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Evolution of Late- to Postglacial River Confluences in Overdeepened Alpine Valleys – Saalach and Königsseeache (Austria)

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Postglacial evolution
Deep Alpine Valley
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Landslide
Salzburg
River

Abstract

A detailed analysis of 150 drill core logs was used to unravel the depositional history in the area of the Saalach and Köngisseeache confluences. The spatial distribution of fluvial and limnic sediments data provided new insights into the evolution of these confluences expanding into the Salzburg Basin, Bad Reichenhall and Piding basins after the Last Glacial Maximum.

The two rivers deposited their coarse sediments in the basin, producing delta fans that subsequently progressed towards the basin center, leaving behind beds of coarse-grained sediments in the otherwise fine-grained lake deposits. Short-term events, such as the melting of glaciers and landslides, played an important role in the sedimentary evolution of the Salzburg Basin.

The area at the Saalach confluence shows a basement high at the Walserberg. The basement high separates two basins: the upper, proximal Bad Reichenhall Basin and the lower, distal Salzburg Basin. The deposits in the upper basin reflect a large delta fan that developed in postglacial times, in combination with a braided-river system on top of the fan. The lower basin was filled by limnic sediments of the former lake in the Salzburg Basin. A large fluvial delta fan progressed into the lake at the time when half of the basin was already filled with limnic sediments. The progression of this delta fan is likely connected to flood events that were triggered by dam failures in fossil lakes near the melting glaciers. The sediment record at the Königsseeache river mouth reveals that several bergsturz events at the Untersberg forced the river to change its direction, leading to its present course.

Eine Studie von 150 Bohrlochdaten ermöglichte die Erfassung der räumlichen Verteilung pleistozäner und holozäner fluvialer und limnischer Sedimente im Ablagerungsraum der Flüsse Saalach und Königsseeache sowie die Entwicklung ihrer Mündungen im Salzburger Becken. Die Flüsse lagerten ihre groben, klastischen Sedimente im Becken unter Bildung von Deltafächern ab. Diese bauten sich gegen das Zentrum des Beckens vor und bildeten Schichtpakete aus grobkörnigem Material in den feinen Seeablagerungen. Dabei spielten kurzfristige Ereignisse wie zurückschmelzende Gletscher und Bergstürze eine wichtige Rolle.

Die Mündung der Saalach zeigt eine Abfolge von zwei aufeinanderfolgenden Becken, die durch eine Schwelle im Bereich des heutigen Walserberg voneinander getrennt waren. Die Ablagerungen im Bad Reichenhall Becken deuten darauf hin, dass sich im Postglazial ein großer Deltakegel in Zusammenhang mit einem verzweigten Flussverlauf auf der Oberfläche des Fächers bildete.

Das Salzburger Becken wurde durch limnische Sedimente des ehemaligen Salzburger Sees verfüllt. In diese Sedimente progradierte ein großer Deltafächer aus fluvialen Ablagerungen, als das Becken bereits zur Hälfte mit limnischen Sedimenten verfüllt war. Diese fluvialen Ablagerungen stehen im Zusammenhang mit Hochwasserereignissen, die vermutlich durch Dammbrüche in ehemaligen Eisrandseen verursacht wurden. Die Sedimente im Mündungsbereich der Königsseeache zeigen, dass mehrere Bergsturzereignisse am Untersberg den Fluss zwangen, seine Richtung zu ändern, was schließlich zu seinem heutigen Verlauf führte.

1. Introduction

1.1 Geological Setting

Numerous studies on the sedimentological evolution of overdeepened Alpine valleys have been carried out, many of them were based on the extrapolation of two-dimensional geophysical data and drill holes (Bleibinhaus et al., 2010; Brückl et al., 2010, Preusser et al., 2010). They revealed that apart from glacial over-deepening (Seiler, 1979; van Husen, 2000), postglacial deposition (Van Husen, 1981, 2000; Brückl et al., 2010) and gravitational mass movements (Abele, 1974; van Husen, 2000) played an important role in the evolution of confluences in Alpine basins.

The Salzburg Basin extends from Golling to Oberndorf. The depth of the valley floor ranges from 160 to 340 m (van Husen, 2000). The maximum of over-deepening was achieved in the southern Salzburg Basin near Bad Vigaun (338 m, van Husen, 1979). In the central Salzburg Basin the amount of over-deepening was lower as the valley floor is reached at a depth of 262 m (van Husen, 1979). Investigations in the Saalach valley near Bad Reichenhall revealed a depth of 133.5 m of the valley floor (Bader, 1981). In the area of the glacier tongues subglacial meltwater may have contributed to the incision of narrow, V-shaped channels into the bedrock surface (Dürst Stucki and Schlunegger, 2013).

Van Husen (1979, 1981) and Bader (1979, 1981) have shown that the glaciers of the Saalach and Salzach joined in the central Salzburg Basin. This confluence possibly led to the development of a bedrock swell (Penck, 1905). The maximum extent of the Salzach glacier during the Last Glacial Maximum (LGM) is marked by the Würmian End Moraine System that can be found 35 km north of the city of Salzburg (Penck and Brückner, 1909; Salcher et al., 2010). Studies investigating ice thickness during the LGM in the Eastern Alps were carried out by van Husen (1987) and Gamerith and Heuberger (1999) who determined the maximum ice cover of the Salzach glacier up to 1000 m a.s.l. (above sea level) at the Salzburg Basin. Bader (1981) estimated an ice thickness of the Saalach Glacier between 700 and 900 m in the Bad Reichenhall Basin.

Lateglacial collapse of the tongues of the Salzach Glacier and Saalach Glacier before the LGM released large amounts of melt water that filled the basins and built up lakes (Del-Negro, 1983). These lakes reached a maximum water level of up to 530 m a.s.l. (Aigner, 1928). Most of the interglacial (Nagelfluh) and glacial sediments that had been deposited before the LGM, were subsequently eroded. The remains build up the hills of the Mönchsberg, Rainberg, Hellbrunner Hügel and northern part of the Kuchlerhügel (Stummer, 1936; van Husen and Reitner, 2011). Preservation of minor parts of pre-Würmian lake sediments on the leeside of topographic obstacles is indicated by 14C-age data (Herbst and Riepler, 2006).

Investigations in the distal areas of the Salzach Glacier by Salcher et al. (2010) provided evidence for ice-contact depositional features, like Kames and gilbert-type deltas in glacial lakes dammed by dead-ice and ice marginal sediments. Aigner (1928), Stummer (1947), and Del-Negro (1963) investigated the development of the ancient postglacial lake in the Salzburg Basin and surrounding lakes at Bad Reichenhall and Großgmain. These lakes developed immediately after the end of the LGM from 18 to 17 ka BP (van Husen, 1997). The lake in the Salzburg Basin reached a maximum water level of 460 m a.s.l. and was separated from surrounding lakes by the hills of the Walserberg (Fig. 1). The lake in the Bad Reichenhall Basin developed after the Saalach Glacier retreated to the south and reached a maximum water level of 485 m a.s.l. (Del-Negro, 1963). Smaller lakes at Großgmain reached water levels of up to 540 m a.s.l.. Bader (1981) found lake deposits in the upper valley near Hallthurm. It is likely that these lakes where separated from each other by dams of sediments or dead ice (Del-Negro, 1963; Bader, 1981). Sedimentation in the postglacial lake in the Salzburg Basin ended as the Salzach river cut through the terminal moraines in the north and the water table began to drop (Aigner, 1928). Seefeldner (1954) and Weinberger (1957) determined several terminal lake levels at 450 m, 440 m, 430 m, 425 and 415 m a.s.l., which prove that the water table of the ancient Lake Salzburg decreased in several steps.

