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Geophysical investigations of large landslides in the Carnic Region of southern Austria

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Abstract

The area under investigation for the past two decades is in the vicinity of the Gailtal lineament, which is the most dominant tectonic feature of the eastern Alps of southern Austria. An area of about 8 km^2 is in a state of constant instability, as documented by movement of road tracks of several centimetres per year. Geotechnical and surveying techniques have been used to measure these movements in the past but without solving the problem of the mechanism of these failure processes. Geophysical methods (seismic refraction, geoelectrics, and electromagnetics) were applied in order to determine the validity of one of the discussed movement models. In-situ velocity measurements were used to identify different lithologies beneath surficial talus deposits. The thickness of these talus deposits, of about 4–30 m, found by seismic refraction clearly demonstrates that huge 'blocks' (i.e. more or less undisturbed lithologic units) within the talus/debris are in close contact with the basement. This basement, which shows lower seismic velocities in different parts combined with low electric resistivities, is obviously strongly disturbed by different failure surfaces. The different gliding velocity of the blocks and the talus/debris deposits leads to a geological model in which huge rock blocks move slowly in relation to the disintegrating basement, whereas the talus/debris deposits move over the surface of these blocks at a higher velocity. The interpretation of these landslide studies is not a straightforward analysis. It is a complex problem with a complex solution, including all information from geotechnical, geophysical, and surveying investigations. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Debris flow; Geophysical investigation; Landslide; Landslide mechanism; Palaeocoic; Rock fall; Southern Alps

1. Introduction

In planning engineering projects, such as highway and railroad cuts, retaining walls, etc., in landslide areas, the best possible description is needed for the characteristics of the moving mass and for the failure mechanism. A combination of geological, geophysical, and geotechnical factors have to be identified and taken into account for the design and the economic evaluation of the project. With the size of the project, the complexity of factors describing the landslide increases rapidly (Selby, 1993).

The available methods for analysing slope systems have been classified by Hutchinson (1983) into two principle groups: moving landslides and stationary landslides. The first group combines surface movement observations, direct measurements of sub-surface displacements, and geoacous-

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tic sensing. The second group utilizes methods such as in-situ observations in holes and characteristics of geologic materials obtained from drill cores. However, even when drilled, when the maximum core recovery is recorded and geotechnical borehole logging has been successful, drill holes represent only a single-point information in lateral dimension. In contrast, geophysical methods are generally non-invasive and give highly resolved two-dimensional distributed data. From these two-dimensional data, if appropriate geophysical interpretation routines are applied, three-dimensional models of the investigated hill slope may be developed. In a case study focusing upon problems experienced during railroad track laying through slope-prone regions (Cotton and Lawrence, 1991), a good agreement between results derived from refraction seismic surveys and borehole data was reported for mapping an undulating bedrock surface beneath inclined and rugged topography; this has supported the use of geophysical means within geotechnical projects. Besides this particular case study, the feasibility of other geophysical methods to resolve details of sliding masses, such as downslope movement, thickness, relief of bedrock, depth of water table, and internal composition of the sliding mass, has been studied by Bogoslovsky et al. (1977), Bruckl (1977), Mueller (1977), Figdor et al. (1990), Mills (1990), Caris and Van Asch (1991), Campagnoli and Santarato (1995), and Gorosabel and Ponsati (1995). In addition to ground-based geophysical surveys, Seiberl et al. (1995) conducted airborne surveys for the delineation of sliding masses by mounting geophysical instruments on a helicopter.

Independent of the method used, the standard performance of individual geophysical methods always depends on fundamental physical constraints, e.g. penetration, resolution, and signal-to-noise ratio. Therefore, information from geophysical surveys is derived only by a suitable combination of several geophysical disciplines and their joint interpretation. This axiomatic concept, in applied geophysics addressed as 'complex interpretation', has been reviewed and evaluated for landslide investigations (McCann and Forster, 1990).

In Austria, as in other alpine regions, landslide hazards cause a major problem for public officials and the civil engineer: damage to property, disruption of life-lines, and disintegration of traffic and communication networks bear a severe financial load for the individual and for the public. These facts, as well as scientific interest, led to a project, supported by the Austrian Academy of Sciences, to find a suitable combination of standard geophysical methods that can be applied to landslide problems under well-known geological and geotechnical conditions. The chosen area of investigation was the 'Schlanitzen Gleitung' (Schlanitzen sliding mass) in the vicinity of the Nassfeld Pass on the Austrian–Italian border (Fig. 1).

Based on long-term monitoring of the kinematics of huge toppling blocks and on observations of block movements, Glawe et al. (1993) developed a model for the disintegration of the top part ($0.25\ km^2$) of this area (approximately $8\ km^2$) on the northern slopes of the Carnic Alps. Notwithstanding, it should be mentioned that such refinements of geological investigations cannot replace the possibilities of geophysics in consideration for rock slope processes.

This paper has two aims:

1. To present results from an integrated geophysical effort utilizing refraction seismic surveys and geoelectrical methods conducted over an area of different rock slope processes.
2. To show that such techniques are feasible not only for shallow landslides, but also for deep-seated landslides. Results from this geophysical study were used in a previousely proposed model of the mountain-splitting processes for

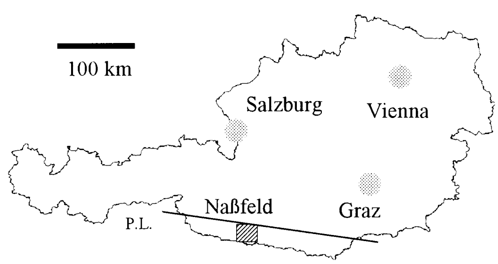


Fig. 1. Geographical location of the case study (P.L. — Periadriatic Lineament).

this region in southern Carinthia (Moser and Glawe, 1994).

2. Location and geology

The area under investigation belongs to the northern rim of the Carnic Alps, immediately south of the Periadriatic Lineament (P.L. in Fig. 1). This lineament, dividing the Southern from the Eastern Alps, with its related right-handed and vertical movements, dominates the tectonic evolution of the area. This tectonic section cross-cuts Devonian, Carboniferous, Permian, and Triassic series between the Italian border and the Gail valley as numerous faults. The rocks involved are limestone, dolomitic conglomerates, and sandstone, as well as marls, shales, and graphitic shales. In the area of the Nassfeld landslide, the lowermost part of the sequence under investigation is composed of Upper Carboniferous Auernig beds, consisting of thin- to medium-bedded limestone, shales and graphitic shales. The overlying Permian rocks consist of thick-bedded to massive limestones of the Rattendorfer beds and Trogkofel limestone with interbedded schists (Grenzlandbänke). The Trogkofel limestone is overlain by Grödener sand- and siltstones and the Bellerophon dolomite.

