"Tapping the potential of one decade of annual repeat altimetry to study glacial and periglacial processes (TapRep)"

Final report

Matthias Huss[1,2], Leo Hösli[1,2], Nathalie Dubois[3], Ian Delaney[4], Andreas Linsbauer[5], Jonas Kubik[5], Daniel Farinotti[1,2]

[1] Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland
[2] Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Sion, Switzerland
[3] Swiss Federal Institute of Aquatic Science and Technology (EAWAG), , Dübendorf, Switzerland
[4] Institut des Dynamique de la Surface Terrestre (IDYST), Université de Lausanne, Lausanne, Switzerland
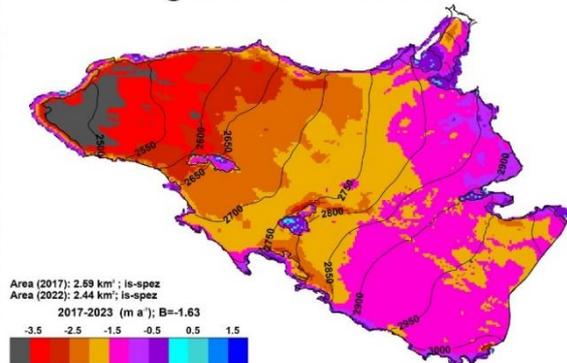[5] Department of Geography, University of Zurich, Zurich, Switzerland

Overview of results on glacial and periglacial change elaborated in the TapRep-project

1. Summary

Recent changes in climate result in a fast retreat of glaciers and shifts in the characteristics of proglacial areas, as well as sedimentation in alpine lakes. The interdisciplinary project "*Tapping the potential of one decade of annual repeat altimetry to study glacial and periglacial processes (TapRep)*" aimed at quantifying, better understanding and visualizing these rapid changes in the Swiss Alps relying on a unique data set of annual orthophotographs and digital elevation models (DEMs), the so-called "Spezialbefliegungen". This data set, acquired since 2012, stands out by its high temporal and spatial resolution which allows a suite of new analyses to be conducted, thus significantly advancing our knowledge of changes in glacial and proglacial areas.

The project was developed around four main strands that were covered by four different Swiss institutions that are at the forefront of research in their respective field: (1) Advancing the extrapolation of glacier mass balance from local measurements to the regional scale. (2) Assessing the abundance and dynamics of surface-collapse features on Alpine glacier tongues. (3) Quantifying periglacial sediment dynamics at the catchment-scale, including lake sedimentation. (4) 3D-visualization of aerial imagery and terrain models for public outreach. During the 2-year project important progress has been achieved both regarding the development of new approaches in glaciological and periglacial research, as well as an improved process understanding derived from the exceptional data set of the "Spezialbefliegungen" that is at the core of the TapRep project. Moreover, ambitious field measurements on glacier lakes have been performed.

In the frame of TapRep, a data evaluation pipeline has been set up connected to the Glacier Monitoring Switzerland (GLAMOS) program to operationally evaluate all available DEMs at the Swiss-wide scale and compute annual to multi-annual glacier mass change. A new approach to extrapolate observed annual mass balance at 20 sites with detailed monitoring to all Swiss glaciers was developed. The results indicate that 10% of the Swiss ice volume was lost in the two extreme years 2022 and 2023 combined. A thorough validation with observed ice loss from DEM differencing was performed. Based on the high detail of the "Spezialbefliegungen", new insights regarding the subglacial component of ice loss in the context of glacier collapse features were gained. The first Swiss-wide inventory of such features was established and a substantial increase in the frequency of formation of these features was found. While the contribution of collapse features to overall glacier mass loss is limited (0.1% over the last decade), a significant increase over time has been inferred.

Based on surface elevation changes in the proglacial area, detailed insights into processes and volumes of sediment erosion or deposition after glacier retreat were gained. New approaches were developed to bias-correct the DEMs to evaluate centimeter-scale changes over time. The results indicate a trend towards stabilization of glacier forefields, however with differences between individual years and basins. Sediment cores in three glacial lakes have been retrieved in a challenging measurement setting to quantify lake sedimentation rates, a yet poorly represented component of the sediment budget of glacierized catchments. Sedimentation rates of around 1 cm per year have been found, which is less than expected. The sediment cores also offer a suite of additional insights into climatic and geo-chemical processes based on laboratory analyses.

In the frame of the project, an interactive website was created that allows exploring the exceptional data set of the "Spezialbefliegungen" in three dimensions. The website is set up in a didactic way and provides explanations of glaciological and geomorphological features and processes. It is therefore a valuable resource for education and public outreach. Aerial images and terrain models visualized in 3D offer an impressive journey through time at very high resolution that is pre-rendered for different sites and view angles focusing on important aspects of the high-mountain environment.

