SEISMIC-STRATIGRAPHIC ANALYSIS OF THE DEGLACIATION AND
DEPOSITIONAL HISTORY OF THE ACHENSEE, TYROL

Masterthesis

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Statutory declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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Acknowledgement

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Abstract

Seismic stratigraphy is an important key to analyse depositional processes during deglaciation. Seismic Stratigraphy Analysis provides information about different phases of sedimentation. This method is used to understand associated processes, which can be reconstructed and interpreted. Our current understanding is based on the experience of lake sediments. Predominantly, the current knowledge was gained in peri-alpine lacustrine sediments.

In this study Seismic Stratigraphy Analysis is applied to an inner-alpine lake (i.e. Achensee). Therefore a dense network of high-resolution reflection seismic data allows a detailed pseudo-3D investigation of the depositional architecture of the lake infill. In addition the evolution of the depositional systems can be comprehended by the evaluation of the seismic data. These sediments are an important geological archive and provide information of dynamic processes. The data can be used for several analyses, e.g. the reconstruction of paleo-earthquake history.

In detail, the focus is on the southeastern part of the Achensee (Pertisau Basin). After the acquisition of the data the results will be compared with previous research. With an interpretation of seismic facies we can discriminate postglacial depocentres from various sediment sources. Comparing to previous investigations, a correlation is made to understand this glacially eroded valley by stratigraphic units.

The seismic stratigraphy can be performed using different physical parameters of the units. The differences can be seen by different reflection amplitudes on the one hand and geometric variations on the other.

Already Ampferer asked himself in 1904 the question about the function of the “Achenseeschwelle”. The basic findings were examined several times and could be proven in the essence. Thus the scientific work started by Ampferer more than 100 years ago.

The results of this investigation are used for an evaluation of previous results (Poscher 1993, Burger et al. 2011 and Fuhrmann 2017). These informations are collected and aggregated. Different deposition in the study area can be identified. The distribution of the seismic stratigraphic facies proves various sediment sources. The hypothesis that the Zillertal glacier crosses the Achenseeschwelle is supported.
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1. Introduction

1.1 Research Motivation

The data collected for the seismic stratigraphy analysis can be used to draw accurate conclusions about dynamic deglaciation processes. The evaluation of high-resolution seismic stratigraphy data will investigate in detail what previous investigations could not clarify. The focus is on the sedimentary development of quaternary deposits and their impact on the “Achenseeschwelle”.

Lake Achensee is one of many numerous glacigenic elongated lakes in the Alps, where in various periods, different lacustrine sediments were deposited. Geophysical methods are applied and interpreted in the Achensee area for the evolution of previous investigations, by using non-destructive and non-invasive methods. Necessary prerequisite for the appropriate use of geophysical methods is the presence of contrasts of the physical material parameters in the subsurface.

In the project of the sedimentary Geology Working Group, led by Ass. Prof. Dr. Jasper Moernaut and Professor Dr. Michael Strasser, of the Institute of Geology at the University of Innsbruck, the sediment evolution and dynamics at the Achensee will be investigated using seismic stratigraphy. Therefore reflection seismic data (~90km – Pinger / ~100km Sparker) were created.

The aim of this research is the construction of a seismic stratigraphy in the sedimentary depocentres in the Achensee, representing phases of glacier retreat and a post-glacial environment. As these lacustrine sediments, with their continuous deposition represent a good climate archive, these records can be accessed to trace environmental variations and alterations. It thus records climate changes and allows a reconstruction of the behaviour of retreating glaciers and the associated sedimentary processes (Heirman et al. 2011).

The stratigraphy should give information about different periods of sedimentation. Based on past scientific work of Ampferer (1904), Poscher (1993), Burger et al. (2011) and Fuhrmann (2017), we can discuss our results within a framework of past onshore studies.
A special question is the origin and function of the Achenseeschwelle, as already investigated by Ampferer in 1904. describes the area as follows:

"The Achensee fills a rocky valley, which originally drained into the Inn valley with its side valleys, but is now separated from the latter by a massive accumulation of various types of debris. This debris dam, meaning the Achenseeschwelle, prevents the water from reaching the Inn valley". On the basis of observations, he concludes that the debris dam can be constructed exclusively from material according to the LGM. In doing so, Ampferer relies on previous investigations of Blaas and Penck (1902).

These spread a theory according to the Achensee was dammed by glacial deposits. The damming initially led to the formation of the lake and subsequently to the relocation of the overspill to the north side of the lake, thus causing the outflow of water to the north.

The Achensee has a continuous sedimentation and is a good archive for investigating of dynamics and processes of inner-alpine lakes during glaciation. The lacustrine sediments of the Achensee are an important key for the testing and evaluation of this hypothesis. In 2017, Führmann investigated for this hypothesis using geophysical methods in western side valleys of the Achensee. With the application of geoelectrics Burger et al. 2011 focused on the Achenseeschwelle in the southeast of the lake. This thesis may enable an interpolation between the data on land (Führmann 2017, Burger et al. 2011) and those in the lake.

1. 2 Geographic setting

The Achensee (47°30'1.29"N; 47°25'31.97"S) is the largest lake in Tyrol with approximately 9km length. This dammed lake is located in a side valley, north of the Inn valley, embedded in a mountain range called the Karwendelgebirge. The Achensee is located at an altitude of 929 m a. s. l. The lake is embedded in the Achental between Achenkirch in the north and Maurach in the south. The water surface is about 6.8 km² and the maximum depth 133 m.

The average depth of the fjord-like lake is ~67 metres. It belongs to the municipality of Achenkirch, in the political district of Schwaz in Tyrol. The investigated area lies in the Pertisau Basin in the southern part of the lake. The geomorphological lake-type is a trough valley lake of glacial origin in the Northern Calcerous Alps.

The Achensee is an inner-alpine lake with four important inflows, the Oberachbach, the Ache, the Wankratbach and the Pletzach (fig. 1).
Figure 1: Achensee overview map, area of interest between Pertisau and Maurach
The rivers contain various amounts of water which is depending on seasonal precipitation. After intense rainfall events there is a regular intake of mineral suspended matter, which temporarily clouds the water. The lake has been used since 1927 as a reservoir for electricity generation.

Artificial water level fluctuations occur seasonally. In winter, the level is usually significantly lower than in summer. These changes are caused by the energy-economical use as storage reservoir (Aigner 2018).

1.3 Geology

The Austroalpine units are part of the northern Eastern Alps. The Northern Calcerous Alps (NCA) strike west-eastwards as a band of Paleozoic and Mesozoic sediments. The units disappear eastwards in the basin of Vienna and then continue in the Carpathians. The NCA are present today as eastern alpine nappes (Pfiffner 2015).

The NCA formed during Late Jurassic, Early Cretaceous and Paleogene Phases of convergence and stacking of cover thrust nappes (Sanders 2009).

The sedimentary rocks of the NCA were formed in a shelf area at the northern margin of the Adriatic micro-plate. The carbonate sediments are composed of massive sequences of mainly Wettersteinkalk and Hauptdolomit (Schmid et al. 2004).

