Postglacial landslides and their impact on Pleistocene lake floor deposits in the Balderschwang Valley as witnessed by geomorphological, sedimentological and geophysical evidence (Vorarlberg, Austria)

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About the authors

Born in Amsterdam (1938), Leo de Graaff studied physical geography and geology at the University of Amsterdam (UvA) from 1960-1968, with geomorphology as a principal subject. Secondary subjects were crystallography, clay mineralogy and soil chemistry. Since September 1968 he has been a staff member, finally in the position of a senior lecturer, at the Department of Physical Geography and Soil Science. After 1970 he mainly specialized on the geomorphology and quaternary geology of alpine and sub alpine environments. With other colleagues he guided student fieldwork and research in and around Vorarlberg during three decades, only interrupted by a two-years stay in Sri Lanka (September 1980 - September 1982).

Harry Seijmonsbergen also was born in Amsterdam (1961) and studied physical geography and soil science at the same department. He specialized on geomorphology, with sedimentology (University Utrecht) and engineering geology (Technical University - Delft) as secondary subjects. In 1992 he published his PhD-study on Gamperdona valley related to natural hazard evaluation and geomorphology and was appointed as a staff member at the UvA as well. Since 1999 he became member of the newly formed research 'Institute for Biodiversity and Ecosystems Dynamics' (IBED - Physical Geography), where he is responsible for student training in geomorphology and geology (including remote sensing and GIS). Fieldwork is carried out in the Alps, in Luxembourg and Southern Spain.

Zusammenfassung

Das Balderschwanger Tal (E-Bregenzerwald) entwickelte sich entlang der SSW-ENE verlaufenden Kontaktzone der gefalteten Molasse und der Vorarlberger Flyschzone. Während den Vergletscherungen wurden die Talhänge durch glaziale Erosion überformt, welche nach dem Rückzug der Gletscher Hanginstabilität und Erdrutsche verursachte.

Während des Gletscherrückzuges (vor dem Ende der Oberen Würm) verwandelte sich das Balderschwanger Tal in einen eisgestauten See (Höhe der Wasseroberfläche bei ~920 m ü.M.). Dieser See wurde hauptsächlich mit feinkörnigen Sedimenten gefüllt, welche Relikte älterer, glazial überformter Seesedimente und subglaziale Grundmoränen überdeckten. Gemäß DE JONG et al. (1995) entspricht der spätglaziale „Balderschwang-See" einer letzten Übergangsphase zwischen Ablagerungen des Rückzugskomplexes II und des Rückzugskomplexes III. In der schweizerischen und deutschen Literatur über den Rhein-Gletscher

werden die Rückzugskomplexe II und III grob den Stadien „Stein am Rhein" bzw. „Konstanz" zugeordnet.

Zwei grössere und einige kleinere Erdrutsche gingen auf die Seeablagerungen im österreichischen Teil des Balderschwanger Tales nieder und beeinflußten die Geomorphologie des Tales maßgeblich. Diese Rutsche wurden ausgelöst durch die glaziale Überformung der nördlichen Molassehänge. Insbesondere die Nagelfluh-Konglomerate waren Gegenstand des Zusammenbruchs. Ein wichtiger Faktor mag die Zunahme eines hohen Grundwasserdrucks in den steil abfallenden Konglomeraten und Sandsteinschichten gewesen sein, da sie mit ziemlich undurchlässigem Mergel alternieren.

Infolge der Einwirkungen dieser Erdrutsche auf den Talboden wurden die darunterliegenden Ablagerungen stark deformiert und zum Teil herausgepreßt. Wegen der instabilen Lage über dem weichen Seeschlamm und Ton erfolgen noch immer sekundäre Bewegungen, besonders an der Spitze der Rutsche, wo Einstürze ein häufiger und immer noch aktiver Prozeß sind.

Um ein passenderes Modell für die Größe und den Effekt dieser Einwirkungen zu erhalten, wurden geomagnetische Profiltechniken angewandt, um das räumliche Ausmaß und die Störung von Erdrutschmassen und ihre Position in und über den darunterliegenden Ablagerungen des Seebodens zu bestimmen. Basierend auf den elektrischen Widerstandswerten konnte ein ungefähr 500 m breiter und 1500 m langer Ausschnitt des Tals bis auf eine Tiefe von mindestens 20 m interpretiert werden. Diese Messungen bestätigten, daß die Balderschwang-Erdrutsche auf die späteiszeitliche Füllung des Seesediments zu liegen kamen. Die Lage des Erdrutschmaterials und des darunterliegenden Sediments werden in einer Reihe von Tiefenprofilen und Karten gezeigt. Auf Basis dieser Daten und der rekonstruierten Hangprofile konnte auch eine genaue Schätzung des Volumens des westlichsten Erdrutsches vorgenommen werden.

