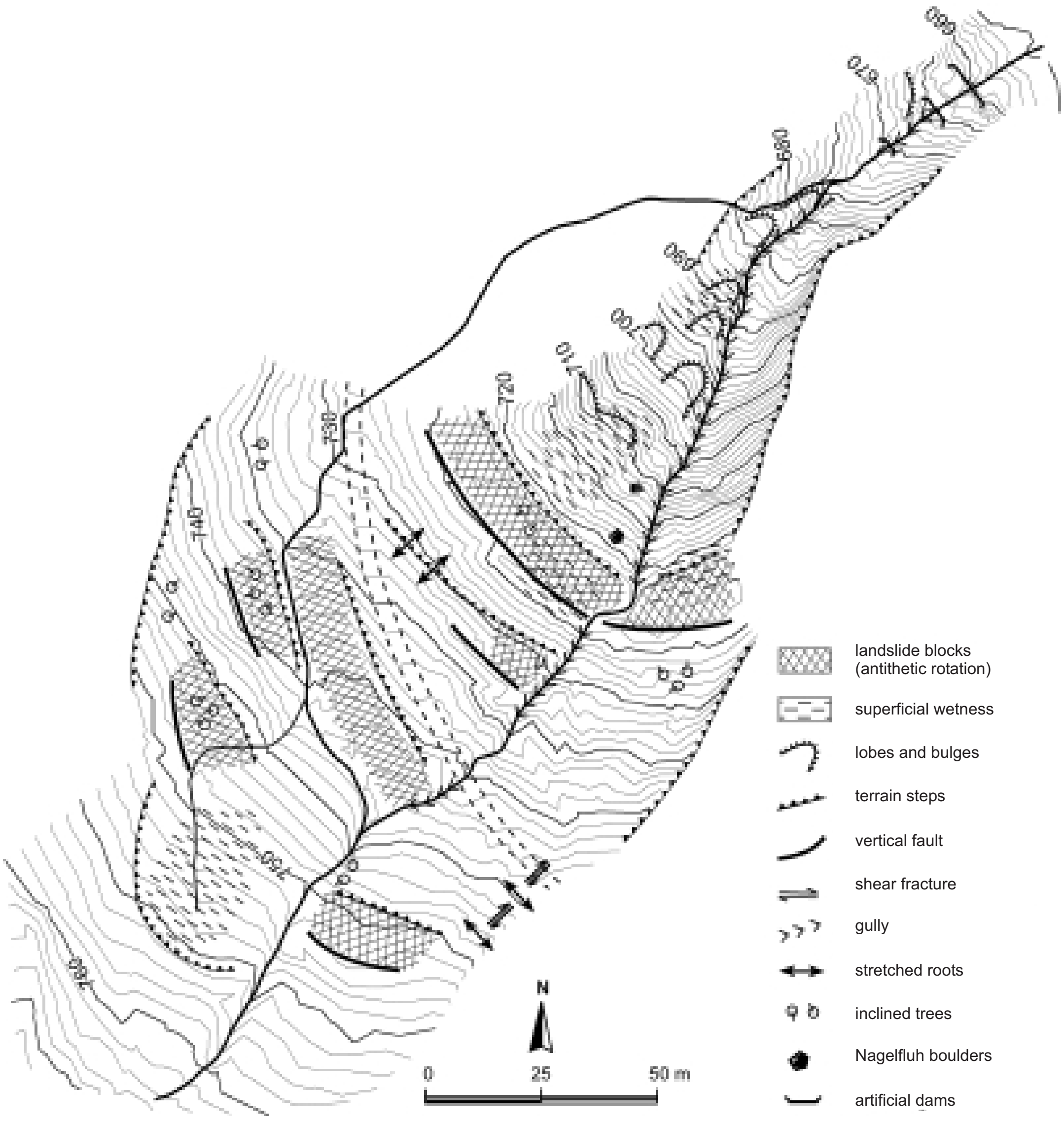


*Fig. 3:* The geomorphology of the Hochgraben landslide
Die Geomorphologie der Hochgraben-Rutschung

of 20 electrodes, which are measured pair by pair. At the first measurement electrode spacing is "a", for the second "2a" and so on, up to all possible spacing are measured. If the subsurface is characterized by horizontal structures, the "Wenner arrangement" is the most suitable approach.

Automatic ERT measurement with the Wenner array was carried out using a *GeoTom* device (*Geolog2000*, Augsburg). The instrument was equipped with two multicore cables. The spacing of the 25 cable contacts was 2 m; thus, 50 electrodes spanning together 98 m were used in the field. For longer profiles, up to three overlapping 98 m profiles were combined. The two-dimensional distribution of the electric conductivity of the ground was established by an iterative "inversion" calculation, using the software tool *Res2Dinv* (Rapid 2D Resistivity & IP Inversion, LOKE 1999). The topography alongside the ERT sections was derived from the DTM. The quality of the estimated resistivity distribution is expressed by means of the RMS (root mean square) error calculated by the software. Almost every measurement had an error smaller than 5%, which means that the calculated models are sound and reliable.

As a result of the inversion, a two dimensional cross-section of the distribution of the sub-surface resistivity is plotted. For a realistic interpretation of the cross-sections, the conductivity of the strata should be known. As shown in table 1, a significant interpretation of the ERT results is not easy because the electric conductivity values of some different strata are overlapping. Only areas with a high electric conductivity (resistance < 30 Ωm) can be related with a high probability to clay or clayey silt with high moisture content. Hence, at least some drillings are needed for verifying the ERT results.

