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Sediment storage quantification and postglacial evolution of an inner-alpine sedimentary basin (Gradenmoos basin, Schober Mountains, National Park Hohe Tauern, Austria)

Joachim Götz, Robert Krisai & Lothar Schrott

University of Salzburg

Abstract

This study investigates the postglacial evolution of the Gradenmoos basin, a glacially overdeepened, semi-closed sedimentary basin in the central Gradenbach catchment (32 km², 1920-3283 m, Schober Mountains, National Park Hohe Tauern, Austria). The infill architecture and postglacial evolution of the basin as well as sediment storage volumes and associated rates of rockwall retreat (RR) are reconstructed using a multi-method approach, comprising field surveying (terrestrial laserscanning, geophysical prospection, core drilling), lab analyses (stratigraphic and palynologic analyses, sampling and radiocarbon dating), as well as GIS and 3D modelling. Surface, subsurface and temporal data indicate a complete and undisturbed sedimentary record archived in the basin since Younger Dryas deglaciation approx. 11 ka BP. After glacier retreat a former lake in the basin could be proved lasting for *ca.* 7500 years. We observed a heterogeneous spatio-temporal infill pattern of the lake followed by moor formation after lake disappearance since 3.5-2.5 ka BP. Total sediment storage within and surrounding the basin amounts to almost 20 x 10^6 m³. Volumetric and temporal data, however, resulted in comparatively low rates of postglacial RR (up to 520 mm/ka) despite of steep slope gradients and coarse and blocky weathering conditions in the associated rockwall source areas.

Keywords

Late and Postglacial, Holocene, Gradenmoos Basin, Lake Infilling, Sediment Storage, Rockwall Retreat

Introduction

Postglacial denudation (D) and rockwall retreat (RR) in alpine environments is often investigated using the sediment budget approach that relates sediment deposition in landforms and sinks to contributing source areas and a time-span of erosion. In this regard, the age, scale, and closeness of an investigated denudation-accumulation-system (HINDERER 2012) controls the observable time period, accuracy, and reliability of the results to be expected. However, the large range of published values of alpine D and RR might be based on variable spatial scales investigated, variable environmental and topographic conditions, and different ways of sediment storage quantification. Quantification approaches range from simple visual estimation to geometrical modelling, drilling, coring, and detailed geophysical surveying (e.g., COSSART & FORT 2008; CURRY & MORRIS 2004; HOFFMANN & SCHROTT 2002; KUHLEMANN et al. 2001; OTTO et al. 2009; TUNNICLIFFE & CHURCH 2011). The analysis of large-scale systems, such as perialpine lakes or large valley fills (e.g., HINDERER 2001; MÜLLER 1999), yields averaged rates of postglacial D since variable rates through time and the degree to which specific source areas contribute to D remain unknown. Few small-scale studies focused on intermediary sediment storage using geophysical techniques and GIS modelling (HOFFMANN & SCHROTT 2002; OTTO et al. 2009; SCHROTT et al. 2003). Remaining uncertainties comprise (1) the quantity of evacuated sediments since deglaciation, (2) initial amounts of glacigenic till deposits underneath present-day sediment storage landforms, and (3) the absolute timing of deglaciation. Detailed small-scale sediment budget studies within (almost) closed systems might close these gaps and improve our understanding of postglacial landscape evolution in alpine environments. Pleistocene glaciations and lateglacial oscillations frequently created overdeepened basins effectively trapping sediments until present. These basins facilitate such studies as they interrupt catchment connectivity and often archive a complete postglacial stratigraphic record. In view of that, we investigate the glacially overdeepened Gradenmoos basin (subcatchment size: 4.1 km²; basin floor elevation: 1920 m, Schober Range) in order to reconstruct the infill history of the basin and to quantify RR within the steep surrounding cirques using a multi-method approach (field surveying, lab analyses, GIS and 3D modelling). More details on this study are given in GÖTZ (2012) and GÖTZ et al. (2013, accepted).