The NCA are part of the Upper Austroalpine and overlying the Greywacke zone. They are detached Paleozoic (Greywacke zone) and Mesozoic (NCA) units (Schmid et al. 2004). Recently forming a thin skinned fold- and thrust belt positioned at the northern front of the Austroalpine nappes and separated from their stratigraphic base by the Inntal fault in the south (Ortner, 2005).

Mesozoic sediments are not to slightly metamorphous (Frey et al., 1999).

The tectonics of the individual nappes faced first stacking by the closure of Meliata Ocean in the Cretaceous. In a second phase folding and thrusting affects the tectonics immensely during closure of Penninic Ocean in the Cenozoic. This thin skinned fold- and thrust belt strikes essentially E/NE, W/SW to NE/SW (Ortner, 2011).
Tectonic map of the Alps

Figure 2: Tectonic map of the Alps (Schmid et al. 2004), area of interest
**Austroalpine Nappes:**

**Northern Calcareous Alps and Grauwackenzone (Upper Austroalpine):**
- Juvacic nappes (Mesozoic cover)
- Tirolan nappes (Mesozoic cover)
- Bavarian nappes (Mesozoic cover)
- Grauwackenzone (Palaeozoic, stratigraphic base of Tirolan nappes)

**Upper Austroalpine basement nappes:**
- Mesozoic cover of Upper Austroalpine basement nappes
- Drauzug-Gurktal nappe system (Tonfan series, Steinsch nappe, basement of Drauzug, Gurktal nappe, Graz Paleozoic)
- Ötztal-Bundschuh nappe system (Ötztal and Bundschuh nappes)
- Koralpe-Wölz high pressure nappe system (Schneebergzug, Millstatt, Wölz, Sauwalpe-Koralpe crystalline units)
- Silvretta-Seekau nappe system (Campo-Sesvenna-Silvretta nappes, Innbrucker Quarzphyllit, Schadming, Seekau, Seeminger nappes)

**Lower Austroalpine nappes:**
- Lower Austroalpine nappes (Elba, En-Bernina nappes, Radstätter Tauern, Wechsel nappe)
- Nappes derived from Margna-Sesia fragment (Margna-Sella, Sesia-Dent Blanche nappes)

**Various units:**
- Plio-Pleistocene (Pra-plain, Pannonian basin)
- Tertiary cover in general (Molasse, Rhine Graben, Intramontane basins)
- Oligo-Miocene post-tectonic cover (unconformable on Ligurian Alps and Apennine)
- Gosau beds (Late Cretaceous to Palaeogene post-tectonic cover of Austroalpine nappes)
- Periadriatic Intrusions

**Dinarides:**
- Tita unit
- Internal Dinarides (including ophiolite zones)
- External Dinarides

**Apennine:**
- Ligurian nappes
- Tuscan nappes

**Southern Alps:**
- Lower crust of the Southern Alps (breccia)
- Upper crustal basement of the Southern Alps
- Post-Variscan volcanic and sedimentary cover of the Southern Alps
- Adriatic micro-plate

**Penninic nappes:**

**Upper Penninic nappes (Piedmont-Liguria ocean):**
- South-Penninic ophiolites, Büchnerschiefer or Schistes Lustrés, Nappes Supérieures des Préalpes, Helminthoid flysch and Matrei mélangé

**Middle Penninic nappes (Briançonnais terrain):**
- Sedimentary cover of Middle Penninic basement nappes
- Middle Penninic basement nappes
- Detached Middle Penninic cover nappes ("Sub-Briançonnais" and "Briançonnais")
- Permo-Carboniferous sediments (Zone Houlleire) and their Mesozoic cover ("Briançonnais")

**Lower Penninic nappes (Valses Ocean):**
- Tertiary flysch sealing Lower Penninic accretionary prism (Cheval Noir Flysch)
- North-Penninic ophiolites and Büchnerschiefer (including Rhenodanubian flysch)

**Sub-Penninic nappes (distal European margin):**
- Mesozoic cover of Sub-Penninic basement nappes (including cover of "Gotthard Massif")
- Non-eclogite Sub-Penninic basement nappes (including "Gotthard Massif")
- Eclogite Sub-Penninic basement units

**Northern Alpine foreland and Helvetic nappes:**
- Helvetic and Ultra-Helvetic nappes (including Combeenot and Tavetsch "Massifs")
- Helvetic flysch
- Subalpine molasse
- Deformed autochthonous and para-autochthonous pre-Tertiary cover of the northern Alpine foreland (including the Jura Mountains)
- Deformed pre-Tertiary cover of the Northern Alpine foreland
- External massifs of the Alps and Variscan basement of the Northern Alpine foreland
1.3.1 Regional Geology

The study area lies in the Northern Calcareous Alps, embedded between the Karwendelgebirge in the west and the Rofan in the east. These are part of the Eastern Alps. The "Cstalpin" makes up almost the entire part of the Eastern Alps (Pfiffner 2015).

These thin skinned nappes are transported several tens of kilometres to the northwest. The sedimentation region of the Northern Calcareous Alps is located on the northernmost part of the Adriatic Microplate (Ortner, 2005).

The sedimentary rocks of the Northern Calcareous Alps lie on a pillow of Pennine nappes. The Northern Calcareous Alps already became a complex during the Cretaceous period (Pfiffner 2015).

This can be seen recently in complicated stacking of different geologic units. Tectonically, this unit lies on the Greywacke zone and has sedimentary contact with it. The Tirolic nappe is stratigraphically located on the Bajuvaric nappe (Ortner, 2005).

The Achensee is not located in a pure rock basin. The valley is filled during several glacial-interglacial periods in the Quarternary. A side arm of the Inntal glacier has excavated a cavity of 11km length and 150m minimum depth into this burial, which remained as Achensee after the melting of the ice masses (Ampferer 1929).

In glacial periods, the previously partially filled valleys are excavated and deepened. This glacially-eroded valley is partially filled with sediments during postglacial times. Subsequently, the excavated morphology is successively filled by sediments, which in turn depend on climatic factors (Ivy-Ochs et al. 2008).

The focus of this thesis lies in the seismic investigation of mainly postglacial deposition.
Figure 4: GEOFAST (Geologische Bundesanstalt 2008, 119 – Schwaz)
Figure 5: Legend for fig. 4 (Geologische Bundesanstalt 2008)
1.3.2 Quaternary

The Quaternary describes the most recent stratigraphic system of the Cenozoic and covers a period from 2.6 Ma to today (Gibbard 2010).

A distinction is made between the Pleistocene and the subsequent Holocene. According to previous observations, the border between the periods is dated to 11,700 ± 99 years B. P. (Walker et al. 2009).

The Quaternary follows the most recent series in the Neogene, the Pliocene. The transition from the Pliocene to the Quaternary is characterized by a climatic degradation. Climatic fluctuations cause changing temperatures and precipitation. Geophysical parameters, for example temperature, determine the prerequisites for isotope ratios. Global climate archives such as the Greenland Ice Sheet (GIS) can be used to compare relative depletions or enrichments (Spötl et al. 2006).

