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SHALLOW SEISMIC REFLECTION STUDY OF THE GSCHLIEFGRABEN LANDSLIDE DEPOSITION AREA - INTERPRETATION AND THREE DIMENSIONAL MODELING

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ABSTRACT

In this study, we present a typical workflow for generating a three-dimensional structural model of a mass movement derived from geophysical data. The inputs to the modeling process are seismic reflection profiles, well information and digital elevation models. The mass movement of the Gschliefgraben, Upper Austria, is used as a case study. In this case, the mass movement is an earthflow system with occasional mudflows and can be interbedded with debris flows and torrential sediments. The mass movement shows various phases of activities since the high glacial stage of the Würm. In November 2007, a huge landslide occurred. In several project phases in the Gschliefgraben, four seismic reflection profiles were recorded. The results of the interpretation of these profiles are geological surfaces and a fault pattern. These geological surfaces and faults are the input parameters for building a high resolution geomodel. The method used for modeling is based on the standard for the oil and gas industry and for modern geothermal studies. As a final result, we present a structural model that can be used for volume calculation of the mass movement as well as a detailed geological image of the subsurface.

In dieser Studie präsentieren wir einen typischen Arbeitsablauf für die Erstellung eines dreidimensionalen Strukturmodells einer Massenbewegung aus geophysikalischen Daten. Die Grundlage für die Modellierung stellen Reflexionsseismikprofile, Bohrungen mit geophysikalischen Bohrlochmessungen und digitale Höhenmodelle dar. Als Beispiel für eine Massenbewegung wird die Rutschung Gschliefgraben, Oberösterreich, gezeigt. Die Rutschung stellt ein System von Erd- und Schuttströmen dar, die bei fallweiser totaler Verflüssigung auch zu Schlammströmen, wechsellagernd mit Wildbachsedimenten,werden können. Diese Massenbewegung ist seit dem Würm Hochglazial aktiv. Im November 2007 ereignete sich eine große Rutschungsphase. Im Zuge mehrerer Messkampagnen wurden vier Reflexionsseismikprofile aufgenommen. Das Ergebnis der Interpretation von diesen Profilen sind Störungen und Horizonte, die als Eingangsdaten für die Modellerstellung verwendet werden. Die verwendete Methodik der Modellierung ist in der Kohlenwasserstoffindustrie und im Bereich der Geothermie etabliert und wird für diese Studie auf Massenbewegungen angewandt. Das Endresultat dieser Arbeit ist ein dreidimensionales Strukturmodell, das für Volumenberechnungen sowie für die Erzeugung beliebiger Schnitte und Strukturkarten verwendet wurde.

1. INTRODUCTION

Mass movements are huge threats to both humans and infrastructure in alpine areas. The description of mass movements can address either the quality (lithology) or the quantity (volume) of the mass movement. The quality of mass movements can easily be determined from the surface together with cores and cutting information from wells, but it is much more difficult to describe the quantity of mass movements. The volume description of mass movements is mostly performed with the help of point information from wells. However, the number of wells is often limited due to financial reasons and poor accessibility. The resolution of models solely built from well information is restricted by the distance between wells. Therefore, depending on the well to well distance, faults can be missed during interpretation. In addition, the spatial position of geological surfaces between wells can be inaccurate and thus volume calculations are mostly vague.

For a more detailed geological description of the subsurface, various geophysical methods can be used. McCann and Forster (1990) reviewed standard surface geophysical techniques for their application at the reconnaissance stage of a landslide. Based on this paper, Jongmans and Garambois (2007) showed various examples for the application of geophyiscal methods for landslide characterization. To describe the body structure of landslides, the volume of mass movement, the location of the sliding plane and the interior of mass move-ments, often multiple geophysical methods are used (Mauritsch et al., 2000; Arndt et al., 2000; Bichler et al., 2004; Bell et al., 2006; Schrott and Sass, 2008; Millahn et al., 2008; Niesner and Weidinger, 2008). The most accurate method for building a three-dimensional geological model with internal structures is the application of seismic reflection. Brückl et al. (2001) used seismic refraction and seismic reflection profiles to describe the volume of the rockslide mass and the initial and average sliding angle of the Köfels rockslide (Tirol, Austria). With the help of seismic reflection, basal planes of the Lesachriegel and Gradenbach deep-seated mass movements could be mapped (Brückl and Brückl, 2006). Several land- and offshore-seismic profiles helped to describe the main landslide body of the Great Ancona landslide and indicated the emergence location of a deep, potential detachment surface, which previous investigations with other methods failed to evidence (Stucchi et al., 2005; Stucchi and Mazotti, 2009). The acquisition of a 3D geophysical data set, which is standard in the hydrocarbon industry, would be the best solution for a high resolution model. Because of the high costs, a 3D-seismic survey for a mass movement study is not yet affordable. Submarine landslides have been revealed by 3D seismic data (Gee et al., 2006). For landslides, no examples for the usage of 3D seismic could be found, but the application of high resolution shallow 3D seismic for a study of glacial sediments deposited within a Swiss mountain valley (Büker et al., 1998; Büker et al., 2000) showed the possibilities for identifying thin and shallow structures with seismic data. In the course of several research projects, funded by the Austrian Academy of Sciences, the United Nations International Strategy for Disaster Reduction, the Wildbach- und Lawinenverbauung and Joanneum Research, four reflection seismic profiles and multiple refraction seismic profiles were acquired. With the help of these profiles, a three-dimensional model of the subsurface was built and the possibility of characterizing recent and historic mass movements was studied.

