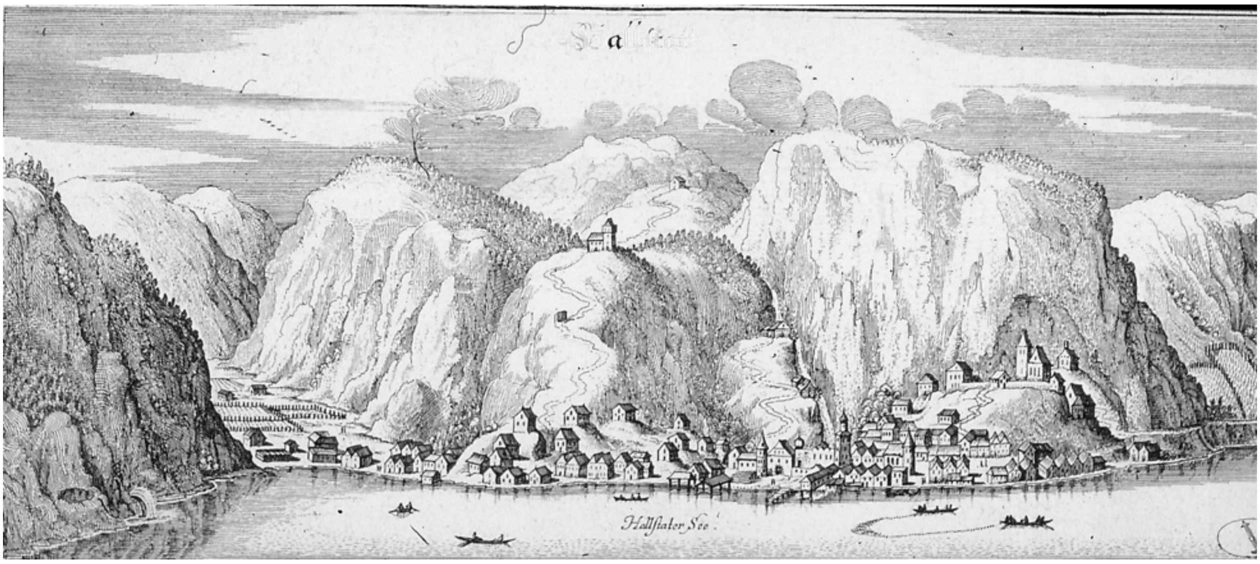
# Facealps: Facing Change in the Alps

## 3500 years of human-environment relations in the UNESCO World Heritage region Hallstatt-Dachstein/Salzkammergut

# Final project report

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Partner Projects:

*"Sediments of Hallstätter See as a palaeoflood archive"* (project no. M 1907–N34), principal investigator Stefan Lauterbach

*"The Alpine Early Anthropocene"* (uni:docs fellowship program for doctoral candidates, University of Vienna), principal investigator Wolfgang Knierzinger

## PROJECT TEAM AND COLLABORATING PROJECTS

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**Dendrochronologic dating of known subaerial mass movements:** Michael Grabner (BOKU, WT), *Hans Reschreiter (NHMW*)

**Bathymetric investigation of the lake basin:** *Flavio Anselmetti (UNIBE, DoG), Thomas Berberich (UIBK, DoG), Stefano Fabbri (UNIBE, DoG), Stefan Lauterbach (UIBK, DoG),* Michael Strasser *(UIBK, DoG)*

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**Palynological investigation Siegmoos bog:** *Andreas Berger (NHMW),* Daniela Festi (ÖAW, IGF), *Heimo Rainer (NHMW), Johannes Walter (NHMW)*

**Human land use: spatial analysis:** *Julia Klammer (NHMW),* Kerstin Kowarik (NHMW)

**Collaborating projects**

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BOKU, WT: University of Natural Resources and Life Sciences, Vienna, Institute of Wood Technology and Renewable Materials

GBA: Geological Survey of Austria

GFZ: Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Section 5.2 Climate Dynamics and Landscape Evolution

ÖAW, IGF: Austrian Academy of Sciences, Institute for Interdisciplinary Mountain Research

NHMW: Natural History Museum Vienna

UIBK, DoB: University of Innsbruck, Department of Botany

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## SUMMARY

The FACEALPS project had two main objectives (i) investigate the impact of natural extreme events on human activities in the Alps during the last 3500 years, and (ii) establish a lasting network linking researchers from the humanities and natural sciences and local transdisciplinary partners as foundation for future inter- and transdisciplinary work.

More precisely the project aimed to examine the evolution of the human-environment system in the UNESCO World Heritage area Hallstatt-Dachstein/Salzkammergut and to establish a highly resolved record of human-environment interactions over the last 3500 years. Specifically, we investigated resilience and vulnerability of prehistoric and historic communities living in this landscape with regards to geologic and climatic extreme events causing natural hazards. To address these issues a series of natural and anthropogenic archives was targeted within an interdisciplinary research framework.

Based on a highly resolved multi-proxy record we were able to gain vital insights into types and mechanisms of natural hazards in the research area, describe the impact of specific types of natural extreme events on the evolution of the socio-ecological systems in the area, characterize the role of prehistoric and historic salt mining in the formation of this landscape and societal response to natural hazards including the identification of risk management strategies.

We also established a lasting network linking researchers from the humanities and natural sciences and local transdisciplinary partners as foundation for future inter- and transdisciplinary work.

# ZUSAMMENFASSUNG

Das FACEALPS-Projekt verfolgte zwei Hauptziele: (1) die Untersuchung der Auswirkungen natürlicher Extremereignisse auf die Geschichte menschlicher Aktivität in den Alpen während der letzten 3500 Jahre und (2) den Aufbau eines dauerhaften, trafähigen Netzwerks von Forscher:innen aus den Geistes- und Naturwissenschaften und lokalen transdisziplinären Partner:innen als Grundlage für zukünftige inter- und transdisziplinäre Arbeit.

Genauer gesagt, zielte das Projekt darauf ab, die Entwicklung des Mensch-Umwelt-Systems im UNESCO-Welterbegebiet Hallstatt-Dachstein/Salzkammergut zu untersuchen und eine hochaufgelöste Rekonstruktion der Mensch-Umwelt-Interaktionen über die letzten 3500 Jahre zu erstellen. Insbesondere befassten sich das Projekt mit Resilienz und Vulnerabilität prähistorischer und historischer Gemeinschaften, die in dieser Landschaft lebten, im Hinblick auf geologische und klimatische Extremereignisse, die Naturgefahren verursachen. Um diese Fragen zu klären, wurde eine Reihe von natürlichen und anthropogenen Archiven in einem interdisziplinären Forschungsrahmen untersucht.

Auf der Grundlage eines hochaufgelösten Multi-Proxy-Datensatzes konnten wir wichtige Erkenntnisse über die Arten und Mechanismen von Naturgefahren im Forschungsgebiet gewinnen, die Auswirkungen bestimmter Arten von Extremereignissen auf die Entwicklung der sozio-ökologischen Systeme in diesem Gebiet beschreiben sowie die Rolle des prähistorischen und historischen Salzbergbaus bei der Entstehung dieser Landschaft und die gesellschaftliche Reaktion auf Naturgefahren einschließlich der Identifizierung von Risikomanagementstrategien charakterisieren.

Darüber hinaus haben wir ein dauerhaftes Netzwerk zwischen Forscher:innen aus den Geistes- und Naturwissenschaften und lokalen transdisziplinären Partner:innen aufgebaut, das die Grundlage für künftige inter- und transdisziplinäre Arbeiten bildet.

## Acknowledgments

This project was made possible through the support of a large number of institutions and private individuals. We are tremendously grateful for the extent of good will, enthusiasm and interest that we encountered throughout the project. Obviously we couldn't have done this without funding and infrastructural support, but in addition research of the type presented here cannot do without support of municipalities, landowners and volunteer associations.

In first instance we would like to thank the ÖAW-ESS program, which funded the FACEALPS project. We also thank the association Freunde des NHM Wien for financial support. For infrastructural support, permissions and much needed general support we thank Salinen Austria AG, Salzwelten GmbH, the Austrian Forestry Service, the municipality of Hallstatt, as well as the Hallstatt fire brigade and water rescue and the federal country of Upper Austria.

# 1. INTRODUCTION

The relationship between humans and mountain environments is long, intense and complex. Already at the dawn of history, human presence is tangible in these environments worldwide. Occasionally they were even the starting point of processes that left the social and physical world deeply changed. For example, centers of early domestication are located in mountain regions such as the Zagros Mountains (Zeder 2008). Mountain regions also represent and represented important resource and mobility scapes (Kowarik and Reschreiter 2020).

Over the long history of human activity in mountain regions complex and specialized socio-ecological systems developed (Bätzing 1991; Mathieu 2015). Understanding the deep history of these systems is a vital aspect in addressing current and coming challenges brought on by the changing Earth System in the Anthropocene (Costanza et al. 2006; Winiwarter 2007: 136; Dearing et al. 2015).

The FACEALPS project aimed to examine the evolution of the human-environment system in the UNESCO World Heritage area Hallstatt-Dachstein/Salzkammergut and to establish a highly resolved record of human-environment interactions over the last 3500 years. Specifically, we investigated resilience and vulnerability of prehistoric and historic communities living in this landscape with regards to geologic and climatic extreme events causing natural hazards (see also chap. 2.2 and 2.3).

*Figure 1: The UNESCO World Heritage area Hallstatt-Dachstein/Salzkammergut. Photo: D. Brandner.*

The Hallstatt-Dachstein region is ideally suited for investigating this type of questions as i) it was the focus of intense human activity for the last 3500 years, ii) natural extreme events are known to have impacted prehistoric societies in the area, and iii) it offers a large spectrum of cultural and natural archives.

# 2. Background and Scientific Aspects

## 2.1 Research Objectives

The Facealps project had two main objectives (i) investigate the impact of natural extreme events on human activities in the Alps during the last 3500 years, and (ii) establish a lasting network linking researchers from the humanities and natural sciences and local transdisciplinary partners as foundation for future inter- and transdisciplinary work.

## 2.2 Research questions

How did natural extreme events influence the socio-economic development of alpine societies during the last 3500 years?

Research activity concentrated on the late Holocene, with a specific focus on the 14th to 4th cent. BCE and the 18th to 21st century as these periods are particular well known.

## 2.3 Case study area

The research area is located at the northern border of the Eastern Alps in the Austrian Salzkammergut and covers the valley basin of Lake Hallstatt and the adjacent mountain ranges of the Dachstein Massif. Lake Hallstatt occupies a N-S stretching fjord-like valley (508 m asl) (figure 2 and 3). The Hallstatt High Valley with its rich prehistoric and historic mining traces is located on the eastern side, 400 m above the lake.

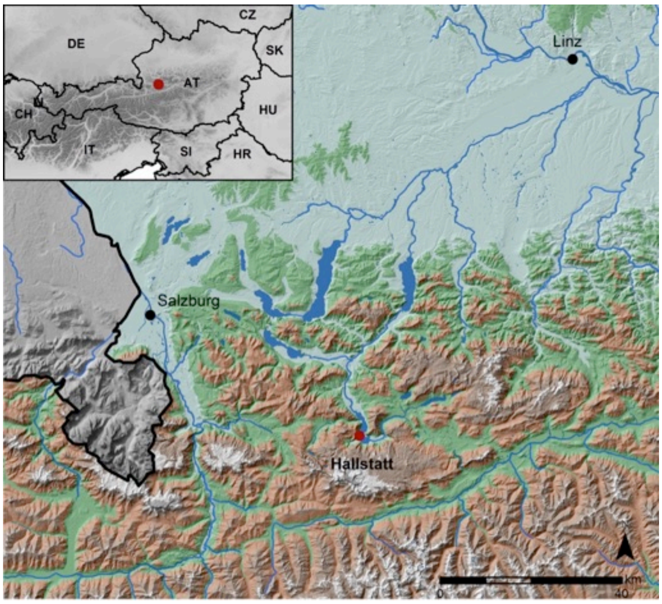


*Figure 2: Topographic situation. Map.: J. Klammer*

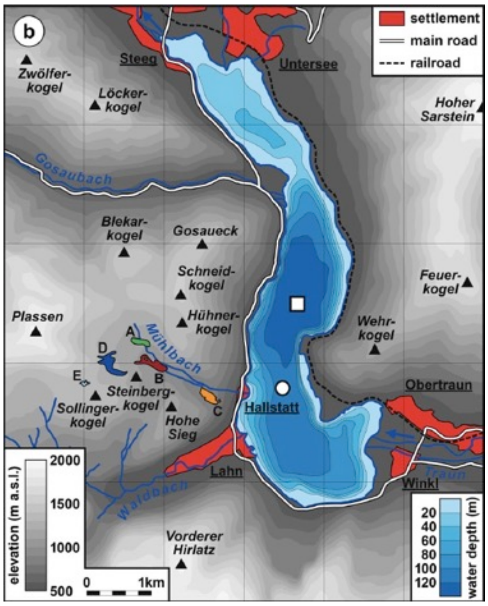


*Figure 3: Research area detail. Map: Lauterbach et al. 2022*

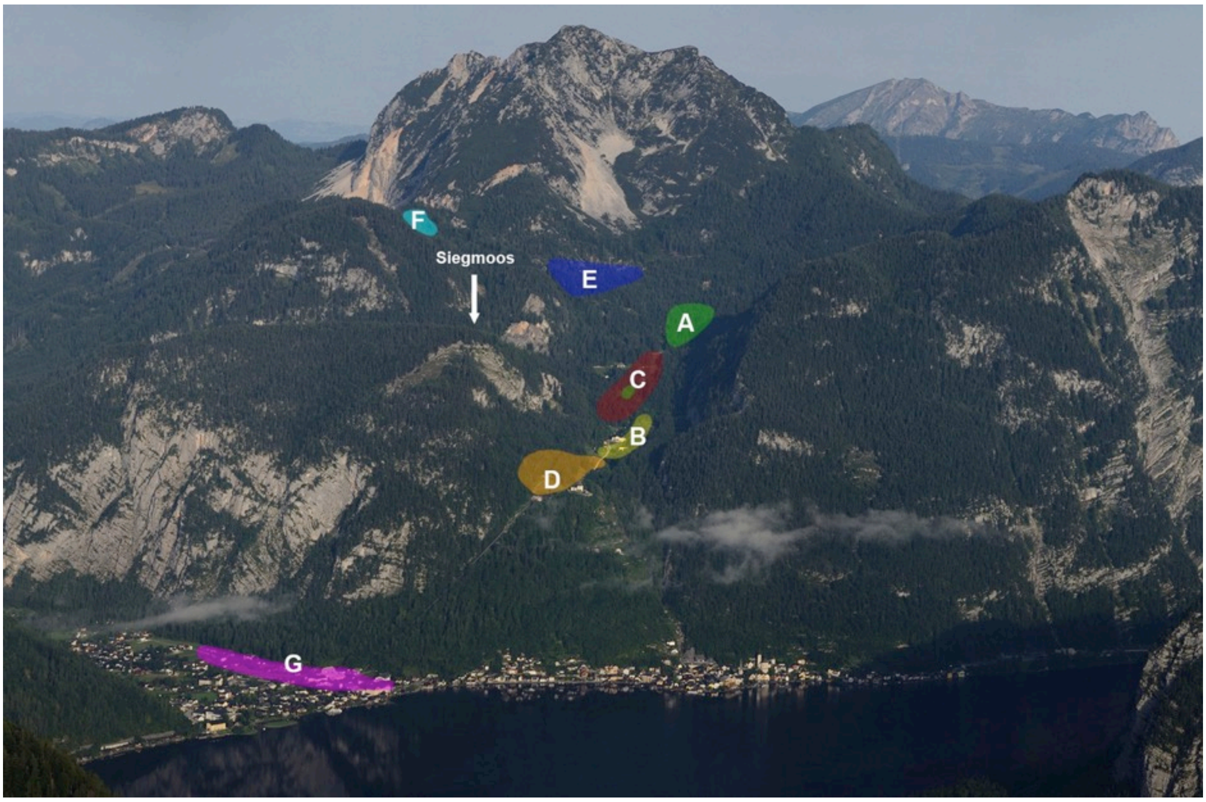


*Figure 4: Archaeological zones on the Hallstatt salt mountain: A, below ground – Bronze Age mine workings (Northern Group), B, above ground – Bronze Age log basin zone (meat curing), C, below ground – early Iron Age mine workings (Eastern group, red) and Bronze Age mine workings Christian-von-Tuschwerk area (green), D, above ground – Iron Age cemetery, E, late Iron Age mine workings (Western Group), F, above ground – late Iron Age settlement and G, above – ground Roman settlement and cemetery and location of the Siegmoos bog. Graphics: Photo and graphics: D. Brandner.*

The research area provides an ideal case study for several reasons: (i) different types of sedimentary archives (lake sediments, bogs) from different altitudinal belts exist; (ii) preliminary studies have demonstrated the considerable potential of these records for paleoenvironmental reconstructions; (iii) extreme events repeatedly disrupted, respectively altered the economic activities in the region by destroying the prehistoric Hallstatt salt mines; (iv) due to the long standing salt mining tradition (14$^{th}$ cent. BCE to the present) and the early onset of tourism (18$^{th}$ century) the area represents a long term focus of intense human activity and must be considered as a heavily human-impacted environment, and (v) socioeconomic activity is well documented through archaeological research and historical records (see below). Thus the Hallstatt/Dachstein region not only represents an alpine environment, where the co-evolving human-environment system can be observed in high detail throughout a long time period, but also offers the possibility to observe the impact of extreme events on the socio-ecological system in high resolution.