Abstract

The valley of Balderschwang (E-Bregenzerwald) developed along the SSW-ENE trending contact zone of the folded Molasse and the Vorarlberg Flysch series (see ZACHER 1973). During glaciations the valley slopes became oversteepened by glacial erosion, giving rise to slope instability and landslides to occur after deglaciation.

At the moment of deglaciation (before the end of the Upper Würm), the valley of Balderschwang turned into an ice-dammed lake (water surface altitude at ~920m N.N.). This lake got filled with fine-grained lacustrine sediments mainly, covering relicts of older, glacially overridden, lacustrine sediments and subglacial till. According to DE JONG et al. (1995), the late-glacial 'Lake of Balderschwang' represents a final transition phase between deposition of the Recessional Complex II and RC III. In Swiss and German literature on the Rhine Glacier, RC II and RC III are roughly referred to as the stages 'Stein am Rhein' and 'Konstanz' respectively.

Two major and some smaller landslides came down on top of the lacustrine deposits in the Austrian part of the Balderschwang valley and strongly affected the geomorphology of the valley (*see figure 1 for location*). These slides were triggered from the glacially oversteepened northern Molasse slopes. In particular, the Nagelfluh conglomerates became subject to failure. An important factor might have been the building-up of high groundwater pressures in the steeply dipping conglomerate and sandstone layers, as they alternate with rather impermeable marls (compare WONING, 1997).

Due to the impact of these landslides on the valley floor, the underlying deposits became subject to strong deformation and were partly squeezed-out. Because of the unstable setting on top of the soft lacustrine silt and clay, secondary movements still occur, especially near the toe of the slides, where slumping is a common and still active process.

In order to establish a more accurate model of the size and effect of these impacts, geomagnetic profiling techniques were used to determine the spatial extent and the distribution of the landslide masses and their position in and on top of the underlying lake floor deposits. On the basis of the obtained electrical resistivity values, an approximately 500m wide and 1500m long section of the valley could be interpreted to a depth of at least 20m. These measurements confirmed that the Balderschwang landslides came down on top of a late-glacial lacustrine sediment fill. The position of landslide material and of the underlying sediments is shown in a series of depth profiles and maps. Also an accurate estimation of the volume of the central westernmost landslide could be determined on the basis of these data and reconstructed slope profiles.

Key words: Postglacial landslides, geophysical profiling, Balderschwang, Vorarlberg, Austria

Introduction

Glacial history of the Lower Bregenzerwald

Ice-dammed lakes were a common feature in the Lower Bregenzerwald during the glaciations of the Middle and Upper Pleistocene (DE GRAAFF & RUPKE 1979, SIMONS 1986; KELLER & KRAYSS 1991; DE JONG et al. 1995; compare also RESCH et al. 1979).

In 'early-glacial' periods of glacial expansion, the Rhine valley became glaciated first and two branches of the Rhine valley glacier then started to penetrate into the Lower Bregenzerwald. This took place over the valley divide of Alberschwende and along the Bregenzerach valley, southeast of Bregenz. In a next stage, these two branches joined and met with the expanding Bregenzerwald Glacier, pushing the latter to the northeast. In the Bregenzerwald these initial phases of glacial expansion gave rise to the formation of ice-dammed lakes in different positions and at different levels.

At the beginning of the Upper Würm, a connected lake system firstly developed in the lower valley sections of the Bregenzerach, Rotach, Weissach and Subersach, with water surface altitudes ranging from 600m to almost 700m. Important in this context is the ^{14}C age dating of a mammoth tusk at 23.900±400 BP

(DE GRAAFF 1992), found in the Hochwacht gravel pit near the 'Langener Straße', southeast of Bregenz. This is the only known age dating in the Alps, marking an advance stage of one of the large alpine valley glaciers at the beginning of the Upper Würm (compare also DE GRAAFF 1993; DE JONG et al. 1995).

In the next stage, the lower valley sections of the fore-mentioned streams also became glaciated, when the Rine Glacier and Bregenzerach Glacier met and expanded farther into the Bregenzerwald. The formation of ice-dammed lakes then shifted to the east and to higher topographic positions, finally reaching the upstream part of the Bolgenach and Subersach valley. Estimated surface levels of these lakes ranged from about 800m near Hittisau, to maximum altitudes at around 920m N.N. in the valley of Balderschwang and in the Subersach valley between Schönebach and Sibratsgfäll.