The main goal of the TapRep-project was to tap into the potential of the unique data set of the "Spezialbefliegungen", now covering 12 years with an extraordinary detail. In an interdisciplinary approach, involving various fields of research, this was highly successful and demonstrated the potential of this so far undervalued data set in glacial and periglacial research. We note that the achievements go far beyond the project duration: Sustainable data pipelines have now been built up to keep using the data stream. Understanding of poorly understood processes has been gained that will spawn continued investigation in the future. Furthermore, fieldwork has resulted in a set of lake sediment cores that offer high potential for in depth research. Finally, our website visualizing the data set in 3D goes beyond the expectations set at the beginning of the project and will allow an efficient dissemination of the results to a broader public.

2. Scientific Report

2.1. Introduction

The project "*Tapping the potential of one decade of annual repeat altimetry to study glacial and periglacial processes (TapRep)*" focused on the unique data set of the so-called **"Spezialbefliegungen"** which, since 2012, have regularly been acquired in the frame of the Glacier Monitoring Switzerland (GLAMOS) program. The data set consists of both aerial photographs and Digital Elevation Models (DEMs) at very high resolution. Thanks to the contribution of the Federal Office for the Environment and the operational capabilities of the Federal Office of Topography, these data now cover more than a decade at yearly resolution and encompass almost 100 individual glaciers and glacier forefields.

In the present project, we utilized this data set to quantify and better understand various glaciological and periglacial processes in the Swiss Alps. More specifically, we developed the project around four main strands:

1. Advancing the extrapolation of glacier mass balance from local measurements to the regional scale.
2. Assessing the abundance and dynamics of surface-collapse features on Alpine glacier tongues.
3. Quantifying periglacial sediment dynamics at the catchment-scale, including lake sedimentation.
4. 3D-visualization of annual aerial imagery and terrain models for public outreach.

These topics define the four work packages (WPs) that were tackled by our interdisciplinary research team with scientists from different Swiss research institutions. Together, the above activities are meant to unlock the full potential of the "Spezialbefliegungen" data set, which documents in detail more than a decade of climate-related changes in the Swiss Alps.

2.2. WP1: Extrapolation of local mass balance measurements to the regional scale

During the TapRep project a complete processing chain to analyze DEMs acquired within the program of the "Spezialbefliegungen", as well as all other surface elevation data sources was elaborated. This results in a homogenous collection of glacier-specific DEMs including metadata that are integrated into the GLAMOS database. In addition, more than 3'000 outlines available for Swiss glaciers beyond the glacier inventories, partly at annual time steps, were collected and homogenized. This data set allows the streamlined computation of ice surface elevation changes (Fig. 1) and, hence, geodetic mass balance at unprecedented detail for all 1400 Swiss glaciers at multi-annual time scales, and for 90 glaciers covered by the "Spezialbefliegungen" at annual intervals during the period 2012-2024 (GLAMOS, 2024a). The results show a substantial glacier mass loss across all regions of Switzerland but also reveal previously unresolved spatial variability (Fig. 2). This data set is an important step towards a better understanding of ongoing glacier changes and facilitates the projection of future ice melt.

Figure 1: Annual surface elevation changes of Silvrettagletscher in 2017-2023 based on the "Spezialbefliegungen".

Fig. 2: Geodetic mass balance homogenized to the period 2015-2023 for all Swiss glaciers, aggregated to medium-scale hydrological basins.

GLAMOS measurements at 20 glaciers have been previously used to extrapolate the annual mass balance to all Swiss glaciers. Such extrapolation is necessary to capture the state and variations in the total ice mass in Switzerland and to raise awareness on the overall changes, e.g. indicating a loss of 10% of the total glacier volume in the extreme years 2022 and 2023 (Fig. 3; SCNAT, 2024). In the frame of TapRep, major effort has been invested to refine and validate this extrapolation procedure (GLAMOS, 2024b).

After applying corrections for the inhomogeneity in the acquisition date of aerial imagery, the density of volume change and potential biases in glacier area, the annually extrapolated results were confronted against independently observed mass changes from DEM differencing (Fig. 2), including the data from the "Spezial-befliegungen". Differences were found to be within the uncertainty of both methods.

Fig. 3: Relative change in overall Swiss glacier volume since 2000 based on a refined extrapolation scheme.

2.3. WP2: Spatio-temporal dynamics of glacier collapse features

Glacier collapse features are related to the formation of subglacial cavities and are expressed by circular crevasses at the surface. This phenomenon is closely related to stagnating ice-flow dynamics on disintegrating glaciers and gains in importance in current times of accelerated glacier melt (Egli et al., 2022). Nevertheless, a complete assessment of the spatial distribution of collapse features and the underlying processes is still lacking.