From a geotechnical point of view, the investigated area belongs mostly to the Schlanitzenalm landslide, circumscribed by the Italian border in the south, by the Rudnigbach (Rudnig Creek) in the west and north, and by the Trögelbach (Trögel Creek) in the east (Fig. 2). The whole area is strongly characterised by geomorphological features. Only the ridge between the Madritschen and the Tressdorfer Höhe (Fig. 2) seems to be in place; all the other domains are in a state of disintegration and are moving toward the erosive gullies of the Rudnig- and Trögelbach (Fig. 2). The top layers of this huge landslide and parts of the internal structure are formed by very large bodies of massive limestone of lowermost Permian (local nomenclature: *Untere Pseu-dosch-wagerinen-kalke*). The tectonic position of these blocks and the overall thickness of the sliding mass were questioned and had to be determined. In order to do so, near-surface geophysical techniques were applied, tested and evaluated. Another uncertainty to be resolved was the nature of the sliding mechanism: the shallow south dipping carboniferous and Permian strata contradict the N–NW dipping sliding surface for the block gliding seen in the outcrops. Hereby, the shaly and graphitic interlayer could not fully serve as the only cause for this problem. A two-step process was conceivable:

1. initial disintegration caused mainly by the opening and network building of fractures, and
2. gravity gliding, including a bending toward the erosion zone.

This assumed mechanism of block gliding is well in accord with the geomorphic terrain analysis. Whereas this process describes well the circumstances on the Tressdorfer Höhe, in most parts of the Schlanitzenalm landslide, deep-seated creep seems to dominate. The complexity of the regional geology is shown in Fig. 2.

According to the proposed characterisation of landslides by Varnes (1978) and Cruden and Varnes (1996), three indiviual landslide domains can be distinguished: the Rossalm, Rudnigalm, and Sonnleiten slides. These individual slides are marked on the ground surface by composite head scarps, inactive in the area of the Madritschen ridge, Tressdorfer Höhe, but active in all the others (Fig. 2).

The lithological circumstances are similar in all cases, with the Auernig formation, mentioned above, forming the weak substratum. This formation tends to disintegrate, forming large blocks and the main mass of the debris. The mechanisms of the landslides can best be discribed as *rockfall-debris slides*. However, in the case of the Rudnigalm slide, the Auernig Formation is overlain by Lower Permian limestones (untere Pseudoschwagerinen Kalke), causing a type of activity described as a rock topple-debris slide. The large blocks, from the Auernig Formation and from the Permian limestones slide much more slowly than the debris, most probably in accord with the continuous disintegration of the substratum.

The geotechnical and geological background information led to the selection of a geophysical survey, consisting of refraction seismics and electromagnetics. Profile 1 [Fig. 3(a) and (b)]

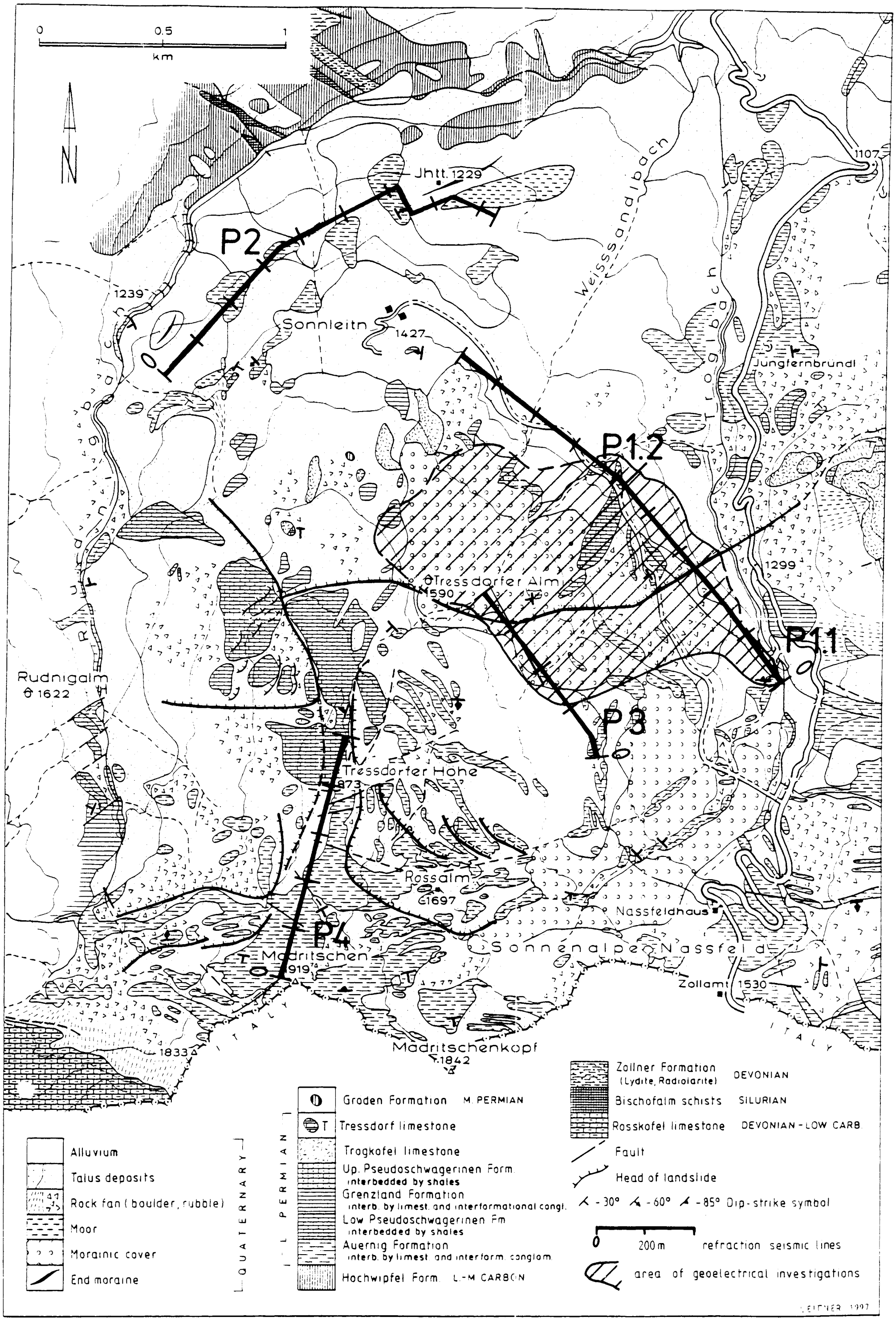


Fig. 2. Geological map showing the directions of the main slip surfaces and the locations of geophysical surveys (Schönlaub et al., 1987).

crosses all stratigraphic and lithological units that are involved. The existing rock velocities, thickness of the slope sediments and determination of a major sliding surface were the points of interest. Profile 2 [Fig. 4(a) and (b)] was oriented in the strike of the Auernig beds in order to find representative velocities, situations of homogenous areas and, again, the depth of the sliding surfaces. Profile 3 (Fig. 5), again in Auernig beds, crosses the major head of the landslide. Profile 4 runs along the rift from Madritschen to Tressdorfer Höhe being probably the only point to observe undisturbed velocities, since this rift is thought to be in situ.