The long-standing and continuous human presence in the area is related to the rich salt deposits in the Hallstatt High Valley 400 m above Lake Hallstatt. Large-scale underground salt mining activity is evidenced since the late Bronze Age (14$^{th}$ cent. BCE), and continued with several interruptions until today (Reschreiter and Kowarik 2019). But various data points to a much longer tradition reaching back into the Neolithic period. Two time periods are especially well documented (i) 14$^{th}$ to 4$^{th}$ cent. BCE and (ii) 18$^{th}$ to 21$^{st}$ century. The earlier prehistoric period (i) is well known through archaeological research (Kowarik 2019; Reschreiter and Kowarik 2019). Due to the excellent preservation conditions in the salt mines resource management, mining organization and working processes can be reconstructed in detail. The historical to modern period (ii) is well documented through written sources and cartographic data due to the economic importance of the salt mines for the Habsburg monarchy and the later nation states. These archival documents are well compiled (Schraml 1932; Idam 2003), but have not been analyzed within an environmental or socio-ecological perspective.

## 2.4 State of the art

At the start of the project three prehistoric mining phases were known (figure 5 upper part) and clear evidence existed that twice slow earth movements had disrupted prehistoric mining activity.

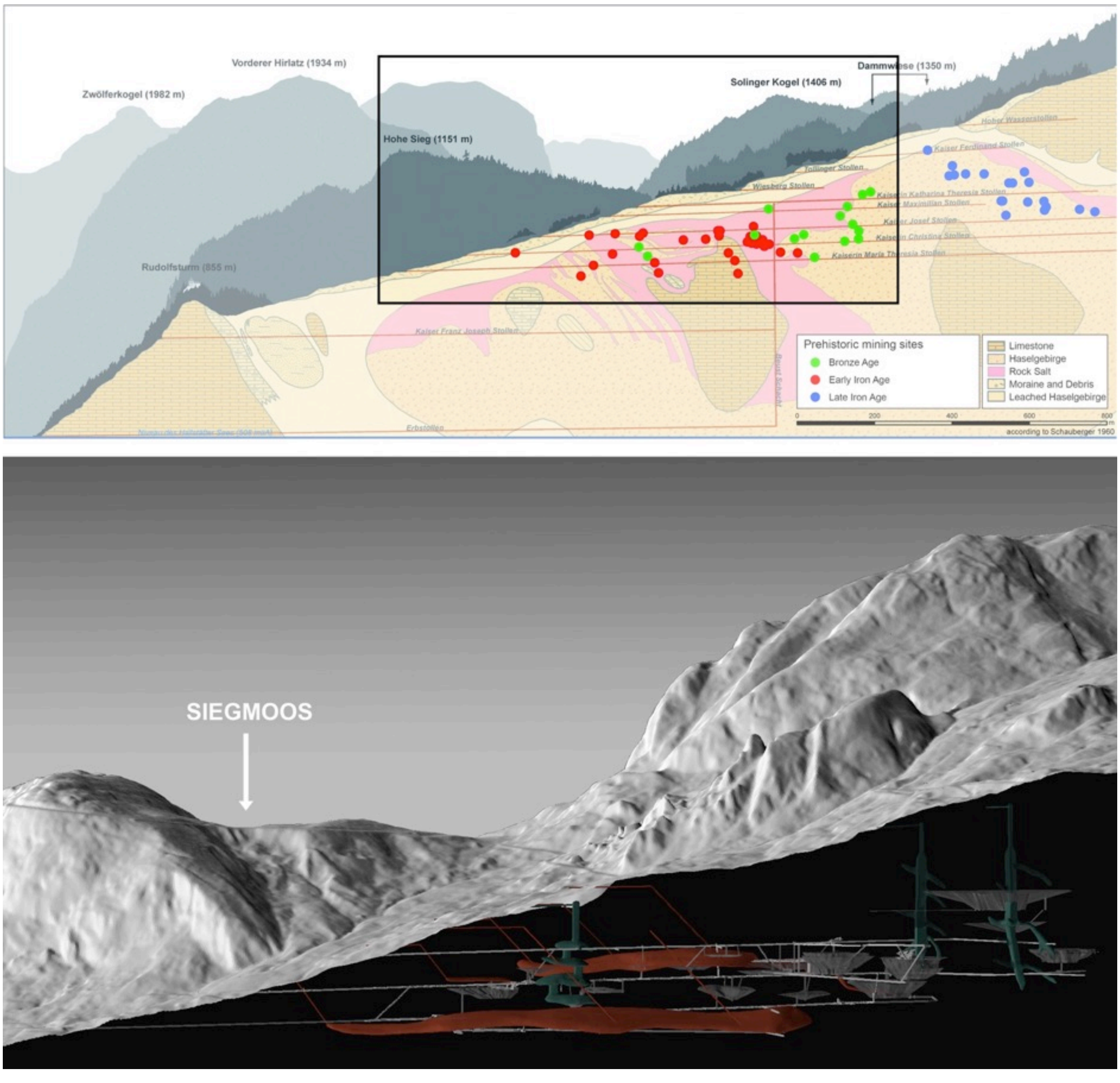


*Figure 5: Upper part) distribution of known prehistoric mining sites, and lower part) reconstruction of selected mine working, in green Bronze Age (Christian-von-Tuschwerk, Northern groups workings), in red Iron Age (Eastern Group) and in grey medieval to modern. Graphics: a) K. Löcker, b) D. Brandner*

The Bronze Age mine workings, reach depths of more than 100 m below surface (Reschreiter and Kowarik 2019). Located in two distinct areas, the *Nordgruppe* district and the mining chamber in the *Christian-von-Tuschwerk* area. The Bronze Age mine workings were at this point only dated by radiocarbon dates to ~1390 to 1040 BCE and ~1260 to 1020 BCE respectively (Barth 1998; Stadler 1999). Bronze Age mining activity was disrupted as mass movements buried parts of the High Valley causing the collapse and backfilling of the mines (Rohn et al. 2005; see figure 6). In addition, findings on the surface of the salt mountain evidence large-scale production of salt-cured meat in the 14th and 13th cent. BCE (Barth 2013; Pucher et al. 2013).

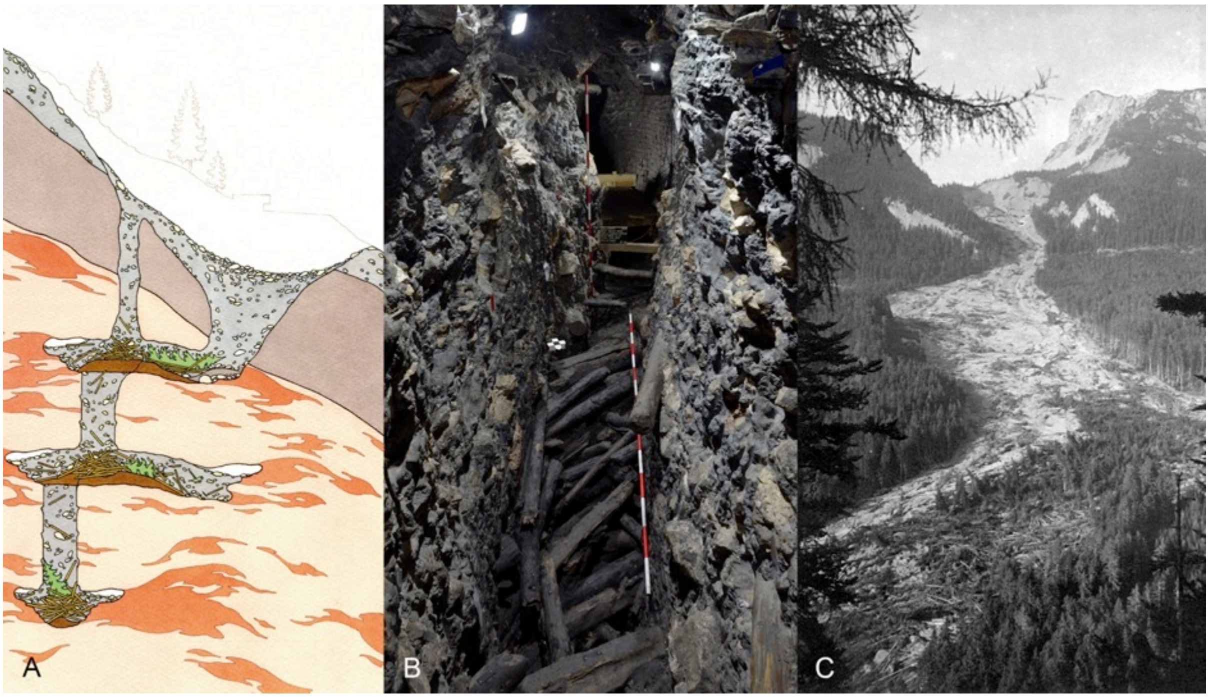


*Figure 6: a) Backfilling of Bronze Age mine working, schematic representation; b) remains of earth flow inside the Bronze Age mine working in the Christian-von-Tuschwerk area, c) modern mud flow event in a neighboring valley. Graphics: a) D. Gröbner, b) D. Brandner, c) WLV Gebiets.leit. SKGT.*

Early Iron Age mining in Hallstatt (*Ostgruppe*) reached depths of 50 to 200 m below surface and the dimensions of these mining chambers are even more substantial (300 m x 10-30 m x 20 m; Reschreiter et al. 2019). Radiocarbon data fall between the 9th and 3rd cent. BCE (Stadler 1999). Significant human presence is also recorded through the Iron Age cemetery located in the vicinity of the mine, with a minimum of 1500 graves excavated so far. Burial activity dates from c. 800 BCE to the 4th cent. BCE with a peak in burial activity in the 8th and 7th cent. BCE and a significant drop in burial numbers in the 6th and 5th cent. BCE (Kromer 1959; Barth and Lobisser 2002; Stöllner 2002: 300-340, 353-361). The cemetery counts among the largest and richest in Iron Age Europe (Nikulka 2016: 246). The extraordinary wealth and variety of cultural influences from regions in Southern and Central Europe documented here are inferred to be the result of salt mining and far reaching trade networks (Kromer 1959, 1987; Frey 1971; Hodson 1990; Glunz 1997; Dörrer 2002; Stöllner 2002: 421-423; Egg et al. 2006). Iron Age mining activity was also disrupted by slow earth flows, which collapsed the mine workings (Ehret 2009).

The youngest prehistoric mining phase (*Westgruppe*) is not as well understood, but the substantial number of known sites and the depths below surface (*c.* 330 m) document that these mining activities were at least as large in scale as the previous ones (Schauberger 1960; Barth and Lobisser 2002). This phase is only roughly dated through two radiocarbon measurements, which give a time span of 110 BCE to CE 240, thus hinting at the possibility of Roman Period mining (Stadler 1999). Archaeological materials recovered from the nearby *Dammwiese*-settlement as well as surface finds in the area mostly date to La Tène D (Hell 1952c; Morton 1956: 86-106; Trebsche 2003: 4-9). Extensive Roman settlement traces and a cemetery indicate substantial human activity from the 1st to the 4th cent. CE (Zabehlicky and Zabehlicky-Scheffenegger 1990). The earliest evidence for salt mining following these phases dates to the

14th cent. CE (Barth and Lobisser 2002). From this time salt mining continued to the present without interruptions.

Thus archaeological data clearly demonstrated that salt mining was taken up again after a certain time periods. It was also clear that the socioeconomic systems operating after these events show marked differences to those before, in terms of mining technology and resource management in the mines (Reschreiter and Kowarik 2015). But while mining technology, organization of production and resource management have been extensively studied in Hallstatt (Barth 1998; Barth and Lobisser 2002; Reschreiter and Kowarik 2015; Reschreiter and Kowarik 2019), no paleoenvironmental studies had been carried out at this point and tree ring chronologies enabling a highly resolved chronological reconstruction of mass movement events and subsequent developments did not exist. This severely limited the possibility to assess the impact of the identified mass movements. The extent of the environmental impact of the mass movements and their impact on human subsistence strategies was poorly understood. Especially, whether those events led to a collapse of the system in place and an entirely new and unrelated system established itself or whether a recovery was possible was an open question. In addition, earlier studies had generated evidence for further mass movement events (Ehret 2002), which might also have impacted on prehistoric and historic mining activities and the communities living in the area. Finally, while archaeological and historical data clearly evidence the substantial environmental impact of salt mining and general human presence on the ecosystem no paleoenvironmental data existed, that allowed to track and characterize human impact on the environment consistently.

To address this gap, we chose to investigate a series of natural and anthropogenic archives with the aim to achieve an integrated reconstruction of past human-environment interactions. This would form the foundation for the discussion of our research questions.

# 3. Methodology and Project Execution

The Facealps project investigated the environmental and socioeconomic impact of climatic and geologic extreme events in the Hallstatt region. For the last 3500 years Hallstatt was a focus of intense and continuous human activity. To establish a highly resolved integrated record of human-environment relations we investigated a series of natural and anthropogenic archives within an interdisciplinary research framework. In the course of the project substantial effort was put in achieving transdisciplinary exchange and discussion.

Our approach was based on:

(a) the establishment of an inventory of extreme events,

(b) reconstruction of paleoenvironmental change and human land use,

(c) and interdisciplinary data interpretation.

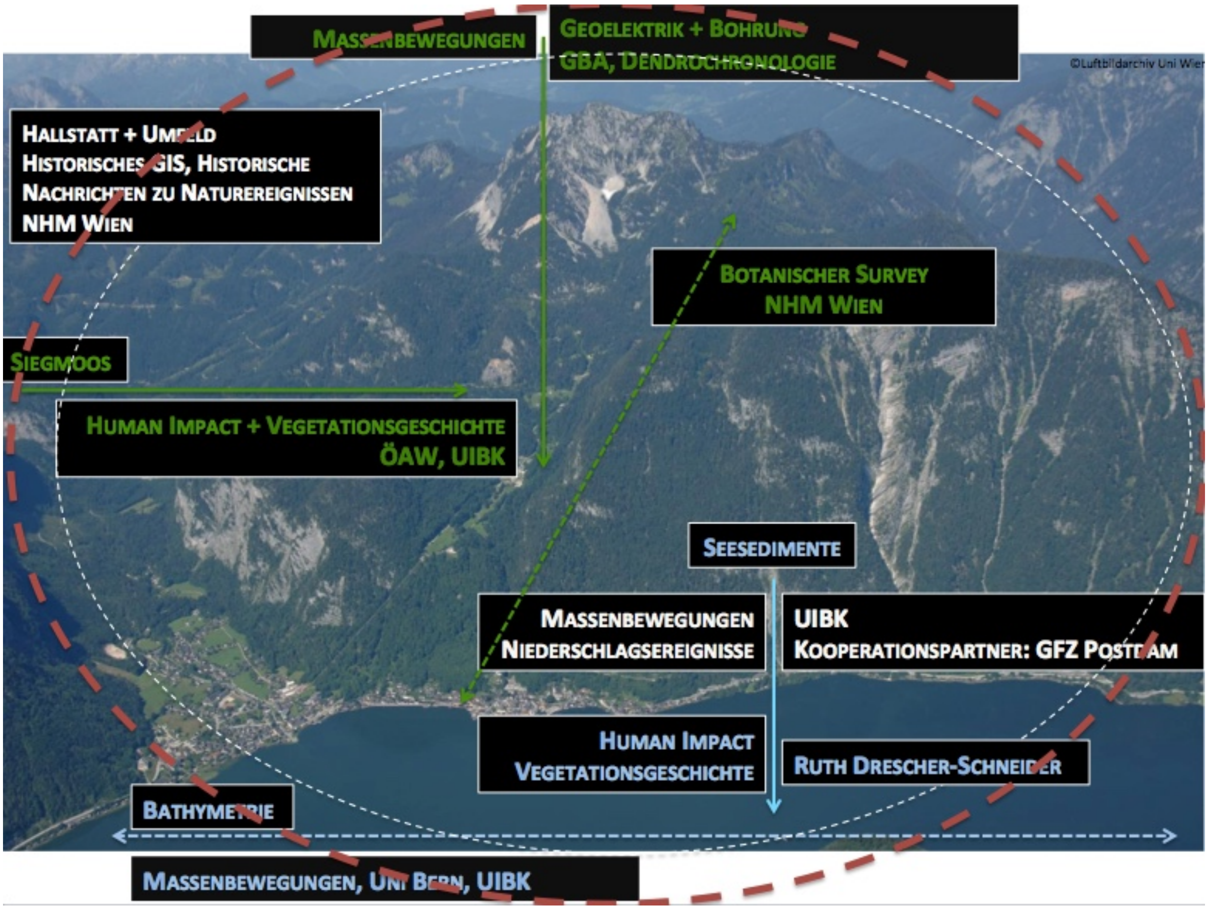


*Fig. 7: Interdisciplinary approach of the Facealps project. Landscape image: Luftbildarchiv Univ. Wien*

## 3.1 Inventory of extreme events

Two subaerial mass movements in the Hallstatt High Valley could be causally linked with severe disruptions in the socioeconomic activities of the research area during prehistory ( Rohn et al. 2005; Ehret et al. 2008; Reschreiter et al. 2010; see also chap. 2.4). But despite committed research on the subject essential aspects remained unclear (in particular the volume of the landslide masses, the chronology of the respective mass movements. In addition earlier geological surveys had revealed evidence for further subaerial mass movements in the Hallstatt High Valley (Ehret 2002).

While subaerial mass movements had been reported in the study area, nothing (or only very little) was known about their sublacustrine counterparts in Lake Hallstatt. Research in other Alpine lakes has shown that large mass movements and sediment remobilization can also occur in underwater settings (e.g. Strasser et al. 2013; Hilbe et al. 2015a; Reusch et al. 2015) and may even trigger tsunami waves (Kremer et al. 2012; Hilbe et al. 2015b).

### *3.1.1 Geophysical survey and borehole analysis in the High Valley*

Geoelectric investigation in combination with borehole information was used to characterize the subaerial mass movements in the High Valley.

Geoelectric investigation: The geoelectric method (direct current DC; usually named Electrical Resistivity Tomography, ERT) is the most routine geophysical method to investigate subsurface geometry and structural pattern of landslide bodies (Supper et. al 2000; Perrone et al. 2001; Jongmans and Garambois 2007; Supper et al. 2008; Baron and Supper 2010). ERT investigations provide the distribution of the specific electrical resistivity of the subsurface, which is a physical property of the substratum, that mainly depends on porosity, water saturation, conductivity of pore fluid and clay content (e.g. Archie 1942, Schlumberger 1987). In general, landslide bodies show a significant difference at least for one of these properties (e.g. water saturation, clay content) in comparison to the underlying stable material.