These ice-dammed lakes gradually got filled with sediments, predominantly with fine-grained sediments, locally with deltaic sands and gravels, before the area disappeared under the overriding glacier. Though the 'early-glacial' sediments may have been partly eroded (initially by the overriding glacier, later by postglacial processes), especially the remains of fine-grained sediments may show much resistance against postglacial erosion and mass wasting, as they became strongly (over) compacted under the weight of the overriding ice body (compare VAN GELDER et al. 1990)

Fine-grained sediments dating from the last deglaciation do not show these compaction characteristics. For this reason, a primary distinction always must be made in the Alps, between glacially overridden sediments ('older' Pleistocene deposits, predating the Upper Würm Pleniglacial) and non-overridden sediments ('younger' Pleistocene deposits, related to the final deglaciation of the Upper Würm). Moreover, deposits from the first group are generally not related to fresh (late-glacial) landforms, as the overriding glacier modified them. 'Younger' Pleistocene sediments usually fit well into the morphology of the final deglaciation.

The valley of Balderschwang

The upper stream section of the Bolgenach drains the valley of Balderschwang. This valley became glaciated only during Pleniglacial periods, when the regional glacier network was fully established (compare DE GRAAFF 1996).

It can be assumed, that the Bregenzerache Glacier blocked the valley outlet frequently (near Hittisau), just before and after Pleniglacial periods, generally giving rise to the formation of ice-dammed lakes. This at least occurred during the Upper Würm, when this glacier expanded ('early-glacially'), as well as during its retreat ('late-glacially'). The materials and the morphology of the valley witness this, by the pattern of Pleistocene deposition.

In the Balderschwang valley, exposures of 'older' and 'younger' Pleistocene sediments can be found along the river bed, especially at places where these sediments were pushed-up by landslides. Relicts of 'older' sediments (mainly lake floor deposits, showing strong overcompaction) and subglacial till are less commonly exposed, as they became covered by an extensive 'younger' sediment fill, mainly consisting of soft, fine-grained lacustrine deposits. This material almost filled the entire valley below 920m N.N., the surface level of an ice-dammed lake, which formed in a final transition phase between Recessional Complex II (~stage 'Stein am Rhein') and R.C. III (~stage 'Konstanz') according to DE JONG et al. (1995). Especially the 'younger' lacustrine sediments are highly sensitive to fluvial erosion and mass wasting. Active solifluction and slumping gradually removed part of the soft lake floor sediments after the Bolgenach incised to recent drainage levels.

The last phase in which lacustrine sediment were deposited and buried below glacier ice in the Balderschwang valley, is estimated to have occurred at around 23.000 BP (just before, or at the beginning of the Upper Würm Pleniglacial). Deglaciation occurred shortly after 15.000 BP (estimations in ^{14}C time; compare DE JONG et al. 1995 and DE GRAAFF & JONG 1996).

At the moment the glacier melted away in the valley of Balderschwang, an ice-dammed lake took over its position, as the valley outlet was still blocked near Hittisau by a lobe of the Bregenzerache Glacier. This lake of Balderschwang may have persisted for one or two hundred years and became almost entirely filled (up to 920m) with fine-grained lacustrine deposits, covering the relicts of older sediment fills and subglacial till.

In the following stage of deglaciation a lake developed in the Hittisau area, at around 800m N.N. Also this lake got filled, mainly with the deltaic deposits, which are still underlying the Hittisau terrace. Soon afterwards the Bregenzerache glacier lost contact with the Rhine glacier and a much larger and connected lake system developed in the lower sections of the Subersach, Weissach, Rotach and Bregenzerach, maintaining its surface level for hundreds of years at around 660m N.N. Drainage then took place over the valley divide of the Rotach valley. This new level of deposition is clearly marked by deltaic deposits, for example by those of the Lingenau terrace. The entire depositional complex in the Lower Bregenzerwald, dating from this period is referred to as RC III by DE JONG et al. 1995. According to these authors R.C.III could have started at ~14.600 BP and could have lasted up to ~13.800 BP (in ^{14}C time).

When the Hittisau Lake developed, the Balderschwang Lake was drained and the Bolgenach gradually removed part of the soft fine-grained, late-glacial deposits from the former Balderschwang Lake already. In was on top of this lacustrine material, that the impact of at least two major landslides took place.

To summarize the ideal sequence of materials in the Balderschwang valley from young to old:

- Recent alluvial deposits of the river Bolgenach (pebbles, gravel, sand), colluvial deposits and peat (Holocene)
- Landslide and rock fall material (latest Pleistocene or early Holocene)
- 'Younger' lake floor sediments, deposited during the final deglaciation (soft, thinly-layered clay and silt, occasional with dropstones); deltaic deposits (consisting of sand and gravel) may occur locally (late Upper Würm);
- Subglacial till (dense diamicts, representing subglacial deposition during the Upper Würm Pleniglacial)
- Glacially overridden, 'older' sediments or b) striated (glacially eroded) or non-striated bedrock

Ad a): 'older' sediments; they generally consist of overconsolidated, fine-grained lake floor deposits (thinly layered clay and silt, with dropstones, deposited during the early Upper Würm); these sediments might locally be underlain by still older sediments, e.g. by older subglacial tills or by fluvial deposits (sands and gravels) of the Bolgenach.
Ad b): striated bedrock normally is found in contact with undisturbed subglacial till, but no exposures yet have been observed in the Bolgenach valley.