At the beginning of the Quaternary, Earth’s climate changes fundamentally. This takes place between 2.8 and 2.4 Ma and influences the atmosphere, the oceans and the morphology of the affected landscapes. The prerequisite for understanding the dynamics of alpine glaciers is detailed mapping and interpretation. This requires a connection between morphological and lithostratigraphic relationships in the field (Ivy-Ochs et al. 2008).

The glaciation in the Northern Hemisphere is associated with a cooling of the climate in the Cenozoic. This is related to the obliquity cycle of Earth’s rotation axis. In connection with this, the ice masses grow enormously. The expansion of the ice sheets, with rising albedo in the Northern Hemisphere, leads to a long-term cooling of the climate (Head et al. 2008).

From the state of research it is known that the last glacial period is characterized by rapid climate changes. Interesting is the rate at which the climate changes. The temperature dependent δ¹⁸O values in stalagmites, from northern European Alps stalagmite chronology (NALPS), show fundamental parallels to the δ¹⁸O values of the GIS (Moseley et al. 2014).

Climate is characterized by an alternation of warm periods (interglacial) and cold periods (glacial). These fluctuations cause several large glacier advances and retreats, which clearly affect the morphology of the formerly glaciated areas. As a result, quaternary deposits remain, which can be used retrospectively to reconstruct the dynamics during this phase. This dynamic leads to a rise in inner-alpine valley floors. Locally, this is due to damming caused by alluvial fans or glacier moraines (Mair et al. 2016).
During climax of the last glacial maximum (LGM) in the Würmian, the glaciation of the Alps is well known. The Achensee area is deeply covered under ice (Reitner et al. 2004).

![Map showing the network of valley glaciers during the LGM](image)

*Figure 6: Network of valley glaciers during climax of the LGM, red: study area (Reitner et al. 2010)*

The contour lines show the altitude of the glacier surface during the LGM. The figure shows the extensive distribution of glaciation in the northern part of the Eastern Alps. The glaciation leads to a network of transfluence passes within the ice streams. At the LGM, the ice sheet extends far into the northern foreland. The area around the Achensee is located in an inner-alpine position between the Inn valley in the south and the Molasse basin in the north.
1.3.2.1 Climatic Fluctuation

Dependent on global climatic variations, the glaciers of the Alps, have been alternately retreating and advancing. This is synchronous to global ice volume maximum of Marine Isotope Stage (MIS).

![Diagram of climatic fluctuations](image)

*Figure 7: δ¹⁸O variations 67 – 34 kyr. Red numbers represent DO events in Greenland Ice Cores. Vertical blue bars indicate periods of speleothem growth cessation; A: Speleothems (NALPS, Höll: Höllloch Cave, green: Höll-16 and Höll-17, red: Höll-7, blue: Höll-7, Höll-16, Höll-17, Höll-18 (VDPD); B: North Greenland Ice Core Project (NGRIP) – (VSMOW); C: Northwest Iberian Margin marine sediment core planktonic foraminifera δ¹⁸O; D: Chinese Speleothems: Hulu Cave (Moseley et al. 2014)*

Speleothems are a good climate archive. Isotope (O-Isotopes) ratios can be compared with standards using a mass spectrometer. Speleothems from Kleegruben cave provide information about climatic fluctuations over time in Central Europe (Spötl et al. 2006).
Changes in δ¹⁸O values from NALPS correspond to those of the Kleegruben Cave. Relative differences in δ¹⁸O values between the two cave sinters can be attributed to altitude and different locality in the Alps (Moseley et al. 2014).

By comparing the δ¹⁸O values from the Alps with global data (Northwest Iberian Margin marine sediment core planktonic foraminifera δ¹⁸O (NW Iberian Margin), Chinese speleothems (Hulu Cave), an equally large similarity can be found.

Dansgaard-Oeschger (DO) events describe abrupt warming periods on a millennial-scale. The DO events have a particular effect in the northern hemisphere. A rapid global warming affects the global thermohaline circulation, which in turn causes a gradual but steady cooling of the atmosphere after warming (Erhardt et al. 2018).

Alpine glaciers are highly sensitive archive of the climate in extension. For better understanding it is necessary to reconstruct glacier recessions with full amplitude of changes in glacier ice (Hormes et al. 2001).

From 18kyr on, in the late Würmian, about 80% of the ice mass had disappeared, with gradually retreating glaciers of the Alps (Ivy-Ochs et al. 2008).

Due to a lack of vegetation and the presence of large amounts of unconsolidated material, coupled with the extensive transport capacity of large river and glacier systems, the transport of sediments reaches a maximum. The sedimentation rates also attain maximum values (Strasser 2007).
1.3.3 Stratigraphy and Sedimentary Evolution

Lacustrine sediments are an excellent climate archive. Sedimentation is the product of erosion processes. These are influenced by the hydrological cycle which is directly related to the climate. Thus lakes act as reservoirs for clastic material coming from the slopes of the catchment area.

*Figure 8: Processes of sediment dispersal and associated deposits within a lake basin dominated by clastic sedimentation. Dimension and thicknesses are not to scale (Schillereff et al. 2014)*

The inflows of a lake cause the sediments to diffuse in their deposition area. Depending on relative density differences between the water and grain fractions, several facies can be distinguished. The physical mechanisms control the movement of the particles leading to sedimentation (Schillereff et al. 2014).

This causes the deposition of coarse-grained material in the delta area and fine-grained material in the basin area.

The sediments in the investigated area are transported by fluvial and glacio-fluvial processes into a lacustrine environment. The features of elongated inner alpine lakes can in many cases be observed (Lago Maggiore, Lake Annecy, Lake Lucerne).

They are characterized by rapid sedimentary filling following glaciation. Many lakes were formed during Holocene. Such fjord-lakes are characteristic for a previously glaciated mountain range (Van Rebensbergen et al. 1997).

In the Achensee area, several extensive glacier systems play a disparate important role as smaller systems. The sedimentary catchment area includes the Inntal glacier, the Zillertal glacier as well as several smaller glaciers of the eastern Karwendel and the western Rofan.
The Inntal glacier is an extended glacier system during the last Glacial. The ice masses reach in the region of Schwaz up to an altitude of ~2100m and close to Achenkirch ~1700m (Fuhrmann 2017).

The sediment sources from the Central Alps as well as from the Northern Calcareous Alps contribute significantly to the sedimentary development. Each of the glaciations is characterized by a depositional sequence. These are usually erased or at least overprinted by following propagations of glaciers. This is referred to as glacial erosion. A sequence usually comprises subglacial erosion followed by glaciolacustrine sedimentation. Afterwards glacio-deltaic sedimentation usually occurs (Reitner et al. 2010).

Since several glacier advances have mostly eroded previous glacial deposits, it is difficult to resolve a complete development. The preserved sediments in the foreland of the Alps, as well as in the inner-alpine sediments, can be useful to comprehend the development and dynamics of these processes.

Four large glaciations (Günz, Mindel, Riß and Würm) are documented for Middle Pleistocene and Young Pleistocene. These are marked with sediment sequences from the advance or readvance phase superimposed by basal till, terminal moraines in the foreland and associated terrace fills and loess accumulation (Van Husen 2011).