Eleven ERT (Electrical Resistivity Tomography) profiles were acquired in the course of three of field campaigns (2017, 2018, 2019) and processed for final data interpretation (Ottowitz et al. project report).


*Figure 8: Survey area (delimited in red). Map: AMAP, ÖK 50*

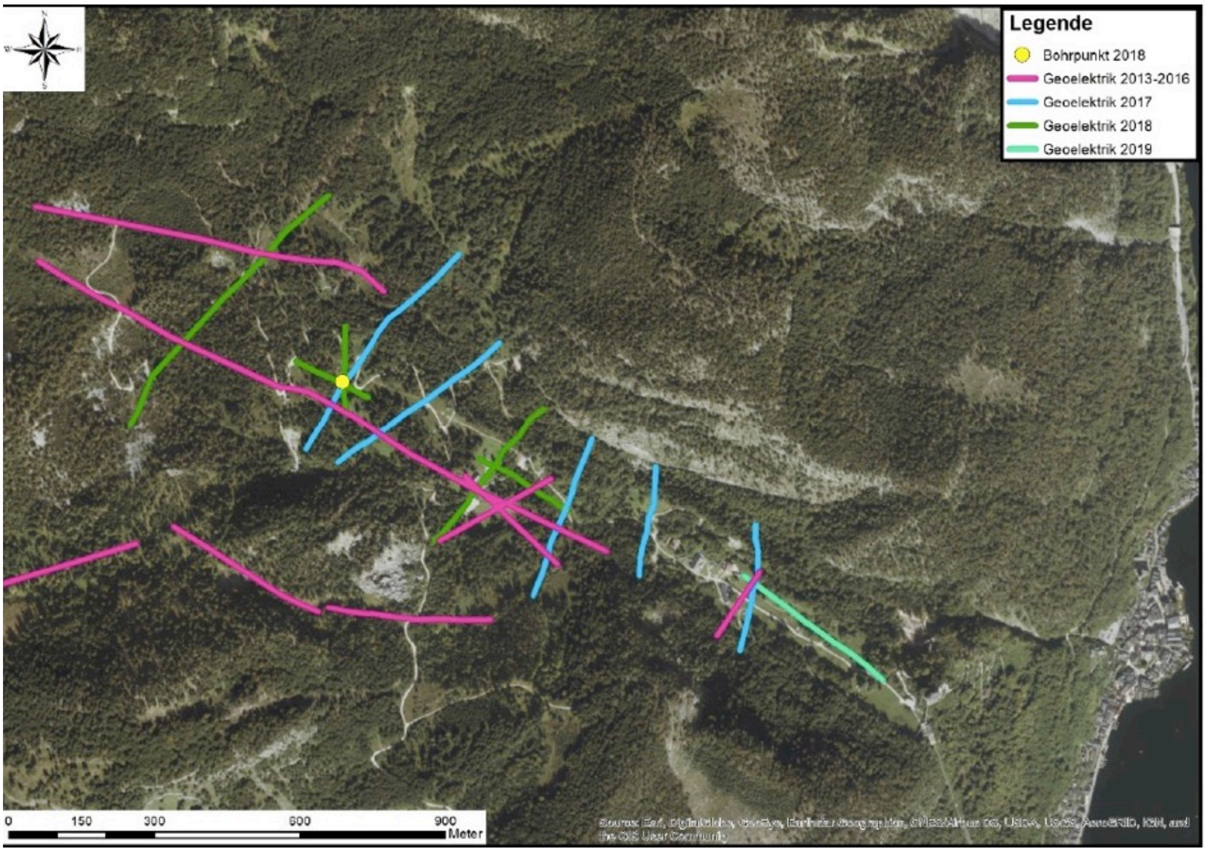


*Figure 9: Orthophoto with geoelectric profiles: previous projects (pink), Facealps 2017 (blue), Facealps 2018 (green), Facealps 2019 (turquois) and borehole location (yellow). Landscape image: DORIS OÖ, Map: GBA*

Borehole information: To improve the reliability of the structural interpretation the verification of ERT results with borehole information (e.g. drilling cores, core analysis, borehole logging) is strongly recommended, since it enables the direct correlation of the modeled resistivity with cored subsurface material. For a detailed verification of ERT results one borehole was drilled to a depth of 45 m. Bore hole location was chosen based on the ERT data acquired in the first field campaign (2017) (see figure 8). One core instead of three was drilled as newly acquired ERT data in the course of the project showed that the boundary between the landslide mass and the stable subsurface material was located deeper than assumed before the start of the project and thus only one borehole could be fully financed. For borehole casing DN 80 pipes were used (Mandl/Peresson in Ottowitz et al. project report). Borehole logging methods were applied (Mandl/Peresson in Ottowitz et al. project report, see also chap. 4.2.1, figure 25). A detailed geological-mineralogical analysis of the core was performed (including water content, grain size distribution, bulk rock mineralogy, clay mineralogy) (Mandl/Peresson in Ottowitz et al. project report).

*Figure 10: Borehole drilling in 2018 in the High Valley. Photo: NHM*

In addition, for a precise determination of the boundary between the landslide body and the underlying stable subsurface data from resolution automatic inclinometer (DMS, for details see http://www.csgsrl.eu/en/index.html) over several months was needed. Since there are evidences that parts of the area still show some displacement, the inclinometer data can provide exact information about the depth of the sliding surface and thus the thickness of the landslide body at the particular location. A resolution automatic inclinometer was installed in Mai 2019 to register even minimal displacements in a depth of 14 to 23 m under surface.

*Figures 10-11: Inclinometer installation in May 2019. Photo: GBA*

Organic material was sampled for 14C dating from the base of three identified slip bodies, one slip body could not be sampled due to lack of organic material.

<u>Work package implementation, data processing and interpretation</u>:

Geoelectric survey and data interpretation: Mag. David Ottowitz, Mag. Anna Ita, Mag. Stefan Pfeiler, Mag. Alexander Römer, Mag. Birgit Jochum; Geological survey of Austria

Borehole information: Dr. Gehard W. Mandl, Dr. Mandana Peresson; Geological Survey of Austria

Organization of field campaigns and data interpretation were carried out in close collaboration with Dr. Kerstin Kowarik and Dr. Hans Reschreiter (Natural History Museum Vienna).

### *3.1.2 Dendrochronologic dating of known subaerial mass movements*

Hundreds of trees were covered by prehistoric mass movements on the surface of the High Valley and partially swept into the salt mines (see chap. 2.4, figure 6). This subfossil wood as well as mine timber and lighting tapers from the prehistoric mine workings formed the basis for dating the subaerial mass movements in the High Valley. Furthermore dendrochronological analysis of mine timber and lighting tapers from the prehistoric mine workings provided further chronological information on the duration of the mining phases (Grabner et al. 2020).

Subfossil wood was retrieved from various sites above ground as well as underground from the Bronze Age and Iron Age mining areas. The retrieved wood was sampled and prepared for dendrochronological investigation (Grabner et al. 2020). Tree-rings were measured to the nearest 0.01 mm using a LINTAB measuring device (www.rinntech.de) (Grabner et al. 2020).

Work package implementation, data processing and interpretation:

Sampling as well as data processing and data interpretation was carried out under the supervision of Dr. Michael Grabner (University of Life Sciences Vienna). Organization of field campaigns and data interpretation was carried out in close collaboration with Dr. Kerstin Kowarik and Dr. Hans Reschreiter (Natural History Museum Vienna).

### *3.1.3 Bathymetric investigation of the lake basin*

A complete identification and process-based interpretation of both subaerial (e.g. from steep lake shore cliffs into the lake) as well as subaquatic (i.e. underwater) mass movements can be achieved by applying hydro-acoustic technology (i.e. multibeam swath bathymetry), (e.g. Hilbe et al. 2008, Reusch et al. 2015). The investigation targeted the identification and morphometric characterization of large-scale mass movement deposits in Lake Hallstatt, which may either result from subaerial and/or subaquatic mass movements. The interpretation of such events in terms of size, extent, source and nature requires a combined approach integrating data from long and short sediment cores (see also chapter below) as well as a full-coverage high-resolution lake floor bathymetric data (Strasser et al. 2020).

For this purpose a bathymetric survey was conducted using a floating platform to acquire data to eventually calculate a digital elevation model of the lake floor with a lateral grid size of 1 m and a vertical resolution in the cm-dm range. The survey covered all areas with water depth exceeding 5 m. A multibeam Kongsberg SIMRCE EM2040 was used. Seismic data acquired in 2014 through a survey with a 3.5 kHz single channel pinger was available to the project. For detailed information on procedures applied for data acquisition and processing see Strasser et al. 2020.


*Figures 12-13: Setting-up for bathymetric survey on lake Hallstatt. Photo: NHMW*

<u>Work package implementation, data processing and interpretation</u>:

The mulitbeam bathymetric device was operated by the University of Bern (Prof. Dr. Flavio Anselmetti, Institute of Geology) and the survey was conducted in collaboration with the University of Innsbruck (Prof. Dr. Michael Strasser, Institute of Geology). First processing of raw data was carried out at the University of Bern and the interpretation of the bathymetric data set was performed at the University of Innsbruck under the supervision of Prof. Dr. Michael Strasser in collaboration with Prof. Dr. Flavio Anselmetti. Organizations of field campaigns and data interpretation were carried out in close collaboration with Dr. Kerstin Kowarik and Dr. Hans Reschreiter (Natural History Museum Vienna).

### *3.1.4 Lake-sediment coring and analyzing*

For ground-truthing of the newly acquired bathymetrical information short sediment cores of up to 3 m length were taken during the second stage of the project after interpretation of the new multibeam data set (Strasser et al. 2020). All cores were logged by non-destructive core-logging analyses using a Geotek Multi Sensor Core Logger (MSCL; measuring magnetic susceptibility, P-wave velocity, gamma density), then split, photographed and further analyzed in the limnogeology lab facility at the University of Innsbruck (Strasser et al. 2020).


*Figures 14-17: Coring campaign (short cores) for ground-truthing on lake Hallstatt. Photo: NHM*

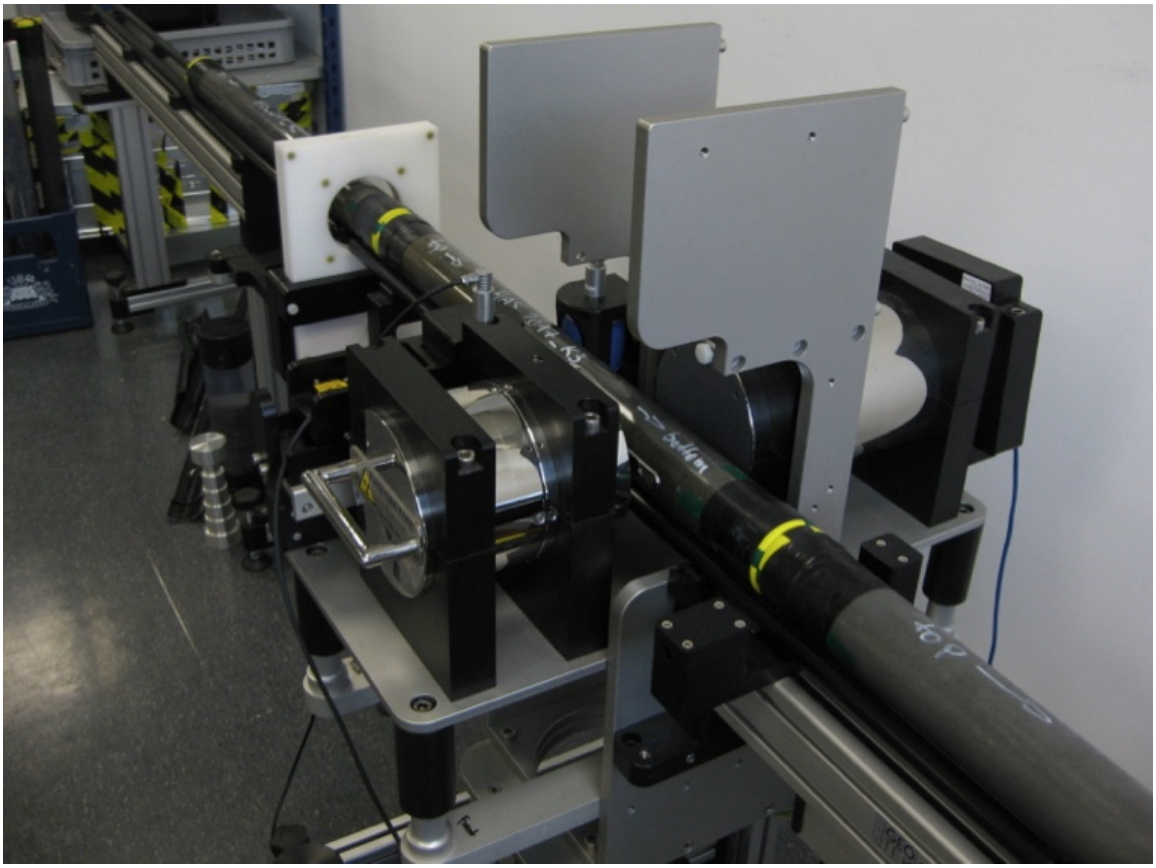

*Figure 18: Core Logging at the Core Facility at University of Innsbruck. Photo: UIBK*

Long sediment cores for diachronic paleoecological analysis were available to the Facealps project through the project collaboration with FWF the Lise Meitner project *"Sediments of Hallstätter See as a palaeoflood archive"* (project no. M 1907–N34). Sediment cores were acquired from two sites during coring campaigns carried out by the GFZ Potsdam in May 2012 and June 2016 (GFZ and University of Innsbruck). Subsequently the following analytical steps were taken: production of large-scale petrographic thin sections from parts of the sediment cores that contain mass movement deposits and microscopic analyses of the mass movement deposits. In combination with high-resolution geochemical analyses (µXRF scanning) carried out within the frame of the Lise Meitner project this enabled the characterization of the mass movement deposits (e.g. mineralogical / geochemical composition, internal structure, stratigraphic contact to under- and overlying sediments) and a parallelization with possible correlatives in the Hallstatt High Valley (Lauterbach et al. 2022). AMS $^{14}C$ dating and modeling for a highly resolved chronology of the sedimentary sequence was carried out within the FWF Lise Meitner project (Lauterbach et al. 2022). The investigations aimed at identification and characterization of mass movements in the lake, their accurate dating and the determination of their origin, e.g. a possible correlation with similar deposits identified in the Hallstatt High Valley (Lauterbach et al. 2022).


*Figures 19-21: Coring campaign (long cores) on lake Hallstatt in 2016. Photos: NHMW*

Data analysis and interpretation of sediment cores was closely integrated with the analysis of bathymetric data and of written records.

<u>Work package implementation, data processing and interpretation</u>:

Short cores for ground-truthing bathymetric data:

Data acquisition, processing and interpretation were supervised by Prof. Dr. Michael Strasser (University of Innsbruck, Institute of Geology).

Long cores:

Data acquisition, processing and interpretation were supervised by Dr. Stefan Lauterbach (during project duration University of Innsbruck, Institute of Geology).

The entire work package was carried out in close collaboration between Prof. Dr. Michael Strasser, Dr. Stefan Lauterbach, Prof. Dr. Flavio Anselmetti (University of Bern), Prof. Dr. Achim Brauer (DeutschesGeoforschungszentrum Potsdam), Dr. Kerstin Kowarik and Dr. Hans Reschreiter (Natural History Museum Vienna).

### *3.1.4 Data collection: historical records data on extreme events*

Data about geologic and climatic extreme events as well as wider socioeconomic disruptions was collected from historical and modern records. For this purpose archival data from local archives (Musealverein Hallstatt), the archive of the federal state of Upper Austria (Oberösterreichisches Landesarchiv) and the archive of the ministry of Finance (Bundesministerium für Finanzen) was used. Collected data was closely integrated with data from sedimentary archives.

Work package implementation, data processing and interpretation:

Data acquisition, processing and interpretation was supervised by Dr. Kerstin Kowarik

## 3.2 Reconstruction of palaeoenvironmental change and human landuse

In order to investigate human-environment relations in high temporal resolution the paleoenvironmental data record of the research area needed to be improved. This required, in addition to building an inventory of short-term processes such as extreme events, the investigation of long term processes. We focused on a diachronic analysis of vegetation history, human impact on vegetation and land use changes. Applied analyses included palynological investigations as well as spatial analyses.

### *3.2.1 Palynological investigation of lake sediments from lake Hallstatt*

The sediment cores were retrieved within the collaborating FWF Lise Meitner project (M 1907–N34) (see chap. 3.1.4). 1–5 $cm^3$ samples were taken with an interval of 5–10 cm maximum, depending on the sediment accumulation ratio. To ensure chronological control approx. 20 AMS $^{14}C$ datings were performed on the core in addition to effort within the FWF project and samples taken to date mass movement deposits. Chronological modeling was carried out by Dr. Stefan Lauterbach.

Palynological analysis was conducted by Dr. Ruth Drescher-Schneider (Drescher-Schneider project report).

### *3.2.2 Palynological investigation Siegmoos bog*

A total of 67 samples of 1 $cm^3$ were collected for pollen analyses with an interval of 5 cm in general and at 0,5 to 1 cm resolution in areas of special interest. Approx. 25 samples were taken for AMS $^{14}C$ dating.

Palynological analysis and chronological modeling was conducted by Dr. Daniela Festi (Festi et al. 2021).