Ideal sections are not exposed, but the 'younger' Pleistocene and Holocene sediments are abundantly present in the Bolgenach valley.

The Balderschwang Landslides

About the mechanisms of the Balderschwang slides, some general aspects on landslides in valleys situated within the folded Molasse in the NE-Bregenzerwald should be mentioned. As ice-surface altitudes always balanced between the Bregenzerwald and the Iller valley during Pleniglacial stages, ice flow probably wasn't very strong. The valley walls nevertheless were modified and oversteepened by glacial erosion, a primary factor to cause slope instability in the synclinal valleys of the folded Molasse in the northeastern Bregenzerwald after deglaciation. Another factor, which is thought to have played an important role in the Balderschwang slides, is the building-up of high groundwater pressures in the steeply inclined conglomerate and sandstone beds underlying the Molasse slopes. These beds commonly alternate with rather impermeable marl layers. This factor, for example, turned out to be a main driving force in case of the Late-Glacial Plattenberg 'Sturzstrom', near the outlet of the Lecknerbach valley, northeast of Hittisau (see Msc-thesis of WONING 1997 and WONING et al., in prep.).

Two large landslides are present in the Austrian part of the valley of Balderschwang. The westernmost landslide shows an impressive mass of large and very large blocks of Molasse conglomerates ('Nagelfluh'), spreading out over the entire width of the valley (see *fig. 1*). This landslide probably developed in one single event. In *figure 2* a stereo-pair of 2 panchromatic air-photos at an approximate scale of 1:20.000 is shown. A classical subdivision into an upslope "removal zone", a transport track and a depositional area can be viewed under the stereoscope. This situation can also be seen in *figure 6*, a *digital terrain model* (DTM) of the central western landslide, showing height contours in the form of a block diagram. The stereo-pair reveals that the position of "Gschwendwiesalpe" (see *fig. 1*) coincides with a sliding block. This block is probably a secondary smaller failure that occurred shortly after the main failure. Large conglomerate blocks cover the terrain around "Sipperseggalpen", especially the forested zones, that are not suited as grassland. The runout distance of the individual blocks is not only restricted by the steep southern Flysch underlain bedrock slopes, but is also limited because a major part of the landslide mass has sunken into the weak lake floor clays. This is confirmed by the geomagnetic profiling (see *figures 4* and *5*).

The easternmost slide is a composite slide. In the west and in the central section (around "Gerisgschwend") this slide mainly consists of Molasse conglome-

Figure 1: Location of the study area in the valley of Balderschwang.
1 = western central landslide area near "Gschwendwiesalpe" and "Sipperseggalpen"
2 = outline of the complex landslide in the eastern part near *„Schonhaldenalpen" and „Gerisgschwend"*

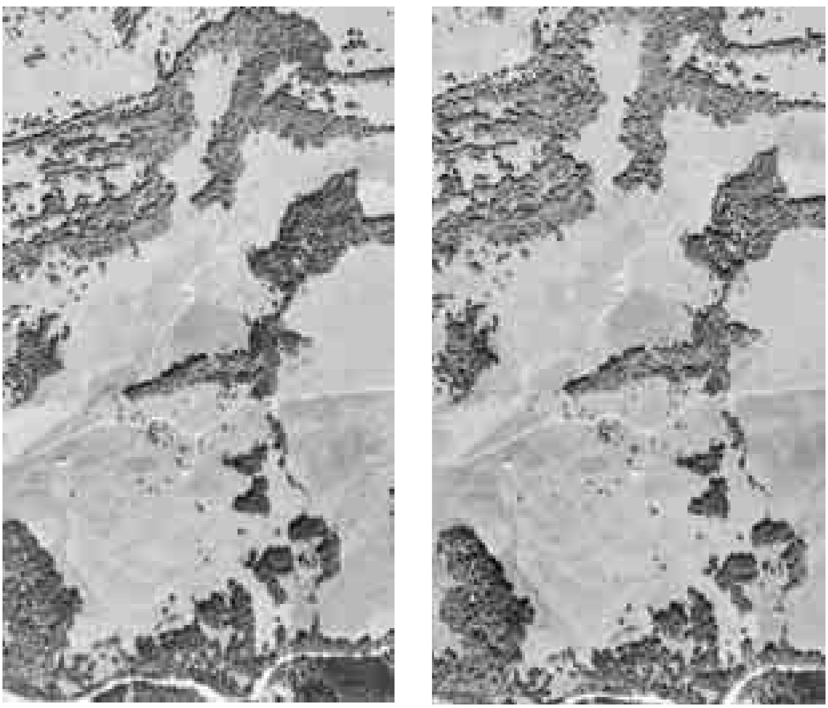

Figure 2A. Panchromatic (black & white) Stereo-pair of the western central landslide showing a classical upslope removal area between „Koppachstein" and „Gschwendwiesalpe" (see *fig. 1*) and the accumulation zone around „Sipperseggalpen"

Photos: Bundesamt für Eich und Vermessungswesen, Wien.

rates. At its southeastern side the slide mass consists of sandstone. Studying aerial photographs of the system, it cannot be excluded, that two different slides had developed. It seems that the 'sandstone' slide mass came down later and was diverted to a southeastern direction along the flank of the (larger) 'conglomerate' slide mass.