The sedimentation in the Salzburg Lake was dominated by limnic deposition under slack water conditions and deposition of fluvial gravel and sand by the nearby rivers (Stummer, 1947; Del-Negro, 1983). Deltas that progressed further into the basin of Salzburg were mainly deposited by the Saalach and Königs-

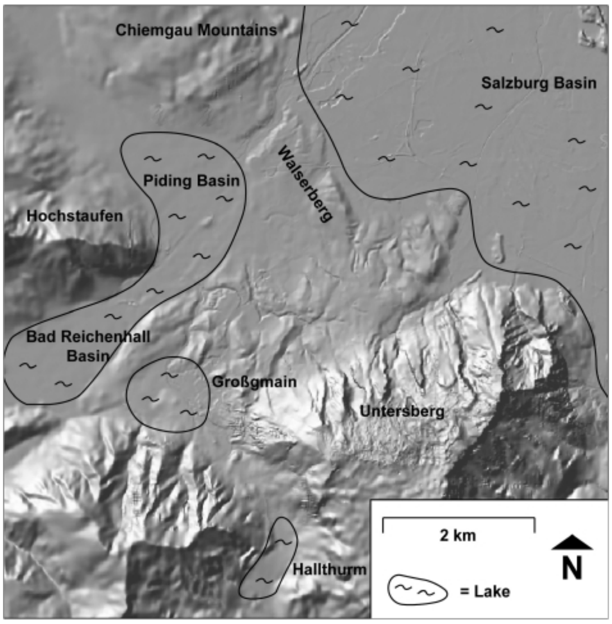


Figure 1: Position of ice-lakes after the Last Glacial Maximum in the Salzburg Basin and the Saalach Valley, superimposed on a digital elevation model for the area.

seeache rivers, and the stream of Rosittenbach (Del-Negro, 1983; Jerz, 1993). Brandecker (1974) showed that the delta of the Königsseeache (Berchtesgadener Ache) river prograded far into the basin, and that a substantial delta fan was deposited by the Saalach. In addition to delta deposits, both coarse and fine-grained braided river deposits were laid down in the Bad Reichenhall Basin (Brunnacker et al., 1976). Field investigations reveal a dark blue and grey color of the limnic sediments with grain sizes ranging from clay to silt, with only a low proportion of sandy material (Pippan, 1961). Fluvial gravels and sands are lighter brown in colour and show horizontal or cross bedding. In the marginal areas of the basin they form delta fans deposited by nearby rivers and streams. In the central areas of the basin they constitute the fluvial terraces that were deposited after the lake had silted up (Pippan, 1957).

Prey (1959) assumed that the Salzburg Basin was filled during the postglacial period because the deposits at shallower depths show little compaction. A pollen analysis in different depths of the lake sediments ("Salzburger Seeton") proved that these sediments were in their entirety deposited in the Late- and Postglacial after the LGM (Klaus, 1967). Samples obtained from the Geological Survey of Bavaria (LFU) revealed an age of 17 ka for the gravels deposited by the Saalach river. Samples were taken in a depth of 4 and 7 m below the surface near the village Schiffmoning and analyzed by luminescence dating methods (Fiebig and Herbst, 2012).

There are indications that the lateglacial deposition in the Salzburg Basin was also affected by mass movements. Brandecker (1974) found deposits near the Königsseeache which showed similar features like those resulting from bergsturz-events. Seefeldner (1954) assumed that the sudden change of direction of the Königsseeache river was caused by a mudflow originating from the eastern slope of the Untersberg. A postglacial landslide in the Salzach valley near Vigaun was caused, for example, by reduced shear-resistance due to infiltrating water in the lower units of the Rossfeld Formation (Uhlir and Schramm, 2003).

In addition, new data were obtained from a coring near the Salzburg Airport interpreted by Geoconsult ZT GmbH in 2011. It gave new evidence for a fluvial deposit in the limnic succession of the "Salzburger Seeton" in the area of the Saalach river, reaching fluvial gravels and sands at a depth of 99 m below the surface. Hydrological investigations that were also carried out by Geoconsult ZT GmbH (internal report 2011) recently at the Königsseeache river showed peculiarities of the groundwater permeability. Groundwater velocities seem to be significantly higher than in other areas of the Salzburg Basin. These peculiarities had been already recognized by Brandecker (1974) and apparently contradict the information on the geologic map of Prey (1969).

Our study aims to investigate the postglacial deposits along the rivers Saalach and Königsseeache, and former circumstances of the river mouths and processes that affected their evolution in late- to postglacial times. In particular at the Saalach river, the main goal has been to locate the spatial distribution of fluvial deposits and delta fans in the limnic silts and clays. Based on this information it can be ascertained whether the river changed its position and which geomorphologic features were formed at the river mouth while deposition took place. A further goal has been to assess whether the deposition took place in one sudden event or continuously over an extended period of time.

On the other hand at the Königsseeache river, the emphasis lies on the explanation of the hydrological peculiarities and the genesis of the deposits, i.e. to assess whether they are of a glacial, fluvial or alternative origin (e.g. a catastrophic event). The deposits are the key to answer the question why the Königsseeache river changed its direction so dramatically and cut through the bedrock of the Rossfeld Formation.

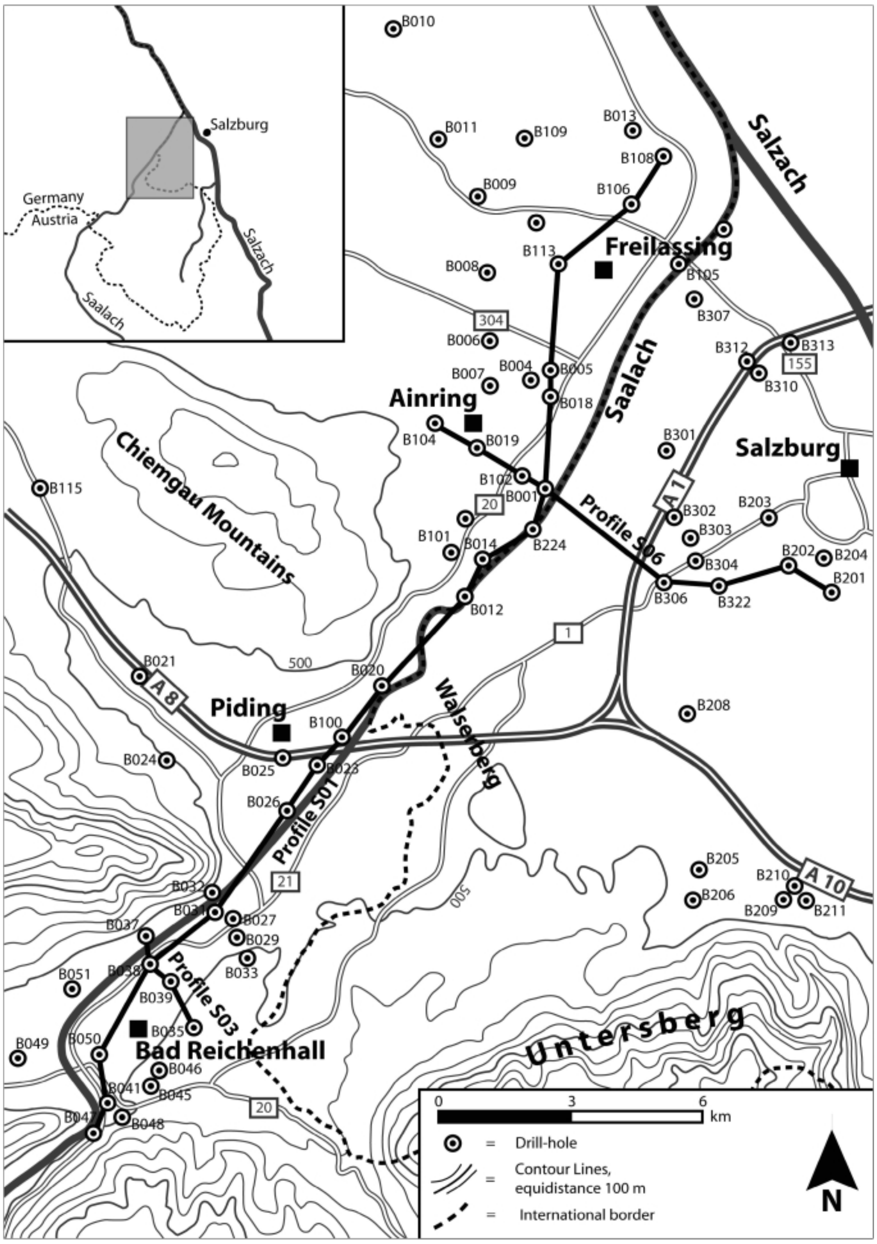


Figure 2: Area of investigation at the Saalach river. Location of drill holes and geologic cross-sections.

1.2 Area of investigation

The study areas are the river mouths of the Saalach and Königsseeache rivers, which are situated west and east of the Untersberg mountain, respectively, where they enter the central part of the Salzburg Basin. The first area of investigation at the Saalach river extends from the storage reservoir of the Saalach in the south to the north where the Saalach joins the Salzach in the central Salzburg Basin (Fig. 2). The Saalach river crosses the basins of Bad Reichenhall, Piding and Salzburg. The Bad Reichenhall Basin and the Piding Basin are situated further upstream and extend from the storage reservoir to the hills of the Walserberg. So far, the Bad Reichenhall Basin and the Piding Basin are only separated by the surrounding mountains. The Bad Reichenhall Basin terminates against the mountains of the Hochstaufen in the west and the Untersberg in the east. As the river passes the mountain ledge of the Hochstaufen, it flows through the Piding Basin, which extends further to the west and terminates at the hills of the Walserberg in the north.