Study Area

The Gradenbach catchment (32 km²) drains the central part of the eastern Schober Mountain Range to the east into the river Möll and belongs to the National Park Hohe Tauern (NPHT) (Fig. 1, map 1-3). The area is climatically well shielded due to its inner-alpine location with relatively continental climatic conditions, at least within valley bottom locations (climate station Döllach: precipitation: 826 mm/a, temperature: 6.1 °C, http://www.zamg.ac.at). South of the Penninic Tauern window formations and the Matrei Zone, the Palaeozoic 'Schober Range lithology' (mainly mica-schist, amphibolite) is characterised by intense, coarse and blocky weathering. The Schober Mountain Range, and particularly the Gradenbach catchment, shows a strong glacial signature with several cirques, hanging valleys, and a stepped longitudinal profile due to tectonics, glacial overdeepening effects, and rockfall damming. In the context of a cascading system (OTTO et al., 2009; SCHROTT et al., 2003), the catchment is structured into five subsystems (I-V) largely decoupled from each other (Fig. 1, map 3). The glacially overdeepened Gradenmoos basin corresponds to subsystem III, is the most pronounced sink in the catchment, and is sharply delineated up- and downstream the Gradenbach creek (length NE-SW: 1 km, width SE-NW: 100-250 m, subcatchment size 4.5 km²). Sediment storage landforms in subsystem III can be differentiated in primary (e.g., talus sheets; created beneath rockwalls by weathering and rockfall), secondary (e.g., debris cones; created by degradation of primary deposits located above) and tertiary deposits (e.g., floodplain; created by fluvial reworking of secondary deposits). The basin facilitates the study as (1) it effectively trapped sediments after deglaciation (output might be restricted to dissolved and small amounts of suspended load), (2) sediment storage can be accurately assessed due to spatial scale, (3) single landforms can be assigned to clearly delimitable rockwall source areas (four cirques, C1-C4, Fig. 1, map 3 and 4), and as (4) it is not affected by human impact until present (protected area, NPHT).