*Table 1: The electrical resistivity of different geological substrates (compilation after KNÖDEL et al. 1997)*

Die elektrischen Widerstände verschiedener geologischer Substrate (zusammengestellt nach KNÖDEL et al. 1997)

| substrate | resistivity range (Ohmmeter) minimum | maximum |
|---|---|---|
| gravel | 50 | $> 10^4$ |
| sand | 50 | $> 10^4$ |
| silt | 20 | 50 |
| glacial till | 30 | 70 |
| clay (slightly wet) | 3 | 30 |
| sandstone | < 50 (jointed, wet) | $10^5$ (compact) |
| mudstone | 50 (jointed, wet) | $10^5$ (compact) |

Additionally to ERT, ground penetration radar measurements (RAMAC GPR) with different antennas (50 and 100 MHz) were carried out. Because of the high clay and silt content of the ground, the radar waves were subject to strong damping resulting in a penetration depth of 1–2 m or less. Therefore, no GPR results are presented here.

## 4 Results

### 4.1 Geomorphological, geological and hydrological mapping

The landslide can be subdivided into three parts dominated by different processes (Fig. 3). After DIKAU and GLADE (2002) it can be termed a complex landslide. In the upper part (765–750 m a.s.l.), inclined and downward-bent trees as well as many bare-lying, stretched roots are pointing to slow movement processes. The upper margin of the slide is formed by a terrain step of about two or three metres. Below the step, the terrain is formed by sliding blocks divided by terrain steps, some of them antithetically rotated. As a consequence, some rather flat terraces have developed. The forest road to the Wirtsalm runs over such a terrace. At the road itself and below it, several indicators for movement processes were found, such as sudden terrain steps or slip faces. The downward end of the lowermost sliding block is marked by a distinct terrain step at an elevation of about 720 m a.s.l. This block stretches right across the landslide, only interrupted by a small creek. A part of the sliding block has been rotated antithetically causing a reverse inclination to the hill slope; a small pond is formed here during wet weather conditions. This sliding block was named "met station terrace" because of the climate station erected here.

Below the met station terrace, a significant increase of the slope angle, together with some diffuse water outlets at the left side of the landslide, can be observed. Here, the second division of the landslide begins where the block slide changes into a more mudflow-like movement process. All terrain structures have been destroyed by the slow movement processes and only a sparse vegetation cover can exist. Two conglomerate boulders (Nagelfluh) more than 1 m long have been transported downhill on the surface of the moving debris. Further downslope the flowing masses have been dammed up by deadwood. In the middle of the landslide the sediments are washed out by a small creek. The creek is incised down into the undisturbed loose Pleistocene sediments. The sediments exposed here show horizontal layers and give no indication of disturbance by slope movement. They consist of a wide range of grain sizes from sandy pebbles, mica rich silty sands, interspersed with varve-like sediments of clay and silt. Figure 4 shows a cross-section of these sediments, which have been interpreted as glaciolimnic deposits in an ice-dammed lake. In positions where the creek is running within clay layers the fluvial erosion is low. Because of calcareous groundwater outflow, the pebble layers are slightly agglomerated by sinter. The moving debris is flowing on the top of these loose sediments.

The third and lowest part of the landslide has been stabilized artificially by wooden torrent dams and by a mighty stony dam at the foot of the slope. In this part of the landslide fluvial processes are dominating. No indicators for sliding processes were found in the field.

### *4.2 The recent movement of the slope*

In summer 2004, the fixed points at the landslide were surveyed again. Three dimensional movement rates have been calculated and plotted from the data (cf. Fig. 5). The figure allows a clear differentiation of areas of similar movement characteristics. In the upper part of the landslide only small movement rates of about 5 cm to 10 cm have been observed (points 48, 49 and 57) during a two year time span. Point 56 without a significant movement rate illustrates the upper margin of the recent movement process. Directly above the forest road several points (44–47, 50–52) stand out as having similar movement rates (12 cm up to 16 cm) and directions. The almost identical displacement highlights the block movement in this part of the landslide. Points 44 and 46 at the lower edge of the sliding block had a nearly horizontal vector of movement, indicating a slight antithetical rotation of the block.

At the points 40 to 43 below the forest road, an accelerated movement of about half a metre was measured. According to field observations, the area of accelerated movement is restricted to a rolling surface near the talweg. Further down at the met station terrace, movement is reduced to 20–30 cm during two years. Again, an antithetical rotation of the block is indicated by a horizontal vector of movement.

Highest displacement rates of about 50–100 cm were measured below the met station terrace at points 31–37. The three-dimensional vectors of movement are related closely to slope angle and direction. The results of the survey underline the transition of the block movement to a more flowing process of the