In this project, collapse features throughout the Swiss Alps were detected on aerial images from swisstopo using both a manual and an automated approach. We used a manually-collected dataset to train a machine-learning algorithm with the geospatial online tool "Picterra" (picterra.ch). Subsequently, we tested the algorithm and improved its performance in several iterations and finally applied it to all available aerial images between 1971 and 2023. Some manual filtering was required after the automated detection to remove false positives. Finally, we then outlined all collapse features and used the data set to create a first Swiss-wide inventory of glacier collapse features. Throughout the last five decades, both the frequency with which aerial images were obtained, as well as the amount of glacier area covered in a single year changed. This could lead to both temporal and spatial observation biases, which had to be corrected for.

To determine the ablation caused by collapse features, we used the "Spezialbefliegungen" DEMs that feature the required very high spatial and temporal resolution. Surface elevation change was quantified by DEM differencing between the first appearance of individual collapse features and the end of their lifespan. We then choose a "reference area", which is assumed not to be affected by subsurface ablation in the same elevation band as the collapse feature. Then, the mean surface elevation change of the reference area was subtracted from the surface elevation change over the collapse feature, to determine vertical ice motion caused by subsurface ablation. The ice volume loss due to the individual collapse feature was then determined based on surface elevation change across its entire extent.

223 collapse features were detected in Switzerland between 1971 and 2023 (Fig. 4, Hösli et al., submitted). They occurred on 77 different glaciers, 47 out of them hosting more than one collapse feature during the observation period. Collapse feature area varies between 700 m^2 and 83'400 m^2 with a median of 8'600 m^2.

The largest features (e.g. on Mittelaletschgletscher) span almost across the entire width of the glacier tongue. Large collapse features almost exclusively appear on the terminus of valley glaciers with a distinct tongue. The lifespan of collapse features in our inventory (i.e. the time interval between their first detection and their melt out) varies between 1 and 28 years, with a median of 4 years. Out of the five longest-lived features, four occurred on debris-covered glaciers and all five appeared before 1994, occurring on glaciers with limited frontal retreat.

Figure 4: Spatial distribution of collapse features in the Swiss Alps. Collapse-feature area is displayed with circles of relative size. The year of appearance (circle colors) indicates the year in which the collapse feature was first observed. Map source: swisstopo.

Collapse features were present throughout the investigated period 1971-2023 with a marked increase since the early 2000s (Fig. 5). 90% of the collapse features appeared after 2000 and 74% after 2010. By accounting for a potential observational bias, we can exclude that this increase in frequency is related to a higher acquisition rate of aerial imagery. Using the "Spezialbefliegungen", we were able to determine the ice volume loss of 32 collapse features, occurring on 11 different glaciers between 2010 and 2023. The median volume loss was found to be 25'200 m^3. Based on an empirical volume-area-scaling relationship we estimated the volume loss of all other collapse features in our inventory not covered by the "Spezialbefliegungen". Spatially focused subglacial ablation in collapse features Swiss-wide thus resulted in an ice volume loss of 19 million m^3 over the last five decades. The relative contribution of individual collapse features to their glaciers' mass loss ranges between almost 0% to 9%. The contribution of all collapse features to overall Swiss glacier mass loss between 1971 and 2023 was only 0.04%. However, this relative contribution substantially increased over time to reach 0.10% in the period 2011-2023. The three glaciers with the highest ice volume loss due to collapse features were Glacier de Zinal, Zmuttgletscher and Mittelaletschgletscher, all of them characterized by gently-sloping, debris-covered tongues with very low ice-flow dynamics. We conclude that collapse features on glacier snouts represent a considerable additional source of ice loss not considered so far in regional assessments. Besides the direct impact on ice loss, they also have the potential to substantially accelerate the retreat of glacier snouts due to feedback processes.
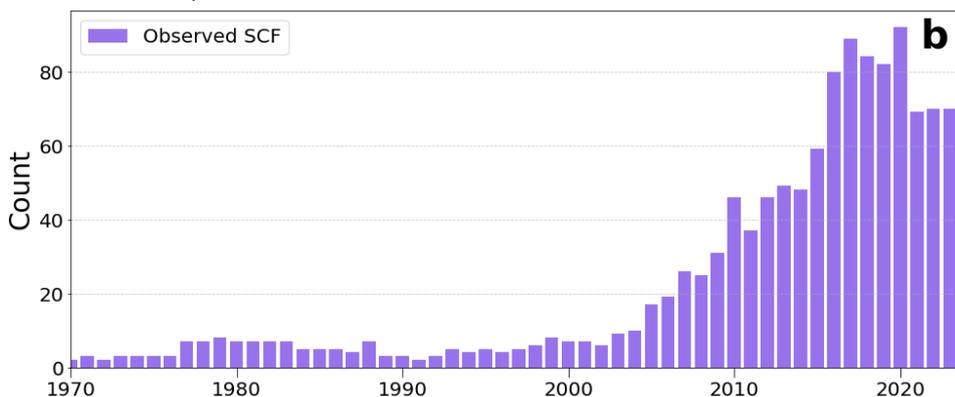

Figure 5: Temporal distribution of collapse features on Swiss glaciers. Bars show the number of observed features visible at any given point in time.