As the river enters the Salzburg Basin, which is situated downstream, it cuts through the hills of the Walserberg, showing a meandering route. The first area of investigations in the Salzburg Basin extends from the Chiemgau Mountains in the west to the city of Salzburg in the east. To the north the town Freilassing marks the boundary of the study area.

The second area of investigation (Königsseeache river) extends from St. Leonhard in the south to the southern border of the urban area of the city of Salzburg in the north (Fig. 3). It extends from the eastern slope of the Untersberg mountain in the west to the Salzach river in the east. Next to the village of St. Leonhard are several hills, which are elongated in N-S direction. It is striking that the Köngisseeache river suddenly changes its direction to the east contrary to the topographic regime in this area.

1.3 Methods

For the purpose of this study, data from 150 drill holes were collated, most of them obtained from the geodatabase of the Geological Survey of Bavaria (Geofachdatenatlas, Bayerisches Landesamt für Umwelt), Salzburg (Baugrundkataster, Landesgeologischer Dienst Salzburg), and from private companies, i.e. Stiegl Brewery (courtesy of Stiegl Privatbrauerei GmbH) and Salzburg Airport (courtesy of Geoconsult ZT GmbH). Only such drill holes were considered that reached more than 20 m below surface or hit bedrock. All logs were recorded and interpreted by geologists and contain petrographic descriptions of the grain size fractions, color and a stratigraphic interpretation of the material. The accuracy of the data within these logs varies a lot. In some instances only the major grain fractions were determined and details about color and stratigraphy are missing. Hence, the data of the drill-logs were generalized to allow a comparison between these logs. If necessary, additional information from field investigations and topographic information were taken into account for interpretation.

Five facies types were distinguished based on the above, rather general data on the sediment properties and stratigraphic position. More detailed descriptions of the drill-cores is only given if useful and appropriate to distinguish different origins or geomorphological features (e.g. deltaic deposits and Kame deposits). Facies types and their features are shown in Figure 4. The Bergsturz facies contains heterogeneous material of all grain sizes ranging from clay to gravel. Besides, large boulders up to 3 m in diameter are very common. The colour varies; stratigraphic information is missing in the drill-logs. Concerning its grain size this facies is divided into two categories: “gravel and boulders” and “silt and boulders”. The subfacies “gravel and boulders“ contains a higher amount of coarse-grained fractions. The subfacies “silt and boulders” contains a higher amount of fine-grained fractions. This facies is very similar to the moraine material of the glacial facies, but features of basal till are missing. In addition field investigations were carried out for an exact discrimination of those two units.

The fluvial facies contains coarse material like gravel and sand in lighter brown, yellow or white colors and a poor sorting of grain fractions. The stratigraphic age assigned to these units is Quaternary in general. The subfacies gravel and sand where distinguished after their major grain size fractions mentioned in the drill-logs.

The limnic facies comprises two fine grain sizes, i.e. clay and silt, is well-sorted and shows fine lamination. According to the information given in the drill logs the colour of this facies varies from dark blue to grey or brown.

Moraine material and basal till from the last Würmian glacial are assigned to the fourth facies. This facies is heterogeneous with grain size ranging from clay to gravel. Typical till features, such as striated pebbles or boulders, are observed. The stratigraphic information provided on the drill-logs appears as “moraine”, “glacial” or “Würmian unit”. Furthermore, the investigations were focused on the younger postglacial units so that the glacial facies marks the lowest of the studied stratigraphic units. Older material deposited in earlier glacial or interglacial periods and Austroalpine and Helvetic bedrocks are classified as basement and are not further discriminated in the following.

Based on this one-dimensional information from several localities, 2D sections were constructed along the rivers.

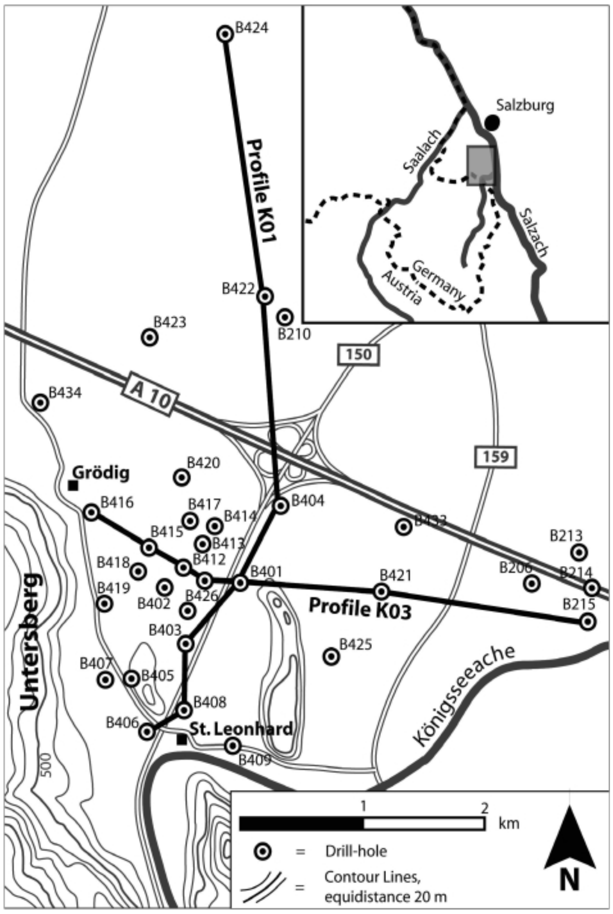


Figure 3: Area of investigation at the Königsseeache river. Location of drill holes and geologic cross-sections.

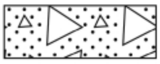
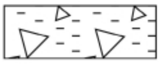
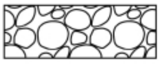
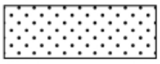
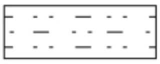
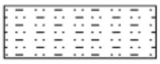
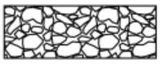
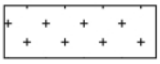
Facies Type	Categorie	Signature	Features mentioned in drill-logs major size fraction / minor size fraction / Color / Stratigraphic Unit
① Bergsturz Facies	a) Gravel and Boulders		Heterogeneous material containing all grainsizes (major size fraction: gravel), large boulders up to 3 m in diameter/ varying colors/ no stratigraphic information
	b) Silt and Boulders		Heterogeneous material containing all grainsizes (major size fraction: silt), large boulders up to 3 m in diameter/ varying colors/ no stratigraphic information
② Fluvial Facies	a) Gravel		Major size fraction: gravel/ minor size fraction: sand and silt/ lighter brown, yellow or white color/ Quaternary
	b) Sand		Major size fraction: sand/ minor size fraction: fine gravel and silt/ lighter brown, yellow or white color/ Quaternary
③ Limnic Facies	a) Silt		Major size fraction: silt/ minor size fraction: fine sand and clay/ varying from darker blue to grey or brown/ Quaternary
	b) Clay		Major size fraction: clay/ minor size fraction: fine sand and silt/ varying from darker blue to grey or brown/ Quaternary
④ Glacial Facies	Moraine		Heterogeneous material containing all grainsizes (ranging clay to gravel)/ till typical features like striated pebbles or boulders/ varying colors/ identified as Moraine, Glacial or Wuermian Unit
⑤ Bedrock	Bedrock		Bedrock/ Interglacial deposits (Nagelfluh), austroalpine rock and Rhenodanubic Flysch

Figure 4: Classification scheme of facies types according to their features mentioned in drill logs.

2. Results Saalach

2.1 Data

Results from analyzing drill logs along the Salzach river indicate two over-deepenings in the bedrock, which are separated by a bedrock swell at the Walserberg, where the basement crops out at the surface (Profile S01, Fig. 5). In the Saalach Valley the over-deepening reaches from Bad Reichenhall to the hills of the Walserberg in the north of the Piding Basin. According to the bedrock morphology, the basins of Bad Reichenhall and Piding are parts of one and the same over-deepened basin. Drill hole B031 (Profiles S01 and S03, Fig. 5) reached the bedrock at a maximum depth of 134 m below the surface. Stratigraphic information is missing in the drill log, but Bader (1981) and Exler (1979) identified the bedrock as Triassic units of the Northern Calcareous Alps ("Haselgebirge"), covered by a 7 m thick layer of basal till.