3. Raw geophysical data

A geophysical survey was conducted, with the principle aim being to provide additional information about the geological framework and the mechanism of slope failure. The location of the geophysical surveys is given in Fig. 2. Following the basic concept of 'Complex Interpretation', different geophysical methods had to be applied in the same locality.

3.1. Seismic refraction

Although much progress has been achieved in recent years in refining reflection seismic methods for near-surface applications (< 100 m penetration depths), refraction seismic surveys are still a standard method used for mapping landslides. Consequently, a refraction seismic survey was conducted along four profiles (P1.1, P1.2, P2, P3, P4). For the instrumentation, a 24-channel seismograph was used for registration; geophone spacing was 5 m for Profiles P1.1 + P1.2 and P2 and 10 m for Profiles P3 and P4. The survey was performed by forward and reverse intra-spread shots, including off-end shots outside the profiles. At first, a sledgehammer struck against a metal plate was used as seismic source; however, this method did not impart enough energy into the ground. Thus, the main survey utilized explosives that were tamped into holes in the ground. In this manner virtually all of the energy released by the detonator was compressive. To provide sound input for the interpretation, in-situ rock velocities were measured on selected outcrops (limestone and Auernig Formation). Based on the good experience for delineating undulating refractors from in-line reverse spreads, the raw data were processed using the General Reciprocal Method (GRM) (Palmer, 1980). The unique strength of the GRM method is to provide the refraction velocity continuously along the survey line, regardless of how many changes in material properties occur. The processed and inverted sections of Profiles 1–4 are shown in Figs. 3–6.

3.1.1. Profile 1

Starting near the Trögelbach at an altitude of 1240 m, this profile runs NNW until it reaches the Schlanitzen Alm. The total length of the profile is 1560 m. The profile indicates a seismic three-layer case. The surface layer, showing velocities between 300 and 500 m/s, represents the weathered layer (soil) with a thickness of 1–3 m. The second layer is characterised by velocities between 1000 and 2000 m/s and is up to 15 m thick. The large velocity scatter is due to the inclusion of large blocks and coarse components in the case of dry material and to water saturation of fine-grained material in the vicinity of springs. The bottom layer, which consists of three different rock types, the Auernigschichten, the Grenzland, and the Lower Pseudoschwagerinen Formations, shows velocities between 3500 and 3800 m/s. The entire model is in accord with existing geological maps (cf. Schönlaub et al., 1987). The relatively low velocities seem to be due to disintegration, following deep-seated creep.

3.1.2. Profile 2

The main selection criterion for location of this profile was the resolution of details from the Upper Carboniferous, here represented by the Auernig Formation. In addition, to provide easy access and to obtain daily work progress in the rugged terrain, the profile had been defined parallel to an existing winding woodland path within the trench of Rudnig Creek. The total survey length of this profile was 1620 m. Here, as well, the refraction seismic method revealed a three-layer model of the

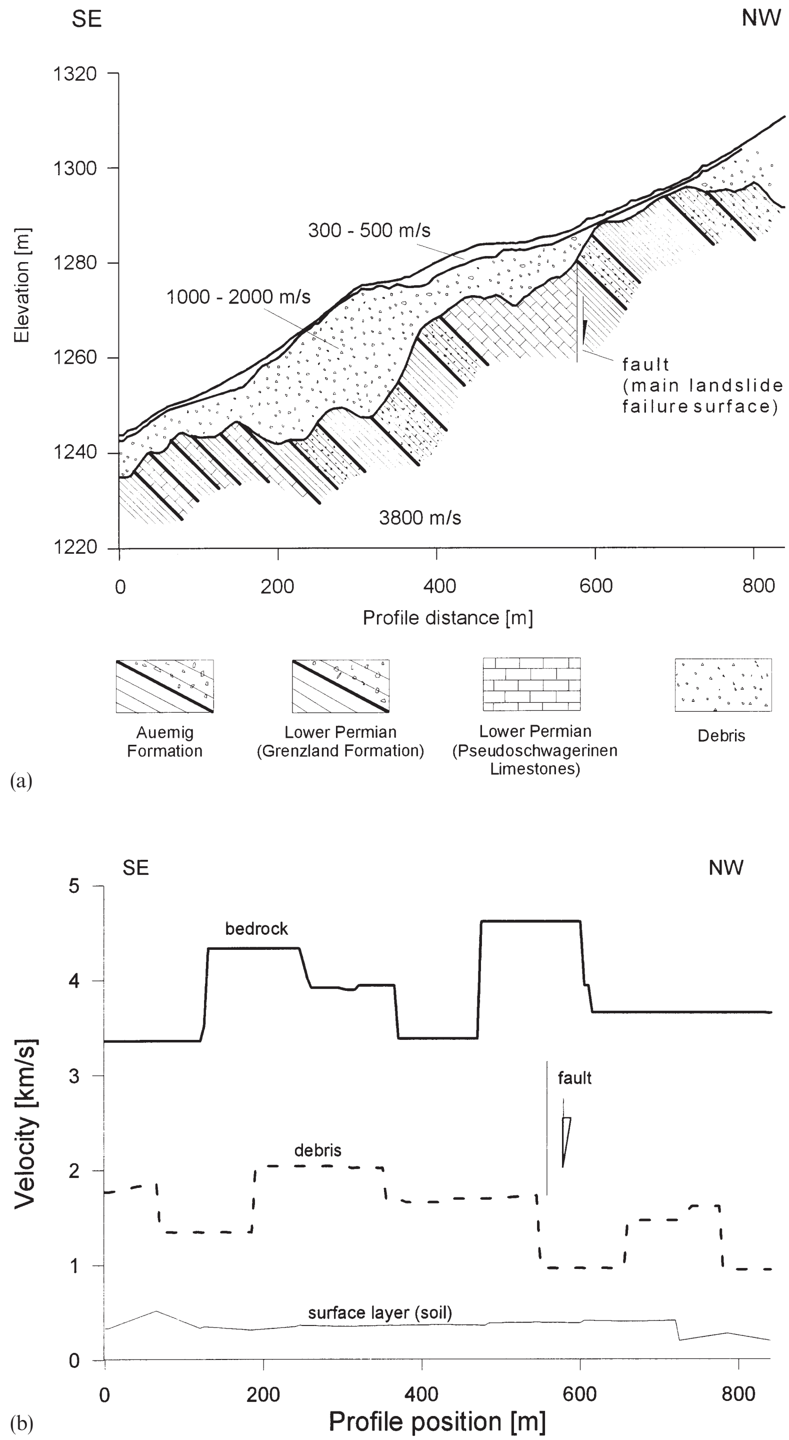
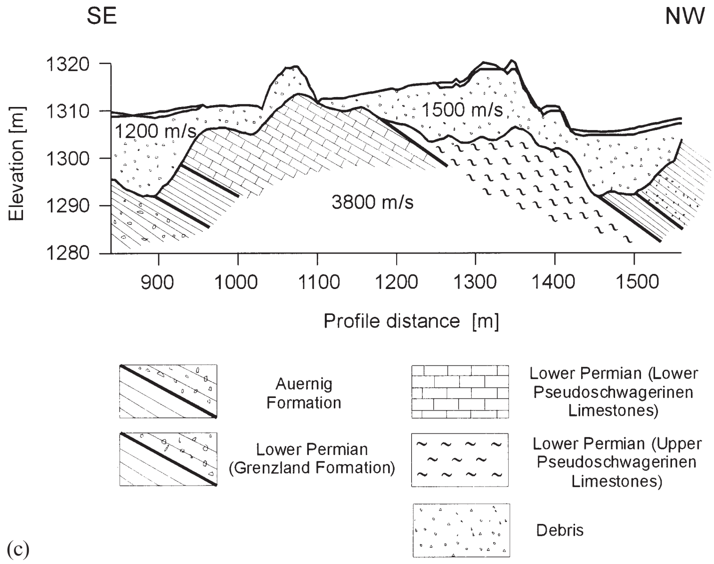