2.4. WP3a: Proglacial sediment mobilization and deposition

Ongoing glacier retreat exposes proglacial areas, i.e. land surfaces previously covered by ice. These areas often consist of unconsolidated sediment not yet stabilized by vegetation. They serve as both sediment sources, as glacier meltwater mobilizes material, and sediment sinks, where mobilized sediment is deposited, often in proglacial lakes. During the initial phases of glacier retreat, proglacial areas exhibit large amounts geomorphic activity, but over subsequent years and decades, they stabilize, enabling vegetation growth and reducing sediment mobilization (Ballentyne, 2002; Delaney et al., 2018). To understand the spatio-temporal changes in proglacial areas, we examined five highly glacierized catchments across the Swiss Alps (Gries, Trift, Findel, Gorner, Silvretta), leveraging data from the annual "Spezialbefliegungen." The investigated catchments vary in glacier size, retreat rates, and water discharge, providing a diverse framework for analysis.

Annual DEMs and aerial imagery were assessed to evaluate height changes and, thus, sediment fluxes. Due to the necessity to indentify elevation changes at the centimeter-scale, this involved masking artifacts in DEMs to minimize uncertainties, such as water bodies (lakes, streams), snow cover, debris-covered ice, and shadowed areas. Control areas were established to evaluate systematic DEM errors. Given the prevalence of artifacts such as banding and doming effects, the xDEM Python package was utilized for DEM coregistration (xDEM, 2024). Coregistration aligns stable terrain between years, correcting horizontal and vertical misfits. Despite these efforts, banding artifacts remained in some post-processed DEMs, contributing to the uncertainties in sediment transport evaluations. Additionally, steep valley walls introduced shadowing, reducing the places were control areas could be established.
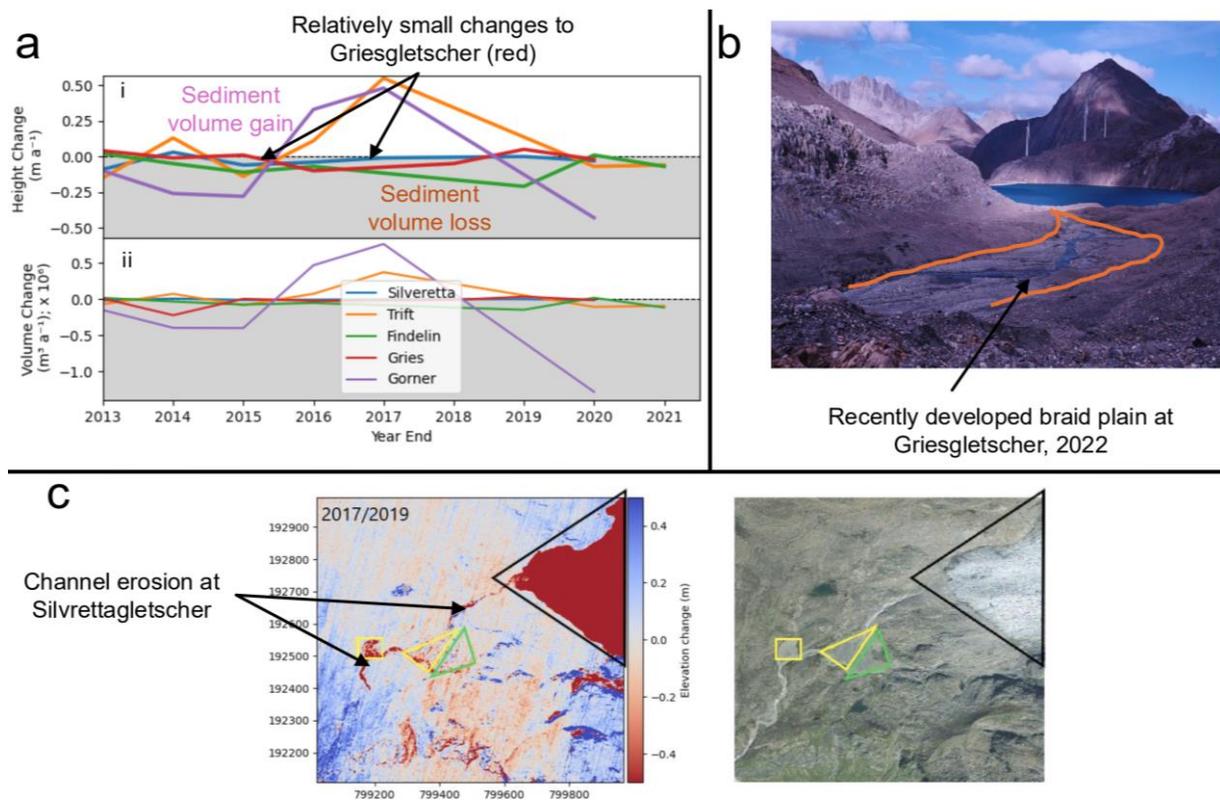