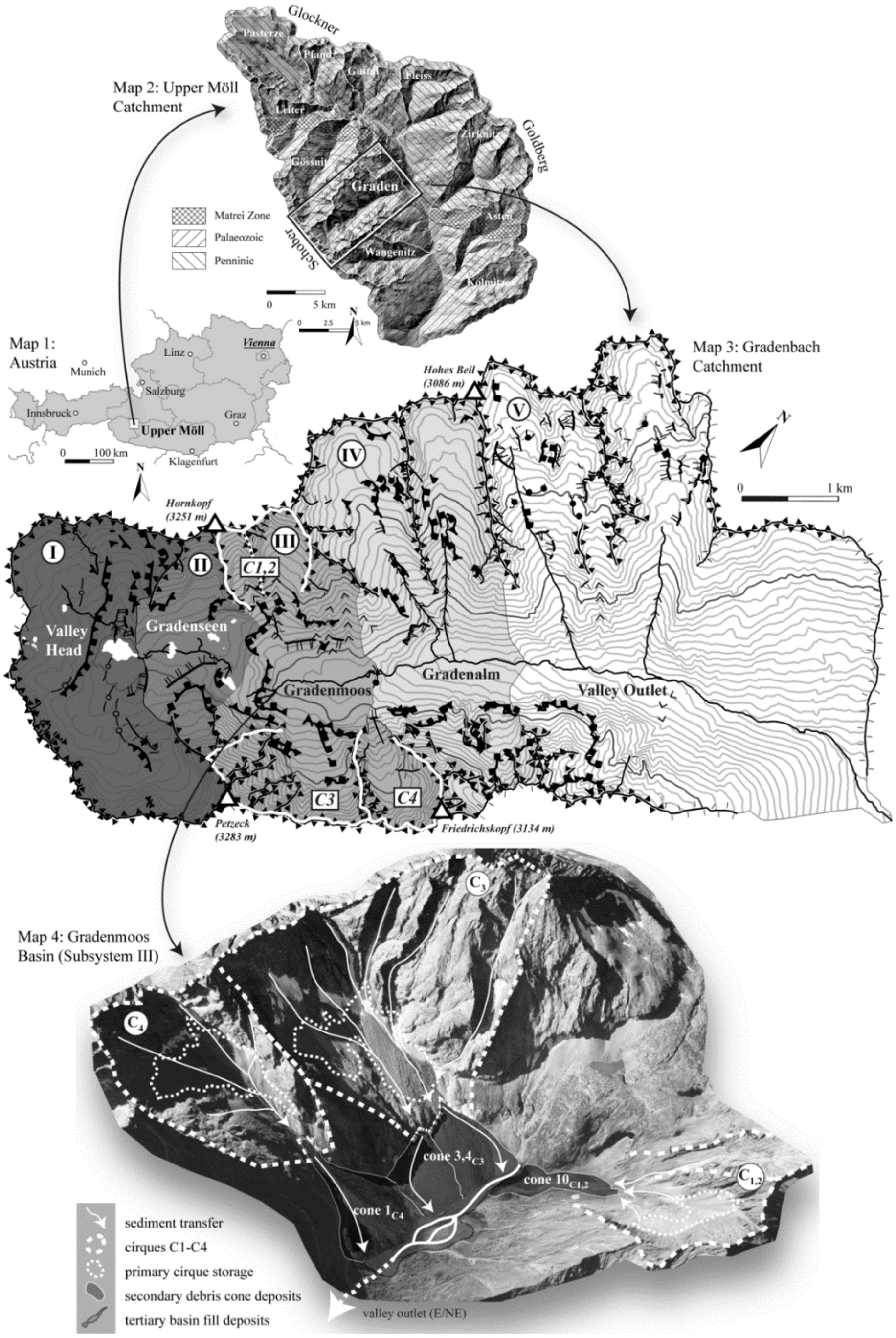


Figure 1: The Gradenmoos basin (4.5 km²; map 4) in the Gradenbach catchment (32 km²; map 3) as a part of the upper Möll catchment (423 km²; map 2) within Austria (map 1). Map 2 additionally shows major geologic units. Map 3 illustrates five subsystems (I-V) and four cirques (C1-C4) within subsystem III. Map 4 indicates source areas (cirques C_1-C_4), areas of primary talus storage within the cirques, secondary debris cones (1, 3, 4, 10), and tertiary basin fill deposits in the Gradenmoos basin (subsystem III).

Methods

Methods are just briefly described here; more details can be found in GÖTZ (2012) and GÖTZ et al. (2013, accepted). First, we mapped the catchment with a focus on sediment storage distribution and landform coupling. Some steep cirques and hanging valleys were mapped remotely using orthophotos, LIDAR data and derivatives (shaded relief and slope grids). Debris cones, talus sheets and cones, glaciers and rock glaciers, moraines, alluvial fans and plains, complex valley fill deposits, in-situ weathered regolith, as well as lakes and peat-bogs have been differentiated. Remaining areas refer to bedrock. We supplemented this dataset by qualitative (e.g., vegetation coverage, rounding, sorting) and quantitative (e.g., slope, area) attribute data resulting in a digital landform inventory, which enables to quickly visualise various geomorphological information.

We additionally assessed the present-day basin topography using terrestrial laserscanning (TLS). Six spatially distributed scan positions covering the entire basin resulted in a point cloud of *ca.* 60 x 10^6 points. During data processing (e.g., registration, 2.5D filtering, elimination of vegetation), the point cloud was homogenised to 4 points/m^2 and reduced to *ca.* 14.5 x 10^6 points.