2. GEOLOGY

The Gschliefgraben (Fig. 1) is situated on the eastern shore of Lake Traunsee in Upper Austria, on the border of the Northern Calcareous Alps to the Flysch Zone (Egger, 1996) and is related to the highly deformed tectonic window of the Ultrahelvetic (Prey, 1951 and 1983). A simplified geological north-south profile of the Gschliefgraben and its surroundings (Fig. 2) can be found in Daurer and Schäfer (1983). With its ideal north-facing exposition and topography the glacier of the Farngrube could fill the Gschliefgraben and the Lidringgraben and interact with the glacier of the lake Traunsee. The mass movement of the Gschliefgraben evolved after the high glacial stage of the Würm, as the glacier of the lake Traunsee melted (Van Husen, 1977). The recent cone of debris between Ram-

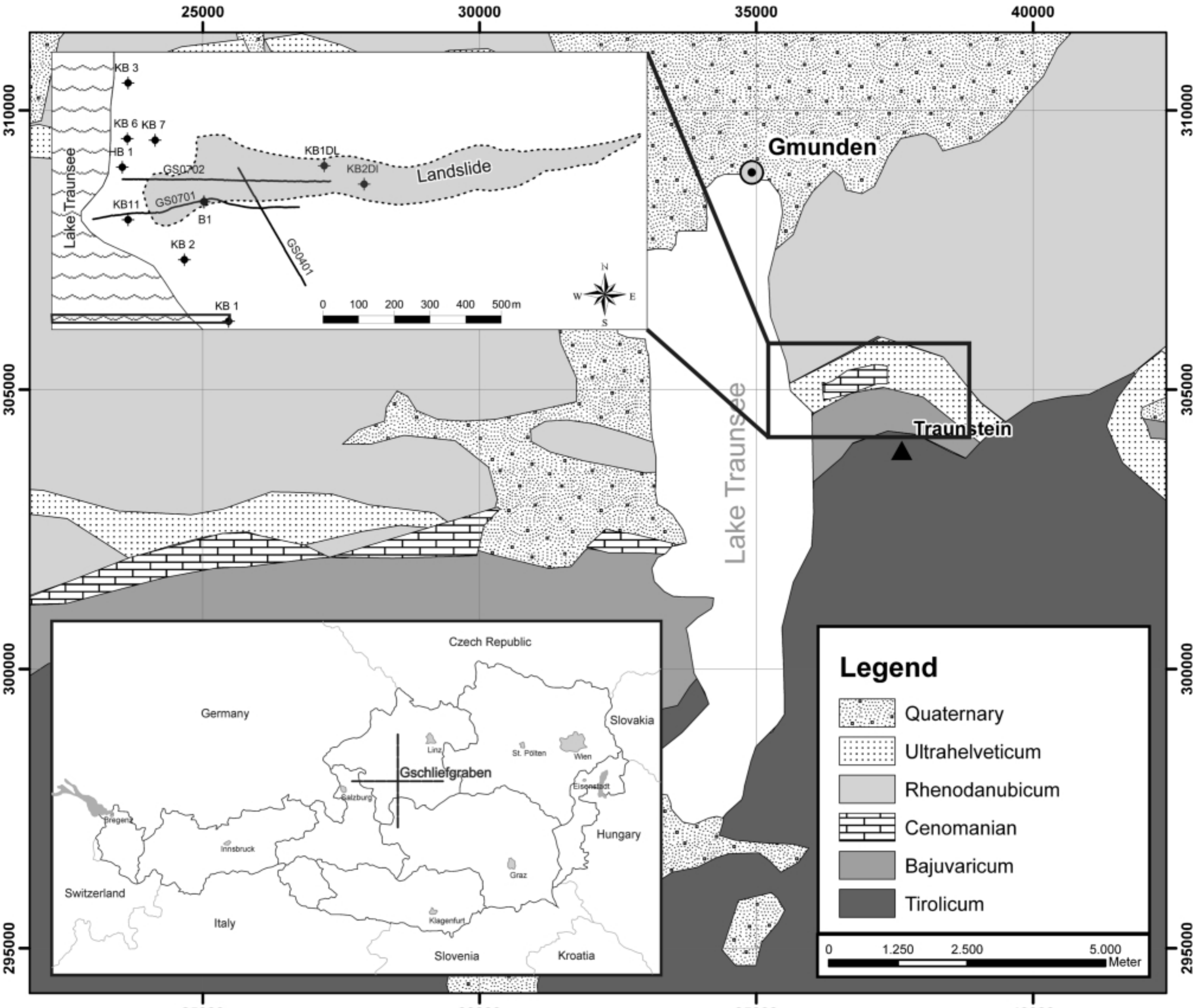

FIGURE 1: Geological map of Upper Austria (after Egger, 1996: Egger and van Husen, 2007). Location of seismic profiles and well positions are indicated in the upper left corner.

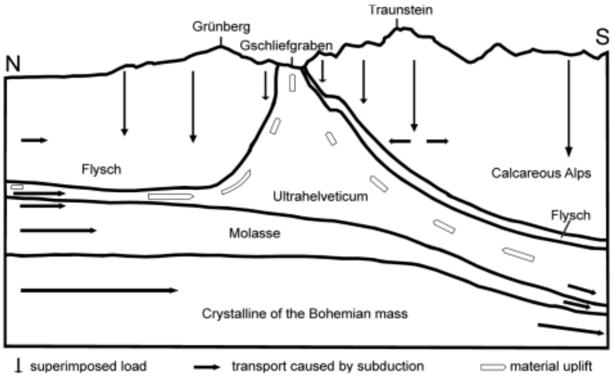

FIGURE 2: Geological north-south cross-section for the Gschliefgraben and its surroundings, modified after Daurer and Schäffer (1983).

sau and Hoisn restaurant is composed of different aged, flat, west dipping, concordant earth flow systems and intercalated torrential sediments with a minimum depth of 170 m (Moser, 2008). In the 15th century, mass movements in the Gschliefgraben destroyed agricultural areas, living and agricultural buildings and in 1660 or 1664, the great Harschgut was moved into Lake Traunsee (Strele, 1932). The problem of the Gschliefgraben mass movement was already described by the K.K. Ackerbau-Ministerium (1895). Weidinger (2009) gives a compilation of historical landslides in the Gschliefgraben and gives a description on the stabilization procedures after the last event. Because of the continuous accumulation of unconsolidated sediments, subaqueous earthslides in the area of the Gschliefgraben can be observed (Egger, 2007). Pre-vious results from geophysical studies in the area of the Gschliefgraben are described in detail by Weidinger et al. (2007), Niesner and Weidinger (2008), Millahn et al. (2008) within a project of the program "Geophysik der Erdkruste" and Amtmann et al. (2009).

3. METHODOLOGY

The seismic reflection method was used to create an image of the subsurface of the landslide Gschliefgraben. Geophones were fixed at the surface of the landslide at a regular distance (2.5 m and 3 m meters) along a predefined line. At the spaces in between the geophones, seismic waves were stimulated using small amounts of dynamite. The invading waves are reflected at surfaces where the acoustic impedance is changing. The acoustic impedance is the product of the density and the velocity of propagation of acoustic waves. For the seismic refraction method, the acoustic impedance has to increase with depth. However, this restriction does not apply for seismic reflection, and hence the internal structure of geological layers can be imaged with seismic reflection. The single shots are stacked together in respect to their spatial distribution in the seismic processing (Yilmaz, 2001). The interpretation of the seismic profiles was done with the concept of sequence stratigraphy, based on the methodology and terminology of Posamentier and Allen (1999), Cantuneanu (2006) and Coe (2003).