Figure 6: (a) Annual changes in average proglacial terrain height and sediment volume change over the study period for five proglacial areas. (b) Stabilization of the Griesgletscher proglacial area with development of a braid plain. (c) Areas of channel incision and downstream sediment deposition are visible at Silvrettagletscher between 2017 and 2019. Green and yellow markers are for reference between differenced DEMs and orthophoto.

Despite the uncertainties in the DEM processing, several key findings emerged. Our analysis revealed substantial proglacial area expansion between 2012 and 2023, driven by the strongly negative mass balance of Swiss glaciers. Notable results include proglacial area growth, such as for Triftgletscher, where the proglacial area nearly doubled in size over the study period. Additionally, across the five catchments examined in the study period, we found that 65% of the observations showed erosion in the proglacial area (Fig. 6a). This

suggests that across these catchments, proglacial sediment moblization due to glacier meltwater is increasing at a faster rate than sediment evacuation from underneath the glacier that supplies sediment to the proglacial area. As some of the observations in each catchment also demonstrate net deposition of sediment in the proglacial area, high meltwater production could intermittently lead to important sediment evacuation (Al Alam et al., 2025). We also noted several areas where geomorphic activity was confined to the main channel, e.g. for Silvrettagletscher between 2017 and 2019 (Fig. 6c).

A multi-decade analysis at Griesgletscher suggested that the proglacial area could be stabilizing by 2011 (Delaney et al., 2018). Our present results support this hypothesis and a braidplane is observed now (Fig 6b. Additionally, analysis of DEMs shows that since 2014, the proglacial area has undergone periods of both erosion and deposition, with no regime dominating. We anticipate that similar patterns may well emerge at other glaciers. However, the relatively short study period covered in the TapRep projects makes it difficult to evaluate the long-term stablization of proglacial areas in light of interannual variability in their dynamics.

2.5. WP3b: Lake sediment coring

In order to reconstruct sedimentation rates in proglacial lakes on longer time scales, short sediment cores were retrieved from four lakes using different techniques and analyzed in detail with a suite of laboratory methods at Eawag. We investigated sediment cores on Triftsee, Griessee, and of a former lake in front of Silvrettagletscher in 2023. Several cores were acquired from a coring platform on Oberaarsee in 2024.

Griessee. The 45 cm long core retrieved from Griessee reveals quite uniform/mixed sediment. A sedimentation rate of ca. 20-30 mm/yr was estimated using the unsupported ^{210}Pb dating method and compared with timeseries of bathymetric data. Due to the absence of laminations we decided not to investigate this core much further.

Triftsee. The lower 15 cm of the 36 cm long sediment core shows a chaotic pattern, which we interpret as deposited below the glacier. Laminations are clearly visible in the upper 21 cm. The XRF-based Zr/Rb ratio, which is an indicator for grain size variations, reveals around 20 peaks in this upper 21cm interval, which we interpret as clay layers (caps) deposited during the winter period. The ^{210}Pb age model provides an overall sedimentation rate of 9.4 mm/yr, suggesting a year of 2001 for the first lamination. This fits well with the creation of the proglacial Lake Trift between 2002 and 2006, since the Trift glacier tongue most likely became afloat before disappearing.

Oberaarsee. Five sediment cores ranging in length from 83 cm to 229 cm were retrieved from a UWITEC piston coring platform in early July 2024 (Fig. 7). All cores reached the former proglacial floodplains that developed before the reservoir lake was dammed up in 1953. There is a clear shift in every core from gravel-rich lithologies or soils at the base to more yellowish and relatively homogenous muddy sediment on top. The average thickness of the lake sediment interval ranges between 50-70 cm, except in core OBA-24-2, where two 40 to 60 cm turbiditic flow deposits increase the thickness of this lake sediment to 175 cm. When accounting for this, the sedimentation rate is similar to the other four cores and corresponds to ca. 6-10 mm/yr. This value compares well with the detected sedimentation rates of ca. 9 mm/yr in Triftsee and 20-30 mm/year in Griessee. Our results suggest that the initial estimates of sedimentary infill of Oberaarsee by Anselmetti et al. (2007) based on seismic profiles are rather generous (sedimentation rate of ~22,000 m^3/yr, or 14 mm/yr) and represent an upper limit for the sedimentation rate.