In the Salzburg Basin, north of the Walserberg area, the bedrock shows a morphology with steep slopes as the depth of the bedrock decreases from 14 m below surface (drill hole B224, Profile S01, Fig. 5) to 111 m below surface (drill hole B001, Profile S01, Fig. 5). The information in the drill logs identifies the bedrock units in drill hole B224 as interglacial deposits (Nagelfluh, Fig. 6), whereas bedrock in drill hole B001 consists of sandstone of the Rhenodanubian Flysch Zone. The drill hole B018 reached a depth of 202 m but no bedrock or basal till was intersected (Profile S01, Fig. 5). The bedrock in drill hole B202 (Profile S06, Fig. 5) was reached at a depth of 262 m below surface, where it is covered by a 38 m thick bed of basal till. The western border is well documented in thedrill logs. Profile S06 shows the termination of the basin to the west near the village Ainring. The bedrock was reached at a depth of 10 m in drill hole B104. Further north, the border can be found 4 km west of Freilassing. The bedrock was hit in drill hole B011 at a depth of 30 m (for location of B011 refer to Fig. 2).

The swell at the Walserberg is a broad zone which expands from drill hole B020 to drill hole B224, where the bedrock (Middle Cretaceous units of the Northern Calcareous Alps) crops out at the surface (Fig. 6). In the central part of this zone the log of drill hole B101 (not in profiles, west of drill hole B012, Fig. 2) shows that in this part limnic clay was deposited and no bedrock is found as far down as 60 m. Fluvial deposits like gravel and sand covering the clay can be found at a depth of 30 m below surface on top of the clay (B012 and B014, Fig. 6).

Younger deposits fill the basins of Bad Reichenhall, Piding and Salzburg. The southern part of the Bad Reichenhall Basin is filled up with fluvial gravels. North of Bad Reichenhall the proportion of limnic clay and silt in these deposits increases. At shallower depths and marginal parts of the basin only limnic clays were deposited (Profile S03, Fig. 5). Lenses of clay and silt (ranging from 5 to 10 m in thickness) are observed in the upper 40 m below the surface and a 13 m thick bed of silt at a depth of 64 m in drill hole B038 (Profile S01, Fig. 5). At the edge of the Bad Reichenhall Basin and the Piding Basin deposits of the limnic facies dominate (B031, Fig. 5). The Piding Basin was obviously filled with limnic clays which are covered by 15 to 30 m thick beds of gravel and sand (Profile S01, Fig. 5).

Thick clay deposits comprise the fill of the Salzburg Basin (Profile S01 and S06, Fig. 5). Larger amounts of gravel and sand were only deposited in marginal areas of that basin (Profile S01, Fig. 5) or on top of the limnic units. In drill hole B018, ca. 69 m thick gravels cover the limnic clay. The clay continues as far down as 202 m below surface, except for two beds of gravel at depths of 134 m (7 m thick) and 151 m (12 m thick) (Profile S01, Fig. 5). Further to the north 48 m thick sands on top of the clay were deposited, covered by a 10 m thick bed of gravel (B005 and B113, Profile S01, Fig. 5). The thickness of the gravel and sand beds decreases as evident from the northernmost drill holes B108 and B106 (Profile S01, Fig. 5). Profile S06 shows that higher proportions of gravel (B019 and B102) were deposited in the western part of the basin.

The lower section of gravel in drill hole B001 (from 68 m to 96 m) shows significant differences from the fluvial gravels in drill holes B019 and B102. Gravels in B001 are very well sorted and comprise several beds which clasts change from coarse- to fine-grained material.

Drill hole B306 reached a total depth of 60 m. A layer of gravel covered by sand was intersected at a depth of 18 m. In drill hole B322 again sand was found at a depth of 100 m and gravel at a depth of 112 m. Further to the east drill hole B202 revealed a 14 m thick layer of sand at a depth of 139 m (Profile S06, Fig. 5). In addition, south of drill hole B306, another bed of gravel was encountered at a depth of 36 m before the drill hole reached its final depth (drill hole B208, Fig. 2).

2.2 Interpretation

The Bad Reichenhall Basin, Piding Basin and the Salzburg Basin were carved out by glacial activity causing over-deepening of the former valley floor. Based on the results from the drill-logs, we estimate amounts of overdeepening of 160 m in the Bad Reichenhall and Piding Basin and more than 250 m in the Salzburg Basin. The strong overdeepening of the Salzburg Basin is a result of the confluence of the ancient Saalach- and Salzach glaciers, which united in this area (van Husen, 1981).

The development of the swell at the Walserberg is probably linked to this confluence zone because of the

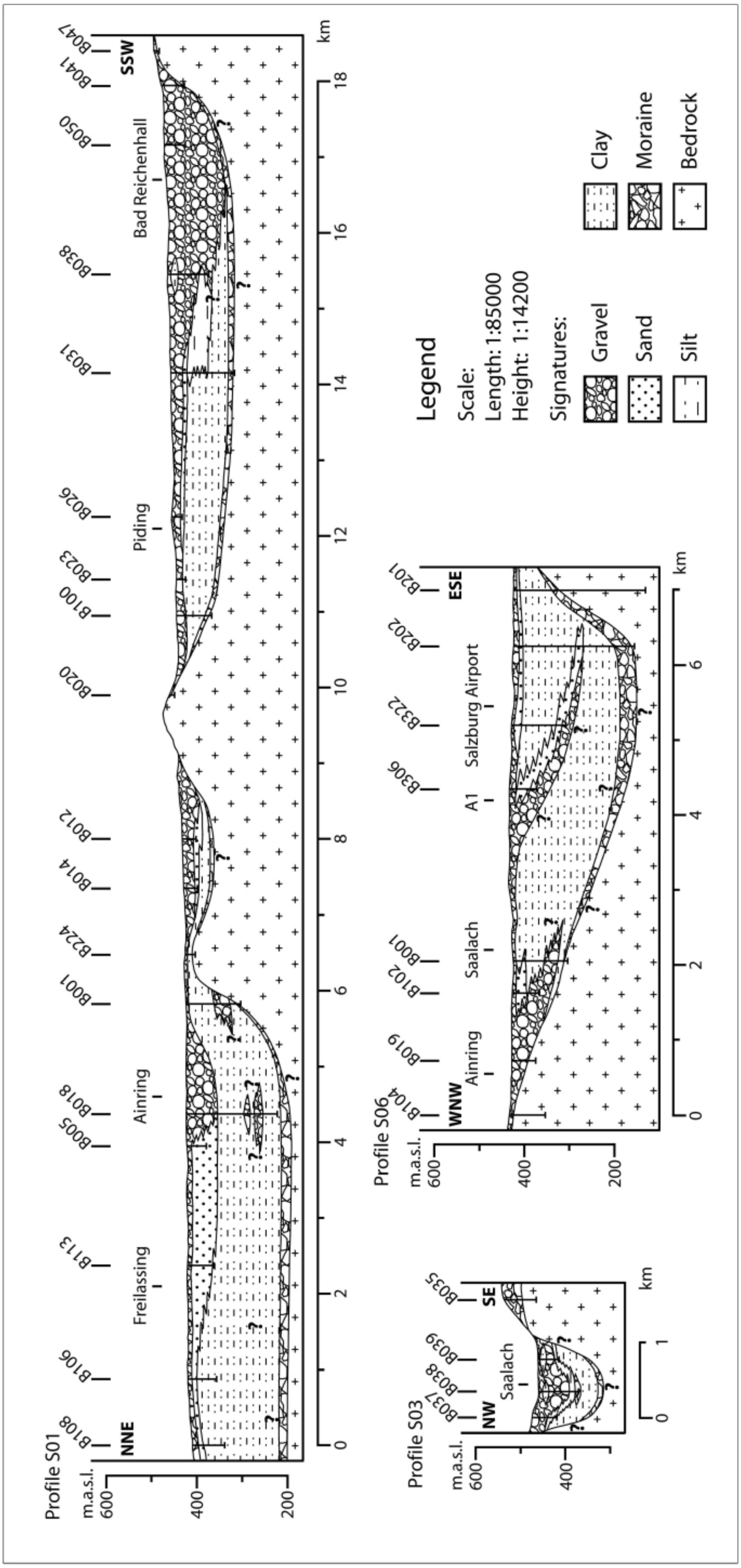


Figure 5: Geologic cross-sections along the Saalach river. For location of profiles see figure 2.