Two typical well logs were used in this study. The Gamma Ray log and the Resistivity log are so called typical lithology-

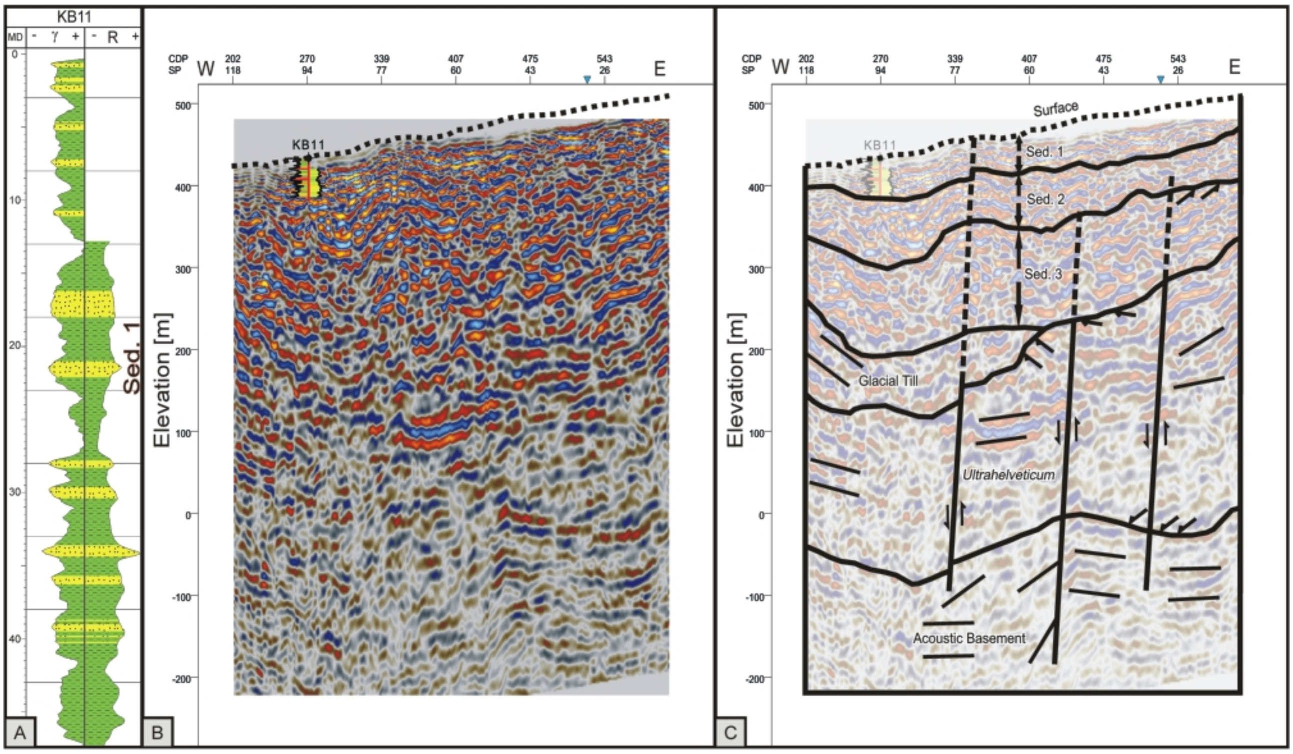

FIGURE 3: W-E seismic section GS0701. Picture B shows the migrated depth converted seismic section with well KB11 showing Gamma Ray (left) and Resistivity (right) measurements. The well section (A) shows the enlarged Gamma Ray and Resistivity logs with a lithological interpretation. The green color indicates zones with higher shale content (earth- and mudflows), whereas the yellow color indicates sandy zones (torrential sediments). On the right is the interpretation of the seismic section (C). The small arrows indicate downlaps and toplaps. The small black lines show the dipping of seismic reflectors. A dashed line indicates that the existence of faults cannot be proven for the unconsolidated sediments.

indicative wire-line logs for siliciclastic sediments. The Gamma Ray tool measures the natural radioactivity of the sediments. The resistivity log measures the resistance of the subsurface with different spacing. Clay-rich earth- and mudflows emit higher amounts of radiation and show lower resitivities than debris flow- and torrential sediments. Therefore, these tools are good for distinguishing between shales and sands.

The purpose of the modeling process is to obtain a simplified representation of the geology and to enable volume estimation. The method used for structural modeling is based on three processes. The first step is to create a Fault Model. In the Fault Modeling Process, the faults are defined, and form the basis for generating the model. The faults are built using key pillars. A key pillar is a vertical, linear, listric or curved line. The fault plane is defined by several key pillars joined together. The faults define breaks in the grid where horizons are offset in depth.

The second step is to perform the Pillar Gridding Process. In this process, a three-dimensional grid is created. The faults from the fault model process are used as the basis for the grid generation. The grid consists of pillars that are placed in a specified interval parallel to the pillars from the fault model.

The third step is the Make Horizon Process. In this process, the vertical layers from the seismic interpretation are inserted into the 3D grid. Surfaces terminate at faults and are offset in depth at these positions. The relationship between all these processes is iterative, usually with several loops.