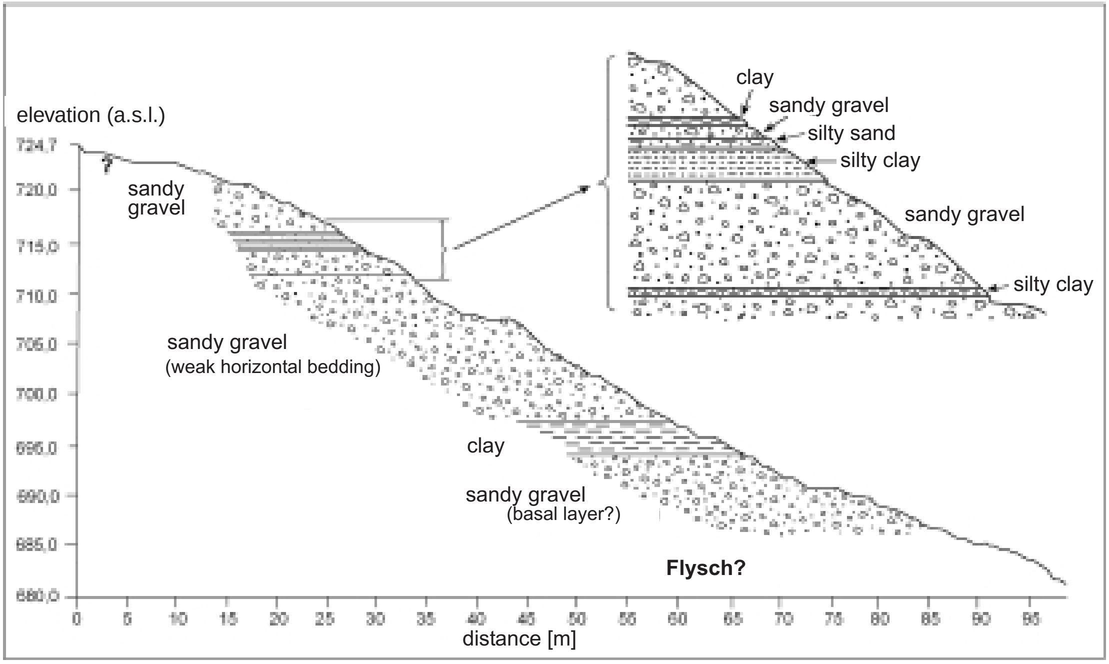


*Fig. 4:* Cross-section of the horizontally layered glaciolimnic sediments in the middle part of the central creek

Profilaufnahme der horizontal geschichteten glazial limnischen Sedimente im Bereich der zentralen Abflussrinne der Hochgraben-Rutschung debris. Further downslope, the intensity of the movement is reduced (points 23, 28 and 29). The vectors of movement are due to small local trenches. Here the sliding masses begin to dam up and fluvial erosion becomes the most important process. At the points 16–22 no significant movement was measured, which indicates the lower reach of the recent sliding process.

### *4.3 Percussion drillings*

Greatest penetration depths were 8.09 m in the middle of the met station terrace (RKS 1, 725 m a.s.l.) and 8.20 m (RKS 2) further south at the same elevation (cf. Fig. 6). Up to this depth in both drillings quite homogenous, greyish sediments were found, consisting of

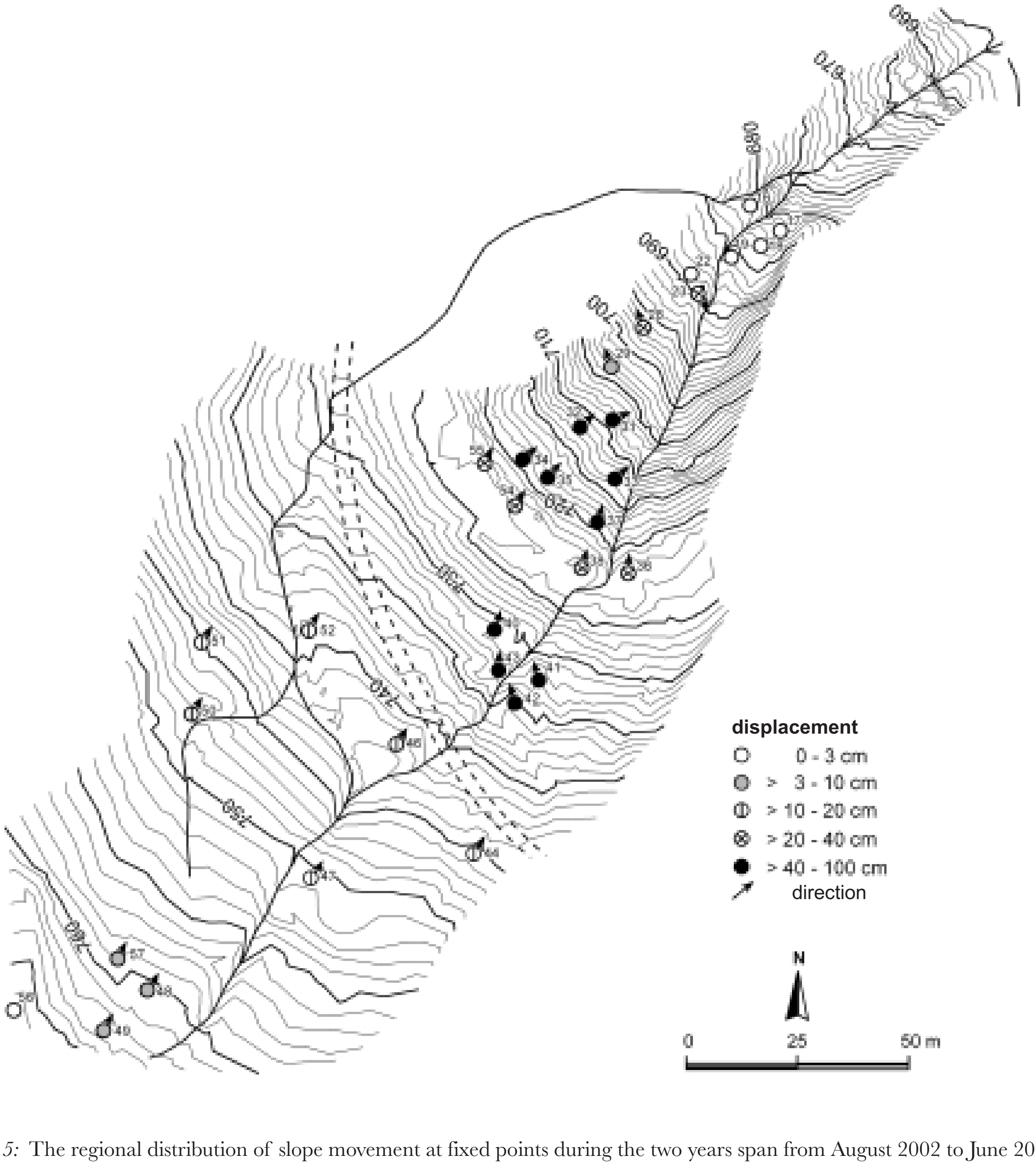


*Fig. 5:* The regional distribution of slope movement at fixed points during the two years span from August 2002 to June 2004