*Figures 22: Retrieved peat core, Siegmoos. Photo: NHMW*

Samples for palynological analysis were prepared according to standard procedure (Faegri and Iversen, 1989). A total sum of at least 1000 pollen grains was counted in each sample. Special attention was given to NPP (Non-pollen palynomorphs) as additional information concerning human impact and climatic changes. The results were presented in form of pollen percentage and pollen concentration diagrams and pollen sedimentation/$cm^2$/yr (pollen influx). High pollen countings ensured the detection of pasture and human impact indicators. Grazing activity was reconstructed according to the presence of pasture indicators such as coprofile fungi, and a reduction in forest cover. The occurrence of cereal pollen is a proxy for agriculture practice.

### *Botanical survey*

A botanical survey of Hallstatt-Salzberg and the Mühlbach catchment was conducted in the course of six survey campaigns. This data enhances the paleoecological record and can serve as reference for future observations on climate change impact. A complete and an actual floristic data list was prepared and a reference collection (complete collection of vascular plants with a particular focus on seed and fruit material plus a representative assemblage of dominant mosses) of the research area was set up. (Covered area: quadrants 8447/2 and 8447/4, resp. along a transect: Hallstatt-lakeshore, forest region along the rivulet Mühlbach, farming land at surroundings of Salzberg, and subsequently the upper forest region along the Mühlbach, alpine area up to peak Plassen). The collected material is stored in the herbarium W at the NHM Vienna and data entered in the botanical information system JACQ (Virtual Herbaria).

The field campaigns and subsequent work were supervised by Mag. Heimo Rainer (NHMW).

### *3.2.3 Human land use: spatial analysis*

Information on human land use (settlement patterns, economic infrastructure, farmed land, traffic routes etc.) from the beginning of salt production in the Bronze Age to the present day was collected in a GIS database. Data collection included cartographical and topographical maps, aerial photographs and remote sensing data. Spatially explicit data on land use change in prehistory and historical land use data generated in the Hallimpact project (PI Kerstin Kowarik) was also integrated. The so formed Historical GIS served as basis for a diachronic analysis of the development of the spatial structure of human land use in the research area (Kowarik 2019; Klammer et al. project report).

*Figure 23: Map by Oberbergmeister Leopold Riezinger produced in 1713 (260a), depicting the High Valley, the town of Hallstatt and neighboring valleys.*

# 4. Research Results

## 4.1 Most important results and conclusion

The Hallstatt High Valley is one of the most important archaeological regions in the world. Millenia of salt production have created a unique industrial and cultural landscape. By combining and synchronizing geophysical and sedimentological, palynological, archaeological and historical data for the first time, it was possible to fundamentally change and refine our understanding of the formation and development of this landscape.

**Project milestones**

- evidence for continuous human presence from prehistoric times to present
- characaterization of the environmental impact of prehistoric mining: Bronze Age impact on landcover comparable to Modern Times
- precise absolute dating of prehistoric mining phases and mass movement events that destroyed the salt mines
- evidence for resilience of prehistoric mining communities
- inventory of geologic extreme events and characterization of natural hazards over the last 3500 years
- evidence for sustainable forestry from the Bronze Age to the present
- For the first time, plausible reasons can be provided for the abandonment of the lower part of the Salt Mountain Valley (after 4600 years of continuous use) and the abandonment of the burial ground around 350 BC and the new start in the upper part of the valley.
- For the first time, land use in the region could be analyzed diachronically by digitizing and analyzing large areas with essential findings on land use, centralization processes and essential processes of change in the Middle Ages and modern times.
- Hereby the foundations have been laid to be able to research and develop this region as a model region for the understanding of the man-environment relationship in mountain regions at the highest level.

**The project contributed substantial insights into:**

**(a) Types and mechanisms of natural hazards in the research area**

Through the creation of an inventory of natural extreme events and dendrochronologic analysis it was possible to demonstrate that subaerial mass movements in the Hallstatt High Valley occured more frequently than hitherto perceived. In fact, the prehistoric mining areas were destroyed at least four (possibly five) times (Grabner et al. 2021; Ottowitz et al. project report). Furthermore the independent analyses of different sedimentary archives and written records suggest that mass movement events of the scale, that destroyed the prehistoric mine workings, did not occur anymore during Modern Era and possibly since the Middle Ages (Strasser et al. 2020; Grabner et al. 2021; Lauterbach et al. 2022; Ottowitz et al. project report). These observations are based on geoelectrical investigations in the Hallstatt High Valley combined with sedimentological and borehole analysis (Ottowitz et al. project report; chap. 4.2.1), dendrochronological analysis of wooden artefacts from inside the prehistoric mining areas and from the slow earth flows on the surface of the Hallstatt High Valley (Grabner et al. 2021; chap. 4.2.3) as well as sedimentological and mineralogical analysis of lake sediments and bathymetric data (Strasser et al. 2020; Lauterbach et al. 2022; chap. 4.2.4, 4.2.5). Finally, we were also able to identify a possible new trigger of subaquatic mass movement events in lake Hallstatt (Strasser et al. 2020; chap. 4.2.5).

**(b) The impact of specific types of natural extreme events on the evolution of the socio-ecological systems in the UNESCO World Heritage landscape Hallstatt-Dachstein/Salzkammergut,**

The integration of archaeological, dendorchronologic and paleoenvironmental data demonstrated the scale of the devastation caused through the subaerial mass movement events in the High Valley and the subsequent unexpectedly quick recovery of the various prehistoric mining communities. Long standing archaeological research had demonstrated the scale of destruction: The prehistoric mine workings were filled by earth masses from the surface, destroying all infrastructure inside the mines and cutting off access to the salt deposit (see chap. 2.4). Thus effectively destroying the livelihood of these highly specialized mining communities. In addition modt working and living areas above ground and any associated infrastructure, e.g. meat curing basins or houses, were also devastated as earth masses covered the valley floor up to several meters . New dendrochronologic data had demonstrated that this hadn't happened twice, but four to five times during prehistory and that the time of recovery was short. The palaeoenvironmental record based on palynological as well as geochemical analysis of a 6000 year old peat core from Siegmoos bog corroborates this observation. On the centennial scale the disruptive effect of the mass movement events is low to non-existent as these cannot be correlated to substantial changes in type and intensity of human activity (Festi et al. 2021; Knierzinger et al. 2021; see chap. 4.3).

**(c) The role of prehistoric and historic salt mining in the formation of this landscape**

Integrated palaeoenvironmental and dendroarchaeological data sets (prehistory) and palaeoenvironmental and archival data (Modern Era) reveal human activity centered around and connected to salt mining as the dominant mode shaping the evolution of the socioecological system in this area and structuring human-environment interaction (Festi et al. 2021; Knierzinger et al. 2021; Drescher-Schneider project report; Klammer project report; see chap. 4.3). The reconstruction of human impact on the environment of the Hallstatt High Valley and the surroundings of lake Hallstatt documents near continuous human presence from the 14th cent. BCE to the present day (Festi et al. 2021; Drescher-Schneider project report; see chap. 4.3.1, 4.3.2). Throughout at least four catastrophic destructions of the prehistoric salt mines, important cultural transformations (e.g. roman conquest, migration period) and substantial climatic changes (e.g. Little Ice Age) only two short periods, where total abandonment seems likely, and one longer period of low human activity could be identified (Festi et al. 2021; Drescher-Schneider project report). In addition, through the integration of dendroarchaeological and paleoenvironmental data we were able to reconstruct a resource management system (espec. forest management) that was clearly aiming at sustainable resource extraction and prioritized that resources be not depleted (Festi et al. 2021; see chap. 4.3.2.).

**(d) Societal response to natural hazards including the identification of risk management strategies**

Firstly, we can conclude with regards to the prehistoric period in Hallstatt, that the mining communities were highly resilient in face of destruction of their subsistence base through natural hazards. We hypothesize that strong transalpine networks were one factor of resilience. Secondly we hypothesize that the careful management of local wood resources observable during prehistory and in the Modern Era demonstrates the knowledge of ecosystem limits and also served the purpose to lower natural hazards through the avoidance of overly large clearances (Festi et al. 2021; see chap. 4.3.2.).

## 4.2 Inventory of extreme events

We used different sedimentary and cultural archives (mass movement bodies in the High Valley on the surface and in the mines, lake sediments, bathymetric, archaeological data, written records) to investigate extent and chronosequence of already known prehistoric large-scale slow mass movements that disrupted prehistoric mining activity and to identify further geologic extreme events such as rock fall, landslides and slow earth movements and we also addressed earthquakes (for background information see chap. 2.4 and 3).

### *4.2.1 Geoelectric survey and sedimentary core analysis in the High Valley*

Analysis of the geoelectric data allowed identifying a surface layer with strongly varying thickness, which shows a very high specific electrical resistance (mostly greater than 150 Ohm-m). By and large, this layer can be regarded as representing the still remaining material of the past large-scale slow mass movements (Ottowitz et al. project report). The partly observable differentiation of this layer can be explained by the interpretation of the present drill core (Mandel/Peresson in Ottowitz et al. project report) (figure 24).

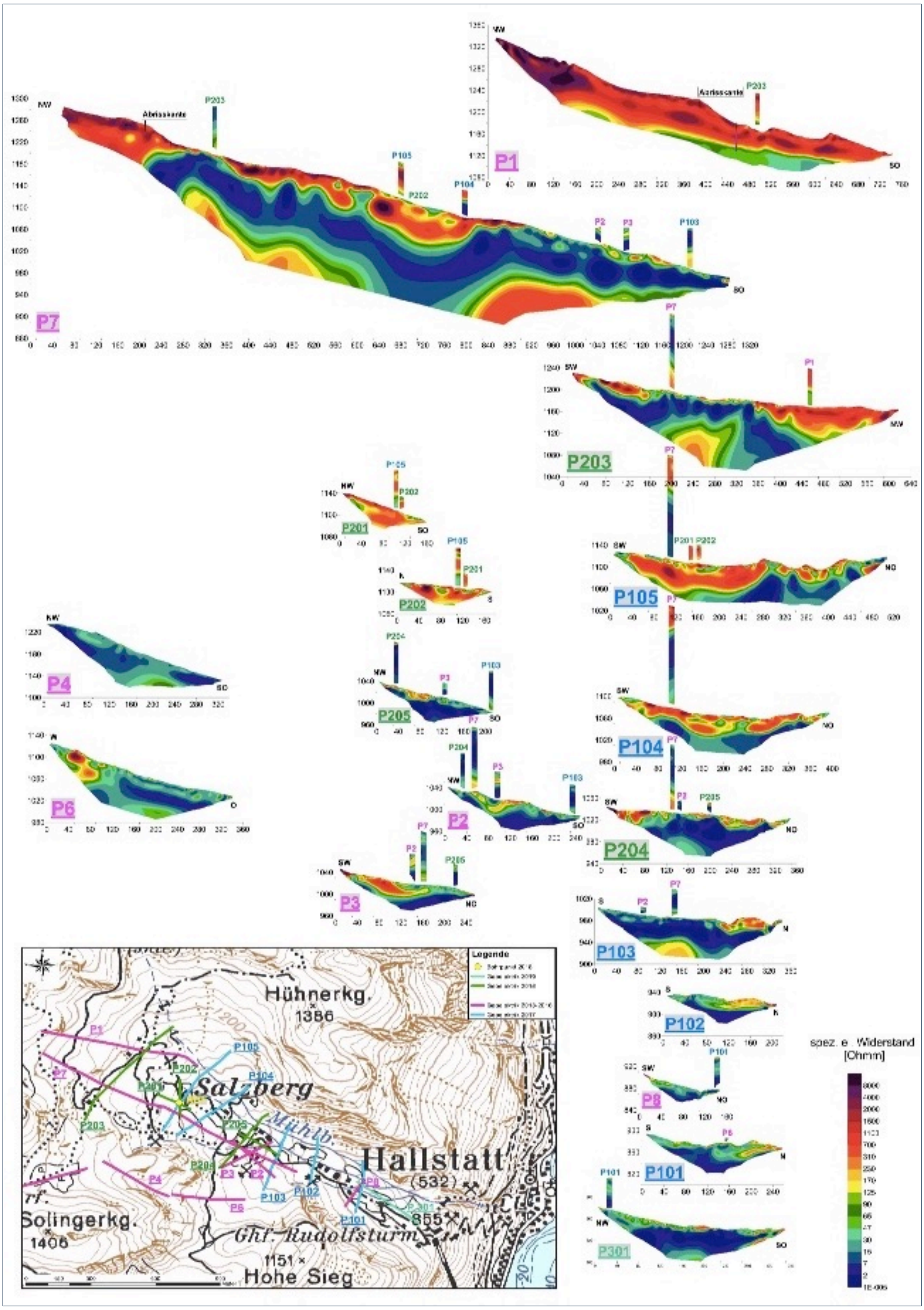


*Figure 24: Topographic situation and interpretation of all relevant geoelectric profiles in High Valley (2012-2019) – distribution of the specific electrical resistance (Ohm-m). Graphic: Ottowitz et al., project report.*

Thus geoelectric investigations in combination with borehole analysis resulted in a macro scale understanding of the distribution and structure of the landslide bodies in the High Valley (Ottowitz et al. project report). Furthermore, analysis of geoelectric measurement profiles that directly pass the borehole demonstrate, as expected, that due to its low resolution geoelectric profiles alone are not sufficient for a systematic stratigraphic description.

In fact, the analysis of acquired drill core and borehole logging data resulted in substantial insights into the complex processes of landscape formation in the High Valley (Mandl/Peresson in Ottowitz et al. project report). For one the borehole data a sequence of alternating layers can be assigned to different mass movement events, that were hitherto unknown (see figure 25).

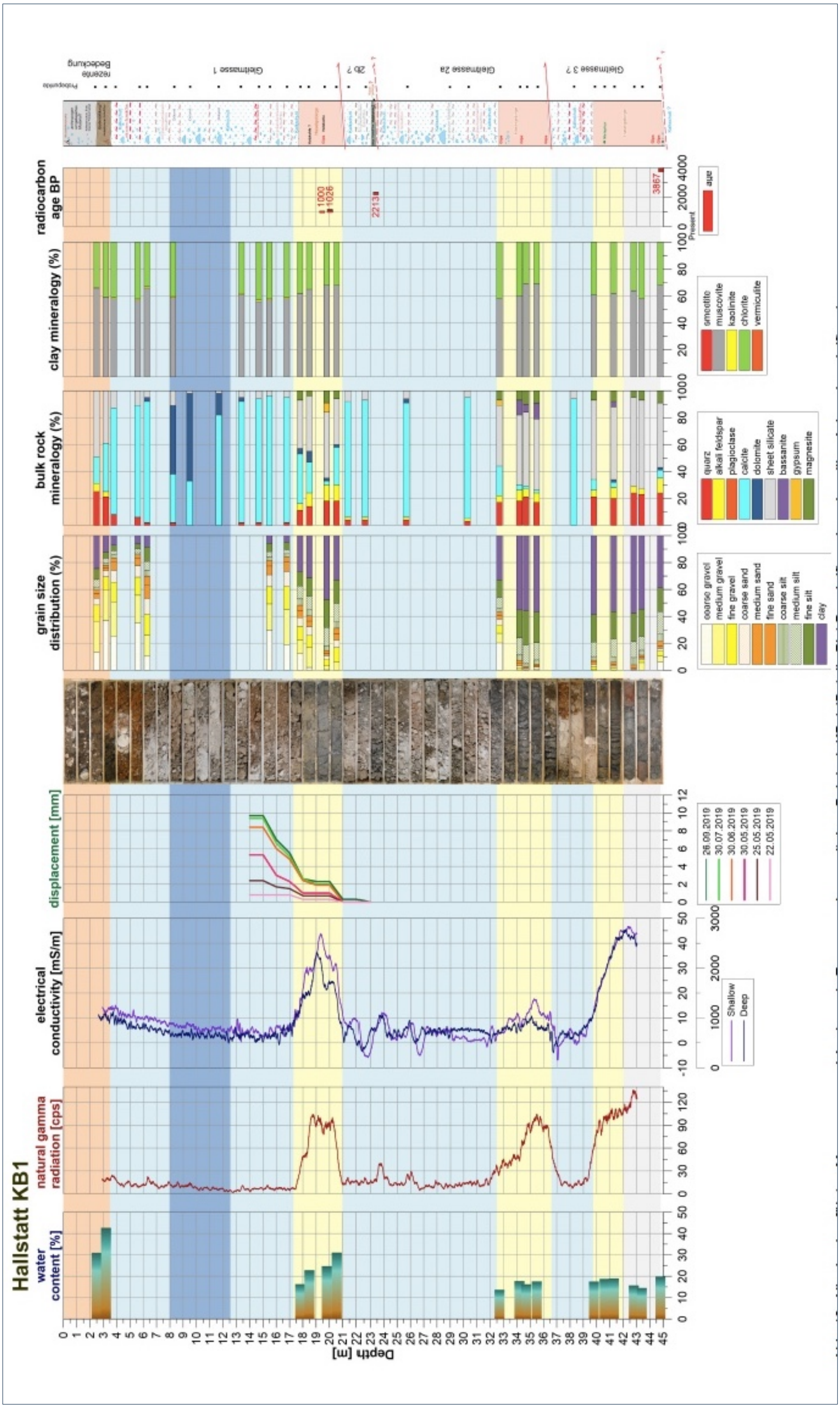


*Figure 25: All analyses performed in connection with borehole KB 1. Graphic: GBA.*

Even more importantly G. Mandl and M. Peresson suggest a dormant phase for this specific type of large-scale slow mass movement events in recent times (Mandl/Peresson in Ottowitz et al. project report): The upper part of the stratigraphic sequence does not show evidence for such events (0-17 m below surface), while in the lower part (17 to 45 m below surface) recurring sliding events pile on top of each other. In terms of absolute dates, we can at present only observe (based on 14C samples from the lowest part of slip body 1) that the youngest of these events occurred at some point after the $9^{th}$ to $11^{th}$ cent. CE. It is important to note that other independently acquired data sets partially corroborate these observations (see also chap. 4.2.4, 4.2.5, 4.2.6). In addition, it is interesting to note that the mass movement event represented through slip body 2b observed in the drill core from the High Valley (KB 1) can be dated to or after the 4th cent. BCE due to 14C date coming from the lowest part of the slip body (see also chap. 4.2.4, 4.2.5, 4.2.6).