Fig. 3. (a) Cross-section showing results of refraction seismic surveys along profile P1.1. (b) Lateral velocity variation along profile P1.1. (c) Cross-section showing results of seismic refraction surveys along profile P1 (part 2).



(c)

Fig. 3. (*continued*).

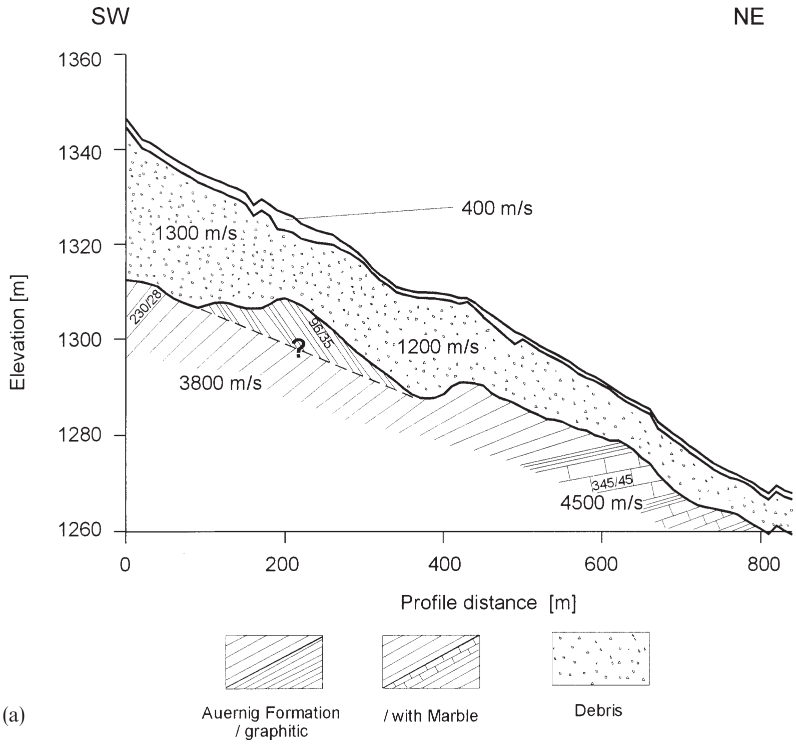
local geology. The velocity of the top layer was constant at about 400 m/s with a thickness of approximately 4 m. The adjacent bed, having a velocity variation between 1000 and 1800 m/s, is interpreted as dry or partly saturated debris. The velocity of the bottom layer ranged from 3300 to 4500 m/s, indicating either an inhomogeneous lithology or different degrees of tectonism. The enormous increase of velocity, from profile meters 400–500 and 700–900, represents the blocky structure (homogenous cores) from the Auernig Formation. Because these cores are definitely larger than the thickness of the second layer, deep-seated creep seems obvious. This model is strongly supported by the existance of lower creep velocities (3 cm/year) for the large blocks compared with (7–8 cm/year) for the talus sediments (Moser, pers. commun.). The model has been confirmed by surface geology.

3.1.3. *Profile 3*

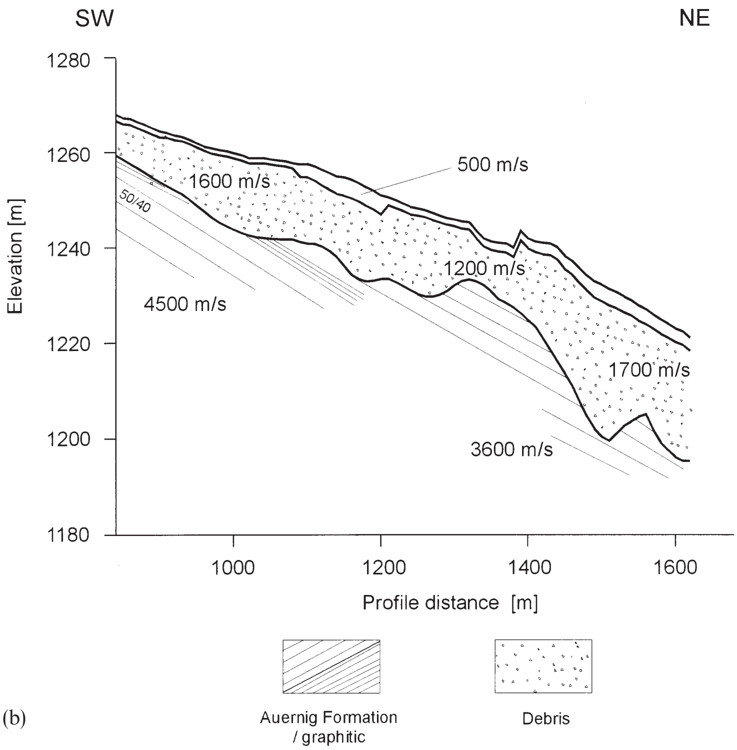
This profile, with a total length of 720 m, runs along the road from the so-called Nassfeldhaus to the Tressdorfer Alm. The velocity of the overburden varies between 400 and 800 m/s. These changes are associated with density grades. An average thickness of 1.5 m is interpreted. The velocity variations of the subsequent layer show similarities: an increase from SSE to NNW (1000–1700 m/s) with a stable zone in the centre of the profile. This distribution of the velocities is controlled by geomorphological features. At the beginning of the profile, a zone of dry, weathered Auernig strata was delineated in the north by an area of high water content. Consequently, the thickness increased from 10 to 25 m. At 460 m, the head of the landslide can be identified: The velocity varied in the bottom layer, ranging from 2800 to 3700 m/s, and coincided with the topography. However, another form of interpretation may address this jump in velocity as a change in the lithology.