We further radiocarbon dated the soils found below the proglacial lake sediments in cores OBA-24-1, OBA-24-4, and OBA-24-5. The age of these soil deposits reveal that Oberaargletscher retreated significantly during the Roman Warm Period (250 BC to 400 AD) and the Dark Ages (500-1500 AD), allowing soils to form in the proglacial area. Important glacier recession was reconstructed for those two intervals for the Aletsch, Grimsel and Bernina Glaciers (Joerin et al., 2006, and references therein).
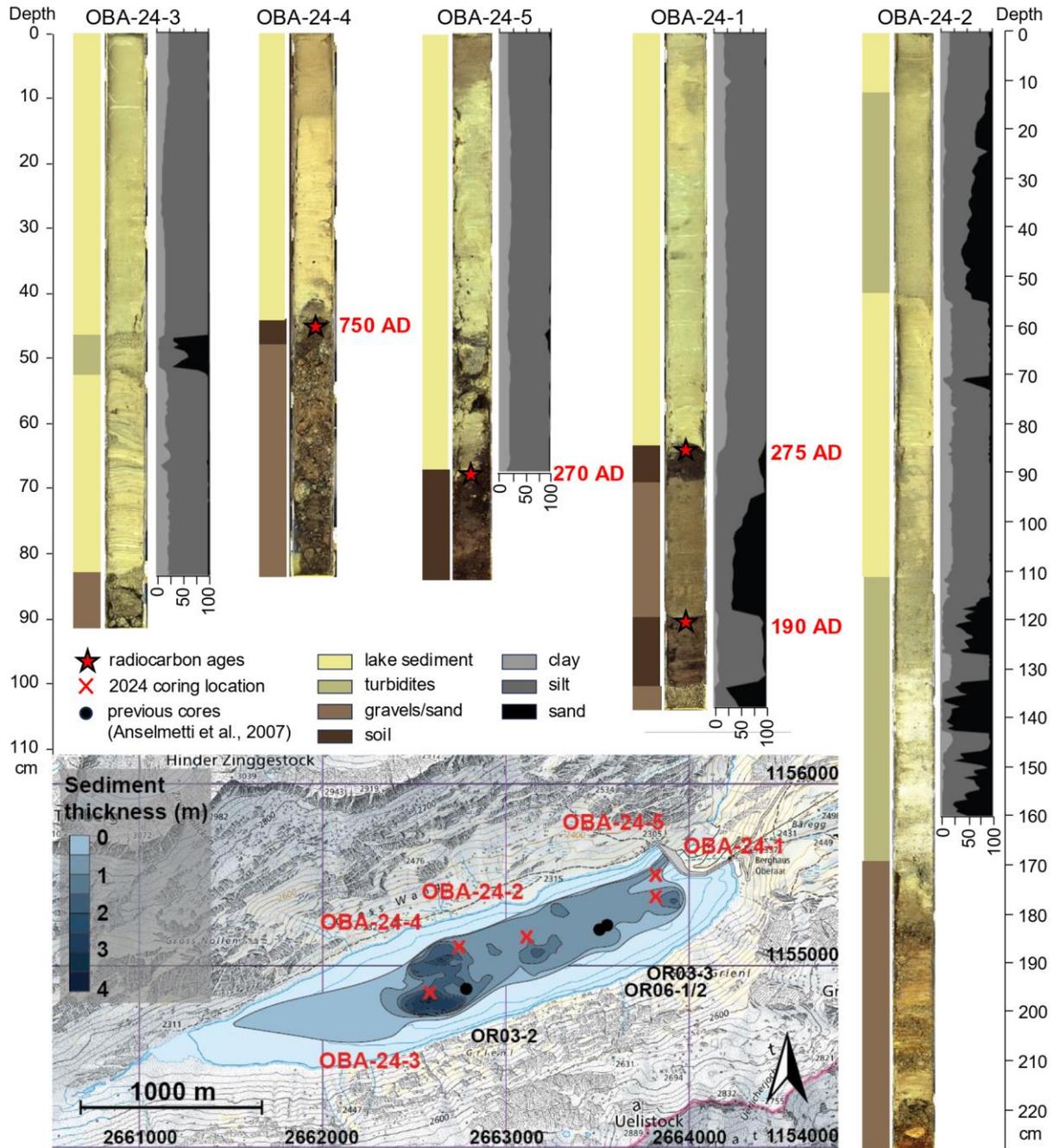
Figure 7. Oberaarsee sediment lithology and granulometry. (Top) Core lithology, linescans and downcore grain size distribution for cores OBA-24-1, OBA-24-2, OBA-24-3, OBA-24-4, and OBA-24-5 acquired in 2024. Bulk soil samples analyzed for radiocarbon are indicated with a red star. The calibrated age is indicated to the left in red. (Bottom) Map of Oberaarsee, overlain by the sediment thickness map modified from Anselmetti et al. (2007). Red crosses indicate 2024 coring locations. Black dots show 2003 and 2006 core locations.