Over time it has turned out that there have been many more glacial and interglacial cycles. In an attempt to obtain older information about the climate, it is therefore necessary to resort to other archives. Sediments from the deep sea, ice cores (e.g. NGRIP, Greenland) or cave sinter are suitable for this purpose. δ18O Data from benthic foraminifera are used as the global climate archive (Fuhrmann 2017).
Figure 9: The diagram shows isotope data of benthic foraminifera from deep sea cores with δ18O on the Y-axis (Lisiecki & Raymo 2005). An increase of the δ18O values correlates with temperature decrease and vice versa. The boundary from Neogene to Quaternary marks a global cooling trend. This is linked to an increase in the amplitudes of climate fluctuations. The most recent period is shown in the lower part B. The last four great ice ages are shown here. Uneven numbers refer to warm periods and even numbers to cold periods. The roman numbers indicate the phases where an ice age was ending (Raymo 1997, changed after Fuhrmann 2017).

Seismic stratigraphy data contains information for the analysis of structures and subsurface geology. The stratigraphy needs to include similarities to references to enable comparisons. At the beginning relevant information is collected from the geophysical investigations. Basically, a discrimination of seismic events and artefacts is needed. The seismic method is influenced by physical restrictions. An advantage of seismic stratigraphy for geological studies is the combination of observations on different scales (Veeken et al. 2013). The analysis of seismic facies is important for the interpretation of seismic data. If there are differences in reflection properties within a profile, seismic facies can be distinguished and characterized in stratigraphy. The units are either glacial or postglacial depositional sequences, including deltaic or lacustrine sediments (Ndiaye 2014).
Figure 10: Active processes during subaqueous moraine formation (Strupler 2012 after Powell et al. 1995)

Figure 10 illustrates the glacio-lacustrine setting in proximal region to a glacier. The sediments are eroded and transported by different processes. The ice mass itself erodes lateral slopes (supraglacial debris) and the basal surface (basal debris) parallel to the flow direction. The sediment input into the water depends on the type of transport. A distinction is made between e. g. gravity flows or subaqueous outwash plume.

The depositional facies are defined according to their character and spatial distribution. During the deposition of glacigenic material a combination of dumping, melting-out, bulldozing and accumulation from subaquatic outwash occurs. A glacigenic sediment is formed which has a wide range of grain size distribution (Strupler 2012).

By considering the differences between proximal and distal sedimentation areas, a decrease in sedimentation rates can be observed. It is possible to differentiate facies based on the glacio-lacustrine environment.

Climate and glacier extent in the Quaternary has a highly dynamic nature. So the deposits can be interbedded with sub- and supraglacial tills (Gilles 2012).
The further we move in the direction of the distal area, the more fine-grained the deposits become. In the area of the topsets, sands and gravel are deposited while the foresets consist of sandy sediments. By slumping during different events, debris-flows are transported from the foreset into the bottomset.

These turbidites are deposited next to the background sedimentation in the basin. This in turn is caused by the settling out of suspending sediments.

**Figure 11**: Glaciolacustrine sediment system (Gilles 2012 after Hambrey 1994)

1.3.4 Development of the Achensee and Achenseeschwelle

The Achensee lies in the north-south running Achental. It is bordered in the north by a rocky barrier near Achenkirch (940 m a. s. l.) and in the south by the Achenseeschwelle. In the west there is a wide delta near Pertisau which recently has a fluvial origin. The catchment area comprises the Gern-, Falzhurn- and Dristental, which were investigated by Fuhrmann in 2017.

Already Ampferer (1905, 1936) and later Poscher (1993) investigated the question of the function of the Achenseeschwelle and outlined a scenario that is still accepted today. In this scenario, the Achensee, as a former glacier-margin lake, first drained to the south into the
Inn valley. The extensive Inntal glacier system, retreated after the LGM of the Würmian-Ice Age was reached.

Then a readvance of the Zillertal glacier occurred and dammed the Achensee which forced the water to drain to the north. The Achenseedamm is constructed on the basis of a construction principle as follows. The built up of the dam can be divided into four phases (Poscher 1993):

Phase 1: An increased sediment accumulation rate in the direction of the Inn valley by lateral alluvial fans causes a barrier and thus a damming of the lake. The increased accumulation rates in the Inn valley and its side valleys are of glacial origin. This is documented by scarified bedloads within the banded clays of the Kasbachgraben (Paläoachensee). These sediment deposits can be interpreted as outwash of the Zillertal.

Phase 2: Western of the Kasbachgraben, the concept of Penck (1902) could be supported. Thus, the Achenseedamm is a product of accumulation nearby to ice in the approach of a glacier advance from the Zillertal. In this phase the silting up of the Paläoachensee by progressive accumulation of pro- and marginal glacial sediments occurs.

Phase 3: Within this phase the dam construction is completed. This is done by a delta complex up to 150m in thickness. Deltasediments can be detected in today's Achensee sedimentary infill. The direction of the debris flow is to the north (Zillertal Glacier). The sediment input from the Inn valley is of secondary importance.

Phase 4: To date of the study by Poscher, there was no evidence that the dam has been overrun by central alpine ice masses. The grain spectrum, the extent of glacial reworking of the components and the small thicknesses argue against a distal moraine. At Eben, close to Maurach, an isolated ground moraine deposit is located at 940m a. s. l., over the level of the Achensee. This can be an erosion relict of the maximum level of the Zillertal glacier.

Later this hypothesis of Poscher could be partially refuted. Based on the findings of Ampferer, who describes a more or less continuous ground moraine, it is described that the Achental was crossed by penetrating glacier from the Zillertal and the basin of the Achensee was excavated (Fuhrmann 2017).
Figure 12: The formation and genesis of the Achensee (Poscher 1993)
Figure 13: Profile through Achenseedamm [Poscher 1993]
According to the outcrops along the Kasbachgraben, carbonate clastic conglomerates lie at the base. In the northwestern part of the profile, these are overlaid by banded clays. Towards the southeast the sediments turn into pro- and marginal glacial deposits. Within the pro- and marginal glacial deposits there is a local ground moraine in the area of Fischl. In the Eben terrace, the deposits are covered by delta sands and delta gravel.

The hydrogeological conditions changed due to a readvance of the Zillertal Glacier, which formed the Achenseeschwelle penetrating from south to north and subsequently leading to the drainage of the Achensee to the north (Poscher 1993).

Previous investigations concentrated on the Achenseeschwelle near Maurach at the southern shore of the lake. The results of the geophysical method and rotational core drilling were compiled and interpreted. A facies model is outlining an advance of the Zillertal Glacier serves as a fundament (Burger et al. 2011).

Within the investigation of Burger et al. 2011, the assumptions of Poscher (1993) were examined. These results can be confirmed in principle. The "Zentralalpinen Kiese" overlay the "Zentralalpinen Sande" and underlie in the southernmost part of the Achensee.