4. DATA

In the course of a project lasting several years, four reflection seismic profiles, 23 refraction seismic profiles, multiple wells and several digital elevation models (DEMs) were recorded. The recording of the data was performed before (2004-2007) and after (2008) the huge landslide and therefore, gives very detailed descriptions of the impact of the landslide on the subsurface. Before this study, each profile was interpreted separately. The presented work shows a combination of all profiles, well information and DEM information. The reflection profiles were recorded using 10 Hz geophones with 2.5 m (GS0401, GS0402) and 3 m (GS0701, GS0702) spacing. Profiles GS0701 and GS0402 overlap in most parts and therefore GS0402 is not shown in Fig. 1. GS0402 has a longer extension to the east. All seismic profiles were finally processed with standard processing using FOCUS 5.3 (Paradigm Geophyiscal Corp) by Joanneum Research in 2007 (Joanneum Research, 2007; Joanneum Research, 2008a - 2008d). In a first project phase, the profiles GS0401 and GS0402 were processed in 2004. In 2007, the new profiles (GS0701 and GS0702) were processed and the cross-profile GS0401 was reprocessed with the same processing parameters as the new profiles. This was necessary to get a good tie between the new and old profiles. For the interpretation and the modeling only the profiles GS0401, GS0701 and GS0702 were used.

In addition to the seismic profiles, wells and well log information were available. In the wells with steel casing (HB1, KB1,

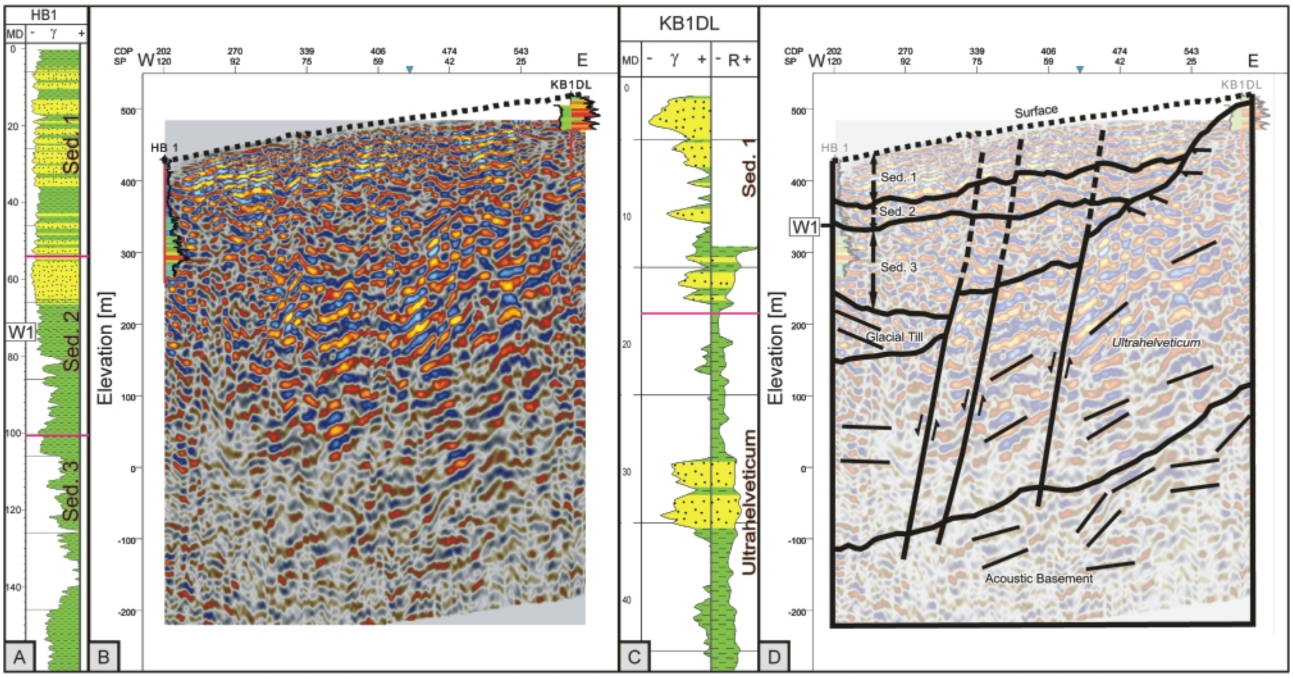

FIGURE 4: W-E seismic section GS0702. Picture B shows the migrated depth converted seismic section with well HB1 and KB1DL showing Gamma Ray (right) and Resistivity (left) measurements. The well section HB1 (A) shows the enlarged Gamma Ray log with a lithological interpretation. The green color indicates zones with higher shale content (earth- and mudflows), whereas the yellow color indicates sandy zones (torrential sediments). The marker W1 shows the position of the wood sample from well HB1. The well section KB1DL (C) shows the enlarged Gamma Ray and Resistivity logs with a lithological interpretation. For the upper part the green color indicates zones with higher shale content (earth- and mudflows), whereas the yellow color indicates sandy zones (torrential sediments). The lower part was drilled into the Ultrahelvetic unit with coarse grained marls (yellow) and fine grained marls (green). On the right is the interpretation of the seismic section (D). The small arrows indicate downlaps and toplaps. The small black lines show the dipping of seismic reflectors. A dashed line indicates that the existence of faults cannot be proven for the unconsolidated sediments.