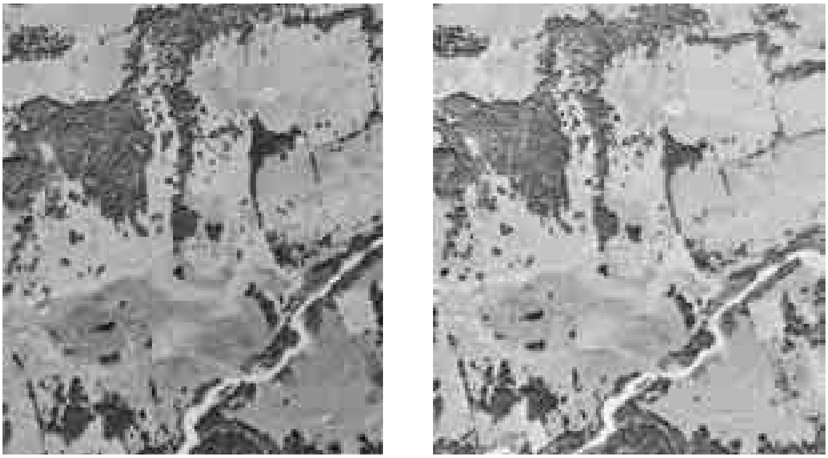

Figure 2B. Panchromatic stereo-pair of the eastern complex landslide. Clearly seen is the separation into a smaller western slope failure and a larger eastern slope filure. The impact of the eastern landslide has deformed the clayey lake floor deposits on the southern side of the „Subersach" river (see also *figure 3*)

Photos: Bundesamt für Eich und Vermessungswesen, Wien

This sandstone slide had an enormous impact on the valley floor, squeezing out and pushing up the lake floor deposits (silty clay) into a curved clay ridge, which still exists at the southern side of the river. This pressure ridge rises tens of meters above the riverbed; a single farmhouse has been built on top of it. Landslide material at the surface is not present at this side of the river. Instead, patches of fluvial gravel and sand were found against the inner side of the ridge. At this side the ridge later became strongly transformed by slumping of material, a process that is still active. In fact, the Bolgenach found a new course and incised again, almost along the outer contact of the landslide mass with the deformed and tilted lacustrine sediments. At the outer side, near the farmhouse, the ridge is hardly affected by mass wasting and erosion.

Towards the southwest, the pressure ridge ends in contact with younger alluvial fan deposits transported by a tributary stream. Coming closer to its confluence with the Bolgenach, the pressure ridge is fully cut off by fluvial erosion, but outcrops of the disturbed 'younger' lake floor deposits still can be observed here, at the southern side of streambed of the Bolgenach. Sediment layers of these lacustrine deposits are exposed in steeply inclined to almost vertical positions. These layers run almost parallel to the riverbed and they show internal folding and other disturbances like shear planes (see photo in *fig. 3*). For a few years, relicts of these 'younger' Pleistocene sediments were also exposed in contact with upthrusted subglacial till and 'older' lacustrine deposits.

The landslides are younger than the moment of deglaciation, the subsequent formation of the late-glacial Bolgenach Lake and the youngest lacustrine fill, which is estimated to have occurred shortly after 15.000 BP (in ^{14}C time). However, there are no further clues about the age. As the individual slides probably developed at different moments, their age may range from Late Glacial to Early Holocene (Subatlanticum?).

Figure 3:
Photo along the Bolgenach near the bridge at point 947 in the eastern part of landslide 2 in the map in *Fig. 1.* Deformed and tilted clays are exposed as the result of the landslide impact from the northern valley slopes.

Geophysical measurements

During fieldwork in the summer of 1997, it became a main objective to establish a more accurate model of the size and impact of the landslides in the Bolgenach valley by means of geophysical measurements. Geomagnetic profiling techniques were used to determine the spatial extent and distribution of the landslide masses and their position in and on top of the underlying lake floor deposits. Electric properties of sediments differ, depending on grain size distribution (especially the clay content), hydrological properties (saturation or not), compactness, and internal structure. Therefore, when variations in electrical conductivity values (measured in mS/m) at the surface and below the surface are known, these variations can be related to different materials and thus to former processes that were responsible for the present distribution of these materials.