3.1.4. *Profile 4*

In order to determine in-situ velocities of the non-weathered Auernig-Formation, a reference profile was established with a length of 960 m. Observations at both ends of the profile revealed open joints, thus indicating significant horizontal displacements that usually accompany early stages of the block sliding process. The seismic model revealed a three-layer case. The overburden was



(a)



(b)

Fig. 4. (a) Cross-section showing results of seismic refraction surveys along profile P2 (part 1). (b) Cross-section showing results of seismic refraction surveys along profile P2 (part 2).

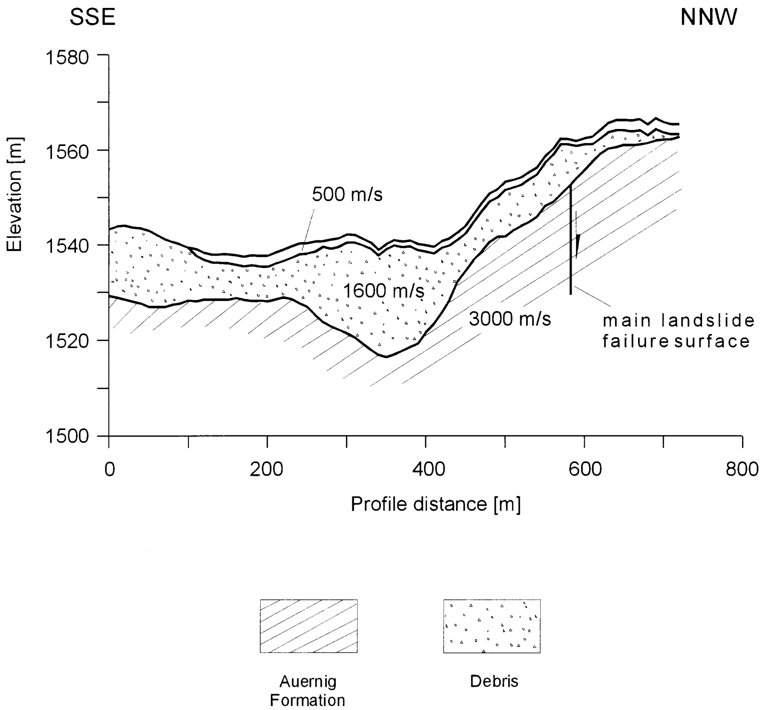


Fig. 5. Cross-section of seismic refraction surveys along profile P3.

identified by a velocity ranging from 300 to 550 m/s, and was underlain by weathered Auernig beds with velocities from 1000 to 2300 m/s, and basement rocks (unweathered Auernig Formation) having a velocity range between 3400 and 4400 m/s. Thus, there is good correlation with the above mentioned in situ measurements on outcropping rocks (mean value: 3550 $\pm$ 356 m/s). Also in this location, changes in the velocities can be identified as indicators of variations in lithology.

3.2. Interpretation of refraction seismic profiles in terms of geology

In all seismic profiles a three-layer case has been noted, the first being the soil with velocities of about 300–800 m/s. The second layer is made up of talus/debris deposits, a decomposed rock mass with velocities between 1200 and 1800 m/s. The third layer, with velocities of about 3300–4300 m/s, is related to the Auernig beds, i.e. clay schists, more or less sandy, with interbedded limestones (marbles).

3.3. Geoelectrical methods

Three geoelectrical methods were tested in the actual area of investigation in order to find the optimal correlation, with the seismic refraction method: d.c. resistivity, dipole–dipole, and electromagnetics.

3.3.1. Electromagnetic surveys

Because of the expected high resistance in the undisturbed surrounding of the landslide and the expected lower resistivity values within the sliding mass, as well as the test results along profile P1.1, electromagnetic surveys were chosen as the leading tool for reconnaissance. Nowadays, inductive electromagnetic survey methods are widely used to map near-surface geology by delinating variations in the electrical conductivity of the ground (McNeill, 1980). These variations are generally caused by changes in porosity, clay content, conductivity of the soil water, and degree of saturation. For instrumentation, a Geonics EM-34, using coil separations of 10, 20, and 40 m, operated in a