Die räumliche Verteilung der Hangbewegung im Messzeitraum von August 2002 bis Juni 2004 silty clays with a variable amount of gravel. According to the geomorphological situation and other field examinations, these sediments are deposits of an ice-dammed lake. The penetration depth was limited in both cases by a distinct drilling barrier. Because of the strength of the barrier only a small amount of material could be sampled. The samples consist of calcareous, light beige, almost whitish material resembling Wetterstein limestone. They point to an older (Würmian or older) consolidated glacial deposit rather than to outcropping Flysch.

Below the met station terrace, the same drilling barrier was detected at RKS 3 and RKS 4 at a depth of 3.20 m. The elevation of the barrier relative to sea-level is constant at 717–718 m. Therefore, a terrace like structure with a horizontally orientated surface can be assumed. The two Nagelfluh rocks described in the geomorphology section were situated only a few meters

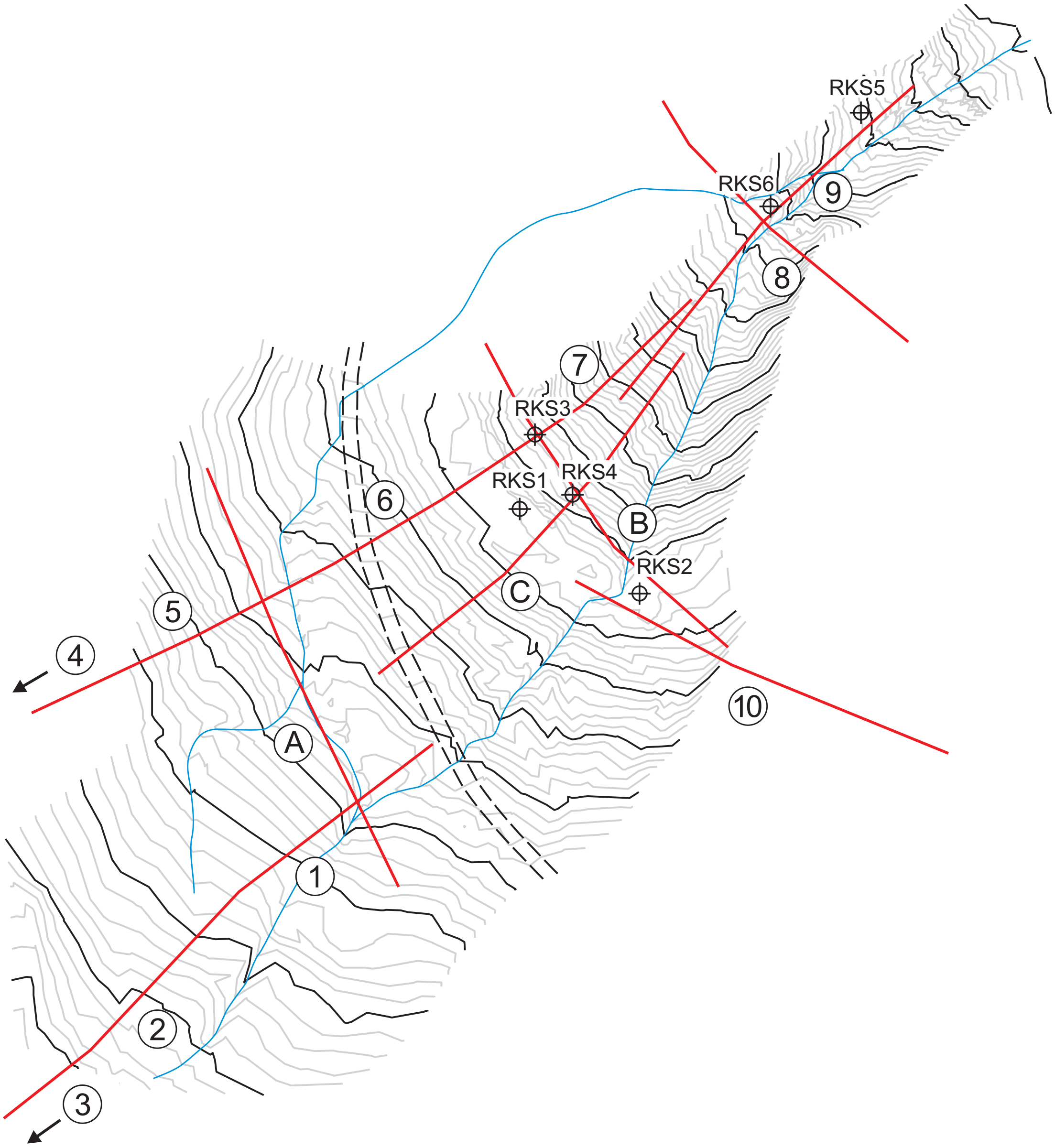


*Fig. 6:* The location of the percussion drillings and the ERT sections
Die Lage der Rammkernsondierungen und die ERT-Abschnitte

beneath this underground structure and may be derived from it.