The (sub) surface terrain conductivity was measured with a Geonics EM-34 Terrain Conductivity Meter. Traverses were carried out on the valley floor on both the landslide impact zone and the non-influenced part of the valley floor (see *figs. 1* and *4* for location). The instrument consists of two coils, a transmitter, a receiver and connecting cables. The transmitter coil generates a time-varying magnetic field. This field induces very small currents in the subsurface. These induced currents generate a secondary magnetic field. The second receiver coil measures both the primary and the secondary magnetic field. (Geonics, Technical Note TN-6, 1980). Lateral variations and different depth penetrations may reveal the subsurface structure and distribution of unconsolidated materials. Therefore, it is possible to determine the nature of the sediment layer present. Since the electrical properties of bedrock are enormously high, deeper penetration is impossible. Depending on the coil separation (10, 20 or 40 m) and their orientation (vertical coplanar or horizontal coplanar), resistivity values depths to approximately 60 m can be measured. In this case however, reliable results were only possible to a depth of 20 - 30m. The profile lines are located on both rock fall/landslide accumulations as in undisturbed terrain, in order to enable comparison between disturbed and undisturbed sediment layers. Spatially homogeneous zones of electric conductivity were interpolated based on the collected data points with the computer program SURFER. Four situations have been calculated and represented for various depths (see *fig.4*). The following resistivity values were used:

< 20 mS/m:	landslide material
20 – 25 mS/m	mixed material
> 25 mS/m	predominantly lake floor deposits

These values were found representative in the field and are also based on earlier work by SEIJMONSBERGEN and VAN WESTEN (1988) and RUPKE et al. (1986). Sections along the various profiles can easily be reconstructed. We only present four of these sections in *figure 5*. The information of hand drillings and information of surface exposures was also incorporated.

Interpretation of the geo-magnetic profiles

Three classes have been recognised in the interpretation of conductivity values. Landslide material has been set to values below 20 mS/m. This includes both rock fall and slide material derived from the upslope source areas. Intermediate zones, probably of mixed landslide and other (clays & gravel) deposits have been set at 20 – 25 mS/m. The third unit, lake floor clays, is characterized by conductivity values exceeding 25 mS/m. Using these calibrated values a distinct pattern of different values is present below the valley floor at several depth intervals (*fig 5*).

The pattern of conductivity at 3 m depth mainly shows low values, corresponding to landslide material at shallow depths. This fits quite well with the observed surface morphology in this area. The corresponding section at 6 m depth shows a distinct increase in clay values, especially near the Bolgenach River in the (south)eastern part. At 10 m depth again lower values predominate and bulge outward in southern direction. The situation at 20m depth shows an almost landslide free eastern part. The central and western part is still occupied by extensive landslide masses at this depth. This corresponds quite well with the central western landslide and indicates that its impact reaches (far) below 20m depth. Striking is also that in between the central western and eastern composite landslide an area free of landslide material exists, probably supporting the observation that the subsurface situation reflects the presentday surface morphology. The four cross sections in *fig. 5* clearly indicate that the volume of landslide mate-