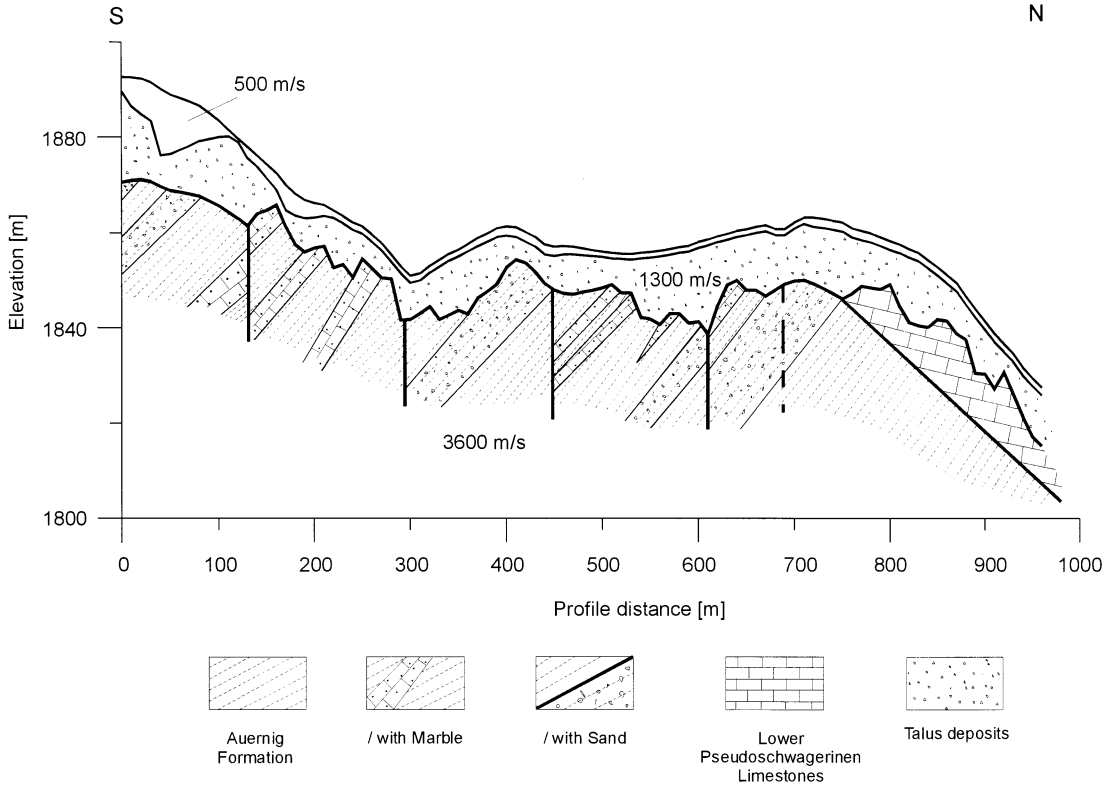


Fig. 6. Cross-section of seismic refraction surveys along profile P4.

horizontally coplanar mode with frequencies of 0.4, 1.6, and 6.4 kHz (dependent on coil separation), were chosen. Under favourable conditions, a penetration depth of up to 100 m can be reached with the Geonics EM-34. In order to verify this observation for the specific geology of the Nassfeld area, theoretical modelling experiments had been conducted to estimate the response of the instrument. Within a simulated two-layer case, the lower layer was kept at a constant resistivity of 2000 Ωm, and the upper layer was altered stepwise between 100 and 500 Ωm. It was found that, under the expected geological conditions, a resolution of as much as 100 m was successfully simulated for the operating frequencies of the instrument used. All profile and grid points in the survey area had been surveyed using the 10, 20, and 40 m coil separations. The station interval chosen was 20 m. The interpretation carried out used a neuronal network approach employing algorithms for a two-layer case. Results show low resistivities ($\approx$redundant 100 Ωm) above a high resistive layer (as much as 2000 Ωm). To map the resistivity distribution of the first (sliding) layer and in order to estimate the thickness of the landslide, a new approach was chosen: by using a two-layer model algorithm for the EM-34 data, the relation between the resistivities in both layers and the thicknes of the debris can be estimated. After the initial results had been obtained, a large variety of basic models were compiled and, in a second step, prioritized by artificial neural networks (NN).

However, the amount of raw data in this case study can be considered to be small; the separation from 'valid' models and 'faulty' models was performed in a relatively short time, thus allowing an estimation of depth of slip-/shear surfaces. Along the selected profile, P1.1 measurement of induced polarisation and dipole–dipole resistivity were used as constraints for the model generated by this neural network application. The result of the NN application is presented in Fig. 7, showing a possible two-dimensional distribution of the bedrock, i.e. possibly a slip surface. It should be noted that zones of higher resistivity can be distinguished in the southeastern part of the survey area — this is interpreted as indicating a thin coverage of the basement.

Profile P1 covers this area and shows a thickness of about 25–40 m, respectively (cf. Fig. 8). The variation in resistivity values in the sliding mass also indicates the appearance of giant block structures that form part of the landslide (higher resistivities). In the western part of the survey area, zones of decreasing resistivity values are interpreted as an increasing thickness.

3.3.2. Direct-current resistivity methods (Schlumberger array and dipole–dipole survey)

Electrical resistivity surveys are used routinely in groundwater and engineering applications (Ward, 1990). These methods are capable of mapping overburden, stratigraphy, faults, and the water regime of hill slopes. The subsequent interpretation is in terms of subsurface electrical properties and, in turn, to the subsurface geology. In this case study, the d.c. resistivity survey utilized the Schlumberger- ($AB/2 = 100$ m) and dipole–dipole configurations.

3.3.3. Summary of geoelectrical methods

In order to compare the accuracy of the depth of the bedrock of the individual methods, all three were carried out on profile P1.1 (Fig. 3). Electromagnetics (EM-34) is providing the best fit compared to seismic refraction. The problem with the d.c. methods obviously arises with the unfavourable geometric circumstances of the field survey. The total thickness of soil and debris requires a certain spacing, which, however, does not take into account the different thicknesses of the layers within the bedrock. The d.c. measurements in the Schlumberger configuration were carried out between profile distances of 135 and 635 m as well as 135 and 780 m for dipole–dipole, respectively. Whereas the soil and debris in their wet state show resistivities below 500 Ωm, the bedrock is always well above their value.

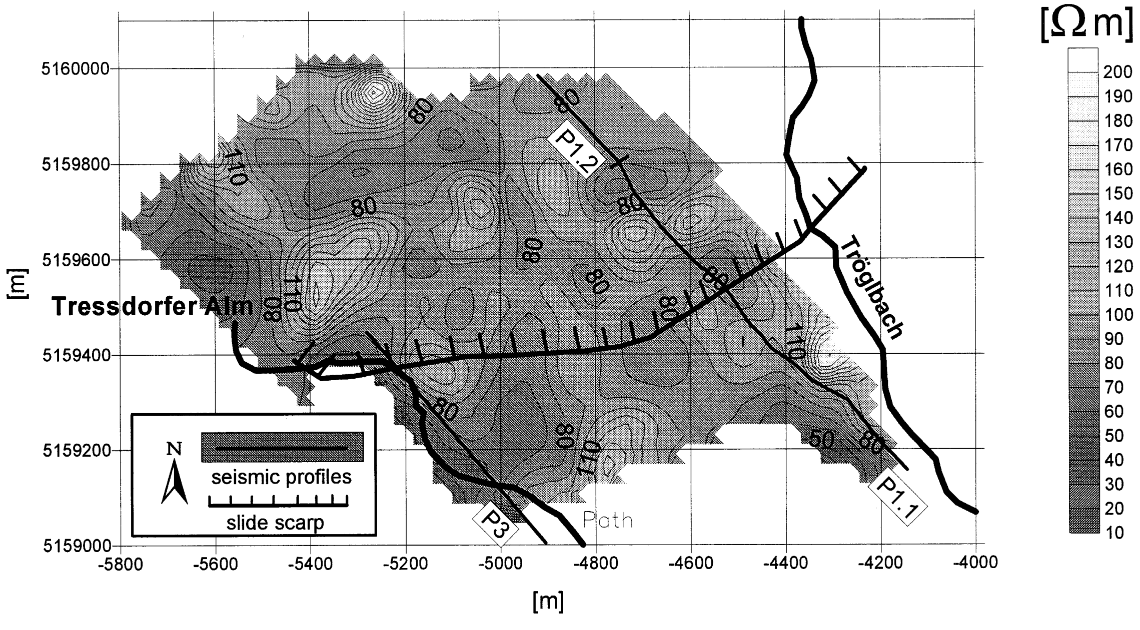


Fig. 7. Two-dimensional distribution of conductivity surveyed with EM-34.