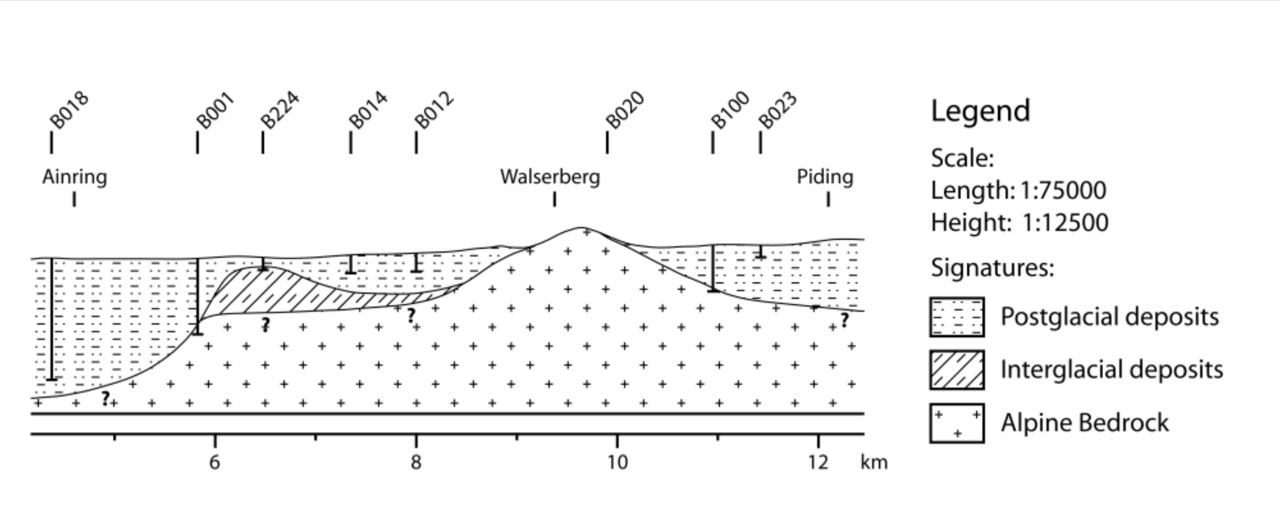


Figure 6: Close up of Profile S01 (Figure 5). Bedrock morphology at Walserberg Zone.

reduced flow velocity of the Saalach Glacier before uniting with the Salzach Glacier. Obviously the swell of the bedrock formed an obstacle for the glacier. In the lee side of this obstacle, parts of the sediments deposited were preserved from being eroded again in the following glacial period as data from drill hole B224 shows. Other parts were easily eroded forming channel-like features that are up to 60 m deep. It remains uncertain if erosion was driven by glacial or glacial-fluvial processes. Subglacial meltwater beneath the glacier tongue may explain the strong incision into the bedrock (Dürst Stucki and Schlunegger, 2013).

Fluvial and limnic deposits cover the bedrock and basal tills that were left behind by the retreating glacier. It seems that the coarse-grained material was not transported further as soon as the flow velocity decreased. Obviously, the flow velocity of the former Saalach river decreased significantly as it entered the Bad Reichenhall Basin. One can infer from the distribution of the deposits that the Saalach river deposited most of its sediment load already in the upstream basin of Bad Reichenhall, producing a large subaqueous delta fan that prograded into the basin (Fig. 7A). It is likely that south of the city of Bad Reichenhall the gravels filled the whole basin from the basement right up to the surface, because previous studies have shown that the upper part of the Saalach Basin is

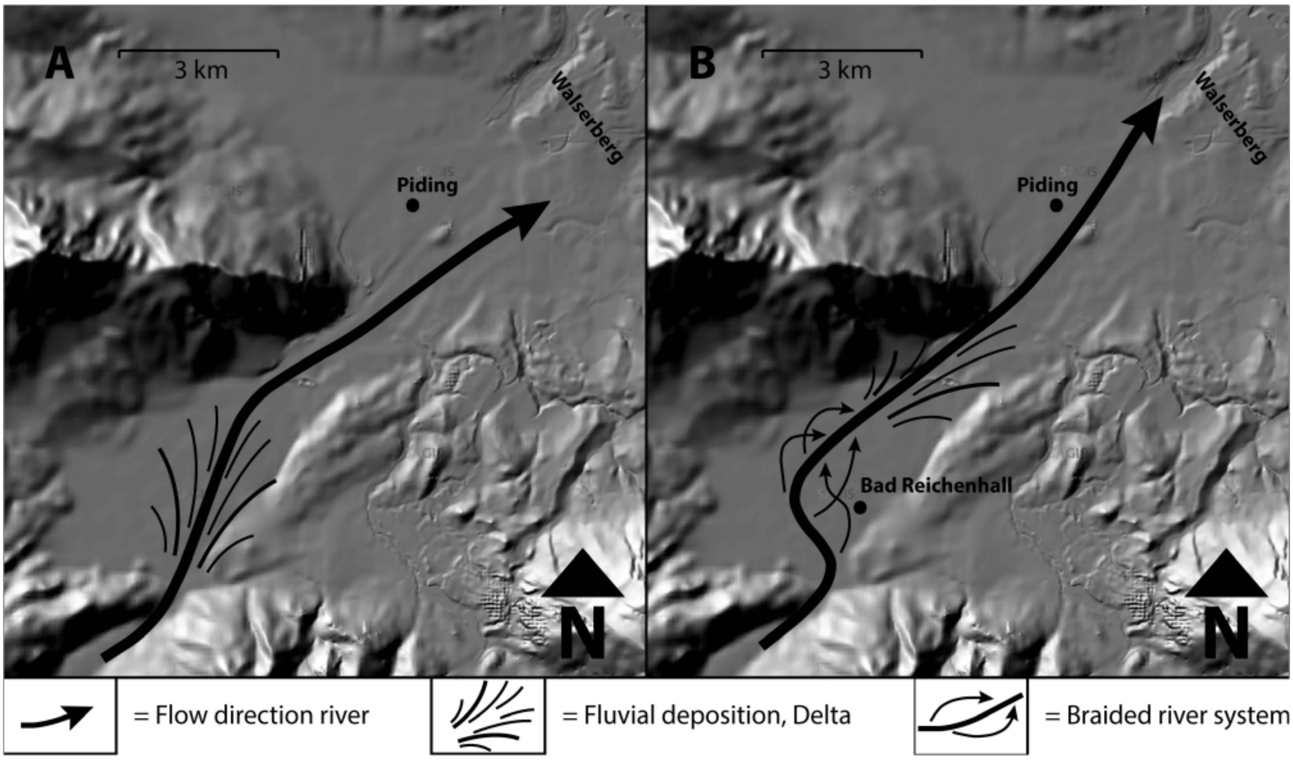


Figure 7: Deposition in the Bad Reichenhall Basin after LGM at 18 ka BP (A) and 17 ka BP (B).

completely filled with coarse-grained gravels (Bader, 1981). During the progradation into the basin a delta plain with changing sedimentation of coarse- and fine-grained material established on top of the delta fan (Fig. 7B). Lenses of clay and silt found in Profile S03 at a depth of 30 m indicate changes of sedimentation from slackwater-conditions to fluvial conditions, which is typical for braided river systems. Gravels below silty deposits in drill hole B038 indicate a stronger progradation of the delta. This progradation happened during a flood and higher amounts of transported material by the river. The flood took place as half of the basin was already filled.

After this flood event the delta retreated and silty sediments were deposited in the distant areas of the delta cone. Drill holes B031 and B038 show silty sediments which alternate with fine-grained clays. This silt-dominated area is interpreted as a transitional zone showing features of fluvial and limnic deposition.

In contrast to the style of sedimentation in the Bad Reichenhall Basin, profiles S01 and S06 show that deposition of fluvial gravels in the Salzburg Basin initially took place in the form of small delta fans at the marginal area of the basin. Gravels found at higher levels below clayey deposits in drill hole B018 were probably transported by streams from the nearby hills in the west. This is consistent with the geological map of Prey (1969), which shows small delta fans at the western edge of the basin. Drill holes B019 and B102 in Profile S06 indicate that the gravels prograded into the basin from the west and cover the older gravels in drill hole B001. According to their properties, it is obvious that the gravels in drill hole B001 are different from the gravels that prograded from the west into the basin. These gravels are likely to represent previously deposited, glacifluvial sediment, and they show features similar to Kames terraces.