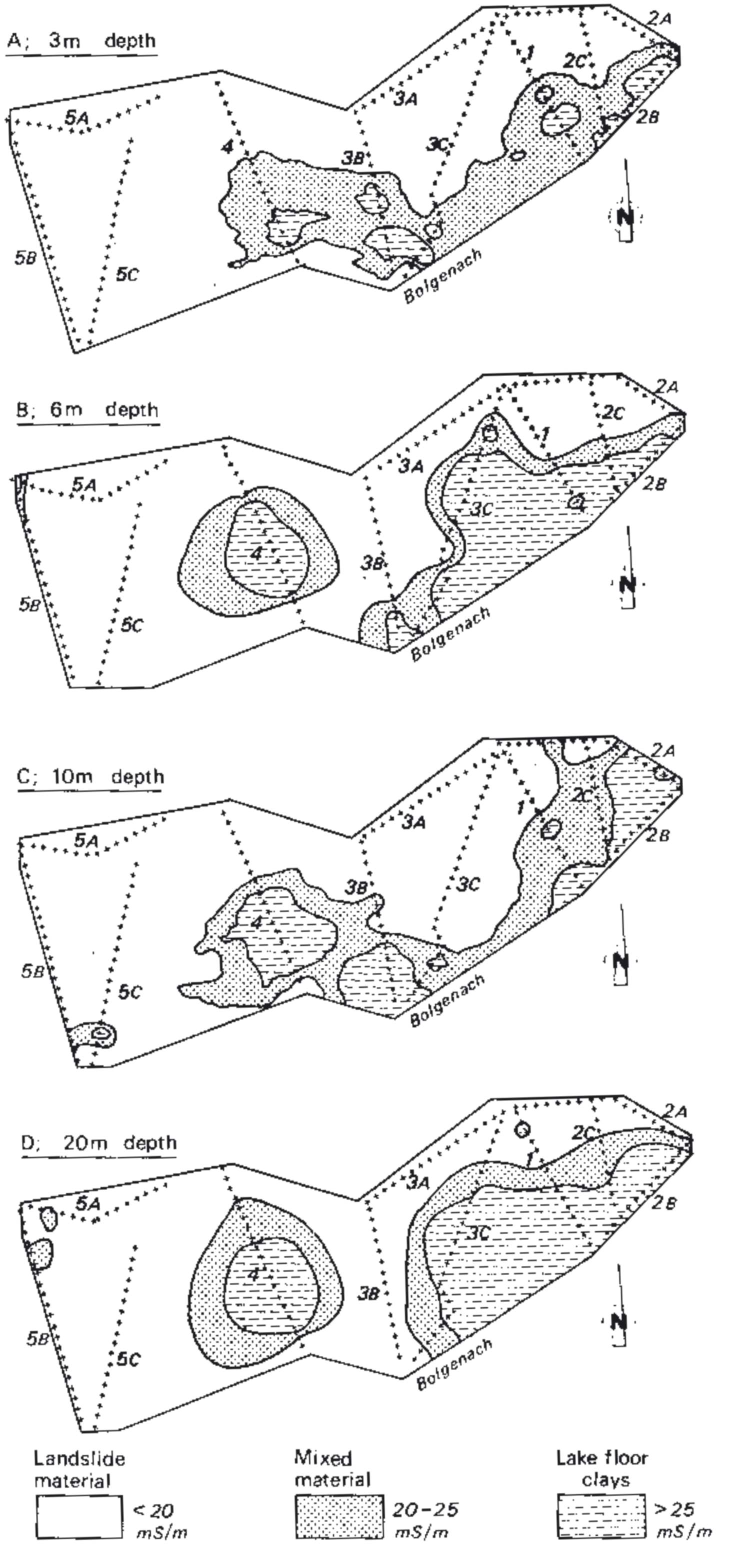

Figure 4: Horizontal sections showing zones of homogeneous electric conductivity values at 3m, 6m, 10 m and 20m depth in the accumulation areas of the 2 landslides.

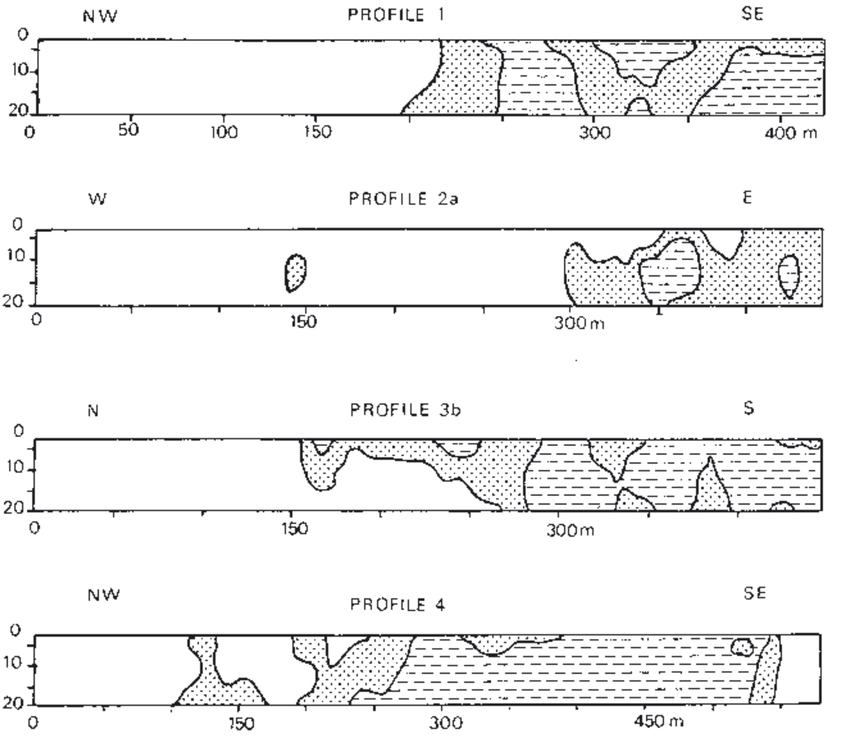

Figure 5:
Four cross sections illustrating subsurface differences in electrical conductivity (see text for explanation).

rial is much larger in the direct foot zone (northern parts) of the valley slope. This is also seen on the distribution of conductivity values. Taken into account that the clay material has been deformed (see *fig. 3*) it can be concluded that the amount of landslide material generally decreases from N to S. The relatively steep conductivity contacts and the pattern changes between 3, 6, 10 and 20 m depth suggests that the landslide material has sunken into the weak clay material instead of running uphill at the southern valley slope as is quite common with landslides of this size. Similar conditions have been described for a known historic rock fall event at the Breitenberg near Dornbirn where Helvetic blocks of the Schrattenkalk limestone have sunken deep into the weak clays, silts and peat present in the valley floor of the river Rhine (see BERKELAAR 1994).