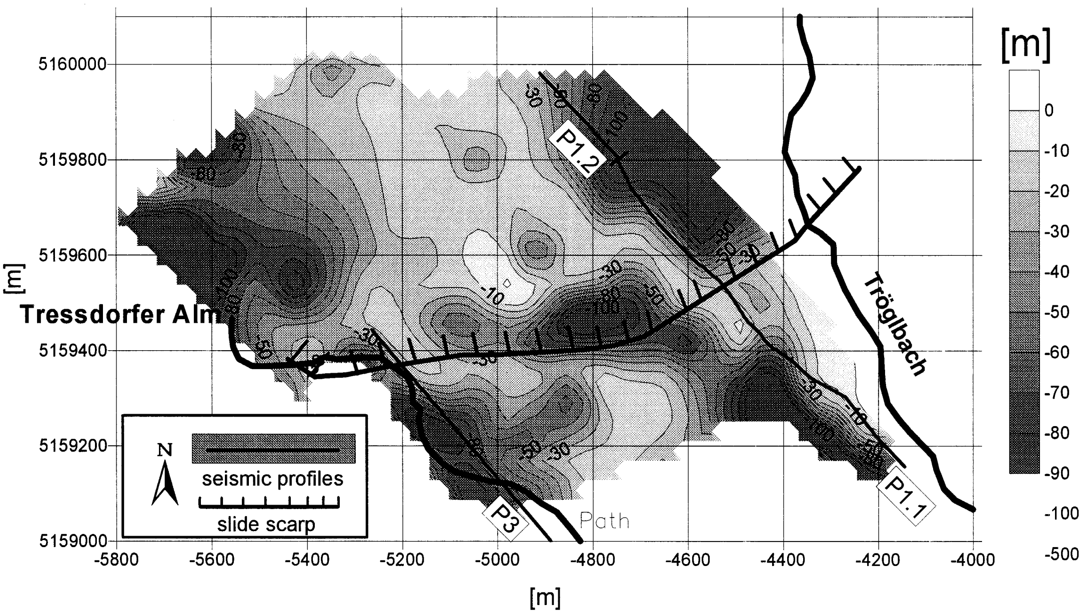


Fig. 8. Two-dimensional model of the basement (landslide removed) according to neural network results. Contours represent depth of basement.

4. Discussion

When discussing complex interpretation of geophysical data in a landslide area, one needs a basic understanding of all kinds of geological, geotechnical, and geophysical data. In the area of the Schlanitzenalm slide, geotechnical data were available from detailed mapping (Moser and Glawe, 1994), which was focused on the slope tectonics, as well as a drilling profile from the Rudnig trench. From the area northwest of the Tressdorfer Höhe, a detailed study of recent block movements (Moser and Glawe, 1994) showed a high degree of mobility for the disintegrating basement rocks. For all areas of the landslides, a detailed geological map (Schönlaub et al., 1987) provided basic geologic information. This map reveals the main problem of the area: slope sediments of different thickness largely cover the area marked for geophysical investigation. Therefore, it is extremely difficult to decide whether masses of limestones are in-situ outcrops or moving blocks.

The locations of seismic profiles P1 and P3 within the area investigated by electromagnetics were initially by chosen to investigate the thickness of the slope sediments at the head of the Schlanitzenalm landslide, as well as to the detect the huge limestone blocks within the slope material.

Starting with the complex interpretation in the southeastern area of the Auernig beds (P1.1), a total overburden of about 6–9 m was detected. This thickness is in good agreement with the model derived from the NN-modelled electromagnetic data. Farther northwest along profile P1.1, it can be seen that thickness of the overburden reached up to 30 m [Fig. 3(a)]. Again, here, a good agreement with the results from electromagnetic data has been obtained. In addition to these two methods, the d.c. geoelectrical measurements were carried out, and similar results were obtained. However, when approaching the head of the landslide, the depth determined by seismic refraction and the electromagnetic differ by 100% (Fig. 9). These diverging results can be understood better by comparing the seismic velocities and electrical resistivity: while a reduced seismic velocity can be correlated with the upper part of the landslide failure zone, the low resistivity indicates the high porosity and saturation of the rocks involved.

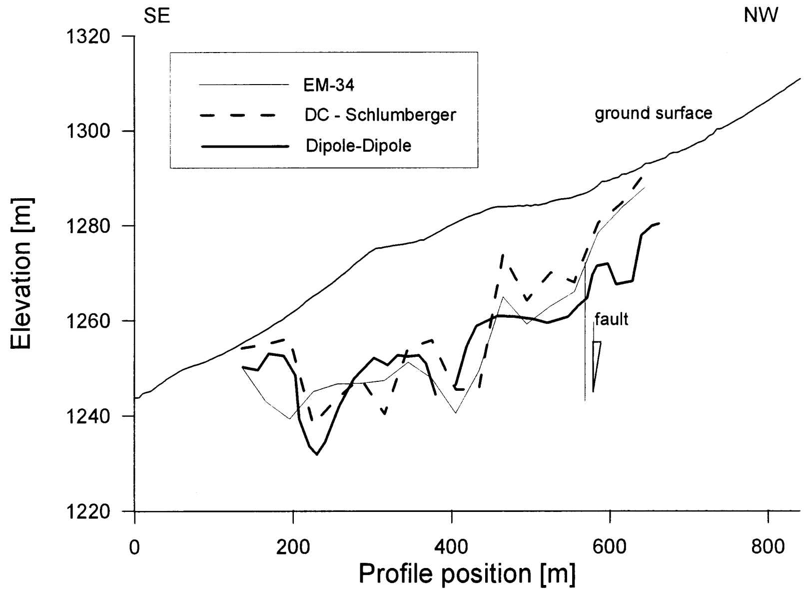


Fig. 9. Comparison of the results of the different geoelectrical results (EM-34 data after neural network interpretation, d.c. Sounding, and dipole–dipole results) along seismic profile P1.1.