Two further percussion drillings (RKS 5 and 6) were carried out near the talweg in the lower part of the landslide, verifying the ERT sections here. The penetration depth of RKS 5 was 5.8 m. Up to this depth only homogenous, greyish, silty clays mixed with some sand and small pebbles were found. No material was sampled from the deepest part of the drilling because of core loss. At RKS 6, a penetration depth of 7.8 m was reached; similar greyish, sometimes light brownish and plastic clays and silts with a high water content, were found. Below 5.3 m depth, the drilling resistance increased markedly. Near the maximum penetration depth (7.7–7.8 m), a layer of silty, gritty sands was sampled. As a result of the geological and geomorphological mapping, it is assumed that the upper 5 m are sediments moved by gravitational flow processes. At greater depth undisturbed ice-dammed sediments with a similar grain size distribution are found, characterized by an increased drilling resistance. The greater portion of sand in the deepest part of the drilling core is probably due to outwash processes above an aquiclude. The aquiclude is indicated by increasing water content of the core near the drilling barrier. As a result of the percussion drill diagrams and the ERT sections (see further down), the barrier seems to consist of a massive clay layer rather than of outcropping Flysch.

### *4.4 2D-geoelectrics*

The geoelectrical measurements proved to be a quick and efficient method for subsurface investigation even in rough terrain. The calculated electrical resistivities ranged from ca. 5 Ωm to 1,000 Ωm. For comparability, the same colour chart was applied to all the profiles presented. The location of the profiles is shown in figure 6.

The longitudinal profile C (Fig. 7) graphically highlights the overall structure of the mass movement. In the upper profile part, a distinct, highly conductive zone stretches a few metres under the surface. The absolute resistivity values point to a layer of wet clay or silt. Isolated occurrences of higher-ohmic (drier) substrate are overlying this layer. From the field results we infer these to be rotated sliding masses on the underlying slip surface. It has to be considered that the inversion routine leads to a more or less smoothed underground model, even if sharp layer boundaries are present in the subsurface. In the current example, the detected slip surface is probably narrower and sharper, especially at its base.

Near the middle of the profile, the slip surface is respectively interrupted or pinches out at the surface. A spatially confined, high-ohmic structure is recognizable in the shallow sub-surface which is probably due to a displaced Nagelfluh block, like the Nagelfluh boulders found at the surface near RKS 4. There is no clear concurrence between the geophysical and the drilling results at RKS 4 while near RKS 1 and RKS 3 the results are in good agreement (see below).

Downslope of this area (< 719 m a.s.l.), the conductive zone is at, or immediately below, the surface. This is the area of the wet, superficial mudflow, which occurs downslope of the topographical step. In greater profile depth (> 4–5 m) much higher resistivities are recognized which are thought to indicate bedrock (Flysch, Zementmergelserie) or ice-compacted Pleistocene sediments (Nagelfluh). Higher resistivities in the subsurface of the right (lower) profile part are probably connected with better drainage in the steeper slope section.

In the parallel-running longitudinal profile 7 (see Fig. 8), the horizontal structure under the steepened slope section is clearly recognizable. The resistivity patterns correlate well with the drilling results. The bar marks the lower threshold of the rotational slide and probably stabilizes the slope above which is in good agreement with the results of the geomorphological mapping. Through the damming effect of the buried terrace, diffuse water outlets occur at this altitude level (see Fig. 3). The soaked loose sediments become deformable, plastic material is pressed out, which leads to the break-up of the landslide blocks to a debris flow.

Cross-profile B right below the met station terrace (Fig. 9) confirms the conclusions from the longitudinal profiles. A horizontal structure can be recognized which is in agreement with RKS 2 and 3. At profile distances of 40–54 m the profile shows a depression of the high-resistive layer which might point to a former run-off channel. Even though this depression is not confirmed by RKS 4, we assume the geophysical result to be reliable, which is backed up by the low RMS error (2.3%) and the consistency with longitudinal profile C (see Fig. 7).

The presented longitudinal and cross-profiles allow us to estimate the thickness of the uppermost clayey/silty sediments. At the met station terrace, the thickness is 7–10 m corresponding to the results of the drillings. Below the terrace where the subsurface bar is closest to the surface, the overlying sediment thickness reduces to 2–3 m (RKS 3 and 4: 3.2 m). The almost horizontal structure at the base of the loose sediments at an elevation of 715–717 m a.s.l. is proved by further cross-profiles (not presented) beside the main landslide body.

Cross-profile A (Fig. 10) runs above the Wirtsalm forestry road on a distinct, antithetically rotated landslide block. Under a superficial wetting zone the landslide block becomes visible, which is indicated by comparatively high resistivity values. At a depth of 10 m, a second wet zone follows, which is once more the slip surface at the base of the block (see Fig. 7 and 8). The edge of the active slide as indicated by the topography is located at 28 m profile distance. However, the slip surface clearly continues under the presently stable, wooded slope to the left. Thus, we assume this slope to be potentially endangered by slope movement.

Profile 9 (Fig. 11) lying in the lower, trench-like area of the study site displays two sharply separated zones of different resistivity under a superficial, wet sediment layer. The higher-ohmic layer, outcropping at a profile distance of 64 m, consists of loose, debris flow-like sliding masses according to the borehole data. The bulge at the downslope edge of the sliding mass is clearly recognizable from the topographical profile. The very low resistivity in the lower part of the profile is probably due to soaked, clayey sediments. According to the drillings, these deposits are ice-dammed lake sediments which are not affected by the present slope movement. Several springs are located at the base of the overlying slide masses which underlines the impermeability of the clayey layer.