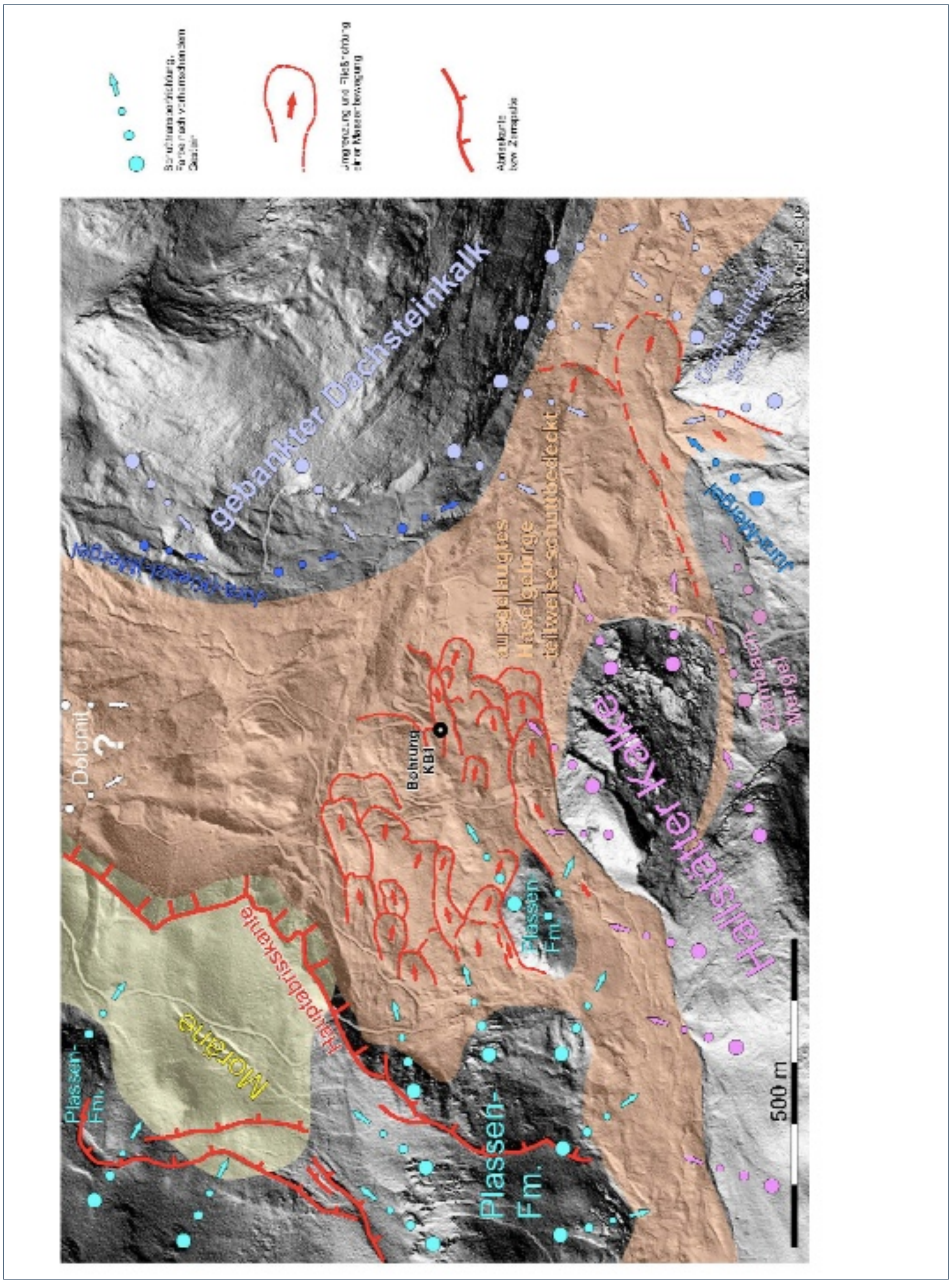


*Figure 26: Situation sketch Hallstatt High Valley: mass movements (selection) and source areas of recent detritus formation. Graphic: GBA. Data: Topography: Land Oberösterreich/Open Data/Digitales Geländemodell; Geology following G. Schäffer 1982: Geologische Karte der Republik Österreich, Blatt 96-Bad Ischl, 1:50.000.*

Finally, based on the combined interpretation of ERT data and geological-mineralogical data from the drill core Ottowitz et al. estimate that the total mass of the summed landslide body presently covering the High Valley amounts to 9.3 million cubic meters (Ottowitz et al., project report). Due to various uncertainties this number can only be regarded as a minimum value (Ottowitz et al., project report). To give a frame of reference for the calculated volume of the mass movement of 9.3 million cubic meters, it is useful to compare it with two prominent mass movements that have been active in recent decades. The best-known landslide, whose reactivation in 2007/2008 set around 4 million cubic meters of material in motion, is the Gschliefgraben (municipality of Gmunden) in Upper Austria (https://www.naturgefahren.at/karten/chronik/Katastrophen_oestr/gschliefgraben.html).

Another example is the Rindberg landslide in Vorarlberg, which was activated in 1999 and in the course of which nearly 70 million cubic meters of material, was moved (http://www.naturgefahren.at/karten/chronik/Katastrophen_oestr/Rutschung1999.html).

### *4.2.3 Dendrochronologic analysis of prehistoric wooden objects*

Dendrochronologic analysis on wooden artifacts and natural wood fragments further refined our understanding of the chronology of prehistoric mass movement events. At project start it was the current archaeological understanding that prehistoric mining activity was brought to a halt twice, once during Bronze Age and once during early Iron Age, by large-scale slow mass movements (see chap. 2.4).

Until recently the mining phases and thus the occurrence of these events could only be dated in a rough chronological framework (Kowarik 2019). Finally, in 2021 after dendrochronologic analysis of more than 2000 samples originating from archaeological sites in the mines and from the buried earth masses below ground, archaeological sites and mass movement bodies on the surface 786 sample could be dated by the means of dendrochronology and $C^{14}$ wiggle matching (Grabner et al. 2021). The Facealps project contributed to these efforts and focused on chronologically constraining the mass movement events.

It is now possible to ascertain that prehistoric mining was disrupted at least four times possibly even five times in a span of 650 years. These investigations resulted in the following chronological model of human activity and disruption (Grabner et al. 2021):

- $14^{th}$ cent. BCE (Bronze Age) earliest direct evidence for large-scale underground salt mining: It must be assumed that the Bronze Age mining phase started earlier as the dated samples come from mining workings at more than 100 m below ground. This mining phase was characterized by underground mines in the north-western (*Nordgruppe*) and eastern-central part (*Christian-von-Tuschwerk* mining chamber) (see figure 5).
- **~1150 BCE *Nordgruppe* mine workings are destroyed by a mass movement event**
- **1062 BCE Bronze Age mine workings in the *Christian-von-Tuschwerk* area are destroyed by a mass movement event**
- $8^{th}$ cent. BCE (early Iron Age) direct evidence for large-scale underground salt mining: As for the Bronze Age it must be assumed that the mining activity started earlier. The Iron Age mine working of this phase (*Ostgruppe*) are located up to 200 m below ground and thus the sampled material for dendrochronologic dating reflects a developed phase (see figure 5).
- **661 BCE: A mass movement destroys the enormous *Ostgruppe* mine workings.**
- Salt mining resumes after this event.
- **570 BCE: Another mass movement event buries the mining sites.**
- Until very recently it was assumed that no underground mining sites dating later than 570 BCE were known after, but dendrochronological samples from newly investigated mining areas indicate mining activity after 570 BCE (pers. comm. Hans Reschreiter). This question is currently the focus of new research activity, including a large-scale coring survey inside the mountain. At any rate evidence for human presence is also clearly indicated through continued burial activity in the cemetery, which is only abandoned in the mid of the $4^{th}$ cent. BCE. Also paleoenvironmental indicates that human presence, albeit in reduced intensity continued into the $4^{th}$ cent. BCE (Festi et al. 2021; Knierzinger et al. 2021, see also chapter 4.3.1).
- 350 BCE: possibly another mass movement occurs and causes the abandonment of the cemetery and of the entire High Valley as activity zone (see also chap. 4.2.1 and 4.2.4)
- After 350 BCE and before the beginning of the $1^{st}$ cent. BCE mining and settlement activity are relocated to the *Dammwiese* (1350 m asl) an area 300 to 400 m above the

older activity zones with harsher climatic conditions but outside the hazard zone for mass movements (see figures 4 and 5).

Not only did the salt mining communities recover relatively quickly and were able to overcome the complete destruction of mining infrastructure and the impossibility to access the salt deposit again through the destroyed mine workings, but they also must have succeeded in maintaining their transalpine networks, which were essential for supplying the mining communities.

### *4.2.4 Investigation of large-scale mass movements in the sediments of lake Hallstatt*

A robust chronological framework for the sedimentary sequence with a total composite length of 15 m was established in the collaborating FWF project "*Sediments of Hallstätter See as a palaeoflood archive*" (project no. M 1907–N34, headed by Dt. Stefan Lauterbach) through a large number of radiocarbon (14C) dates and Bayesian age modeling. The sedimentary sequence covers the last 2350 years and thus reaches back from present into the crucial time period around the mid 4th cent. BCE, when the late Iron Age cemetery in the Hallstatt High Valley was abandoned (Lauterbach et al. 2022)

Three large-scale event layers (E 1 to 3) were identified in the sediment record. Analysis focused on the characterization and dating of these layers followed by the investigation of possible trigger mechanisms and potential source areas. The overall aim of these efforts was to evaluate whether these layers might be related to events similar to those that affected the mining district in the High Valley during prehistory or even be directly connected to these events (Lauterbach et al. 2022).

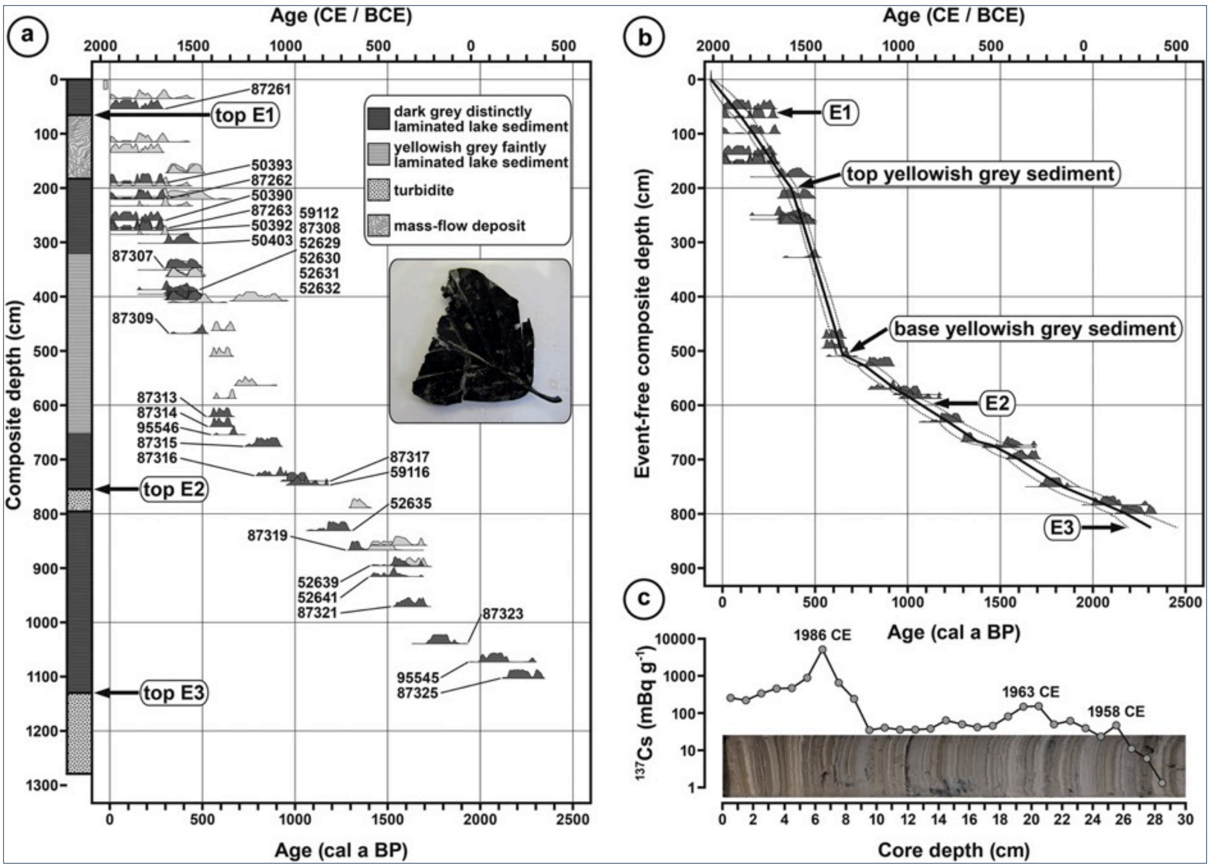

*Figure 27: Simplified sedimentology of the master composite sequence HAS_2012/2016 with the positions of the obtained AMS 14C dates. All AMS 14C dates are displayed as 2σ probability density functions (calibrated with OxCal 4.4 (Bronk Ramsey, 2009). From: Lauterbach et al. 2022, fig. 4.*

Chronological modeling determined that only event layer 3 might bear a direct relation to prehistoric mass movements as it was dated to 363 ± 131 BCE which puts this event in the chronological vicinity of the abandonment t of the Iron Age cemetery in the High Valley. As event layer 3 is not fully covered by the retrieved sedimentary sequence trigger mechanisms and source areas could not be investigated. Here, the newly recovered sedimentary record through the Hipercorig project will shed further light on these questions. In addition, it is interesting to note that the mass movement event represented through slip body 2b observed in the drill core from the High Valley (KB 1) can be to dated or after the 4th cent. BCE due to 14C date coming from the lowest part of the slip body. As this demonstrates that at some point after this timeframe this specific mass movement event occurred, several possible chronological relations can be inferred: a) the mass movement event KB 1-2b and the event indicated through layer 3 in the lake sediments are synchronous, b) in close chronological vicinity, or c) the KB 1-2b event occurred substantially later than the layer 3 event indicated in the lake sediments. We thus might hypothesize either:

- that the same event was observed in two different sediment archives or one trigger event caused two different events (in case of a) holding true),
- or that this period saw a sequence of recurring natural hazards (in case of b) holding true),
- or these events are unrelated (in case of c) holding true).

Instances a) and b) might explain, why the Iron Age cemetery and the High Valley itself were finally abandoned for a relocation to a safer area (*Dammwiese*).

Event layer 2 dates to the early Middle Ages (CE 892 ± 60) (Lauterbach et al. 2022). Again a possible chronological synchronicity with the High Valley drill core (KB 1) can be hypothesized as the mass movement event represented through slip body KB 1-1 can be to dated or after the 9$^{th}$-10$^{th}$ cent. CE and thus again opens up the same possibilities as discussed above for KB 1-2b and layer 3 (lake sediments). This is of special note as Lauterbach et al. identify the source area of the event layer 2 event not in the High Valley, but in the neighboring Steingraben and Hausgraben gorges (Lauterbach et al. 2022). Thus in case of an actual synchronous event we might be looking at a period an event of higher intensity event affecting a larger area.

Event layer 1 dates to the Modern Period (CE 1866 ± 48) (Lauterbach et al. 2022). For event layer 1 no potential chronologically synchronous layer can be observed in the High Valley record (KB 1). Also, the fact that in the most upper part of the profile soil formation can be observed is suggestive as this indicates that since the formation of the soil layer no large scale slow earth mass movement passed over this area scraping off the soil layer in the process. Also, a debris flow in the High Valley would very likely have been reported in the Hallstatt chronicle, as the consequences of such an event in the High Valley would have been severe for the ongoing salt mining operation. This enables us to say with high confidence that the event resulting in event layer 1 did not result from a subaerial large scale slow earth mass movement in the High Valley. On the other hand written records do report a number of mud flow events (rapid mass movement events) in the 1880s and 1890s caused by heavy rainfall and originating in the High Valley. Based on the analysis of the lake sediments and historical records Lauterbach et al. suggest a mass movement event possibly triggered by heavy rainfalls with a source area in the High Valley (Lauterbach et al. 2022). In addition, using high-resolution bathymetry, seismic data and short cores Strasser et al. suggested a possible connection to earthquakes, more precisely an earthquake-triggered slope instability causing a subaquatic mass movement (Strasser et al. 2020).

Sedimentological analysis of the core also gives insights into human impact on the environment. For one Lauterbach et al. note an abrupt shift in sedimentation rates and sediment composition at 650.5 cm MCD (~CE 1300) (distinctly sub-mm- to mm-scale laminated, organic-rich sediments to faintly laminated, carbonate-rich sediments). In concordance with palynological and historical data this can be taken as evidence for an intensification of salt mining in this time period (Lauterbach et al. 2022; see also chap. 4.3.2.-4.3.4). Another more gradual change in sedimentation rate (~CE 1580) might be related to the introduction of a systematic forest management around the mid-16th century CE (Lauterbach et al. 2022; see also chap. 4.3.2.-4.3.4.). Also the construction of a pipeline allowing the transport of brine over a distance of 30 km from Hallstatt to Ebensee falls in this time frame.

### *4.2.5 Recent mass movement processes in lake Hallstatt*

Bathymetric, hydroacoustic and sedimentary core data was used to establish the geomorphology and event stratigraphy of recent mass movement processes in Lake Hallstatt over the last 210 years (Strasser et al. 2020).

In a first step a basin-wide geomorphological characterization of a high-resolution bathymetry map was conducted and a geomorphological map generated. This represents the first such map for a steeply incised valley-occupying intra-mountainous lake in the Eastern Alps. The combination of the new geomorphological map of Lake Hallstatt with high-resolution reflection seismic and sedimentary core analyses enabled the documentation, characterization and dating of subaquatic landslides (Strasser et al. 2020).