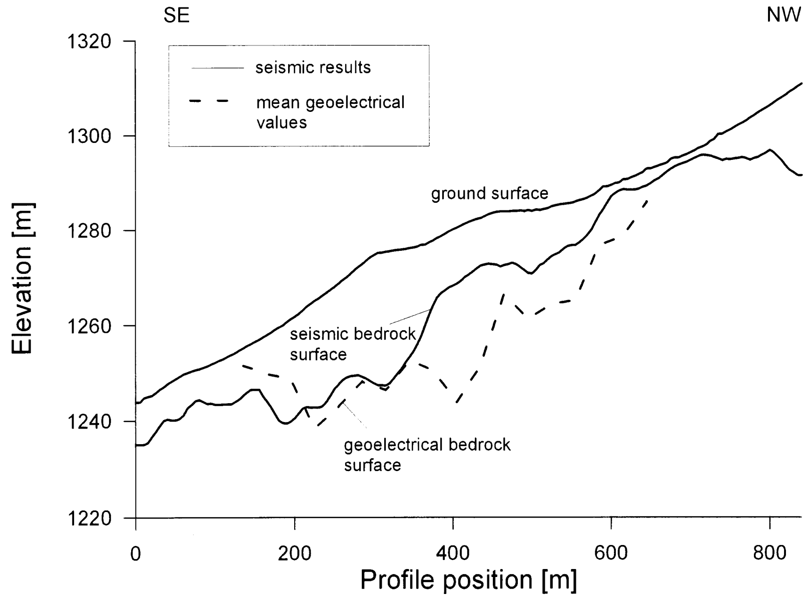


Fig. 10. Comparison of the results of the mean values of EM-34 data after neural network interpretation, d.c. sounding, dipole–dipole results with lowest seismic horizon, along Profile P1.

Crossing the head of the landslide, which showed an increase in seismic velocity at about profile position 500 [cf. Fig. 3(a)], a lithological change is also indicated on the geological map (Fig. 2). The sandstones are more resistive than the schists, which indicates a strong decrease in the weathered zone. The huge limestone block, covered by electromagnetic and seismic refraction at a profile distance of about 1000–1150 m, is indicated by a relatively low resistivity of about 80 Ωm [Fig. 3(c)]. This low resistivity can be understood by a network of fractures filled with shaly and/or water-saturated materials. The calculated depth of these blocks, approximately 30–50 m, compared with the basement relief found by seismic refraction, documents the close contact of these huge blocks with the basement. The southwestern part of the electromagnetic investigation (seismic profile P3) covers a remarkably low resistivity zone. This is also in good agreement with the maximum thickness of the saturated overburden of about 25 m derived from the seismic section. The relief development is interpreted as being of tectonic origin close to the head of the landslide. Comparing this zone with the information given by the geological map, a strongly disturbed zone with a width of about 200 m can be identified as the head of the landslide (Schönlaub et al., 1987). West of the Tressdorfer Alm, the electromagnetic results indicate an increasing thickness of the sliding mass characterised by high resistivities.

Profile 2 follows a forest road along the strike of the Auernig beds. The detected velocities are in good agreement with the saturation of the slope materials. Between profile positions 600 and 800, the second layer has a rock velocity of 1600 m/s (due to the vicinity of a spring!), whereas a velocity of 1700 m/s starting from profile position 1400 m and the end of the profile is explained by a flat and swampy area at about the 1200 m contour. The variation of basement velocities, between 3300 and 4500 m/s, documents lithologic changes. The centre part of the profile, between position 400 and 1000 m, reveals the lowest depth and an overburden approximately 10 m thick. This is interpreted according to M. Moser (pers. commun., 1996): outcropping areas are not domed areas of the basement. They are so-called homogeneous blocks within the slope materials. Sliding surfaces postulated by M. Moser at a depth of about 70–80 m, based on geotechnical and morphological observations, were not identified by the selected geophysical means, e.g. in the seismograms of the distant shots. The reason for this is obviously the lack of density contrast between the homogeneous blocks and the basement.

Profile 4 (Fig. 6) was planned on geological recommendation to measure the in-situ velocity of the authochtonous Auernig beds. Below the soil, a whethered basement with a variable thickness was established (Fig. 6). Shots spaced at a long distance (beginning and end of the profile) over a total distance of 720 m did not reveal any increasing velocity with depth. The average velocity of 3600 m/s is in very good agreement with the velocities found in the other seismic sections of the basement rocks, (Fig. 10).

5. Conclusions

Referring to Section 1, the authors were able to prove that the determination of downslope movement, estimated thickness, relief of the bedrock surface, the presence of water saturated areas, and the internal composition of sliding masses were possible by applying refraction seismic and electromagnetic surveys. Because the contrast in the petrophysical parameters (velocity, density, and resistivity) appears to be very small across the sliding-/shear surfaces, the aim of identifying a distinct slip surface was not reached. Outcropping areas were identified as ‘homogenous blocks’ even when the impression on Profile 1 was contradictory. The general conclusion is that the complexity of a landslide requires a complex investigative approach by using a combination of different geophysical methods. In this respect, the main question for the sliding mechanism cannot be answered straightforwardly.

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Appendix A: Application of neural networks in the investigation of landslides

Following the formulas of McNeill (1983), University of Saskatchewan, the connection between the measured values of the apparent specific conductivity (c_a10, c_a20 and c_a40) gained by the field measurement and the parameters of a two layer-model (z, $c1$, $c2$) is given by:

$$c\_a = c1.(1 - R(z, s)) + c2.R(z, s),$$

with $R(z, s)$ as response function.

$$R(z, s) = \mathrm{sqrt}(2.z/s + 1) - 2.z/s.$$

Based on those two formulas, it is possible to establish a database and train a neural network for a two-layer case.

1. Database — For a well-chosen range of values, this base provides the connection between the three values of the apparent resistivity and the three values of the two-layer model.
2. Neural network — By using the data of the base as input and output, a net can be trained.
3. Application of the neural network — Measured field values put into the net. This provides an estimation of the landslide thickness (Fig. 10).

The advantages and disadvantages of interpretation by means of NN are as follows:

- Advantages — The employment of a neural network is a quick and simple method. The computing time required to create a neural network ranges from a few minutes to 1–2 h (depending on the quantity of data and the complexity of the problem). A new approach is needed to deal with the increasing number of data (e.g. aerogeophysics). Conventional modelling programs often take too much time and may fail.
- Disadvantages — The accuracy of data output depends on the configuration of the neural networks; during training, it is necessary to acquire considerable experience to be able to handle a neural network correctly. Depending on the training data, it is possible that a neural network will fail.

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