The thickness of the Zentralalpinen Kiese (gravel) varies between 30m and 50m. The thickness decreases from east to west. The gravel shows a coarsening upward. Within the gravel, the degree of rounding and the proportion of crystalline components are conspicuous. The components are also coarser to the southeast and sandier in their matrix. To the northwest, the grains become finer and the matrix of the unit more silky.

The gravel is locally overlaid by debris, which in turn are overlaid by matrix-supported gravel. These have a high density and carry scarified debris. Thus they are called moraine. The moraine is buried under thin debris which changes into fine-grained, lacustrine sediments (clays, silt and fine sands) towards the west.
The unit of the Zentralalpinen Sande is characterized by components with a finer grain size. The base could not be drilled during the investigation.

The geological cross section in fig. 15 illustrates the stratigraphic situation of the Achenseedamm.

*Figure 15: Geological map of the Achenseedamm (Burger et al. 2011), Legend: figure 14*

- Seetone bis Silte
- Murschutt
- Moränenmaterial
- Wechsellagerung zentralalpine Kiese und Schwemmkegelablagerungen
- Zentralalpine Kiese
- Zentralalpine Sande kiesführend
- Zentralalpine Sande
- Hangschutt
- Ton
- matrixgestützter Kies
- sandiger Kies
- kiesführender Sand

*Figure 16: Legend of the geological map (fig. 15)*
Figure 17: Geological cross section along profile between S2/01 – S10/02 & S6/02 – S11/02 (Burger et al. 2011). Legend fig. 16
2 Methods

2.1 Principle of reflection seismics

In general it is about the determination and distribution of physical parameters by using non-invasive measurements. The applied methods are chosen according to the physical properties of the material to be investigated. Seismic reflections are generated by impedance contrasts. A high quality of the data is of fundamental importance. This is directly related to the resolution. A source emits waves with low and high frequency over a certain bandwidth. Furthermore, a good signal to noise ratio plays an influential role. The base for this is the avoidance of disturbing factors: noise (Nanda 2016).

Differences in density between various materials cause changes in propagation velocity of seismic reflections. The acoustic impedance (AI) is defined as follows (Veeken et al. 2013):

\[ AI = pV \]

\((p = \text{density})\)
\((V = \text{propagation velocity})\)

At a transition from medium 1 to medium 2 the density and propagation speed changes, the waves break according to the laws of Snell's Law:

\[ \frac{\sin \theta_1}{V_1} = \frac{\sin \theta_2}{V_2} \]

\((\theta_1 = \text{angle incident wavefront})\)
\((\theta_2 = \text{angle transmitted wave in second medium})\)
\((V_1 = \text{propagation velocity of seismic energy in first medium})\)
\((V_2 = \text{propagation velocity in second medium})\)

Rock physical parameters like density and seismic velocity of the traversed lithological unit play a key role and affect the amplitude of the reflected wave. The amplitude is proportional to reflection strength (Veeken et al. 2013).

Fig. 18: Acoustic sound waves are affected by the density and velocity of the interface. The interface is an acoustic impedance contrast. The figure shows reflected and transmitted plane wavefronts. Snell’s Law applies to the interface.
When calculating the seismic wave velocity, the propagation velocity and density have a major impact. In addition, a number of parameters are important, such as mineralogy, porosity, grain size distribution, saturation, pore fluids, temperature, etc. Based on these physical parameters velocity and impedance can be related to rock properties (permeability, porosity, stress, lithology, pore fluids and temperature). Rock specific values in nature can only be modelled since their modulus of elasticity increases more than their density (Avseth et al. 2005).

E.g. the Sparker system setup has a near-vertical incidence on the sediment layers, the emitted waves hit the ground vertically. With a short length of the streamer, which means a close position to the seismic source, we are able to analyse the depth of the Achensee. Seismic impedance and their contrast is a product of seismic velocity and rock density. The amount of energy reflected at a boundary layer is called reflection coefficient. The seismic structural attributes can be discriminated by differences in the subsurfaces (Zhang et al. 2015).

The vertical resolution of the seismic data is significantly influenced by the following parameters: frequency of the seismic signal and its bandwidth, interval velocity and acoustic impedance contrast (Veeken et al. 2012), while the horizontal resolution is depth-dependent of reflections in the investigated area (Fresnel Zone).
Depending on different frequencies the collected data shows variable results in penetration depth and resolution. As a „rule of thumb“, we can assume that the resolution is quarter of the wavelength. The wavelength is defined as the P-wave velocity divided by the frequency (Rayleigh Criterion).

2.1.1 Seismic Data
In this investigation, seismic reflection method is used to image sedimentary deposits overlying substratum. Above all we get a detail view of quaternary sedimentary infill. For this purpose, a spatially dense grid of data was created to provide complete information about the depositional architecture of the subsurface. The focus is on the southeastern part of the lake, between Pertisau and Maurach. The created data set can be applied for a division of the stratigraphic and seismic units.

The instrument principles that are most commonly used for single channel Seismic methods are Pinger- and Sparker systems. Depending on the proportions of reflected and transmitted wave energy it is possible to calculate the reflection coefficients of different facies.

There is a need for balance between penetration depth and resolution quality for the seismic profiles. By balancing pros and cons for the best results we have to fit different frequencies to different settings in the field. Using high frequency systems (Pinger) will provide shorter wavelengths which lose energy much faster through attenuation than low frequency systems with larger wavelengths (Sparker). Additionally the Pinger system uses piezoelectric transducers whereby the sender is simultaneously the receiver. Within the Sparker system, an electric discharge is used as a sender and a streamer functions as a receiver. For recording the location, there is a handheld GPS device (GARMIN GPSMap 78 GPS) which allows relative exact navigation.

For the collection of the Pinger data an aluminium boat connected with a cataract is used. The vessel was provided by Toni Kandler (TIWAG) during the research project. For the collection of Sparker data the vessel "Luna" of the Research Department of Limnogeology (UIBK) is used (Oswald 2017).
2.1.2 Pinger Reflection Seismics

Pinger system transmits single frequency (3.5 kHz) in a single pulse with a shot interval of 0.3sec. With this method we get a vertical resolution of 10-20cm and a horizontal resolution (in 100m depth) of ~9m. Pinger system is using high frequency (3.5 kHz) leading to high resolution with low penetration depth. The Pinger data allows us to analyse shallow layers and their structures. We can distinguish natural and artificial structures, such as a multiple of the Stratigraphy which can be identified by a double slope angle or seismic artifacts like hyperboles. Furthermore we need to process with the bandpass filter to reduce noise from the environment.

*Figure 19:* Equipment for Pinger data collection, top: aluminium vessel with cataract; sender adapted to cataract, lower: Seismic data acquisition on board
2.1.3 Sparker Reflection Seismics

The Sparker system is using lower frequency (1 kHz) for deeper penetration and hence the result is a lower vertical resolution of 37-75cm and a horizontal resolution of ~17m. The advantage of deep penetrating waves allows the identification and discrimination of deeper facies concretely.