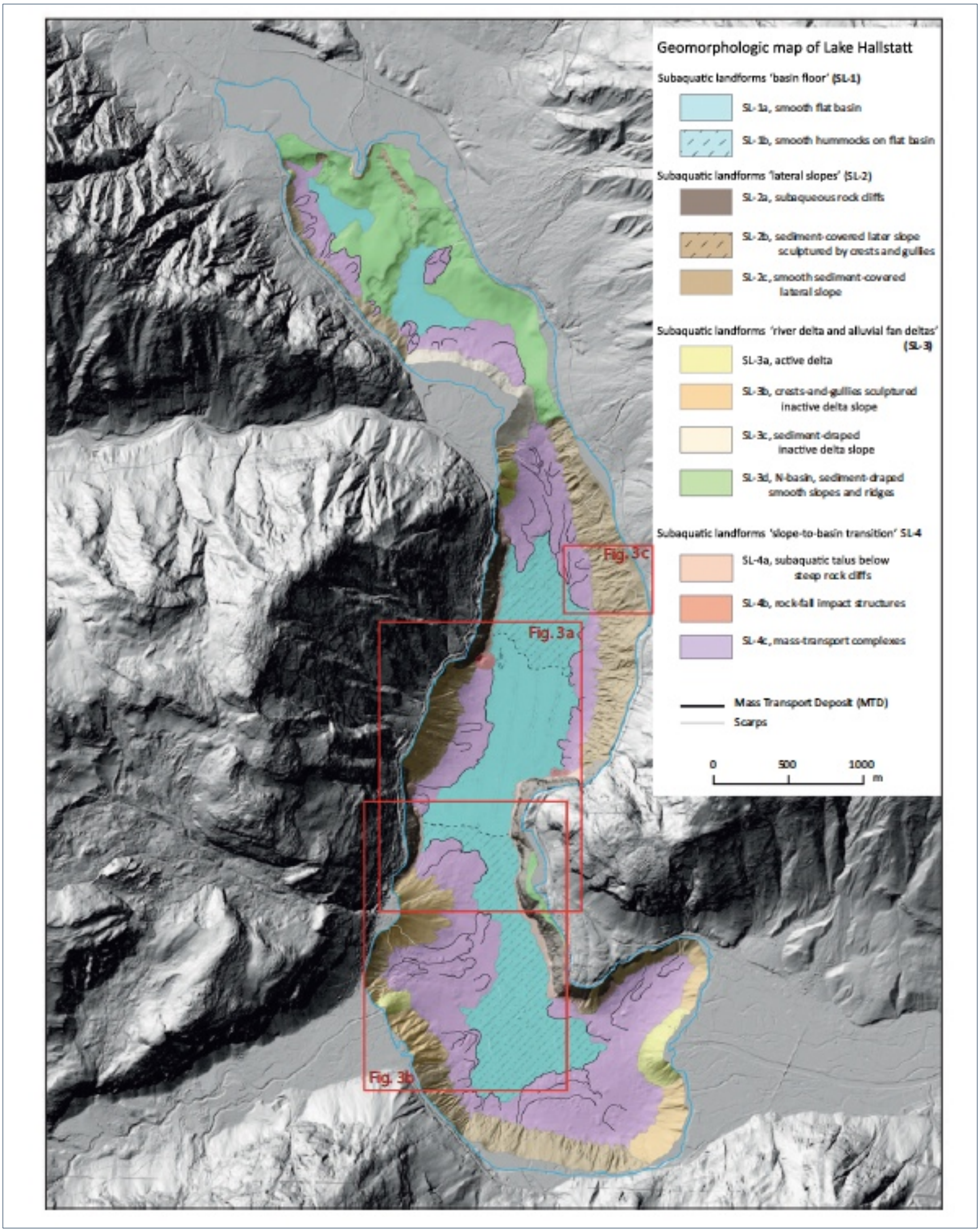


*Figure 28: New subaquatic landform map of Lake Hallstatt. Graphic: Strasser et al. 2020 fig. 2.*

A multitude of different mass transport deposits (MTDs) linked to rock falls, subaqueous slope failures and shore collapses are documented through the hydro-acoustic data (Strasser et al. 2020: espec. Fig. 4). Sediment cores evidence laminated background sediments intercalated with distinct event deposits that can be linked to historically documented major flood events (e.g. 1920, 1899, 1892) and moderately strong earthquakes (e.g. 1892) (Strasser et al. 2020; see also discussion in Lauterbach et al. 2022).

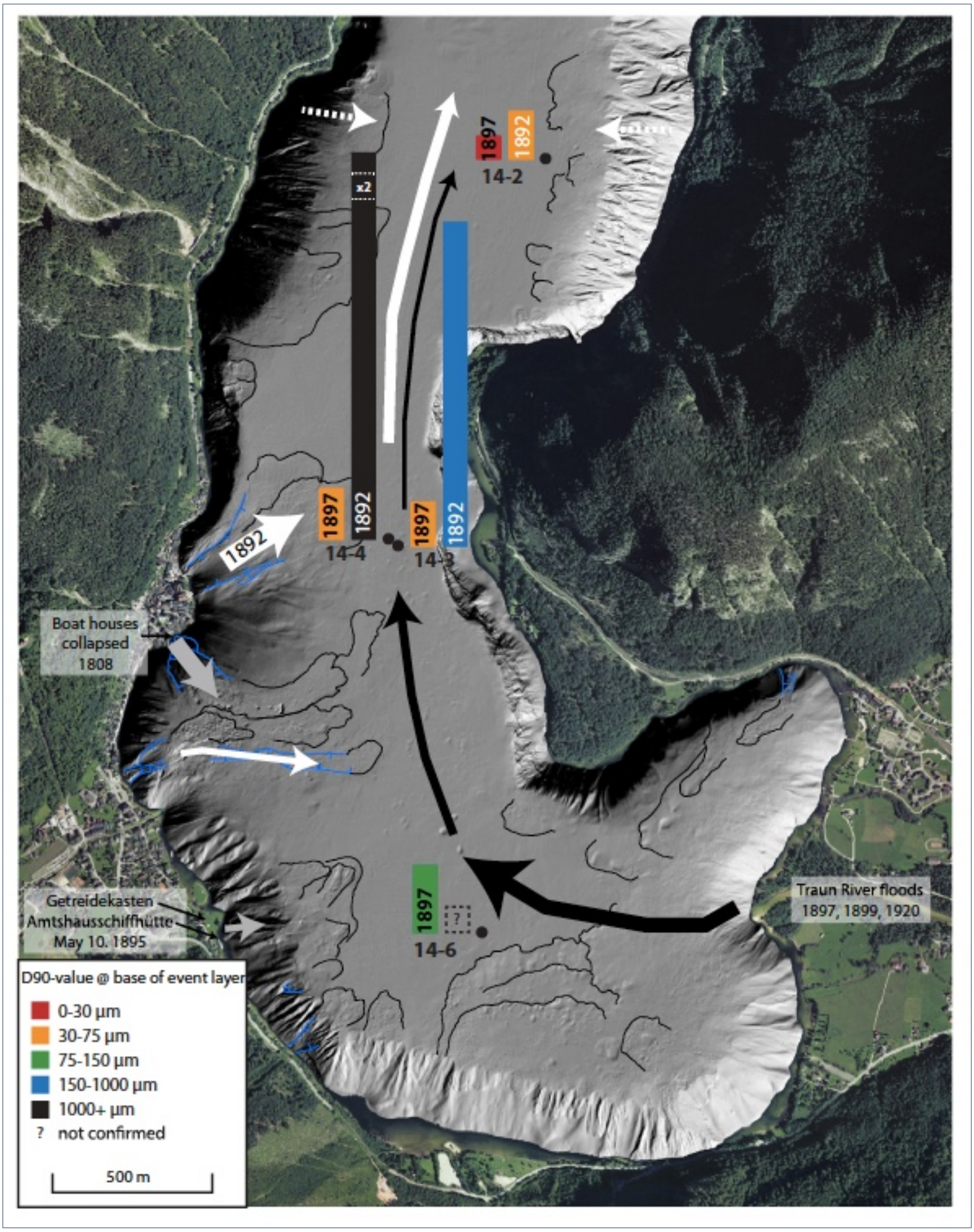


*Figure 29: Summary map of mass movement processes in Lake Hallstatt over the c. 211 years. Graphic: Strasser et al. 2020 fig. 8.*

Strasser et al. (2020) suggest that alongside other trigger mechanisms for lake Hallstatt earthquake trigger might be a key process for initiating subaquatic slope instabilities, subsequent landslides and mass transport into the deep basin. This is a notable finding for subaquatic mass-movement processes in such steeply incised valley-occupying intra-mountainous setting, where different types of mass-movement processes, including subaerial rock falls and debris flows, entering the lake are expected (and documented). These processes, however, result in smaller MTDs compared to those induced by earthquake-triggered subaquatic mass movements.

Strasser et al. (2020) also found that the deeper subsurface provides evidence of even larger mass-movement processes older than at least 800 years. (At the point of publication the authors had to conclude that this had still to be validated by longer core, which in the meantime has been achieved through the publication of the 15 m composite sedimentary core by Lauterbach et al. (2022), see also chap. 4.2.4, and the Hipercorig project which succeeded in retrieving a sedimentary sequence of 52 m length.) This observation holds important implications to be pursued in future research efforts: As here arises the question whether the inferred 'mega' MTDs might be linked to the prehistoric catastrophic landslides in the salt mining area? If so, this would support the idea advanced be Mandl and Peresson, that large-scale slow earth movements processes became dormant at some point during the Modern Period (Mandl/Peresson in Ottowitz et al. project report and chap. 4.2.1).

Thus, Lake Hallstatt is a potential natural laboratory for studying causes and consequences of subaquatic landslides in steeply incised intra-mountainous lakes and comparable fjord settings. At present this archive is studied within the framework of the Hipercorig initiative (https://www.uibk.ac.at/geologie/sediment/research/projects/h3-project.html.en) and the project "S4LIDE - Hallstatt: Studying the Significance of Subaqueous Slides in Lake Hallstatt (PI Michael Strasser, funding ESS-ÖAW) (https://www.uibk.ac.at/geologie/sediment/research/projects/s4lide-hallstatt.html.en).

## 4.3 Human impact: resource management, vegetation history and spatial analysis

Here we focused on the impact of geologic extreme events on prehistoric mining communities. We also looked at the extent of the human impact on the ecosystem, especially the impact of prehistoric salt mining. The investigations aimed at clarifying whether identified extreme events led to a fundamental change in human subsistence strategies or even an abandonment of the area for a time.

We used different sedimentary and cultural archives (Siegmoos bog, lake sediments, archaeological data, written records).

### *4.3.1 Impact of prehistoric mass movements*

Through the paleoecological analysis of a peat profile from the Siegmoos bog in the direct vicinity of the prehistoric mining districts (covering the last 6000 years) by Festi et al. (2021) we are now able to investigate the impact of natural hazards on the prehistoric mining community in the Hallstatt High Valley and evaluate the environmental impact of prehistoric salt mining. Palynological and non-pollen-palynomorph data by Festi et al. (2021) can be integrated with geochemical data generated in the framework of a project collaboration "The Alpine Early Anthropocene" (PI Wolfgang Knierzinger) (Knierzinger et al. 2021). For the final stages of the prehistoric epoch we can also draw on the chronologically highly resolved lake sediment record (Drescher-Schneider, project report; Lauterbach et al. 2022).

In the period following the destruction of the Bronze Age mine workings ($12^{th}$ and $11^{th}$ cent. BCE) the landscape remains quite open, suggesting that humans remained in the area. A slight decrease of the diversity in human impact, i.e. a reduction in agro pastoral activity, can be observed. This might either be interpreted as a sign of slightly reduced human presence and activity or it might be speculated that the lack of signs of agricultural activities reflects a choice of the community to invest labor in reestablishing the profitable salt production and reducing the production of goods of consumption that could also be imported (Festi et al. 2021). In fact, the new paleoecological data from Siegmoos demonstrates that it took only 100 years for intense human activity to restart, as around 900 BCE a sharp reduction of spruce and fir can be identified (Festi et al. 2021). This most likely expresses the renewed beginning or intensification of mining activities and it associated need for timber and space. In addition, Knierzinger et al. (2021) detected relatively high Sn concentrations in peat sections corresponding to a time between ~1210 BCE and ~550 BCE through geochemical analysis. These geochemical signals might be taken as evidence for intensive bronze casting processes during this time.

In the wake of the first destruction of the early Iron Age mines in 661 BCE a decrease in anthropic pressure can be observed (since 600 BCE). Archaeological data shows that this event did not bring salt mining to a definite halt, as mining operations resumed a few decades later (Grabner et al. 2021 and chap. 4.2.3). In 570 BCE the early Iron Age mine workings are destroyed again, new data indicates that salt mining was continued (Grabner et al. 2021 and chap. 4.2.3). A constant albeit lower human impact that includes signs of agriculture, is evident until about 350 BCE and archaeological data points to a still considerable human presence as burial activity in the Iron Age cemetery continues until the mid of the $4^{th}$ cent. BCE (Barth and Lobisser 2002; Stöllner 2002: 300-340, 353-361). We might thus be looking at substantial resilience, but also a slow grinding down of resources brought on by a series of catastrophic events.

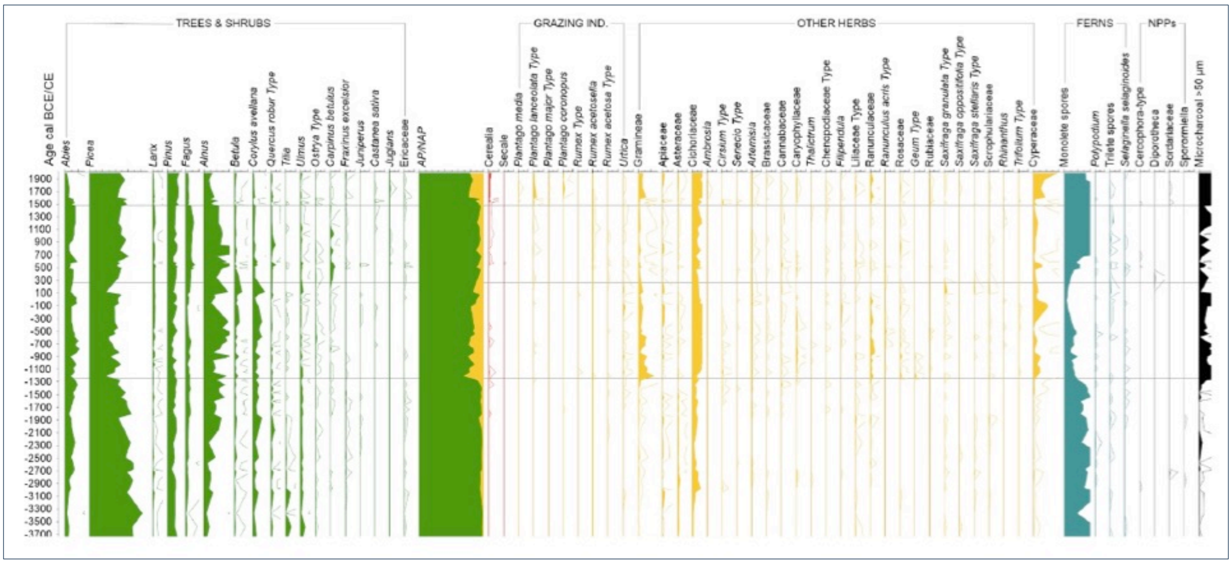


*Figure 30: Pollen diagram of Siegmoos. From: Festi et al. 2021*

Finally a fifth large-scale landslide probably caused the abandonment of the cemetery. Still this is not the end of prehistoric salt mining in Hallstatt (see chap. 4.2.1. to 4.2.4 and Grabner et al. 2021; Lauterbach et al. 2022). Archaeological data as well as paleoecological data from the Siegmoos bog and the lake sediments evidence a new salt mining phase in the late Iron Age (Barth and Lobisser 2002; Reschreiter and Kowarik 2015; Festi et al. 2021; Grabner et al. 2021; Drescher-Schneider project report). The archaeological record documents the enormous scale of this new phase, but does not allow further insights. Palynological analysis of the lake sediments offers a deeper understanding of this crucial phase of transition (Drescher-Schneider project report): Drescher-Schneider observes light settlement activity after the abandonment of the cemetery until about 280 BCE. For the time span of approx. 80 years we might then indeed be looking at a complete stop of human activity, but already at around 200 BCE the palynological data indicates the beginning of a new activity phase, which comes to full bloom between 157 to 50 BCE. This is again corroborated by Festi et al. (2021), who observe substantial human impact in the form of a series of major burning events between 100 BCE to 100 CE. The lake sediment record further resolves this, where between 50 BCE and 110 CE human activity seems extremely reduced, possibly even ceases (Drescher-Schneider project report). Thus for this time period again we might be looking at a short phase of abandonment, before the start of Roman Period settlement activity (see chap. 4.3.3).

Finally, the prehistoric mining communities faced destruction of their subsistence basis at least four times without system collapse and complete abandonment of the area. The relocation of the late Iron Age activity areas (mine workings and settlement) to an area outside of the hazard zone for landslides documents that the community was prepared to act upon perceived natural hazards.