Subsurface information is based on core drilling and geophysical prospection comprising electrical resistivity tomography (ERT), ground-penetrating radar (GPR), and refraction seismic (RS). Thickness of water-saturated alluvial deposits in the central and distal basin was assessed in greatest detail by ERT (13 survey lines 3.2 km total survey length) and a number of core drillings reaching bedrock several times. To detect bedrock depth beneath surrounding hillslope deposits, six additional GPR and RS surveys have been carried out (115-420 m length). Survey locations are shown in Fig. 2.

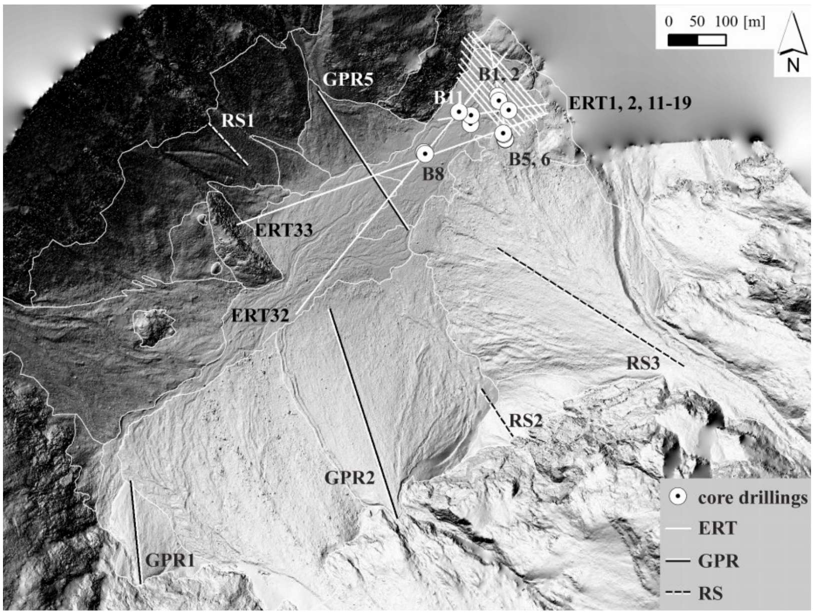


Figure 2: Locations of core drillings, resistivity (ERT), ground-penetrating radar (GPR), and refraction seismic (RS) surveys in the Gradenmoos basin based on hillshaded TLS data (spatial resolution: 50 cm).

Based on mentioned bedrock data derived from TLS, drillings, ERT, GPR, and RS, we interpolated bedrock surfaces in a GIS using different spline algorithms. Single 3D landform volumes were modelled afterwards by means of surface and bedrock meshes.

Temporal information was obtained through stratigraphic analyses and radiocarbon dating of 21 samples taken from the sediment cores (AMS ^{14}C-dating, carried out at CEDAD laboratories, University of Salento, Italy). Presented dates correspond to average values within the 2□ probability range. The core B2 was additionally analysed palynologically with a spacing of 20 cm.

To obtain postglacial sediment storage, landform volumes were reduced by an assumed layer of pre-Holocene basal till covering the entire basin with a mean thickness of 1.85 m as derived from the drillings.

Postglacial RR is based on the equation

$$RR = SV * \rho s / (\rho b * A * T)$$

where *SV* is the landform volume, *A* is the source area (cirques C1-C4, Fig. 1, map 3 and 4), and *T* is the time since deglaciation. RR is further based on a bedrock density *(ρb)* of 2.8 g/cm^3 and a porosity of sediment *(ρs)* of 2 g/cm^3 according to literature values.

Results and Discussion

ERT models show a sharp increase in resistivity representing the bedrock interface. Sediment thickness successively increases towards the central basin from 5-10 m (ERT11) to 15 m (ERT19). Bedrock edge in the central basin is provided by ERT32 and ERT33. ERT 32 shows an increase to 23 m at metre 130 (verified by B11) before dropping to a maximum depth of 55-60 m. Bedrock depths derived from core drillings (B1, B2, B11) agree with this data and determine the local bedrock resistivity to 2 k□m. Fig. 3 illustrates selected tomographies and core drillings in a 3D scene. GPR and RS data indicate sediment thicknesses of 30-35 m beneath debris cones 3 and 6 and up to 65 m beneath cone 1 (Fig. 1). Smaller talus sheets surrounding the basin reach 10-15 m.