Immediately after the withdrawal of the glacier, predominant limnic sedimentation established. This implies that in the lateglacial period there had been either no transport and deposition of coarse-grained sediment by the Saalach at all (due to a lack of a fluvial connection between the Salzburg Basin and the upstream Bad Reichenhall Basin), or the position of the river mouth must have changed during the lateglacial period. Previously, it has been assumed that the ancient river mouth of the Saalach deposited its sediment load further to the east (Stummer, 1947), following the direction of the gorge at the Walserberg. Indications to this effect are observed in the log of drill hole B208. The gravel bed marks an early state of deposition of the Saalach.

The gravel and sand deposits encountered in the drill holes B306, B322, B202 in profile S06 indicate that a large delta fan started to prograde from the south-west into the basin when half of the basin had been already filled (Fig. 8A). This progradation is possibly linked to the same flood that caused the delta to prograde in the Bad Reichenhall Basin due to ist similar relative position of the deposited clays. Sands only cover the gravels, but a bed of sand beneath the gravels is missing. This points to a sudden flood event and a delta that prograded very quickly into the basin. In contrast the delta retreated slowly, covering the gravel with sand in the distal areas of the retreating fan. Possible explanations for this flood event are climatic changes to warmer and more humid conditions or dam-failures of lakes near the ice margin dammed by dead ice or glacial debris. The fluvial deposits in the western part of the Salzburg Basin indicate that the Saalach changed ist direction to the north after this flood event (Fig. 8B).

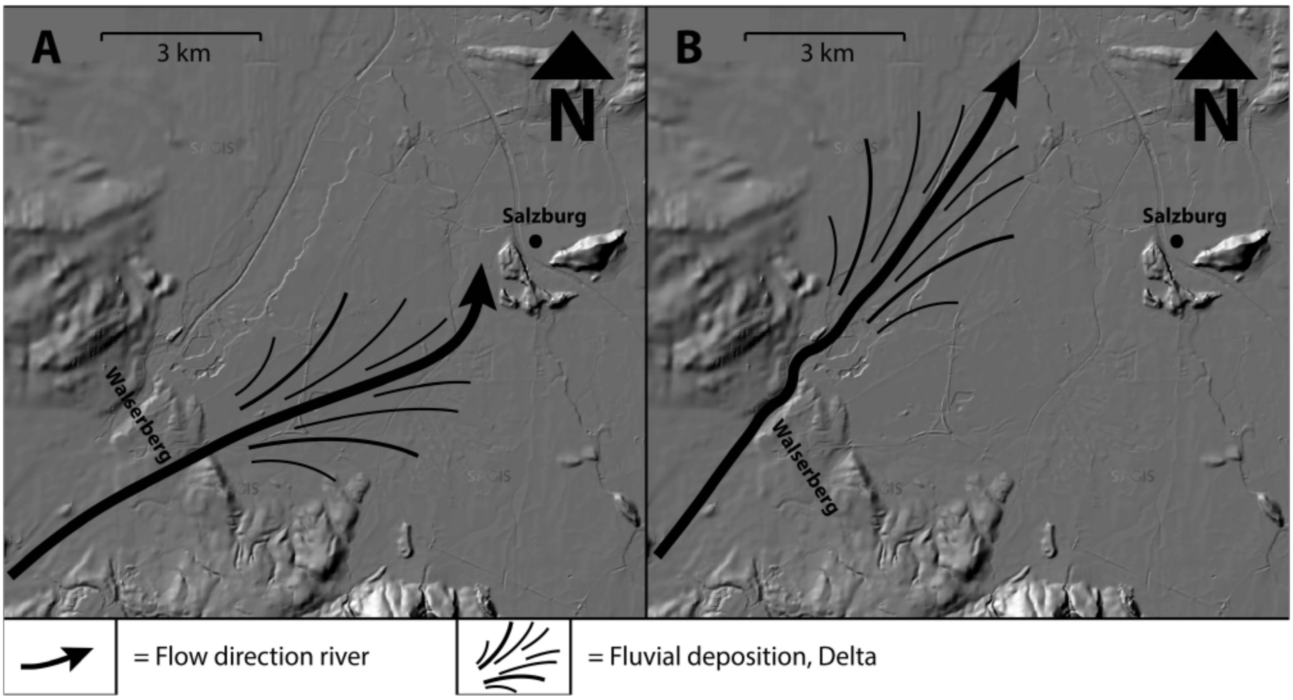


Figure 8: Delta progradation into the Salzburg Basin after an inferred dam failure of an ancient ice-lake upstream (A) and deposition after the last glacial decay at 17 ka BP (B).

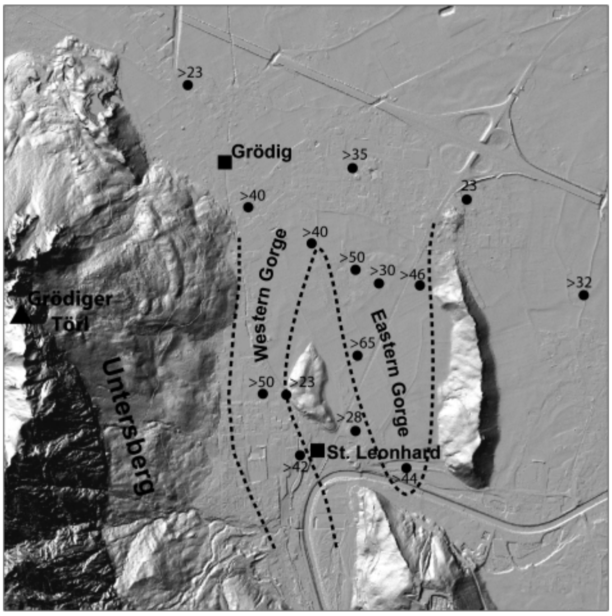


Figure 9: Bedrock morphology and gorges at the Königsseeache river mouth (Numbers indicate bedrock depth in meters below surface).

3. Results Königsseeache

3.1 Data

The bedrock morphology in this area is very varied and marked by two deeper gorges separated from each other by outcropping rocks of the Rossfeld Formation in the east of the Untersberg (Fig. 9). The bedrock units dip to the north and thus do not form outcrops in the north (Profile K03, Fig. 10). Bedrock was reached in drill hole B404 at a depth of 15 m. It is related to the units of the Lower Roßfeld beds which crop out at the surface in Profile K03 (Fig. 10).

Profile K01 (Fig. 10) shows that in the northern part of the study area, limnic clays occur beneath a gravel bed. Drill holes indicate a thickness of the gravel bed ranging from 18 (B424) to 32 m (B422). In the eastern part of the study area a sand bed is situated beneath an up to 27 m thick gravel bed (Profile K03, Fig. 10).

Subsequent sedimentation was varied, leading to gravel and boulder beds in the south-west of the area, covering the surface. Drill logs B406 and B416 revealed that their thickness is significantly higher near the eastern slope of the Untersberg. West of St. Leonhard and around the village of Grödig these deposits reach a thickness of more than 45 m, filling almost the whole gorge between the Untersberg and the bedrock units of the Upper Roßfeld beds. The second gorge in the east of St. Leonhard is filled with gravels up to a depth of 65 m (B403). On top of the gravels a 18 m thick bed of boulders and gravel was encountered (Profile K01). Obviously the thickness of this boulder and gravel bed decreases towards the northeast. Drill logs B416, B415 and B412 (Profile K03, Fig. 10) revealed a 8 m thick bed of large boulders of calcareous rock and silty beds at a depth of 15 m near Grödig. Beside that minor amounts of sand and gravel were documented. None of the drill logs gave any indication of a glacial deposit like basal till. Field observations on outcrops in this area revealed a gravel- and sand-rich, unsorted matrix with larger boulders covering the eastern slope of the Untersberg. These deposits are not compacted at all. The topography of the slope west of Grödig indicates significant steepening of the slope uphill.