The high voltage Sparker is equipped with 400 electrodes, for underwater spark, by producing sound at a shot interval of 750ms. With this method in fresh water it is better to pack the Sparker in a plastic bag and to fill it with salt water. The electrodes discharge better in salt water. In order to achieve the best results, variable energies (300J - 600J) were used at the inception of the examination. At 400J it appears that the recordings were the best and so the work is done by now. In the acquisition unit a bandpass filter is applied (High pass 100-200Hz/Low pass 50-100Hz).

*Figure 20: Equipment of the University of Ghent, top: Sparker in plastic cover, lower: data acquisition*
2.1.4 Acquisition of data on Achensee

Pinger source seismic surveys were collected during a class led by Jasper Moernaut and Michael Strasser between 28-06-2016 to 29-06-2016 and 06-06-2017 to 09-06-2017. Students of the University of Innsbruck took measurements of about 90km in total, especially in the SE basin.

The Sparker seismic surveys were conducted between 30-10-2017 and 03-11-2017 using a so-called "Centipede". This Sparker represents the seismic source and a single-channel streamer equipped with a total of 10 hydrophones functions as a receiver. This device was developed at Ghent University. The seismic source and the receivers are attached to the end of the vessel and pulled over the surface of the water by a cable with 20 meters distance to the boat. The positioning is guaranteed by a GPS system, which is also attached to the vessel. The GPS has an accuracy of +/- 5m and is positioned in the middle of the vessel. The total length of the measuring device is about 22m.

On board there are also two generators which are responsible for the energy supply, one for triggering the electric discharge, the other one for two laptops, one for navigation and the other one for seismics. For the depiction and profiling the data we need to convert (DA-Converter) the raw data into a digital SEG-Y format.
2.1.5 Seismic Stratigraphy and Modeling

The seismic data processing was accomplished with KINGDOM SUITE 8.5 package (The Kingdom-Software 2018). Based on a detailed seismic stratigraphic analysis, four different units are defined. These units can be observed over the entire sedimentary infill in the Pertisau basin.

Figure 21: Seismic overview Profile, general introduction
The figure 21 is intended to give an overview for seismic reflections. In the lowest part of the profile the first multiple of the stratigraphy is clearly visible. Due to double reflection within the layers, multiple stratigraphy is produced. This is characterized by a double slope angle and can thus be definitively identified.

Unit 1 is lying on an erosive unconformity and Unit 4 is the uppermost unit. The reflection amplitudes of the four units vary. It is important that the profiles are provided in time domain and not in depth domain. The depth can be calculated via the two-way-travel time (TWT). Since the different units have different wave specific velocities, the vertical scale is given in TWT. The absolute thicknesses were calculated and shown in Chapter 3. 2: Isopach Maps. Thus, pay attention to increase of velocity acceleration with burial depth in vertical direction.

3 Results

3.1 Seismic Units

Due to different geophysical properties different units can be defined. In the following, these are described and the main properties are mentioned. These differences lead to different reflections with variable amplitudes. If the amplitude changes, it is possible to follow a laterally trackable signal and create a horizon. From several 2D profiles, grids can be calculated which are shown in the chapter 3. 2 (Isopach maps, fig. 29). The horizons from Kingdom are exported as .dat file. To convert the data into a grid they were imported into the Surfer software 11 and the interpolation method “kriging” as gridding method was used. These grids can then be imported into the ArcMap 10.6 software and be georeferenced there. The individual profiles without interpretation are included in the appendix.

3.1.1 Acoustic Basement

The unit described here as acoustic basement refer to the lowest, still detectable reflections. The transmitted seismic waves decrease with increasing distance due to attenuation. This is caused by the inelastic properties of the material and the geometric spreading of the energy. In lower sections, the reflections are often in the range of the first multiple. As a result, discrimination can be difficult.
In the study area, the horizons were picked conservatively. In places where the horizons can be definitely identified, the line is drawn through. In order to establish a logical connection, the continuous lines are supplemented by dashed lines. The example shows a profile from the middle of the Pertisau Basin. When considering the acoustic basement it can be observed that the valley incision, before the sedimentation of the following units, was much narrower than today.

3.1.2 Unit U0

Between the acoustic basement (light blue – fig. 22) and the main unconformity (dark green – fig. 23-27) is the unit U0, which is the remnant of a previous deposition sequence. The seismic unit is the erosion residue left over from the advance of the ice masses during the last glaciation. All following units are deposited on the unit U0. If we look at the substratum under the unconformity in the southeastern part, in the area of the mud flat, several reflections can be distinguished.

Figure 22: ACHSP107 - Acoustic Basement in a WSW – ENE profile, dashed line represents interpolated correlation.
Over an older unconformity (dark purple – fig. 23) several horizons can be differentiated. In direction of the Achenseeschwelle chaotic reflections appear at the old unconformity. In direction of the basin, these are overlaid by parallel reflections. Above it follow low amplitude reflections, which in again are overlaid by high amplitude reflections. If we consider the geometry of the reflection horizons, we notice that they run horizontally until the unconformity cuts through. Here the geometry changes by a truncation, which is an erosional structure. The presence of hyperboles additionally point to an uneven surface below the unconformity in the southeastern part.

*Figure 23: ACHSP01 - Transition from mudflat to Pertisau Basin in SE – NW profile, note the structural differences under dark green unconformity.*
3.1.3 Unit U1

3.1.3.1 Subdivision Unit U1a and U1b

The unconformity cuts these reflections. The higher reflections of the units 1-4 differ considerably in amplitude and geometry. Unit 1 is characterized by high, continuous amplitudes of the reflections. It is located between the unconformity and the U2 unit above it. Geometrically, an onlap of the reflections can be detected in this area. In the deeper Pertisau Basin the unit U1 can be subdivided into two further units, U1a and U1b.

![Diagram of stratigraphic section with hyperbolae and onlap](image)

*Figure 24: ACHSP29 – Detail view of the substratum structures in SE – NW profile, two generations of unconformities*

U1a - High amplitudes can be observed in the lower part of Unit 1 - U1a. The continuous distribution of the high amplitude reflections can be determined in the entire unit. The unit is characterized by a medium continuity. The stratification of the unity is rather chaotic. The irregular reflections are deposited as an onlap.
U1b - The upper part of the subdivided unit U1 is characterized by lower amplitudes. Especially in the middle of the profiles the low amplitudes of the reflections are distributed highly continuous. In the marginal areas close to the lateral slopes some high amplitude reflections can be detected (fig. 25). The reflections are characterized by lower amplitudes and higher continuity than U1a. The principle stratatal configuration of stratification is subparallel. The unit can also be called onlap which fills up the existing surface.

Geometrically, the entire unit U1 can be expressed as sedimentary infill. The deposits fill the deepest part of the morphology created by the unconformity. Here the term onlap fill is used (Mitchum et al. 1977).

*Figure 25: ACHSP25 – WSW – ENE profile*
3.1.4 Unit U2

Low to medium amplitudes can be observed in unit U2. The signals run within the unit with a high continuity. High amplitude reflections are only observed in a few areas, such as in the southeastern region, in the direct proximity of the Achenseeschwelle. The structures within the unit are subparallel to parallel. The Unit U2 On the relative regular top of the unit U1b, the sediments of the unit U2 are an onlap which is called onlap fill. The unit U2 is massive in the area of the Pertisau Basin. Towards the Pertisau Delta the unit becomes increasingly thicker.