2.6. WP4: 3D-visualization of aerial imagery and terrain models for public outreach

Glaciers are powerful and dynamic forces that shape landscapes. Work package 4 aimed to leverage the high-resolution data from the "Spezialbefliegungen" to create 3D-visualized time series. These visualizations not only document ongoing changes in selected glacier forefields but also provide a valuable tool for exploring and understanding these dynamic processes in detail.

The available data are exceptionally accurate and highly resolved, but their detail poses challenges, as the aerial imagery overlayed on DEMs requires significant storage and computational power for full-resolution rendering. A browser-based solution was identified as the best approach, offering seamless access to 3D

visualization without specialized software, making the data broadly accessible across devices. This method, however, requires optimizing the datasets for efficient rendering and interaction within the constraints of standard web environments (Fig. 8). To achieve these goals, a systematic approach was adopted. The initial focus was on exploring how aerial imagery and elevation models from the "Spezialbefliegungen" could be used to create virtual time-lapse photography series showcasing changes in glacier tongues and forefields. This required establishing efficient data handling processes, including the transfer, storage, and rendering of the large datasets. Software packages (Q-GIS, Blender) were tested to determine the most effective tools for processing and visualization.

Figure 8: The key challenge in creating time-lapse 3D visualizations from high-resolution annual aerial images and digital elevation models is achieving a balance between the level of detail and browser display performance.

Figure 9: Block diagram locating glacio-geomorphological phenomena in the public website.

As a pilot study, methods were developed and applied to the data of Findelgletscher. This study enabled the creation of a workflow for generating interactive 3D visualizations compatible with web browsers. However, balancing detail and performance proved challenging when using multiple years of data to depict changes over time, leading to the adoption of two complementary approaches that were combined:

Interactive 3D overview diagrams: The most recent high-resolution image and elevation data were optimized and compressed to create interactive 3D diagrams of glacier forefields. These diagrams allow users to explore glacio-geomorphological features in a web-friendly format (Fig. 9).

3D time series in video sequences: To preserve the exceptional detail of up to 100 pixels per square meter, selected 3D scenes were rendered as video sequences on high-performance computers. Videos require less bandwidth and computing power than interactive presentations, enabling viewers to experience dynamic changes in glacier forefields in their original resolution (Fig. 10).

The usability of this workflow was further refined by testing ways to present the resulting visualizations in an accessible and engaging format on a browser and was finally applied to three individual sites, resulting in 29 perspectives of 3D time-series visualizations (Fig. 10). In parallel, the project explored ways to use these 3D visualizations for public outreach and education. This included acquiring the necessary knowledge for website programming and developing a dedicated website to present the results interactively.

Fig. 10: View on tongue and forefield of Findelgletscher in 2018 and 2022 based on the high-resolution data of the "Spezialbefliegungen" and visualized in pre-rendered 3D time series video sequences.

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The primary outcome of Work Package 4 is a website designed for classroom use, enabling students to explore the glacio-geomorphological features of glacier forefields (https://microsite.geo.uzh.ch/tap-rep-web/). Its educational potential is thoroughly detailed in Linsbauer et al. (2025), including factual, didactic, and methodological analyses, along with accompanying worksheets. Beyond education, the resources are also suitable for outreach and presentations, with all pre-rendered 3D time-series videos available for direct download or via a dedicated YouTube channel.

The website opens with an overview page interlinked with its main content. The first section features an interactive schematic block diagram of an alpine glacier landscape, highlighting erosion and sedimentation processes. Users can explore specific phenomena, localized within the diagram, with web links providing further information (Fig. 9). The central feature of the site is the 3D diagrams of Findel, Oberer Grindelwald, and Silvrettagletscher. These interactive models allow users to scale, rotate, and move the view to examine the forefields from various perspectives. Overlay labels identify key locations of interest, linking directly to pre-rendered 3D time-series video sequences that depict changes over time in high detail (Fig. 10).