## 5 *Interpretation and conclusions*

### *5.1 Structure of the Pleistocene deposits*

The Pleistocene deposits of the Jenbachtal are not uniform at all, which is probably valid for the majority of valley-fill deposits along the northern edge of the Alps. The following course of events is presumed to have led to the deposition of the landslide-prone sediments: In the early Würm, the Inn glacier moved forward into the Jenbachtal from the north, blocking the valley outlet. At this time a dammed lake with a lake level of 800–900 m a.s.l. may have existed, as BUNZA (1992) deduces from field observations. On the Flysch bedrock, basal gravel was deposited through glaciofluvial and glaciolimnic processes while the glacier advanced further into the valley. The deposited sediments originate from the Inn glacier and from the local Wendelstein glacier as well. WOLF (1973) supposes a high glacial ice surface at 1,200–1,300 m. Accordingly, the Inn glacier must have overthrusted and solidified the early valley fill deposits.

Analogous to the findings in the geologically similar Lainbach area (BECHT 1989), the consolidated sediments found at RKS 1–4 may thus be classified as basal moraine or (because of the horizontal surface) consolidated basin sediments from the early Würm. This finding gives evidence for an at least two-phase formation of the Pleistocene valley deposits. In the first phase, the glacier deposited basal moraine and glaciofluvial sediments, which were synsedimentary compressed by overlying ice. During the glacier retreat in the late glacial period, stratified sediments were deposited in the still ice-dammed basin between the local ice and the foreland glaciation. A co-existence of fluvial and limnic deposition can be expected. The resulting unconsolidated deposits form the present-day land surface. With the gradual unblocking of the Rosenheim basin the Jenbach could erode deeper by degrees. In late glacial periods of stagnating or slightly advancing glaciers, the resulting temporary basins were filled with fluvial and limnic sediments. This process is witnessed by local terrace formation along the valley sides. The totality of these unconsolidated, mostly bedded, clayey to gravely sediments is partly underlain by the compressed and largely impermeable basal moraine layer (GROTTENTHALER a. LAATSCH 1973). The thickness of the glacial and postglacial sediments in the small valley of the Hochgraben slide is comparatively high, given that Flysch bedrock crops out at both edges of the trough. Thus, we assume the existence of a pre-glacial V-shaped valley at the site of the present-day landslide.

A multi-phase formation of Pleistocene alluvial fills can also be expected in other valleys at the fringe of formerly glaciated mountain ridges. Interposed, ice-compacted layers are probably a common feature in comparable environments. The resulting damming wetness and perched ground water may cause a considerable risk of slope failure.

### *5.2 Kinematics of the landslide*

A basic landslide disposition is caused by the clayey, weakly consolidated sediments on the one hand and the strong downward erosion of the Jenbach on the other hand, which is steepening and destabilizing the adjacent slopes. According to the results, the shear planes are situated between consolidated and unconsolidated sediments or along internal clay layers, rather than between sediments and bedrock. The Flysch marlstones (which are known to be landslide-prone) only play a tangential role in the type of landslide investigated.

At the upper stretch of the slope, the landslide is characterized by antithetically tilted blocks of loose Pleistocene sediments. Presumably, the local slip surfaces are connected to impermeable clay layers within the sediment body. On this part of the slide, older, ice-

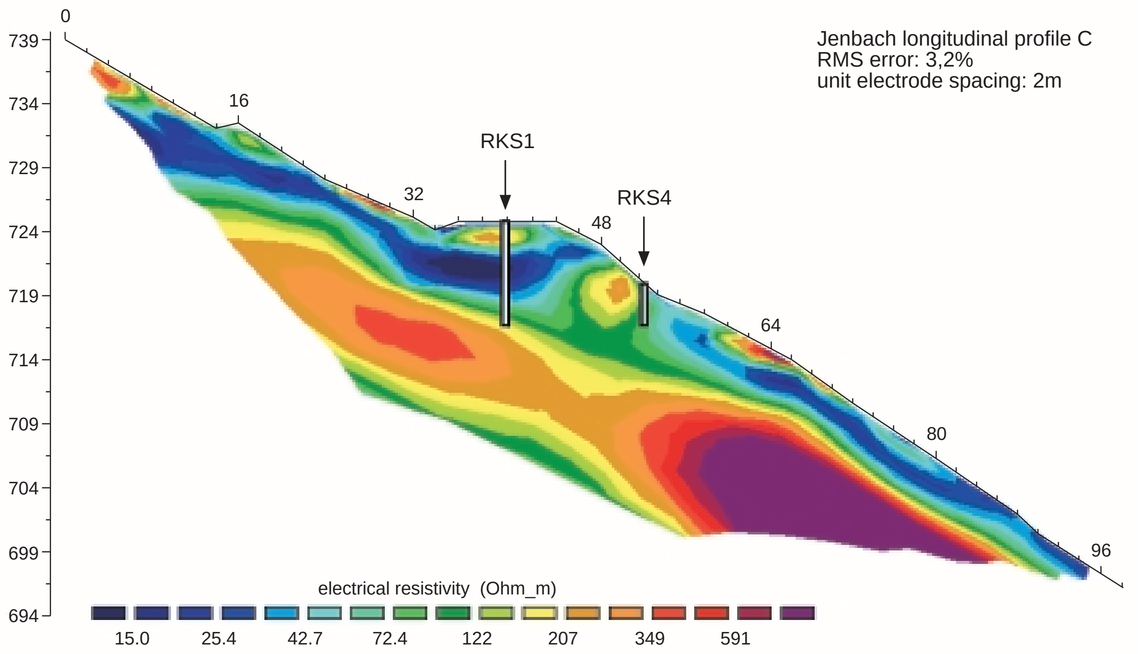


*Fig. 7:* 2D-geoelectrical longitudinal profile C and location of the percussion core drillings