*Figure 26: ACHSP08 – Distribution of seismic units in shallow to medium deep Pertisau Basin*
3.1.5 Unit U3

On the Unit U2 lies the Unit U3. This unit is composed of reflections with variable amplitudes and variable continuity. Low and high amplitudes alternate.

If we look at the structures in detail, we notice that apart from irregular, chaotic and discontinuous reflections there are also areas with subparallel geometry. Particularly in the transition area into the deeper basin prograding clinoforms with sigmoid structure can be observed. The filling system is a chaotic infill.

*Figure 27: ACHSP78_002 – Seismic unit distribution from medium to deep Partisau Basin*
3. 1. 6 Unit U4

The uppermost unit in seismic stratigraphy is U4. Here, low and medium amplitudes alternate in the reflection characteristics. These are present in the entire investigation area with a high continuity.

The reflections are distributed continuously and parallel. The structures remain the constant over the Pertisau basin. This unit is the result of recent sedimentation. The geometry of the deposits within this unit is called drape and this top unit U4 is well stratified.

The inflows (e. g. Falzthurnbach, Pletzachbach, Oberaubach) lead to different sedimentation rates over the annual course in connection to seasonal fluctuations in precipitation.

*Figure 28: Pinger 060617.082507 – Recent lacustrine sediment structures in WSW – ENE profile*
3. 2 Isopach and Isodepth maps

The Isodepth maps show the lower limit of each unit. For the calculation of the total depth of the different layers the water surface at a height of 929 m a. s. l. was used as zero point. Subsequently, different wave velocities (Pinson et al. 2013) for the different units and the water for the true depth are calculated by converting from time to depth.

<table>
<thead>
<tr>
<th>Seismic stratigraphic facies</th>
<th>Key characteristics</th>
<th>Velocity (ms⁻¹)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1a</td>
<td>high amplitude, low continuity</td>
<td>~2300</td>
<td>proximal proglacial</td>
</tr>
<tr>
<td>U1b</td>
<td>low / medium amplitude with high amplitude domains, medium continuity</td>
<td>~2100</td>
<td>glaciofluvial</td>
</tr>
<tr>
<td>U2</td>
<td>medium amplitude, high continuity</td>
<td>~1500</td>
<td>distal proglacial</td>
</tr>
<tr>
<td>U3</td>
<td>low / high amplitude, low continuity</td>
<td>~1500</td>
<td>mass transport deposits</td>
</tr>
<tr>
<td>U4</td>
<td>low / high amplitude</td>
<td>~1490</td>
<td>lacustrine sediments</td>
</tr>
</tbody>
</table>

Figure 29: Table with key characteristics for seismic stratigraphic facies, velocity calculation and interpretation after (Pinson et al. 2013).

A) The through shape of the valley at the base of Unit 1 is remarkable. This isochronous map shows the surface of the unconformity.

B) The thickness of the unit U1a is heterogeneously distributed along the unconformity. As can be seen in chapter 3. 1. 3. 1, the unit becomes thicker from southeast to northwest. The sediment filling takes place on the unconformity and is strongly focused on the deepest parts.

C) By the sedimentation of the unit U1a, the valley incision of the unconformity is filled and thus the valley shape is wider and flatter.

The following Isodepth maps with their contour lines always illustrate the base of the unit. The depth U1 (fig. 30) is the total depth of the main unconformity (dark green).
Figure 30: Isodepth map: depth U1 = unconformity; Isopach map: thickness U1a
Figure 31: Isodepth map: Depth U1a; Isopach map: thickness U1b
D) It is obvious that the upper part of the unit U1 - U1b in the deeper area of the Pertisau Basin gains significantly in thickness. Sediment input is expected to occur from southeast to northwest.

E) The subdivisions U1a and U1b are actually distinguished by their amplitude changes. The upper part U1b is characterized by lower amplitudes. In detail, some areas within U1b have high amplitudes. Along the lateral slopes of the Pertisau basin, sediment input from the channels leads to the distribution of the U1b high amplitude at the margin of the investigated area.

F) The sediment input of unit U1 leads to a flatter valley bottom on which unit U2 is deposited.
Figure 33: Isodepth map: depth U2; Isopach map: thickness U2
Figure 34: Isodepth map: depth U3; Isopach map: thickness U3
Figure 35: Isodepth map: depth U4; Isopach map: thickness U4
G) In the distribution of the thickness of the unit U2 we can observe the unit becoming thicker towards the Pertisau delta. This indicates that the input comes from the direction of the Pertisau delta. As shown in Figure 33, the unit is homogeneous and continuously deposited. The thickness in the Pertisau Basin increases from east to west. A big difference to the underlying U1 is the direction of the input.

H) The figure shows the absolute depth at which the unit U3 is deposited. The sedimentary input from the Pertisau Delta changes the shape of the valley. The inflow from the Pertisau delta is leading to the deposition of Unit 2 which affects the surface becoming broader. So the unit U3 is deposited on a flatter valley shape.

I) Thickness of the unit U3 is variably distributed in the investigated area. There is no clear direction of sedimentary input. This indicates that the unit, which is characterized by chaotic amplitudes, comes from several directions. In other words, the debris comes from lateral slopes as well as from surrounding deposits. During this deposition phase, mass transport deposits occur irregularly as a result of gravitational processes. There is a clear difference to fluvial processes which lead to sediment deposits.

J) After the deposition of the unit U3, the lake bottom can be differentiated into a deeper area, the Pertisau Basin and a flatter part, the Mudflat in the direction of Maurach. The flat course of the contour lines clearly shows the flat path in southeast direction.

K) The thickness of the unit U4 varies in meter range. Recent sedimentation takes place over the entire investigation area. The distribution of the reflections is relatively homogeneous. The unit is consistently continuous and can thus be discriminated as a drape.
4 Interpretation and Evaluation

After the evaluation of the seismic stratigraphy the following interpretations can be presented. With a comparison to other studies, the distribution of seismic stratigraphic facies indicates different sediment sources. According to other studies, parallels and differences can be detected for glaciogenic basins in the Alps and the Achensee.

In comparison with the study by van Rebensbergen et al. (1999) there are many similarities. Lake le Bourget has a glacial lake origin during the last glacial, the Würmian. The erosion surface originates from this phase and is characterized by a distinct unconformity. The investigation is a detailed evidence of sedimentary processes and their evolution during deglaciation. The basin fill is composed of five units. The sediment input is the result of major changes in sediment supply and style of discharge into the lake.

The substratum has parallel reflections and various reflections, as well as structures cut by an unconformity. The lowest unit is glacial deposits and corresponds to U0 in Achensee, followed by glacio-lacustrine sediments in Lake le Bourget which can be compared to U1 here. Above this, proglacial lacustrine fans were recorded, which in turn have large parallels with the unit U2. Next follow alluvial fan deltas that resemble the unit U3. This sediment load originates predominantly from steep lake slopes and became loaded with sediment that was prone to gravitational instability, leading to failure and downslope slumping. The lacustrine drape is described as the uppermost unit. This unit is formed after glacial, when terrestrial sediment input decreased and authigenic sediment production in lake increased forming this drape unit.