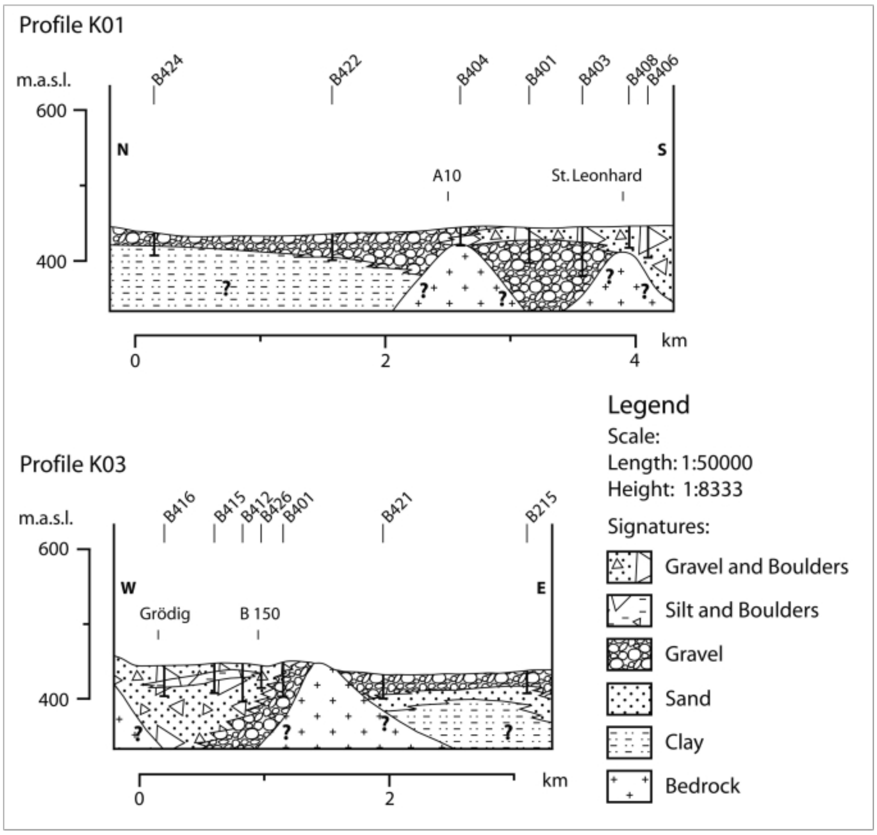


Figure 10: Geologic cross-sections along the Königsseeache river. For location of profiles see figure 3.

3.2 Interpretation

The previously deposited coarse-grained basin fill appears re-worked on the eastern slope of the Untersberg by lateglacial bergsturz events (Brandecker, 1974). The insights from field investigations and outcrops in this area match a description of bergsturz deposits in the southern Salzburg Basin near Vigaun (Pippan, 1956). So far features typical of glacial tills have not been reported. In contrast to glacial deposits, which are impermeable to water, the groundwater permeability in these heterogeneous deposits is very high (Brandecker, 1974). The features of the bed of calcareous rock and silty beds are likely to form in deposits of high groundwater permeability. In the northern part of the study area these heterogeneous deposits rest above the postglacial limnic clays and fluvial gravels. Basal till would be deposited earlier below those units. Consequently, the overlying boulder and gravel deposits must be younger than, or at least contemporaneous with, the postglacial clays. Hence, a glacial origin of these deposits can be ruled out.

The geological setting in this area is similar to that around the landslide near Vigaun, where infiltrating water and hydrochemical solution of evaporates reduced the shear-resistance of the Rossfeld Formation (Uhlir and Schramm, 2003). Other triggers of a bergsturz event are possibly the lack of stabilizing ice-masses after glaciers retreated (Gruner, 2006) and erosion of the Königsseeache itself in combination with oversteepening of the slope of the Untersberg.

The gorges carved into the bedrock are orientated from south to north, which implies that the ancient Königsseeache drained in the same direction. In its initial state the river must have followed the first gorge west of St. Leonhard blocked by the basement to the east (Fig. 11A). The fluvial gravels northeast of St. Leonhard and east of Grödig indicate that the river changed its direction and was able to deposit gravels in the second gorge east of St. Leonhard. Subsequently, the river changed its direction after a bergsturz event, which blocked its way to the north and forced the river to cut through the bedrock of the Upper Roßfeld beds (Fig. 11B). A similar event must have happened a second time, blocking the way of the river in a northward direction (Fig. 11C). The Königsseeache river was forced again to cut through the units of the Lower Roßfeld beds situated east of the second gorge.

The terraces in the east of St. Leonhard show that the Königsseeache river formed terraces in the Schlern- and Gschnitz-stadials (Prey, 1969) as it was already deflected by a bergsturz to the east (Fig. 12). Incised terraces formed by the river in the north are missing. Consequently, the bergsturz event must have happened before the Schlern and Gschnitz-stadials. The absolute age for the older Gschnitz-stadial has been estimated at 15,4 ka BP (Ivy-Ochs et al., 2008), thus providing a minimum age for the postulated bergsturz deposits.

3.3 Discussion

The amounts of glacial overdeepening in the Salzburg Basin (over 250 m) and in the Bad Reichenhall and Piding Basin (160 m) is consistent with estimates of van Husen (2000), who suggested overdeepening in the range between 160 and 340 m. Geophysical exploration in other Alpine valleys revealed similar extents of glacial overdeepening (Brückl et al., 2010; Preusser et al., 2010). It still remains unclear if the hills of the Walserberg are a result of reduced glacial erosion or of reduced erodibility of the bedrock or both.

Subglacial drainage systems possibly eroded parts of the interglacial sediments deposited in the lee side of the Walserberg. Salcher et al. (2010) described subglacial channels typi-

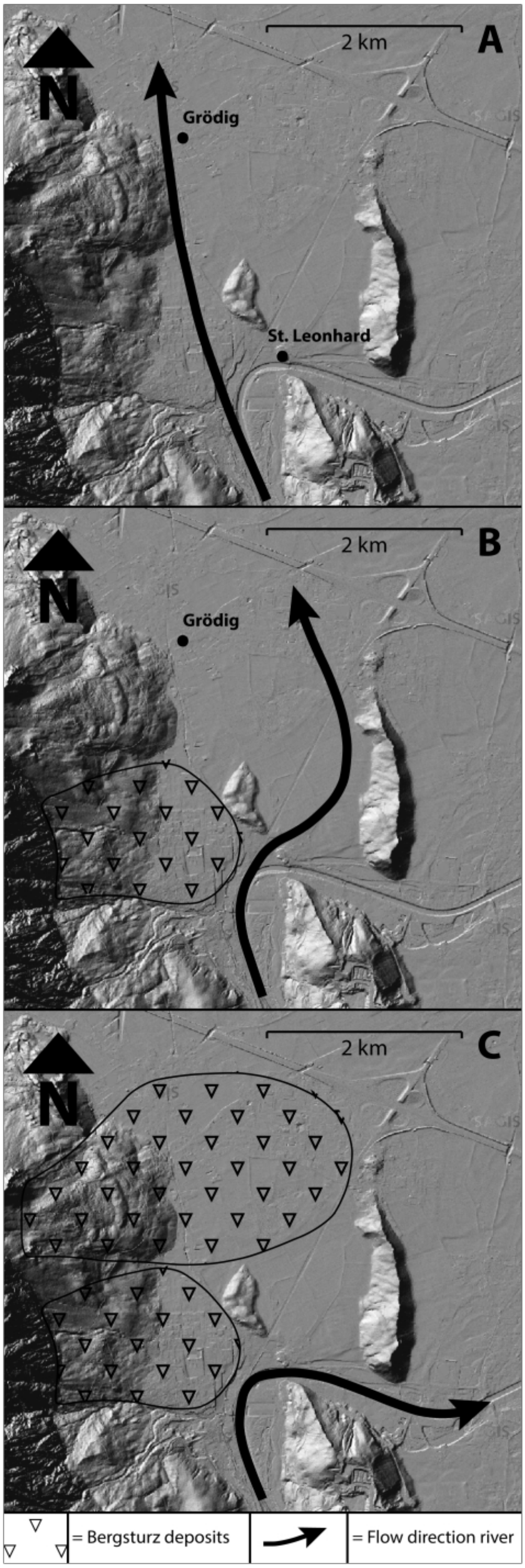


Figure 11: Flow direction of the Königsseeache river at 18 ka BP (A), after a first (B) and second (C) bergsturz-event (17 ka BP).