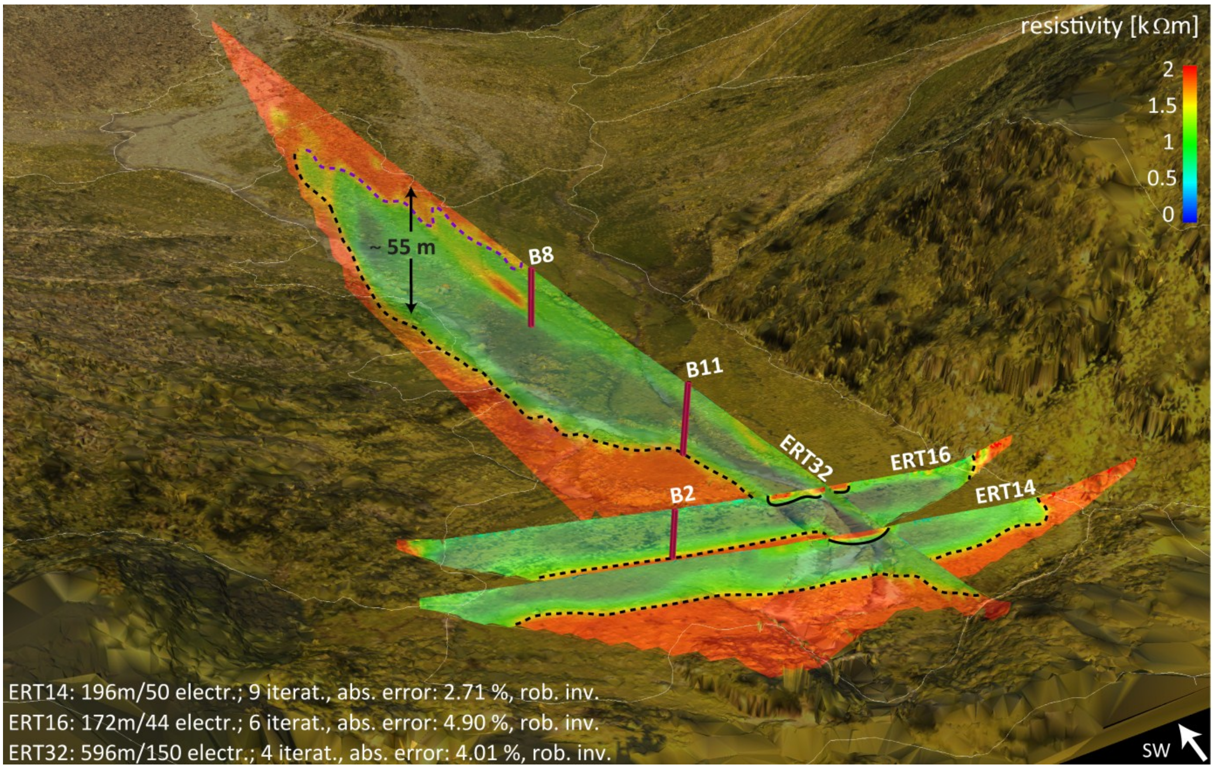
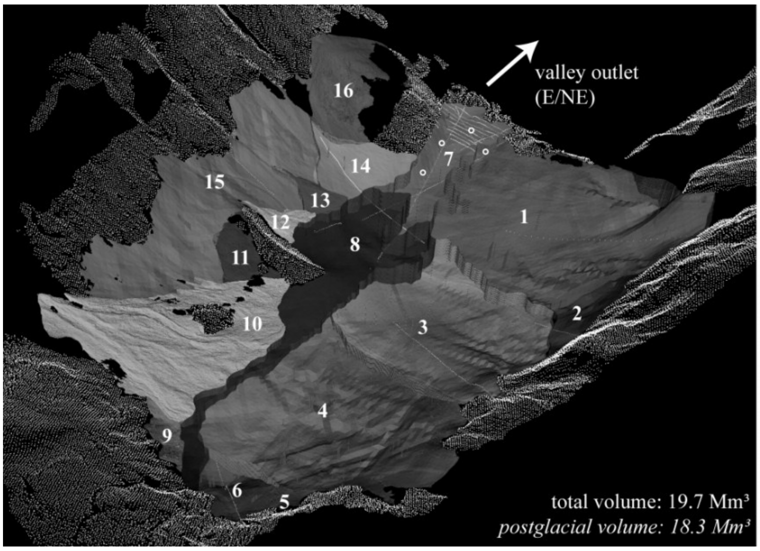