The largest difference to the study in Lake le Bourget is the position of the lake. While Lake le Bourget lies in the molasse basin as peri-alpine lake, the Achensee lies within the NCA and is therefore an inner-alpine lake.

A comparison with the study by Beck et al. (2001) reveals just as many similarities but also differences. The sedimentary infill of Lake Annecy is divided into five units. The lower two units 1 and 2 are an imbrication of subglacial and glacio-lacustrine deposits, which have similarities to the two units U1 and U2 in the Achensee. Unit 3 in Lake Annecy dates from a time of fast retreat of a glacier.
We can see a progradation on the lacustrine slopes in the form of slumps and debris flows. These phenomena take place in an alluvial regime and can be compared to unit U3 in the Achensee. A sediment drape follows above. This is a signature of Holocene interglacial climatic conditions.

In contrast to the Achensee, Lake Annecy, like Lake le Bourget, it is in a peri-alpine position in the molasse basin. Lake Annecy's infill cross-section is predominantly symmetrical. In addition, the infill thickness toward the basin edges (from ENE to WSW) decreases.

From this we interpret the lacustrine sediments of the Achensee as follows: Within Unit 1, the thickness maps indicate a southeast to northwest infill. The filling of the former valley bottom takes place along the valley, cut in by the unconformity, and is characterized by clastic sediment input which is indicated by stronger amplitudes of the reflections. Furthermore, the formation of artifacts (i.e. hyperbolas) at the unconformity in fig. 24 is an indication of an uneven surface. In addition, the unconformity cuts through older structures and enables the subsequent superposition by onlap structures. Both observations indicate an erosive unconformity.

Unit U2, on the other hand, decreases in thickness from the Pertisau Delta to the Pertisau Basin. It is obvious that the direction of the sediment comes from the delta from NW to SE. The deposition of this unit is homogeneous and continuous and has little impedance contrast. This lower energy environment is likely distal proglacial setting with typical fine-grained clastic varves and can be addressed as fine-grained glacio-lacustrine sediments. The then superimposed unit U3 has its origin in gravitational mass movements. After the strong delta propagation during U2, the delta slope instability leads to mass transport deposits into the basin. Furthermore, there is a clastic input from all sides as a result of instabilities from the steep lateral slopes of the lake.

The sediment infill of the investigated area is the result of dynamically variable sediment sources. Therefore these sources can be clearly distinguished.

The conclusions of Poscher (1993) and Fuhrmann (2017) raise the question whether the Achental was overrun by ice masses penetrating from the Zillertal and, in the process, scraped out the basin of the Achensee.
The damming of the Achensee against the Inn valley is realised by a loose sediment terrace. It elevates in two steps about 400m above the Inn valley. The construction is completed in four phases (chapter 1. 3. 4). Given the limited distribution of glacial sediments of the Zillertal glacier in the area of the Zillertal outlet and the restricted distribution of limestone base moraine in the western sector of the Achenseedamm, a late-glacial origin cannot be ruled out (Poscher 1993).

With the formation of the Achenseedamm in the Würmian, the erosion base rises to its present level. According to Heißel (1950), the three Karwendel valleys near Pertisau were once bays of the Achensee, but they rapidly silted up. The once deep valleys are now filled with up to 170m of loose material due to massive sedimentation. An investigation with geoelectrics and boreholes can lead to the conclusion that this is a closed area in which lacustrine silts and clays influence the landscape development. In shallow water, massive fine sediments could settle before a subsequent event deposited coarse clastic sediments. However, the lacustrine silts and clays were not deposited in a proglacial lake. In Falzthurntal and Gerntal there were no indications for proglacial settings, e. g. dropstones, during the Holocene, as Fuhrmann investigated in 2017.

If we now compare the results of this study to previous ones, many common features stand out. If these findings are compared with those of Burger (2011), parallel conclusions can be drawn. The "Central Alpine Sands" correspond to the characteristics of the Substratum and the unconformity, represented by unit U0. With low to medium reflection amplitude it clearly can be differentiated from the higher "Central Alpine Gravel". This unit causes stronger reflection amplitudes than the sands. The sedimentary units underlie the mudflat in the southeast of Lake Achensee and are structurally cut by the unconformity.

The structure of the transition area from the Achenseedamm to the Pertisau Basin represents an erosive unconformity of the surface on which the Zillertal Glacier traversed the Achenseedamm. The erosive surface cuts previous deposit structures discordantly. After erosion, coarser sediments such as gravel and sand are deposited (U1). Later massive fine sediments are deposited. Lacustrine sediments are deposited over the lateral valley of the Achensee (Falzthurn-/Gerntal) as far as the Pertisau Basin (U2). Then coarse, clastic sediments are deposited in various events (U3). Thus the assumptions of Poscher (1993) and Fuhrmann (2017) can be supported.
Water level = ca. 929 m a.s.l.

- Murschutt = debris flow deposit
- Zentralalpine Kiese / Schwemmkegelablagerungen = Central Alpine Gravel / alluvial fan
- Zentralalpine Kiese = Central Alpine Gravel
- Zentralalpine Sande = Central Alpine Sands
4.1 Deglaciation model

Figure 37: Deglaciation model under influence by the Zillertal glacier
Figure 38: Deglaciation model; top: lateral sediment input from distant small glacier systems; low: high amplitude reflections as a result
Figure 39: Deglaciation model; top: rivers from Pertisau delta with high sediment load; low: sediment input from lateral slopes and mass-transport deposits
4.2 Outlook

The Achensee contains an interesting sediment archive for geophysical investigations. Because this investigation only covers part of the sediments, the Achensee offers great potential for future investigations. A Seismic Stratigraphy Analysis north of the Pertisau Basin would be interesting. It would be advantageous to study the stratigraphy in the deeper part of the lake. Under certain circumstances such an analysis can trace the extent and distribution of terminal moraines and basal till.

Furthermore, the direct relationship of the quaternary sediments within the study of Fuhrmann 2017 and this study is unknown. The dynamic processes and correlations should become clear through a Seismic Stratigraphy Analysis and geo-electrics of the Pertisau delta. Thus it would be possible to correlate the separated depocentres, in the Falzthurn- and Gerntal, with the results of this study.
An investigation based on boreholes also promises success. In the southeastern part of the Achensee (mudflat) it may be possible to drill the unconformity which proves the overrun of the Achenseeschwelle by the Zillertal glacier. In this area the units are relatively thin and could be accessed by longcoring. The extraction of lake cores and the execution of onshore drillings are recommended. The seasonal and artificial fluctuations of the water level have to be taken into account when drilling in the southeastern part of the lake.

All in all, a future research promises further insights into the processes of quaternary lacustrine sediments in an inner-alpine milieu for better understanding of the influence of glacial to postglacial sedimentary evolution.

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