KB2, KB3, KB6 and KB7), Gamma Ray and Density logs were measured. The newer wells (KB1DL, KB2DL and KBBL11) have PVC casing, so it was possible to measure resistivities, temperatures and flow rates in addition to Gamma Ray and Density. For wells KB1 and KB2, cores were available. On this core data, the natural radioactivity was measured. For the petrophysical interpretation, it was necessary to apply a casing correction, which considered the absorption of the Gamma Ray due to the casing thickness. The logs of the Gschliefgraben wells show alternate bedding of silty or shaly sediments with random occurrence of sand layers.

In some of the newly drilled wells (HB1, KB1, KB2), wooden particles were found, which were dated using the ^{14}C method. This is the second attempt to date the sediments and therefore the different phases of mass movement in the Gschliefgraben. Baumgartner and Sordian (1982) describe the absolute dating of wooden particles in well B1 and B2 and give a brief description of the characteristic and the age of the four identified earthflow systems. For well B1, five wooden particles and for well B2, only one wooden particle were dated using the ^{14}C method. Comparison of the old and new dating results show a good fit between the two data sets. The results of the ^{14}C dating are listed in Tab. 1.

Well	Measured Depth	Sealevel	^{14}C Age (BP)
HB 1	76.3 m	349.7 m	11275 ± 375
KB 1	24.8 m	405.2 m	13030 ± 130
KB 2	43.2 m	388.8 m	13175 ± 75
B1	4.6 m	461.4 m	≤ 220
	29.0 m	437.0 m	2250 ± 80
	39.0 m	427.0 m	9550 ± 160
	43.5 m	422.5 m	9690 ± 150
	53.0 m	413.0 m	10080 ± 180
B2	0.6 - 1.7 m	572.4 - 571.3 m	≤ 220

Table 1: ^{14}C age dating from wood particles (BP - before present). Wells B1 and B2 after Baumgartner and Sordian (1982). All wells except well KB1 were drilled into the earth- and mudflow system. Well KB1 was drilled into the torrential sediments of the Kaltenbach creek.

Before and after the last huge landslide, several high resolution digital elevation models (DEMs) were recorded. The input for the DEMs were laserscan data of the area of Gschliefgraben with a horizontal resolution of 1 m. The vertical resolution is about 10 cm. The DEMs were used to determine the borders of the actual landslide, its change in mass distribution and the volume of flow on the surface.

5. Seismic Interpretation

The number of wells and their depths in the project area was very small, and so it was not possible to clearly correlate well tops with seismic reflectors. Therefore, it was necessary to do the interpretation of the seismic lines solely on the identification of prominent changes in seismic facies like amplitude, frequency and continuity of reflections, or with the identification of abrupt terminations of reflectors with the help of the sequence stratigraphy method. The seismic profiles GS0701 (Fig. 3) and GS0702 (Fig. 4) were interpreted in detail, while the profile GS0401 was used as a connection profile only.

5.1. Basement

The acoustic basement represents the surface under which no strata can be clearly imaged with seismic data. Often the acoustic basement is the deepest relatively continuous reflector. The acoustic basement can coincide with the geologic basement. For a clear identification of whether or not the acoustic basement coincides with the geologic basement, at least one deep well down to the basement is needed.

The acoustic basement in the seismic reflection profiles GS0701 (Fig. 3) and GS0702 (Fig. 4) is characterized by changes in dip of the reflectors, by downlaps of the overlying strata and by low amplitudes. Below the acoustic basement reflections, rapid changes in dip can be observed. The range of dip is between zero degrees and approximately 60 degrees. Above the acoustic basement, the reflectors show a continually westward dipping at approximately 30 degrees. Due to the absence of deep wells, the lithology of the basement cannot be determined.

5.2. Ultrahelvetic Rocks

Overlying the acoustic basement is a zone with relatively continuous reflectors dipping to the west. Most of the reflectors are parallel or subparallel, with some high amplitudes and low frequency. The bottom of the zone is delimited by downlap facies. Based on the presence of toplaps, the top of this horizon is interpreted as an erosional surface. The lowest part and the most western part tend to lack reflectors. This zone is interpreted as Ultrahelvetic rocks, which is confirmed by well top data in well KB1-DL.