Figure 3: Selected ERT models and core drillings intersecting a TLS-based surface mesh with true colour information. Dashed lines represent bedrock edge (black) and coarse-grained deposits overlying the fine-grained basin fill (purple). Solid black lines delimit channel deposits showing higher resistivities. Drillings are indicated red. Survey/inversion parameters and measures of model fit are given lower left (data inversion: Res2DInv). For scale see Fig. 2.

Three core drillings reached bedrock (B1: 12.3 m; B2: 12.6 m; B11: 23 m) and provide a stratigraphy covering the entire Holocene. Above bedrock edge, a layer of basal till (average thickness: 1.85 m) is characterised by brownish colour, isolated pebbles in a fine matrix, and the absence of organic matter and pollen. Large sections between basal till and the lowest layers of peat near the surface show mainly clayey-silty, partly laminated deposits fading upwards to slightly coarser grain sizes. Subsequently, numerous layers of peat appear in the uppermost sections of the sediment cores above 1.75 m (B1, B2), 3.21 m (B11), and 4.27 m (B8)

Derived from these subsurface data as well as GIS and 3D modelling, total sediment storage within and surrounding the basin amounts to 19.7 x 10^6 m^3 whereas the postglacial volume is reduced by 8 % to 18.3 x 10^6 m^3. Around 70 % of sediments are stored in three debris cones (Fig. 4, Nr. 1, 3, 4) and another 15 % correspond to the central alluvial basin fill (Fig. 4, Nr. 7, 8).



land-form [nr]	total volume [10^6 m^3]	postgl. volume [10^6 m^3]	mean thickness [m]
1	6.26	5.97	40.28
2	0.26	0.24	19.08
3	3.90	3.71	37.11
4	3.67	3.46	32.19
5	0.01	0.01	4.19
6	0.32	0.29	22.52
7	1.21	1.15	32.79
8	1.91	1.80	31.28
9	0.03	0.02	5.90
10	0.50	0.35	6.22
11	0.03	0.01	3.46
12	0.04	0.03	6.85
13	0.13	0.12	23.20
14	0.60	0.56	29.43
15	0.63	0.47	7.45
16	0.17	0.08	3.59

Figure 4: Volumes and thickness of 3D landforms (Nr. 1-16). For scale see Fig. 2.

Rockwall retreat is derived from these volumes. A most realistic scenario (incl. approximates of intermediary cirque sediment storage and shares of tertiary basin fill deposits, Fig. 1, map 4) provides RR rates of 160 mm/ka (C1/2), 360 mm/ka (C3), and 520 mm/ka (C4), if true 3D rockwall source areas are taken into account. Planimetric 2D rockwall source areas in contrast result in significantly larger rates of 260 mm/ka (C1/2), 610 mm/ka (C3), and 930 mm/ka (C4).