Geoelektrisches Längsprofil C mit Lage der Rammkernsondierungen

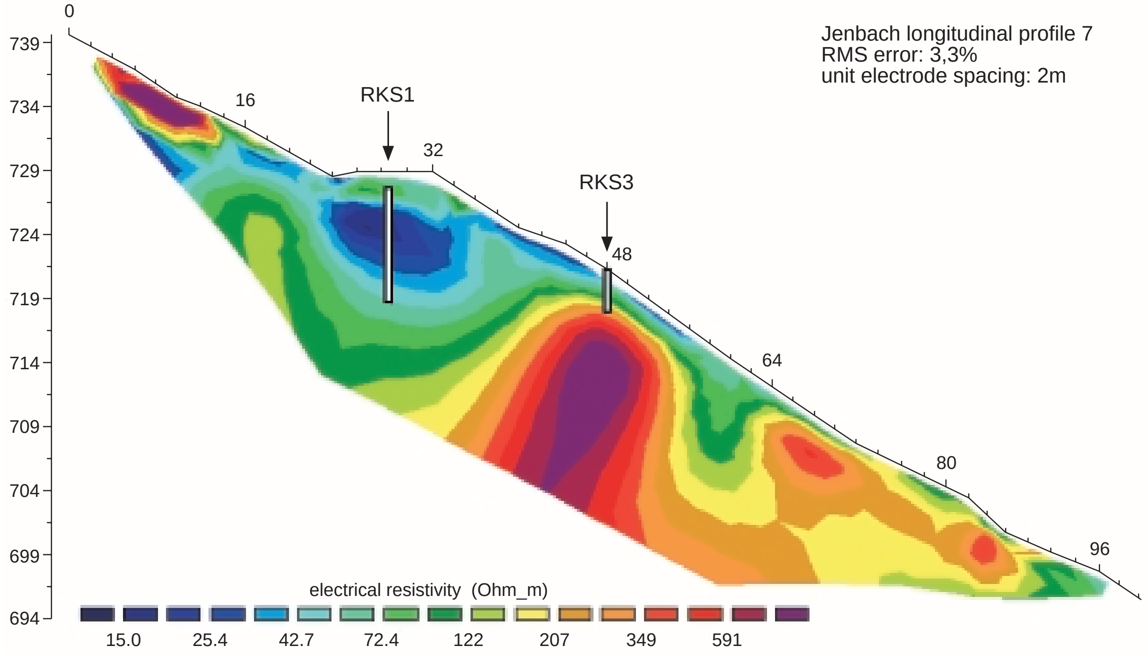


*Fig. 8:* 2D-geoelectrical longitudinal profile 7 and location of the percussion core drillings (RKS 1 is not exactly on the profile line)

Geoelektrisches Längsprofil 7 mit Lage der Rammkernsondierungen (RKS 1 liegt nicht genau auf der Profillinie) compacted glaciofluvial sediments in the subsurface act as the lower limit. The sliding masses move over this inhibiting barrier as a pulpy, relatively shallow debris flow. Further downslope, the material is eroded by the creeks which have their sources above impermeable clay layers and is transported fluvially into the Jenbach. The erosion around the water outlets contributes to the destabilization of the foot of the slope but is not the primary reason for the slope movement. The crucial factor are the gullies between 690 and 720 m a.s.l. which lead to a steepening of the slope. Thus, the support of the upper slope parts is removed by degrees, which is leading to the observed rotational movement. A portion of the soaked sediments is pressed out and moves downslope beside the gullies. The detected subsurface terrace structure has a stabilizing effect preventing the overlying sediment blocks from sliding down as a whole.

### *5.3 Options for geotechnical influencing*

Forestry and road construction may act as short-term triggers of slope destabilization. However, on grounds of the basic landslide disposition of the loose Pleistocene sediments, slope failure may occur without any anthropogenic influence. Geomorphic evidence for widespread, older slope movements is also found above and beside the current landslide. Building measures at the foot of the slope, as carried out at the Jenbach by local water authorities, may act as a temporal protection for the infrastructure below the barriers. However,

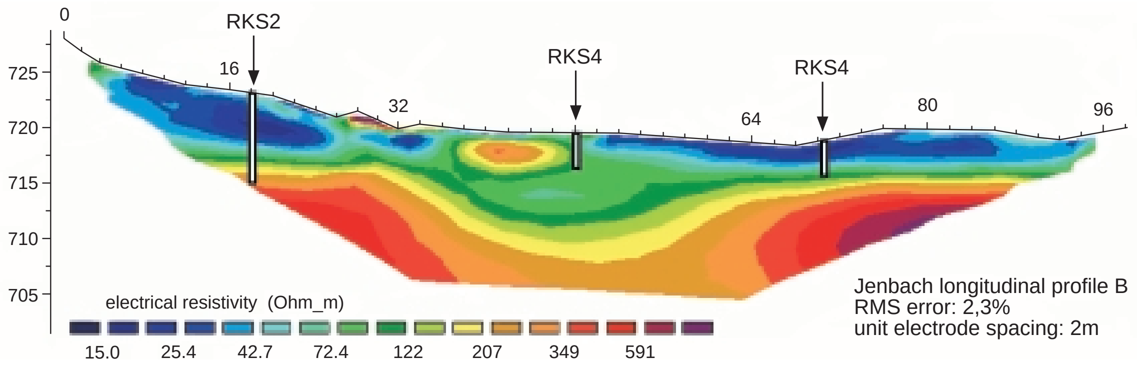


*Fig. 9:* 2D-geoelectrical cross profile B and location of the percussion core drillings
Geoelektrisches Querprofil B mit Lage der Rammkernsondierungen