Estimation of the amount of removed slope material

A reliable estimation of the volume of the central major landslides can be made by combination of the data collected from both the zone of removal and the zone of deposition. Data of the deposition zone was derived from the geophysical profiles and by exposure information. In the zone of removal a *digital terrain model* (DTM) of the present slope outline was constructed based on the 1:20.000 map contour lines (see *fig. 1*), which were digitised using the Arc/Info GIS (Geographical Information System) software package. The reconstructed pre failure slope outline was also digitised and transformed into a DTM. Overlaying of these two digital terrain models gives an indication of the volume removed from the slope. It is evident that the depth of the failure plane reaches >100m in places. Therefore this type of slope failure is referred to as a deep reaching landslide. The volume is estimated at approximately 1.5 x 10*7 cubic metres, which is approximately 30% higher with respect to the data of KORF (1998), who estimated a volume between 5.1 and 11 x 10*6 m3. The volume of the deposited material always increases by a factor in between 1,25 and 1,5. The deposits of the central landslide have mean surface dimensions of 800m (from N-S) and 500 wide (W to E). This would mean that the depth of the landslide mass would reach almost to 40 depth. Since the effective geomagnetic profiling depth is only 20m this could not be verified. However, the profiles do indicate a full landslide cover in the central western part of the measured area (see *fig.4*), except for some isolated spots, up to 20m depths. Therefore it is quite plausible that the central landslide material has penetrated to approximately 40m in the soft sediments.

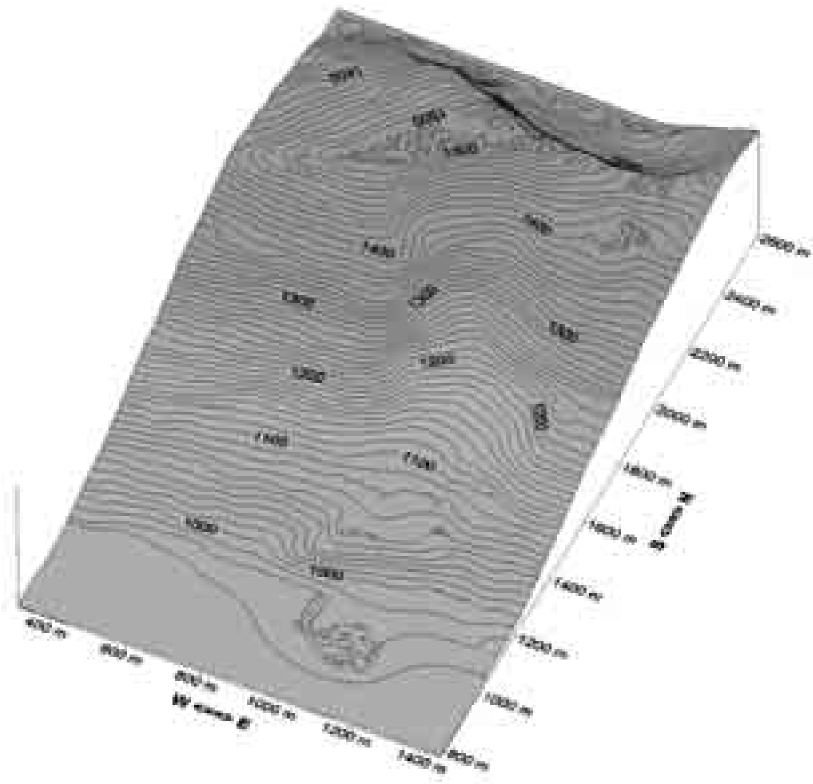

Figure 6: Digital terrain model covering the western central landslide (nr. 1 in *fig. 1*). Area covers almost the same terrain as seen in the stereo-pair of *fig. 2A.*

The present day stability of the Molasse valley slope seems to relate to the weathering rate of the rock material, especially the decay of strength parameters (cohesion and friction angle) of the Molasse marls. Therefore large and deep reaching failures are not to be expected on the slopes underlain by Molasse rocks anymore in the valley of Balderschwang under present climate conditions. Glacial oversteepening and subsequent development of failure planes, reacting on the loss of support of the ice, primarily triggered large failures such as the central fossil landslide in the Balderschwang valley. The existence of an ice marginal dammed lake in the valley of Balderschwang probably contributed to reduced strength in the oversteepened valley slopes. Although the time of failure could not absolutely be determined, the occurrence of such large failures is likely to relate to periods directly following deglaciation (Late-Glacial periods).

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