We reconstructed the infill of the basin using complementary surface, subsurface, and temporal information. As sediment thickness is strongly variable, sedimentation rates show a large range as well (0.6-7.3 mm/a) but a general decline towards the distal basin. Basin sedimentation is shown in Fig. 5 together with the core stratigraphies, ^{14}C dates, several isochrones, and sedimentation rates. As already proposed by LIEB (1987), Early-Holocene ^{14}C-dates of the lowest samples above basal till (10375 cal. BP, 9475 cal. BP) indicate that the basin was glaciated for the last time during the Younger Dryas (Egesen oscillation) and that the Egesen glacier effectively scoured the basin. Until 3-4 ka BP a lake could be proved by palynology since *Pediastrum* (a green alga inhabiting freshwater environments) appears above basal till until a depth of 3.60 m within the core B2. In direct subsequence *Equisetum* (horsetail) comes up, an indicator that the lake disappeared. During the presence of the lake, sedimentation remained below 2.5 mm/a within the cores B2 and B11 but provides values of 5-7 mm/a in B8. This pattern indicates that the deepest part of the (central) basin 'had to be filled up' before sedimentation could also increase in the distal basin. If sedimentation rates derived from the cores are compared, a uniformity of the plots and delayed peaks of sedimentation can be observed towards the distal basin. This is interpreted as a fluvially induced 'sedimentary wave' advancing into and finally flattening the basin during lake disappearance between 2.5 and 4 ka BP. The idea is supported by several isochrones and stratigraphic data, where the termination of sand accumulation in B8 agrees with the onset of similar sequences in B2 and B11 (Fig. 5). Moor formation finally started between 2870 a cal. BP (B1, B2) and 2066 a cal. BP (B8). Well agreeing with these data, KRISAI et al. (2006) dated this transition to 2320 a cal. BP (depth: 1.65 m) *ca*. 25 m apart from B1.