5.3. Glacial Till

Overlying the Ultrahelvetic unit, a change of dip can be observed. In the western part of the two profiles, an angular unconformity occurs. Reflectors in this area show eastward dipping. The seismic character of this formation is completely different to the lower Ultrahelvetic unit and the upper sediments. The reflectors have rather low frequencies with sometimes low amplitudes. Due to the lack of wells reaching this depth, it is not possible to definitely explain the origin of this change in dip. One possibility would be to describe this formation as earthflow toe deposits. Another possibility would be to describe this formation as glacial till. Gruber and Weber (2003) performed a seismic facies analysis on 6 seismic reflection profiles in the Upper Inn Valley and describe glacial tills with short, low frequent and uneven reflectors, and mass movements with short, strongly dipping reflectors with downlap character. For the case of the Gschliefgraben, the characteristics of the formations are similar with low frequent and rather short reflectors with uneven surface for this zone.

5.4. Unconsolidated Sediments

The uppermost parts of the profiles have reflectors dipping westward at a low angle. These areas are interpreted as unconsolidated sediments. With the help of the seismic sections, three different zones of sediments or sediment phases can be distinguished. These zones differ in amplitude, frequency and continuity of the reflectors.

The lowermost zone (Sed. 3) shows chaotic, low frequency reflectors with sometimes poor continuity. The wood samples from well HB1 are from the upper part of this zone. Therefore, the uppermost zone should be younger than 11.275 years.

The middle zone (Sed. 2) has a slightly higher frequency with mostly parallel reflectors. The reflectors show some discontinuities.

The topmost zone (Sed. 1) has the highest frequency and shows the highest amplitudes. The reflectors are parallel and show good continuities. The measured well logs are all within this zone and show silty or shaly formations. Baumgartner and Sordian (1982) give a detailed lithological description of well B1 with differentiation of four phases of earthflows. These phases can also be observed in wells KB11, HB1 and KB1DL. Well KB11 is solely in the topmost zone. With the help of the logs various alternations of shaly (earth- and mudflows) and sandy zones (torrential sediments) can be performed (Fig. 3). Well HB1 is the deepest well which penetrated all zones of unconsolidated sediments (Fig. 4). The topmost zone is again an alternation of sandy and shale zones. The middle zone shows a coarsening upwards sequence. The lowermost zone consists of earth- and mudflow formations with varying shale content. Well KB1DL shows an alternation of shaly and sandy zones in the topmost zone (Sed.1) and reaches the directly underlying Ultrahelvetic rocks (Fig. 4). The alternation of the earthflow and torrential sediments can only be seen on well logs, but it is not possible to distinguish them on the seismic sections.

Therefore the seismic interpretation of three different phases of sediments does not necessarily mean three phases of landslides, but describes three packages of different seismic character. These differences can be the result of different lithology, changes of energy of the landslides, or compaction of the sediments.

The most recent mass movement cannot be seen on this reflection seismic because the vertical resolution is too low. In the acoustic basement and in the Ultrahelvetic unit, north-south striking faults can be interpreted. These faults are identified by discontinuities in the seismic reflections and by ben-