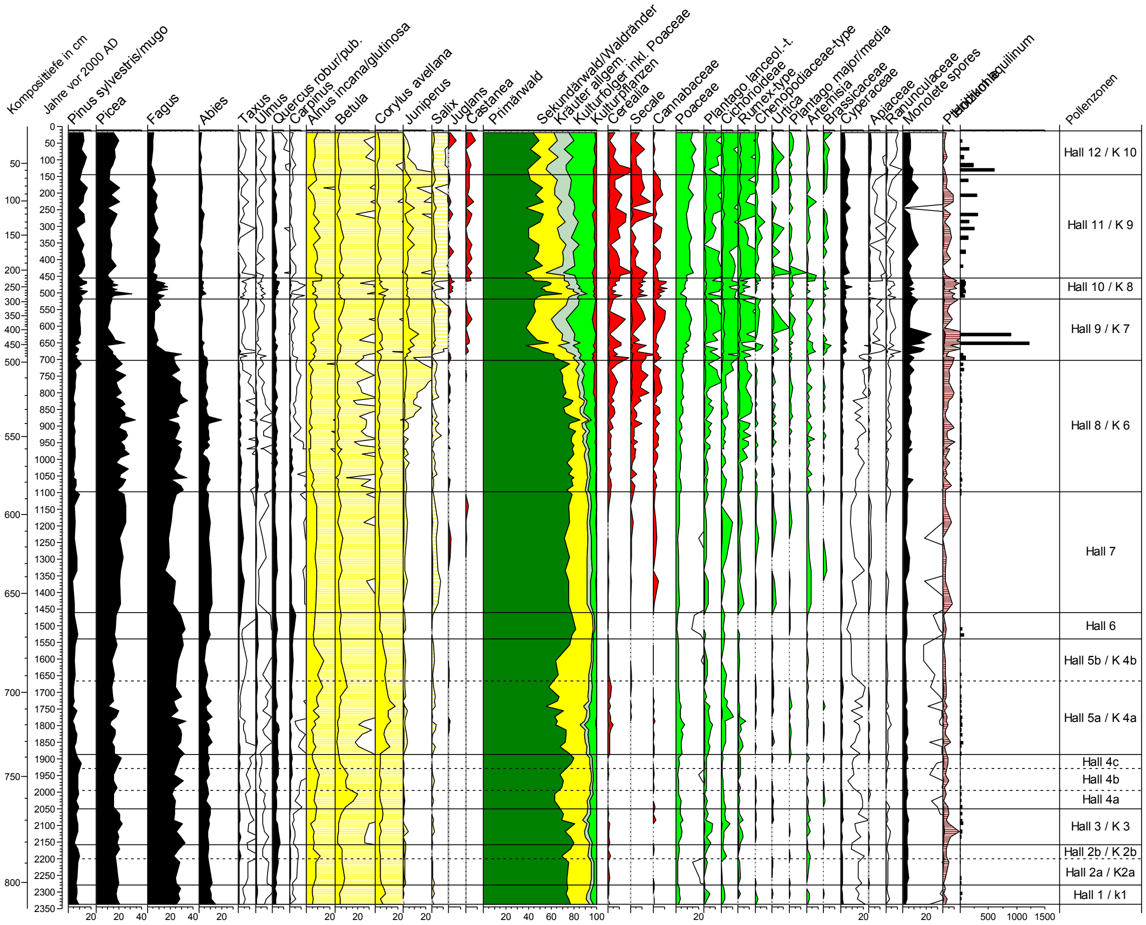


*Figure 30: Pollen diagram of Siegmoos. R. Drescher-Schneider*

#### *4.3.2 Environmental impact of prehistoric salt mining*

The resource needs of the prehistoric salt mines were substantial in terms of quality criteria as well as in scale (Grabner et al. 2019; Kowarik 2019; Grabner et al. 2021b). The paleoecological record now confirms the substantial impact of resource needs on the environment (Festi et al. 2021; for the final phase of prehistoric salt mining also Drescher-Schneider, project report). In fact, the impact on tree cover, at least during Bronze Age, is comparable to the impact of industrial scale mining in Hallstatt during Early Modern Era (Festi et al. 2021). Furthermore, for the final phase of prehistory Drescher-Schneider is able to illustrate substantial scale of human prehistoric human impact, which can be detected through the substantial development of secondary forests in this time period (Drescher-Schneider, project report). But both paleoecological records demonstrate that forest cover was not destroyed. In fact the integration of archaeological, wood technological and paleoecological data enables us to reconstruct a strategic, coordinated resource and landscape management and to infer infer a sophisticated understanding of ecosystem limits as well of certain natural hazards (Kowarik 2019; Festi et al. 2021; Grabner et al. 2021b).

Around 110 cal. CE the environmental impact distinctly changes. A sharp opening of the forest is observable (Festi et al. 2021; Drescher-Schneider project report;). This represents the Roman period settlement phase, which is also well documented through the archaeological record with a large and rich settlement as well as a cemetery in Hallstatt at lake level. The lake sediment record then enables substantial insights into the transition from Roman dominated culture to Migration period in Hallstatt, as it is not only clearly observable that the demographic pressure distinctly drops in the 2nd half of the 4th cent. BCE, but also that large parts of population left the area already before 488 CE (the official withdrawal of Roman administration and military) (Drescher-Schneider project report). Between the 4th century and the 14th century archaeological and historical evidence for human presence is poor, but the sedimentary record sheds new light on human activity in the area (Festi et al. 2021; Lauterbach et al. 2022; Drescher-Schneider project report): A very reduced population remained in the area throughout the late Antiquity and Migration period. Increased activity can observed from the 9th century onwards, with strongly intensifying anthropic pressure from the 12th century CE onwards. This phase might well be correlated with an initial stage of the medieval salt production. With the 14th century CE, when written records finally attest medieval salt production, truly massive landscape opening can be observed (Festi et al. 2021; Drescher-Schneider, project report). In the lake sediment record tree pollen drop to 50-60 % and primary forest even to 40 % (Drescher-Schneider project report). Drescher-Schneider observes that in the span of a few decades forest stands are nearly reduced by half. In addition, Lauterbach et al. describe an abrupt shift in sedimentation rates and type around 1300 CE, which they consider to represent substantially increased availability of erosional material in the catchment as can be caused by massive forest clearances (Lauterbach et al. 2022 and chap. 4.2.4). The pressure on forest cover, due to the demands of constantly increasing salt production, remained at high levels until the mid 19th century (Drescher-Schneider project report). The ensuing wood shortage and subsequent socioeconomic problems are well documented through the written records (Schraml 1932, 1934). By the end of the 16th century these attest that the demand for wood largely exceeded what could be harvested in and around Hallstatt (Schraml 1932: 372-373). In this context Lauterbach et al. suggest that another change in sedimentation from ~CE 1580 onwards might be seen as result of a change in forest management including an externalization of resource costs through the construction of a brine pipeline and the estahblishment of new salt pan 30 km from Hallstatt (Lauterbach et al. 2022 and chap. 4.2.4).

Also, the impact of the Little Ice Age is not easily identifiable in the palynological record as the massive anthropogenic processes mask the effect of LIA on the vegetation but the written record paints a very clear picture of its effects in terms of socioeconomic consequences for the local population (Drescher-Schneider project report).

Finally, as already mentioned the Siegmoos record documents that Bronze Age and Iron Age mining (14th to 1st cent. BCE) had a comparable impact on tree cover as industrial scale salt mining in the Modern Era (15th to 19th century). This is rather remarkable. By the end of the 16th century, according to the written records, the demand for wood largely exceeded what could be harvested in and around Hallstatt (Schraml 1932: 372-373). The situation was further aggravated by the fact that other mines and saltpans in near vicinity (Ebensee, Bad Ischl) had been opened. As salt production in the Salzkammergut was of fundamental economic importance the Habsburg monarchy tried to implement a number of policies that would tightly control forest use, subordinating all other forest related socioeconomic activity to the demands of salt production (Schraml 1932: 372-413). This resulted in a highly controlled and complex landscape structure, a substantial level of regional wood trade, and a stabilization of local wood resources (Schraml 1932: 372-398), albeit at a high level of forest clearance (Festi et al. 2021; Drescher-Schneider project report;).[1] We derive several conclusions from these observations, i) an awareness for the natural limits of this landscape existed in Early Modern Era, ii) these limits were constituted by the amount of wood that could be harvested without destabilizing the woodland resource, but possibly also with regards to the protective value of forest against natural hazards in alpine terrains, iii) that the imposed limit on tree cover reduction is so close to prehistoric conditions is suggestive, and iv) consequently a certain perception of ecosystem limits must be assumed for prehistoric Hallstatt, and probably also an awareness for natural hazards (Festi et al. 2021).

### *4.3.3 Spatial land use dynamics in the Hallstatt area*

Archaeological information was used to track the spatial land use dynamics from the Neolithic period to the early Middle Ages in the Hallstatt area (Klammer project report).

The spatial data corroborates the findings of the paleoecological investigations confirming again the long settlement history of the Hallstatt area (Klammer, project report). It also visualizes in another manner the changes in the intensity of human occupation and it expands these findings through the geographic-topographic dimension identifying preferred and avoided areas. Klammer (project report) observed that in general stability of used and non-used areas is substantial. Areas of high use are the Hallstatt High Valley and the corridor of the Traun River. One notable exception is the use of the karstic Dachstein plateau. In the human presence on the Dachsteinplateau we see the use of a different ecosystem niche, which seems relevant in certain periods and not in others (Cerwinka and Mandl 1997; Mandl 2009; Kowarik 2019). These changes in land use have been linked to changing climatic conditions, i.e. use in warmer periods and abandonment in colder periods, but conclusive evidence is still lacking (Kowarik 2019). At present paleoecological research focuses on this question in a case study on the Grafenbergalm (Kowarik et al. 2022; https://www.dainst.blog/crossing-borders/2021/10/29/zu-besuch-in-der-salzlandschaft-hallstatt/). However, during Modern Era we see a definite decoupling from climatic conditions as for socio-economic reasons (scarce subsistence base) the plateau is used for pasturing before and during the Little Ice Age.

[1] In this context it is of special importance to note that the restructuring of forest use and management as evidenced by various *Waldordnungen* throughout Europe represented a centralization and monopolization of the resource forest and thus a fundamental societal renogotiation of resource access (Winiwarter and Sonnlechner 2002). In fact, forests had been open to be used by a large array of societal groups for diverse reasons until the late Middle Ages. Winiwarter and Sonnlechner have shown that the picture painted of the deplorabel state of forests and the given reasons for this state of things does also have to be understood as a political instrument used by the ruling elite in the effort to gain full and exclusive control over this resource (2002).

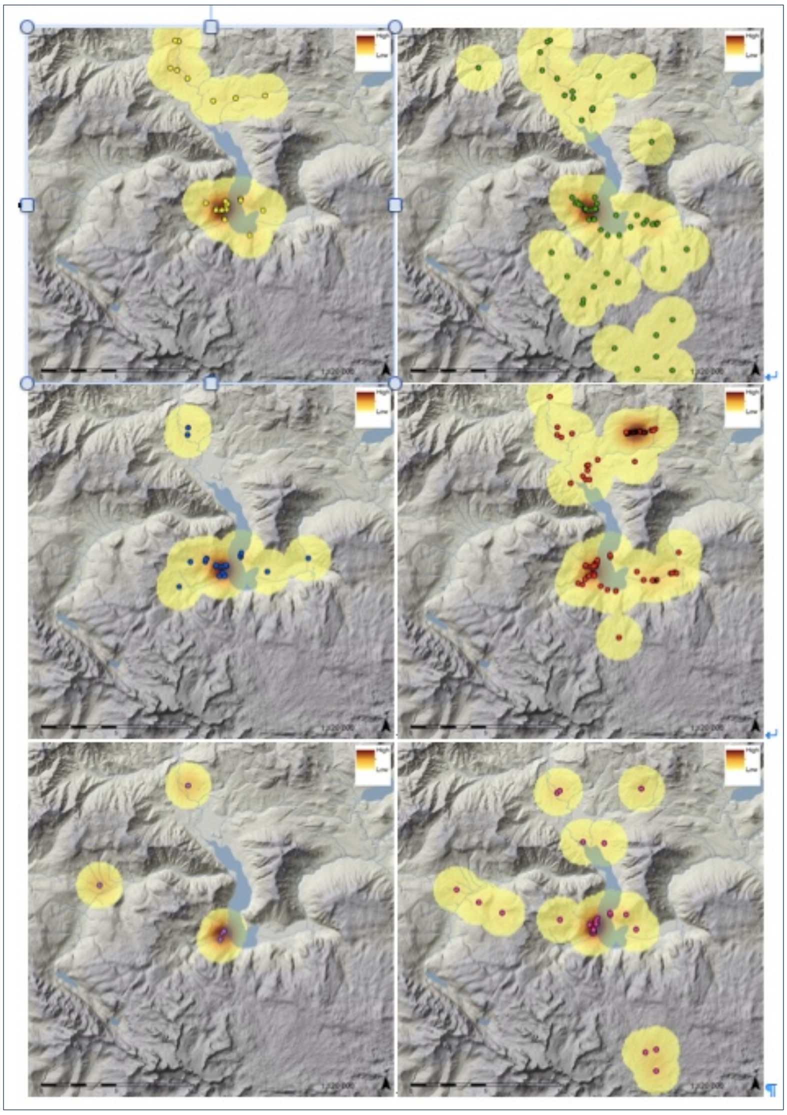

*Figure 32: Kernel Density analysis (radius = 1500 m): Neolithic (yellow), Bronze Age (green), Iron Age (blue), Roman Imperial times (red), early Middle Ages (purple), Middle Ages (pink). Graphic: J. Klammer*

To acquire more detailed insights into spatial dynamics we looked at change in archaeological evidence by means of a direct comparison of the density calculations from period to period (Klammer project report).

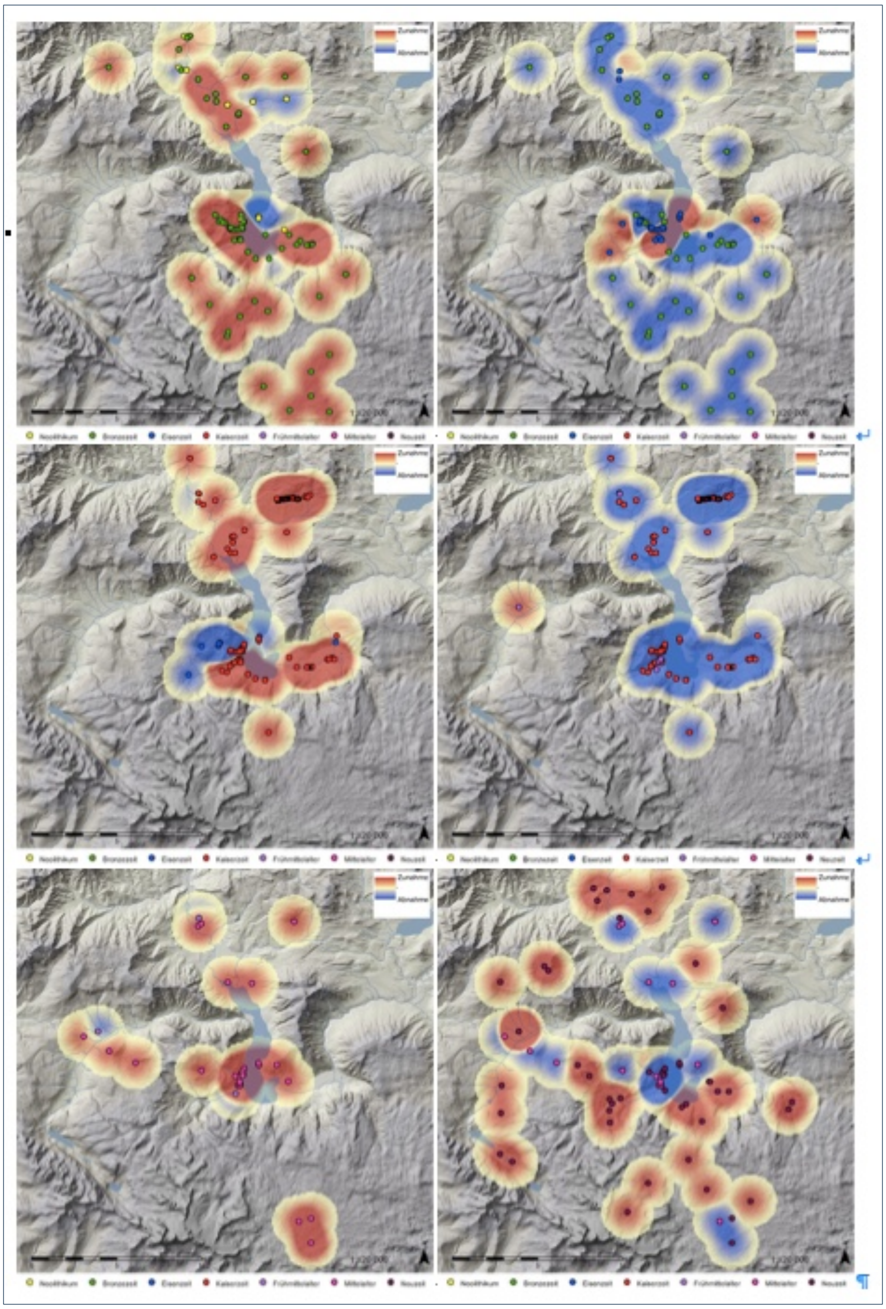

*Figure 32: Spatial dynamics of human land use: representations period to period: Neolithic/Bronze Age, Bronze Age/Iron Age, Iron Age/Roman Imperial times, Roman Imperial times/early Middle Ages, early Middle Ages/Middle Ages, and Middle Ages/Modern Times. Graphic: J. Klammer*

Klammer (project report) observes that the above-described findings are mostly confirmed by the analysis of spatial dynamics (see also fig. 32), thus identifying change in population density as one substantial factor of land use. This does not hold true for the Iron Age though, where the archeological record clearly indicates the presence of a substantial population (a weighted distribution calculation would show this more clearly), but the use of space is more restricted at least seen through the lens of site distribution. One possible explanation would be that a more centralized settlement system becomes established. Also the reduction of sites in higher altitudes might be linked to climatic reasons. This aspect requires further study, espec. paleoecological analyses, as, again, we might simply be looking at changing land use processes that are less visible through archaeological data. One other observation can be made based on these calculations. With the transition from Middle Age to the Modern Era land use changes substantially; in particular as more space is required and new areas are being used. Whether these areas are being used/settled for the first time or had been subjected to land use forms not visible through archaeological data during prehistory remains a question for future research (Klammer, project report).