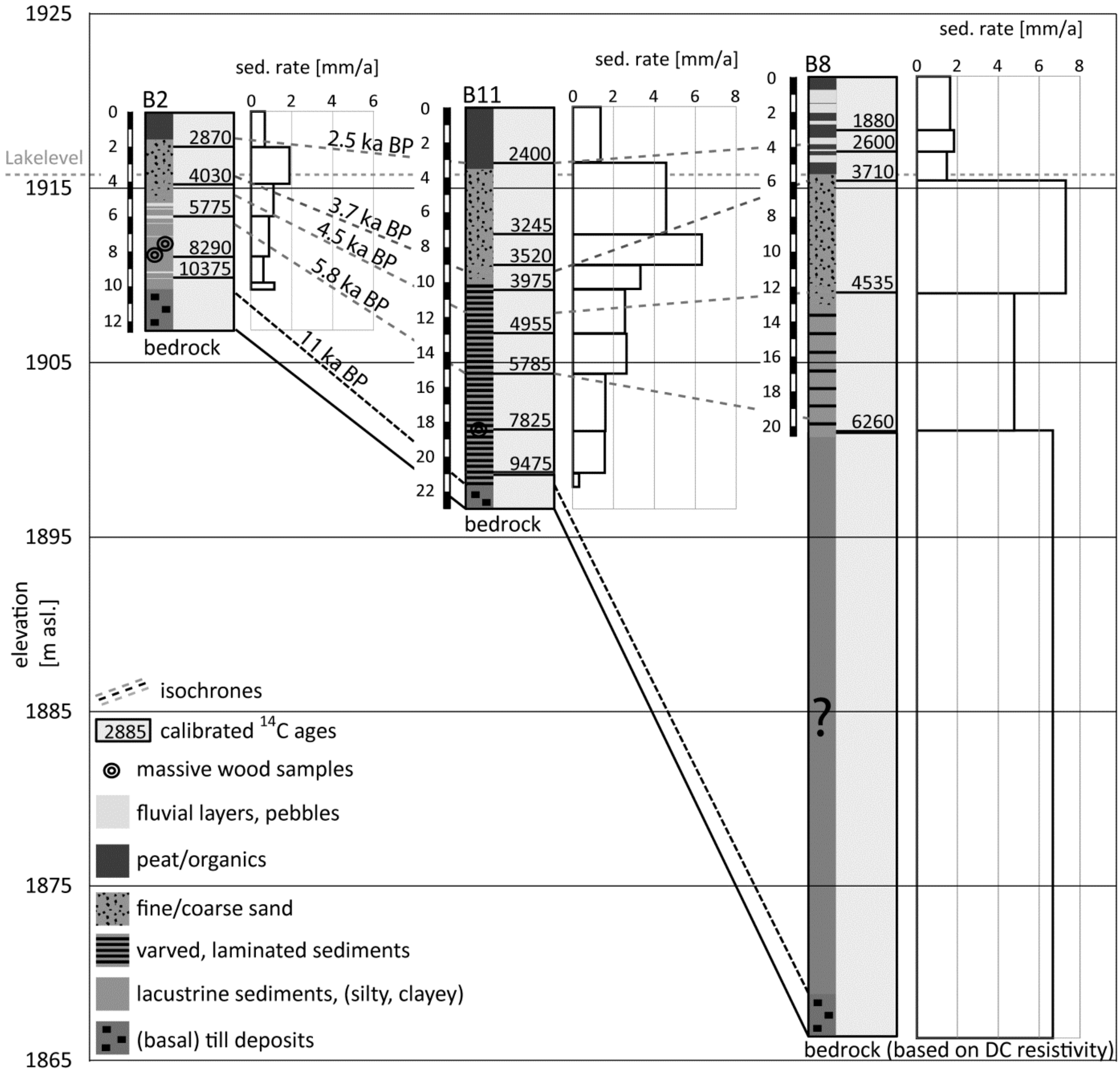


Figure 5: Drilling cores B2, B11 and B8 incl. a simplified stratigraphy, ^{14}C samples, bedrock base, isochrones (dashed lines), and sedimentation rates (for location, see Fig. 2 and 3; basin drainage to the left).

Conclusions

Most important outcomes of this study are as follows.

- Basin deglaciation and the onset of postglacial sedimentation could be determined to 11 ka BP by ^{14}C-dating of sediment core samples. The Younger Dryas (Egesen) glacier seems to have effectively scoured the basin leaving just a shallow layer of pre-Holocene basal till (8 % of total basin storage).
- The sedimentary record is completely preserved due to lake existence after deglaciation for around 7500 years as derived from stratigraphic and palynological data. Output might be limited to dissolved and small amounts of suspended load after lake disappearance.
- The lake infilling progress is interpreted as a 'sedimentary wave' advancing into and finally flattening the basin towards its distal part before moor formation started 3.5-2.5 ka BP.
- Total (postglacial) sediment storage amounts to 19.7 (18.3) x 10^6 m^3. Hillslope storage overbalances the alluvial basin fill by a factor of five.
- Corresponding rates of RR amount to max. 520 mm/ka considering 3D source areas.

Several uncertainties so far not addressed are included this study comprising the approximation of pre-Holocene basal till underneath present-day landforms, the incorporation of primary, secondary and tertiary sediment storages, and the absolute dating of postglacial sedimentation. However, despite of weathering and rockfall prone topographic, lithologic, and topo-climatic conditions, observed rates of RR are comparatively low. Since data is limited and based on different approaches covering a range of scales with different levels of detail, the dataset on alpine RR needs to be extended and knowledge about the factors governing the process (e.g., morphometric parameters, rock-mass strength, freeze/thaw cycles, influence of permafrost) needs to be enlarged. Comparable studies in similar environments but different lithologies might help to better understand the scatter of alpine RR and advance the interpretation of averaged signals of large-scale denudation.

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Contact

Joachim Götz
joachim.goetz@sbg.ac.at

Department Geography and Geology
University of Salzburg
Hellbrunnerstraße 34
5020 Salzburg
Austria