To optimally reach students and educators, the website was integrated into an article on glacier flow, erosion, and sedimentation processes, published in a geography didactics journal aimed at teachers and schools in German-speaking countries (Linsbauer et al., 2025). The article focuses on the experimental exploration of glacier flow through hands-on activities using a "glacier goo" model and emphasizes the dual role of glaciers as landscape shapers and climate change indicators. Students engage with fundamental processes of glacial dynamics, connecting these to real-world glacio-geomorphological features. Worksheets and resources facilitate independent research, enabling the use of experiments, digital maps and 3D visualizations. This comprehensive approach enhances scientific knowledge while fostering communication, evaluation, and inquiry skills.

By integrating innovative visualization techniques with an emphasis on accessibility and education, the project enhances public understanding of climate-driven changes in the glacier forefields of the Swiss Alps. The website, YouTube channel, and downloadable resources ensure broad accessibility, while the related journal article will amplify the project's impact in German-speaking countries.

2.7. Outreach and publications

The topic of glacier melt has received major attention in the national and international media during the project due to extreme weather conditions. All institutions involved in TapRep were very active in outreach. Both public talks were delivered and various interactions with the media occurred (TV, radio, print/online). We note that these often are not immediately related to TapRep, but the project activities significantly contributed to boosting this area of research. Project results were also presented to a scientific audience with several contributions at the Swiss Geoscience Meeting, and at the European Geosciences Union (Hösli et al., 2022; Delaney et al., 2023; Hösli et al., 2024). In terms of outreach, the output of WP4 addressing both teaching environments at the secondary schools and gymnasiums, as well as the broader public is most important for the TapRep project. A website allows visualizing and exploring glacier changes for three sites in 3D, both with pre-rendered videos from various locations, and using a didactical approach tailored to the use in classrooms (https://microsite.geo.uzh.ch/tap-rep-web/). An article focusing on educational aspects supports the dissemination of the produced visualizations (Linsbauer et al., 2025).

The output of WP1 is openly accessible to the scientific community via published data sets for geodetic ice volume change and geodetic mass balance (GLAMOS, 2024a), as well as Swiss-wide extrapolated volume change (GLAMOS, 2024b). The results are the basis of the regular national assessment of glacier changes at the end of the hydrological year via a media release by the Swiss Academy of Sciences (SCNAT, 2024), taken up by the main News outlets both in Switzerland and internationally. The resulting data sets are also important contributions to several scientific studies that are already published or submitted (e.g. Cremona et al., 2023; Menounos et al., submitted; van Tiel et al., submitted). An article summarizing the results of WP2 directly emerging from the TapRep-project has been submitted for publication to the Journal of Glaciology (Hösli et al., submitted). The method to assess proglacial lake sediment dynamics, as well as the resulting data sets are available via an open data repository on Zenodo (Al Alam et al., 2025). The lake sediment data generated as

part of WP3b has been submitted to PANGAEA Data Publisher for Earth & Environmental Science (www.pangaea.de) and will be openly accessible once accepted for publication.

2.8. Conclusions, limitations and outlook

We consider the TapRep project to be successful over the duration of two years, leading to significant progress in the use of the unique data set of the "Spezialbefliegungen" for various glaciological and periglacial applications. The project has clearly laid the foundation for future applications, mainly in the frame of GLAMOS, where the developed data pipelines and evaluation procedures will remain a central element in the operative processing of glacier data and their dissemination to the public. Scientific insights gained in WP2, only possible due to detailed analysis of these so far untapped potential of the "Spezialbefliegungen" data set, have been impactful in shaping a future research focus in ETH Zürich's glaciology group on quantifying basal ablation on Alpine glaciers. The approaches developed in the project will thus be highly relevant in supporting future investigations regarding this aspect.

The application of the DEMs from the "Spezialbefliegungen" to studying proglacial sediment dynamics, both in the glacier forefields recently becoming ice-free, as well as in proglacial lakes, was more experimental. Several obstacles, both related to data quality and fieldwork, were discovered. Nevertheless, interesting insights were gained. For example, the sediment cores acquired on four alpine lakes during this project offer new insights into sedimentation processes in this environment and hold a significant potential for further research on the sedimentation processes and long-term dynamics in the context of climate change. Also, for sediment dynamics (erosion and deposition), insightful trends have been detected and differences between catchments linked to their characteristics have been defined. Future research efforts will investigate these findings in more detail. Work package 4, focusing on visualization of the data sets and public outreach, has established a public website that allows different user groups to explore the highly resolved data from the "Spezialbefliegungen" for selected sites. We will advertise this site for broader access and use.

2.9. Acknowledgements

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