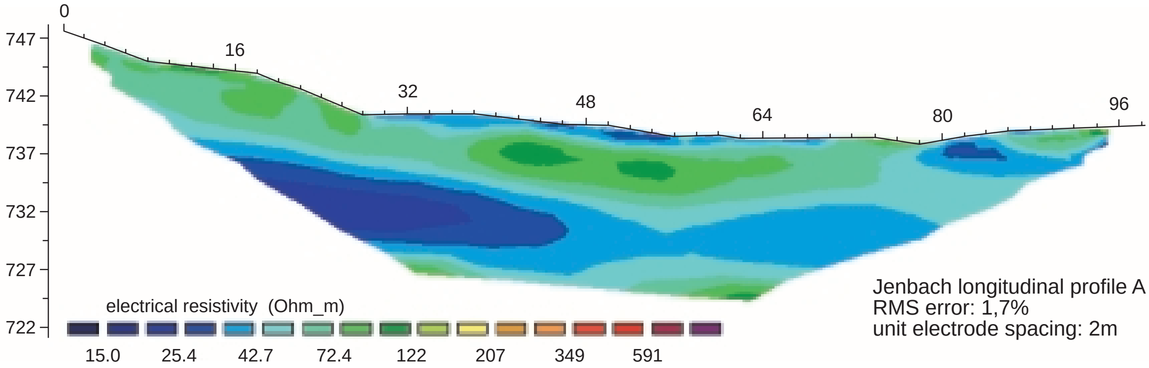


*Fig. 10:* 2D-geoelectrical cross profile A
Geoelektrisches Querprofil A

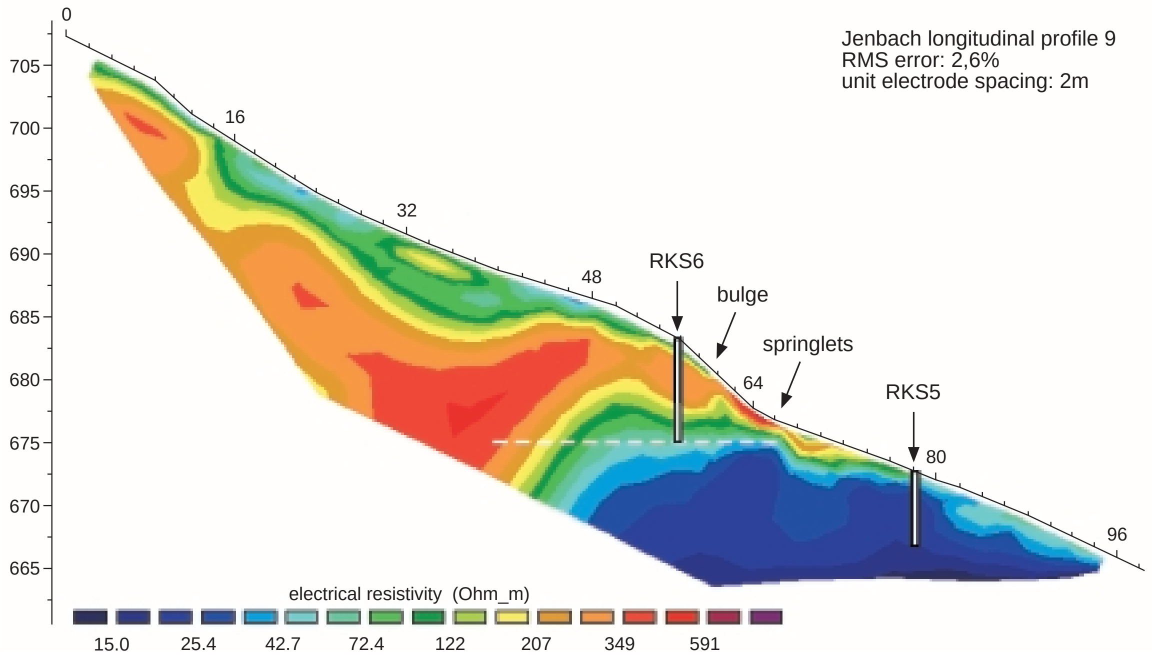


*Fig. 11:* 2D-geoelectrical longitudinal profile 9 and location of the percussion core drilling
Geoelektrisches Längsprofil 9 mit Lage der Rammkernsondierungen

no stabilization of the landslide itself can be expected from such protective measures. In the longer term, it makes more sense to keep the superficial runoff away from the landslide. Currently, overland flow even from parts of the forestry road beside the slide can trickle away unhampered. At tension cracks this infiltrating water is directed straight to the slip surface. By at least the 1970s, attempts had been made to drain superficial water from the area of the slide. However, the water is currently diverted through a small channel to the next run-off path some tens of metres north of the current slide. Probably as a consequence of this measure, a small but active gully has developed in this position which, in the long term, may lead to a new slope failure. Therefore, the water should be piped down to the Jenbach or to a tributary creek where quick run-off is guaranteed.

### 5.4 *Evaluation of the methods applied*

The broad combination of conventional geomorphological and geological mapping, drilling and geophysical sounding proved to be suitable to gain insight into sub-surface structure and kinematics of the slide. The geoelectrical measurements yielded extensive and detailed sub-surface information from a comparatively low amount of field work (13 profiles were measured in two days). Loose debris, clayey layers, consolidated sediments and bedrock obviously produce considerable contrasts in resistivity, which makes 2D-geoelectrics a powerful tool for sub-surface investigation in comparable environments. However, at least some drillings have to be carried out to facilitate the interpretation (and, to avoid serious misinterpretation). The very quick 2D-geoelectrical measurements can help substantially to minimize the drilling effort. Assigning the resistivity areas found in the geoelectrical sections to geological units is only possible by verification with other methods. Thus, detailed geomorphological and hydrological field mapping should be the starting point for this type of investigations. After a first idea of the landslide dynamics is devised, a combination of targeted geoelectrical profiles and exemplary drillings can yield plenty of further information to validate the starting model.

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