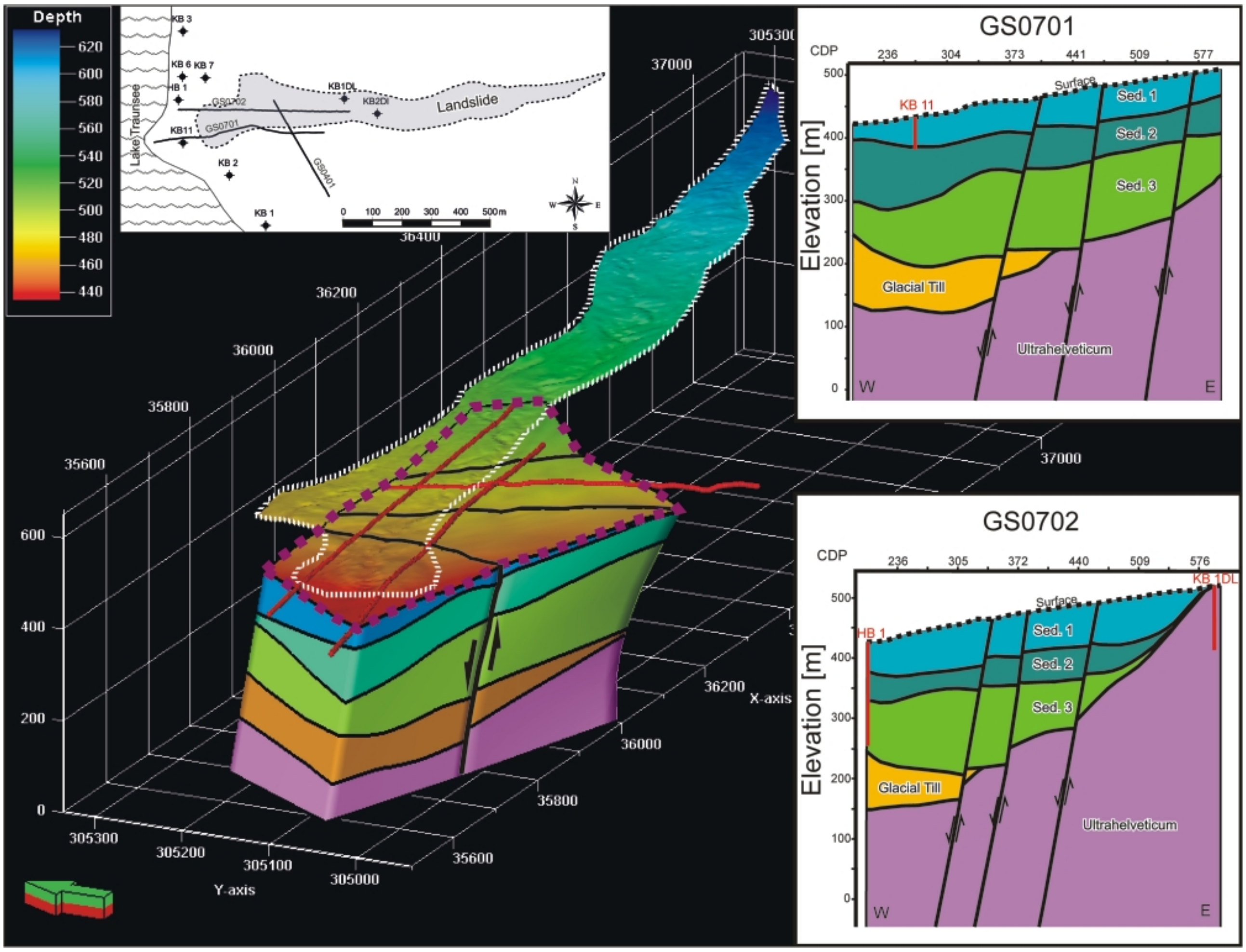

FIGURE 5: Final model derived from seismic reflection data. The red lines indicate the seismic profiles according to the basemap. The black lines at the surface of the model give the position of the modeled faults. The area with the dashed white border represents the most recent landslide in November 2007, while the pinkish dotted line shows the model boundary. On the right, two cross-sections along the seismic profiles GS0701 and GS0702 are shown.

ding of reflectors. In general, the faults can clearly be identified in the basement and in the Ultrahelvetic. Above this formation, flexures might indicate the presence of faults. This would mean that some of the faults were still active after the sediments were deposited. Daurer and Schäffer (1983) postulate that for the area of the Gschliefgraben, neotectonic events with intensified seismicity occur along the Traunsee fault system (Geyer, 1917). It is not possible to determine the extension of the faults in the area away from the seismic profiles.

6. CONCLUSIONS

The final result of the study is a structural model (Fig. 5) of the subsurface in the western part of the mass movement. With the help of the model, three phases of mass movements prior to the recent one, with similar seismic character, can be distinguished. The final model has a length of 550 m, a width of 230 m and a vertical extension of 450 m. The total volume of this model is 56x10^6 m^3. There are 4928 cells are used to build the model. The model consists of five geological horizons. The modeling of the seismic data led to the following improvements:

- Spatial overview of the geology of the subsurface beneath the recent mass movement
- Spatial distribution of each of the geological bodies
- Structural maps of each of the geological bodies
- Structural model can be improved by further data
- Depth conversion of the model with different velocity models
- Arbitrary sections of the model (depth slices, vertical slices)

The volume of each geological subunit, interpreted on the seismic profiles, can be determined within the area of the model.

For a correct calculation of the total volume of each phase of mass movements, longer seismic profiles are needed. The profiles should at least reach the outcrops of the Ultrahelvetic units in the north and the Northern Calcereous Alps in the south. With these long profiles, it would be possible to clearly correlate seismic reflectors with the geological bodies in lithology and stratigraphy and to better map the basement of the unconsolidated sediments. The best method for describing the different phases of mass movements and the tectonics of the underlying rocks is with the help of 3D-seismic. With the current configuration of seismic profiles, it is not possible to see east-west striking faults. This problem can only be solved with the addition of several north-south profiles.

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