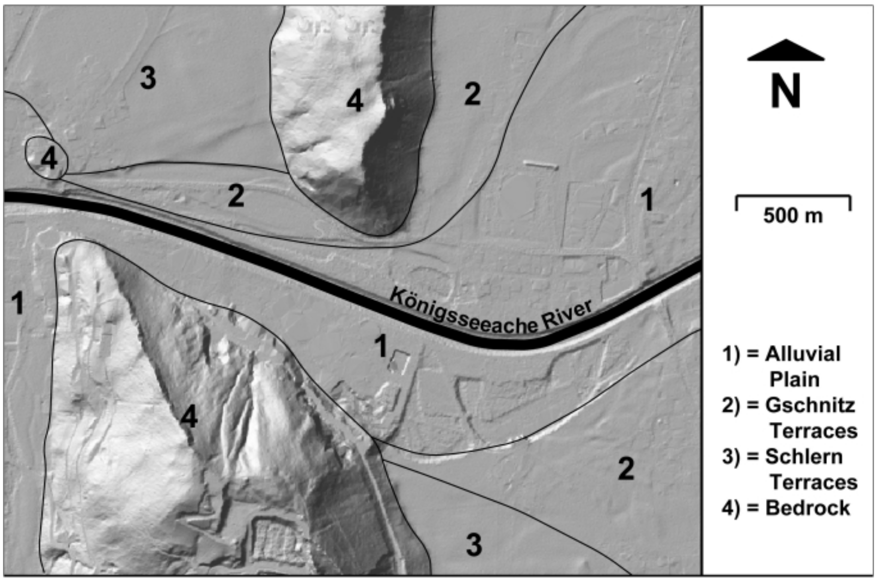


Figure 12: Terraces formed by the Königsseeache river after deflection to the east. (modified from Prey, 1969, and Höfer-Öllinger, 2012)

cally incised by gullies formed beneath the Salzach Glacier, which drained towards north. The feature found between drill hole B020 and B224 is possibly the result of similar, subglacial erosion processes.

After the retreat of the Würmian Glacier, the Saalach river followed this eroded channel as it entered the Salzburg Basin from a western or south-western direction.

The high amounts of fluvial gravels deposited in the Bad Reichenhall Basin are linked to significantly higher sediment loads in times of deglaciation (Hinderer, 2001) and rivers which deposited their sediment load primarily in the Alpine valleys (Hinderer, 2003). The development of former braided river systems on top of fluvial delta fans has been also observed in the Inntal near Telfs (Herbst et al., 2009) and in the intra-Alpine basin of Hopfgarten (Reitner et al., 2010) and is possibly a result of reduced sediment loads of the rivers.

The sedimentation pattern (gravel fans) in the marginal areas of the Salzburg Basin indicate that deltas prograded from the margins into the basin. Fluvial deposits have been observed in other Alpine basins like the Inn Valley and the basin of the Mondsee, and show typical features of prograding deltas (Poscher, 1994; van Husen and Reitner, 2011; Starnberger et al., 2013), but bottomsets, foresets and topsets could not be distinguished in the central Salzburg Basin. However, marginal, layered deposits documented in drill hole B001 are very similar to those described from Kame terraces as found in the Gurk Valley (van Husen, 2012). The thickness of 28 m coincides with results of Salcher et al. (2010) who estimated an average height of Kame deposits in the Salzach foreland of approximately 20 m, in places reaching as much as 45 m.

Thick gravel beds in the central parts of the Salzburg and Bad Reichenhall Basin were deposited only by the Saalach. We infer that the stronger progradation of deltas into the basins was caused by a flood event. A possible explanation for the postulated flood could involve drastic change towards warmer climate. According to this hypothesis, the ice melted very quickly leading to higher amounts of melting water. If that was the case, similar flood-related deposits should exist also in other Alpine basins of similar age, e.g. the basins of the Traun and Salzach rivers. So far, no evidence of a sudden simultaneous delta progradation in the Alpine basins has been described. Moreover, it seems as if the Salzburg Basin fill was achieved too quickly for any climate change having been able to significantly affect the evolution of deltas (van Husen, 1981). Consequently, climatic variations that were severe enough to cause such dramatic events happened later than 14 ka before present (van Husen, 1981). The results of luminescence datings in drill hole B322 at the Salzburg Airport prove that the clays of the “Salzburger Seeton” were deposited in lateglacial time (Starnberger et al., 2014). The luminescence dating of gravels near Schiffmoning points to an age of 17 ka (Fiebig and Herbst, 2012) by which time the Salzburg Basin must have been already filled.

It seems that a peculiar, regional incident happened and triggered the postulated flood event. This flood is therefore more likely connected to a dam failure of a coeval hypothetical lake located further upstream, which led to a tremendous amount of released water and thus transport of large amounts of coarse sediment. During this flood event deltas deposited by the Saalach prograded further into the basins of Bad Reichenhall and Salzburg. Such ancient lakes existed near Großgmain and in the valley at Hallthurm and their dams consisted of sediments and dead ice (Del-Negro, 1963; Stummer, 1947). As the ice melted due to rising temperatures, the dam broke and the stored water was released. Possibly the water was not released in one catastrophic event leading to one flood wave, but took place gradually.

In the area of the Königsseeache river, bergsturz events influenced the evolution of the river mouth. Blocked rivers by dams of bergsturz debris are a common feature (Abele, 1974) and have been observed in various regions in the Alps (van Husen et al., 2007; Ortner, 2007; Prager et al., 2006). Topographic features of the slope of the Untersberg west of Grödig indicate that a large debris cone accumulated in this area. The topographic landmark “Grödiger Törl” probably marks the main scarp of the source area (Fig. 9). Seefeldner (1954) already mentioned mudflows that influenced the direction of the Königsseeache river. Data from drill logs and field observations at the slope of the Untersberg west of Grödig agree with descriptions of bergsturz deposits in general (Abele, 1974). In fact, the similarity of these deposits to basal-till is very high. But as Profile K01 shows the deposits cover the fluvial gravels. Basal till would be expected to be deposited below fluvial gravels.

East of the slope of the Untersberg near the villages of Grödig and St. Leonhard these bergsturz deposits form a very smooth surface as they plunged into the ancient lake of Salzburg. Towards the northwest, near St. Leonhard, the topography reveals that the deposits of the first and earlier bergsturz filled the basin up to an absolute height of 460 m a.s.l., which most likely corresponds to the maximum water level of the lake in the lateglacial time (Seefeldner, 1954; Ivy-Ochs et al., 2008). The previous pathway of the Königsseeache to the north was blocked by these deposits and the river had to change its direction. Outcropping basement in the east of the Western Gorge near the church of St. Leonhard reaches an absolute height of 453 m a.s.l. and indicates that the lower altitude enabled the Königsseeache to cross the bedrock in this area. The second bergsturz event had a similar effect as the first one although the altitude of the surface with bergsturz deposits is only at 450 m a.s.l. This corresponds to estimations of Seefeldner (1954) who determined a lake level of 450 m a.s.l. after the water table of the lake had already begun to decrease and the basin was almost filled with sediments.

The results along the Saalach profile show that the lake was already filled 17 ka before present. According to these observations the bergsturz events happened between 18 ka and 17 ka before present.

4. Conclusion

The geomorphology in the investigated areas differs significantly with regard to the sedimentological processes that shaped the surface of the river confluences. Along the Saalach river, the morphology of the basement shows that the Bad Reichenhall Basin and Salzburg Basin were separated by a swell at the Walserberg, which developed due to glacial confluence of the Saalach- and Salzach Glacier in the Salzburg Basin. After the termination of the glacial period, ice masses melted quickly leaving behind larger lakes, which were obviously not connected to each other in the form of a shared water table. Thus, most of the coarse sediment load transported by the Saalach river was deposited into the Bad Reichenhall Basin. This resulted in the development of a large subaqueous delta fan building up a top-set, leading to a braided-river system and changing conditions of fluvial and slack-water deposition. The amount of sediment transported further into the Salzburg Basin was significantly lower because of the reduced flow velocity of the river.

In the Salzburg Basin the lateglacial and postglacial sedimentation was dominated by the deposition of limnic silt and clay in the center of the basin. Around the melting glacier, glacifluvial sedimentation in particular formed Kames-like terraces in marginal areas of the basin. Nearby streams from surrounding hills deposited only small delta fans. As half of the basins were filled up, a flood probably arose due to a dam-failure of a smaller lake further upstream. This flood caused a progradation of delta fans in both basins. After the water level had decreased, silt and clay were deposited on these coarse gravels in the Salzburg Basin.

The flow direction of the Königsseeache river was essentially affected by bergsturz events originating from the eastern slope of the Untersberg in the west of the study area. The river initially flowed through a gorge in the bedrock in a northerly direction when a bergsturz near St. Leonhard built up a dam and caused the river to change its direction to the east. By cutting epigenetically through the units of the Upper Roßfeld beds, the river's direction changed again to north following a second, eastern gorge in the bedrock. Another bergsturz near Grödig happened as the water level of the lake of Salzburg had already started to decrease. This event forced the river to change its direction a second time to the east and cut through the units of the Lower Roßfeld beds.

A comparison of both study areas shows that, on the one hand, the main factors determining the evolution of the Saalach confluence were floods that gradually led to a higher amount of water and deposition of vast delta fans. On the other hand the evolution of the Königsseeache confluence was largely driven by bergsturz events originating from the slopes of the Untersberg, which built up dams and changed the river's course from north to east.

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