For more detailed insights into land use changes in the Modern Era (18th cent. CE to present) four different historical maps were analyzed (for information on maps, see below) and Corine Landcover data integrated (Klammer, project report). In a first step all representations on the maps were digitally redrawn. An unfiltered recording of all signatures was made. In summary, a total of 14,159 polygons were created. In a next step generalized categories were created to enable comparison between the different maps. These categories were very roughly defined and resulted in six object groups: settlement, transport, water, forestry and agricultural areas, with the latter still distinguishing between upland and lowland areas.

| | |
|---|---|
| **Purpose and content, author, date**<br><br>**Source of digital copy** | **Salzbergkarte mit Tagrevierkartierungen inkl. Lahn, Markt und Ort Hallstatt,** Leopold Riezinger, 1713<br><br>Oberösterreichisches Landesarchiv |
| **Scale and extent** | Scale unknown; ca. 15 km$^2$: Salzberg – Plassen – Dachstein – Hallstatt, without lake Hallstatt |
| **Detailedness** | Building elements are depicted in great detail, all other representations are rather symbolic; mappings in general are rather schematic and in perspective view; they therefore occupy larger areas than top-view photographs would; it is interesting that up to four different forms of fences (hunter's fence, picket fence, board fence and paddock fence [one- to threefold] ... ) were depicted around gardens and meadows; obviously, particular attention was paid to this detail; people and animals were also drawn in, as well as economic objects, which are to be understood in the context of the infrastructure of the salt mountain; a difference between coniferous and deciduous forests is also visible. |
| **Position accuracy** | Mapping in the area of survey points (e.g., mouth holes) and for construction elements is accurate; cutbacks here are mainly due to perspective views |
| **Resolution** | Very good |

*Table 1: Meta data on Salzbergkarte mit Tagrevierkartierungen inkl. Lahn, Markt und Ort Hallstatt, Leopold Riezinger, 1713. Adapted from Klammer project report.*

*Figure 33: Map by Oberbergmeister Leopold Riezinger, 1713 (260a). Oberösterreichisches Landesarchiv, Karten- und Plansammlung*

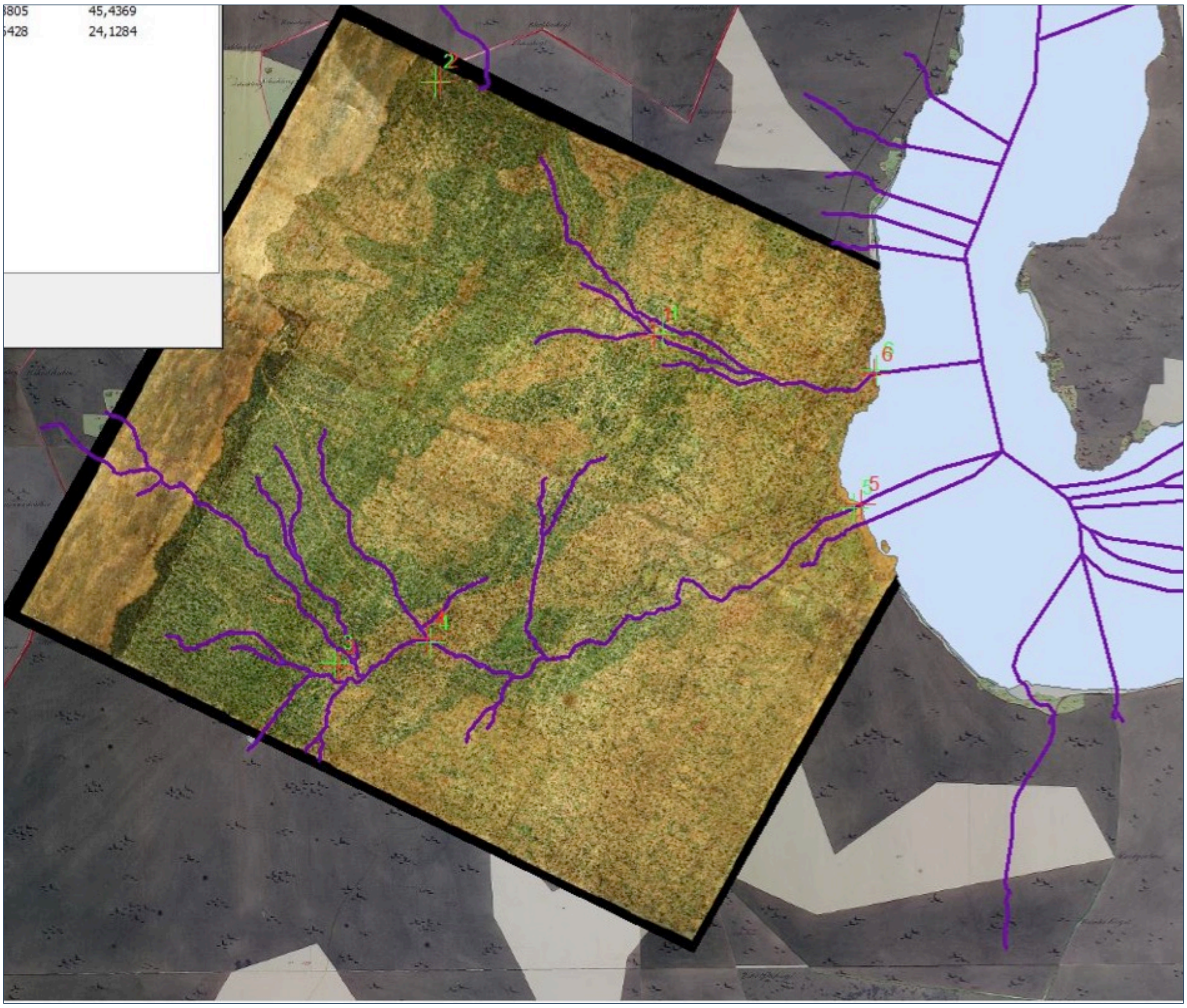


*Figure 34: Riezinger 1713 (260a): Pass points used for georeferencing. Graphic: J. Klammer, maps: Oberösterreichisches Landesarchiv, Karten- und Plansammlung*

| | |
|---|---|
| **Purpose and content, author, date** | **Salzbergkarte mit Tagrevierkartierungen inkl. Lahn, Markt und Ort Hallstatt,** Leopold Riezinger, 1743<br>Map depicting those forest districts that supplied the necessary firewood and timber for the Hallstatt saltworks/recording of towns, rivers, lakes and the market |
| **Source of digital copy** | Oberösterreichisches Landesarchiv |
| **Scale and extent** | 1:24.000 Bergstabl; ca. 296 km$^2$: Dachstein – Gosau – Bad Goisern (incl. Weißenbachtal) – Obertraun |
| **Detailedness** | Not very detailed and not executed with much care; elements have a symbolic rather than a real character; the legend entries for the Weißenbachtal could not be reconstructed and are possibly erroneous |
| **Position accuracy** | Mapping in the area of survey points (e.g., mouth holes) and for construction elements is accurate; cutbacks here are mainly due to perspective views |
| **Resolution** | Very good |

*Table 2: Meta data on Salzbergkarte mit Tagrevierkartierungen inkl. Lahn, Markt und Ort Hallstatt, Leopold Riezinger, 1743. Adapted from Klammer project report.*

*Figure 35: Map by Oberbergmeister Leopold Riezinger, 1743 (259a). Oberösterreichisches Landesarchiv, Karten- und Plansammlung*

*Figure 36: Riezinger 1743 (259a): Pass points used for georeferencing. Graphic: J. Klammer, Digital data: Oberösterreichisches Landesarchiv, Karten- und Plansammlung*

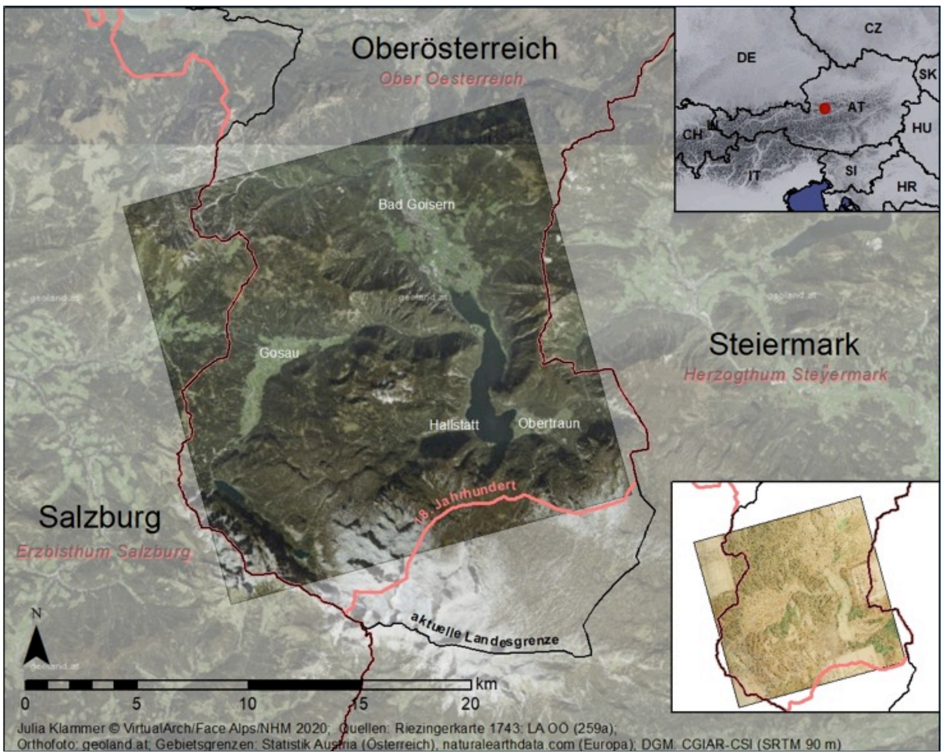


*Figure 37: Riezinger 1743 (259a): Extent and boundary of map. Graphic: J. Klammer*

| | |
|---|---|
| **Purpose and content, author, date**<br><br>**Source of digital copy** | **Franziszeischer Katasterplan 1824-1830**<br>Parcel documentation for tax assessment/primarily plots of land are mapped<br>Oberösterreichisches Landesarchiv |
| **Scale and extent** | 1:2.880 m, ca. 314 km$^2$: Dachstein – Gosau – Bad Goisern – Obertraun |
| **Detailedness** | Tax-relevant areas and contents are very precise; less tax-relevant areas, e.g., low-yielding areas such as in the high mountains, were recorded with less precision and detail |
| **Position accuracy** | Areas were surveyed with the help of triangulation, therefore the mappings are very accurate and according to the scale, for this reason deviations are only in the meter range |
| **Resolution** | poor, available digital copy does not reflect quality of original |

*Table 3: Meta data on Franziszeischer Katasterplan 1824-1830. Adapted from Klammer project report.*

*Figure 38: Compound plan sheets of the Franciszean cadastre, 1824 to 1830. Oberösterreichisches Landesarchiv, Karten- und Plansammlung*

| | |
|---|---|
| **Purpose and content, author, date** | **Kartenblätter der Franzisco-Josephinischen / Dritte Landesaufnahme,** 1873 to 1874<br>Military geographic survey; landscape features were documented with a strategic focus |
| **Source of digital copy** | Bundesamt für Eich- und Vermessungswesen |
| **Scale and extent** | 1:28.000 m, ca. 315 km²: Dachstein – Gosau – Bad Goisern – Obertraun |
| **Detailedness** | good; adequate landscape image according to the scale |
| **Position accuracy** | Surfaces were measured with the help of triangulation, very accurately according to the scale |
| **Resolution** | poor, available digital copy does not reflect quality of original |

*Table 4: Franzisco-Josephinische Landesaufnahme / Dritte Landesaufnahme, 1873 to 1874. Adapted from Klammer project report.*

*Figure 39: Compound plan sheets of the Francisco-Josephine survey, 1873 to 1874. Bundesamt für Eich- und Vermessungswesen*

| | |
|---|---|
| **Purpose and content, author, date**<br><br>**Source of digital copy** | **Corine Landcover Data 2018**<br>Monitoring the earth's surface; categorical land cover units. |
| **Scale and extent** | 25 x 25 cm, cell size, 314 km$^2$: Dachstein – Gosau – Bad Goisern – Obertraun |
| **Detailedness** | the freely available data are very roughly generated |
| **Position accuracy** | fundamentally accurate, but coarse; according to the resolution |
| **Resolution** | 25x25 m |

*Table 5: Corine Landcover Data 2018. Adapted from Klammer project report.*

Since the maps display different areas (and surface extents) a direct comparison of positions was not feasible. Even a comparison of positions reduced to the lowest denominator (Riezinger 1713 260a) would not have been effective. Here, the problems lie above all in the inaccurate drawings, the differences in size between perspective views in relation to top views, and the diverging qualities of location with the accompanying distortions. Consequently, instead of using absolute surface values percentages were compared, which allowed the application to the entire extent of the representations. The area-dependent percentage assessment thus indicates how much of a map area was used for the entries of the respective categories. Although no absolute results can be obtained in this way, the mappings become comparable with each other on a relative level (Klammer, project report).

Although the previous study (see above) indicated that modern land use shows fundamental differences from prehistoric to medieval land use, the high stability of land use in the 17th to 20th cent. CE is also evident in the present study. In detail, however, differences are discernible. The settlement areas of the two oldest maps are very similar, although a slight increase can be noted. The settlement areas on the Franziszeischer Katasterplan, however, are much less represented in terms of area. This can probably be explained less by a decrease in the number of buildings than by the way the buildings are depicted. The objects in perspective view of the Riezinger maps occupy far more area per building than the top views in the cadastral plan. On the other hand, the increase in settlement area from 0.24% of the cadastral plan to more than twice as much settlement area (0.57%) in the Third Land Cover is probably due to an increase in settlement area. The value calculated by the Corine Land Cover data, on the other hand, is much higher. However, this is primarily due to the coarse resolution of the data (Klammer, project report).

Traffic areas are represented to the same extent in almost every map series. Only the Franziszeische Kataster stands out here. It shows only very few areas as traffic areas. This is due to the fact that the Franziszeische Katasterplan mainly shows parcels of land (Fuhrmann 2007). Water areas should not be evaluated in the comparisons, as they are primarily purely natural or little influenced areas (especially with regard to their extent). Apart from that, they could be assigned to both transport and economic areas, as they were used for both purposes. However, a sensible division did not seem feasible (Klammer, project report). Agricultural areas in the lowlands, similar to the transport areas, are also almost equally represented. Only the older Riezinger map from 1743 stands out with a higher value. It cannot be plausibly explained why so much agricultural land is recorded on this map. Presumably, the value is due to a slightly different mapping. Nevertheless, the percentage seems questionable, because this very map is supposed to depict the forest districts and thus the forest areas that supplied the firewood for the salt works. Therefore, a correspondingly high percentage of forest area would have been more expected than agricultural land in the lowlands (Klammer, project report). Agricultural land in the highlands can only be compared to a limited extent. This is due to the fact that the areas include not only fenced pastures and fields, but also hut pastures. These are extensive areas where grazing cattle could graze. However, these were often only vaguely defined on the maps. Precise boundaries are therefore seldom ascertainable. A comparison of areas is therefore difficult to interpret. Nevertheless, the values indicate an interesting overall relationship of the respective contemporary situation (Klammer, project report). Forestry areas are very similarly represented on all maps. Nevertheless, a slight downward trend can be discerned. Whether forestry areas have actually receded over the centuries can only be speculated on this basis, even if such a development seems quite plausible in view of population growth and the increasing demand for resources (Klammer, project report).

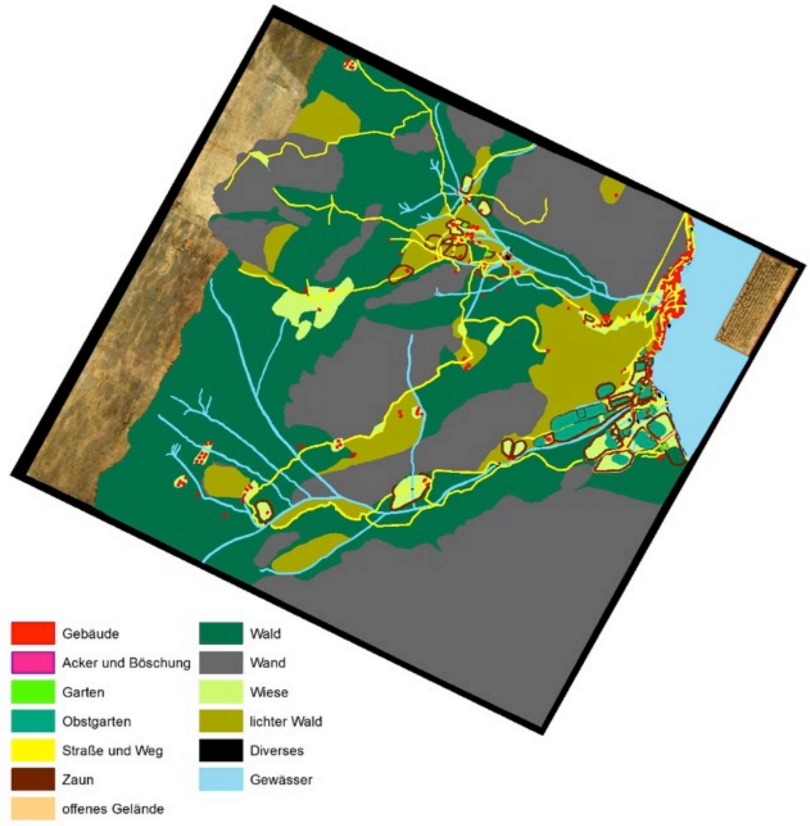


*Figure 40: Riezinger 1713 (260a): 953 drawn polygons with source specific class division. Graphic: J. Klammer*

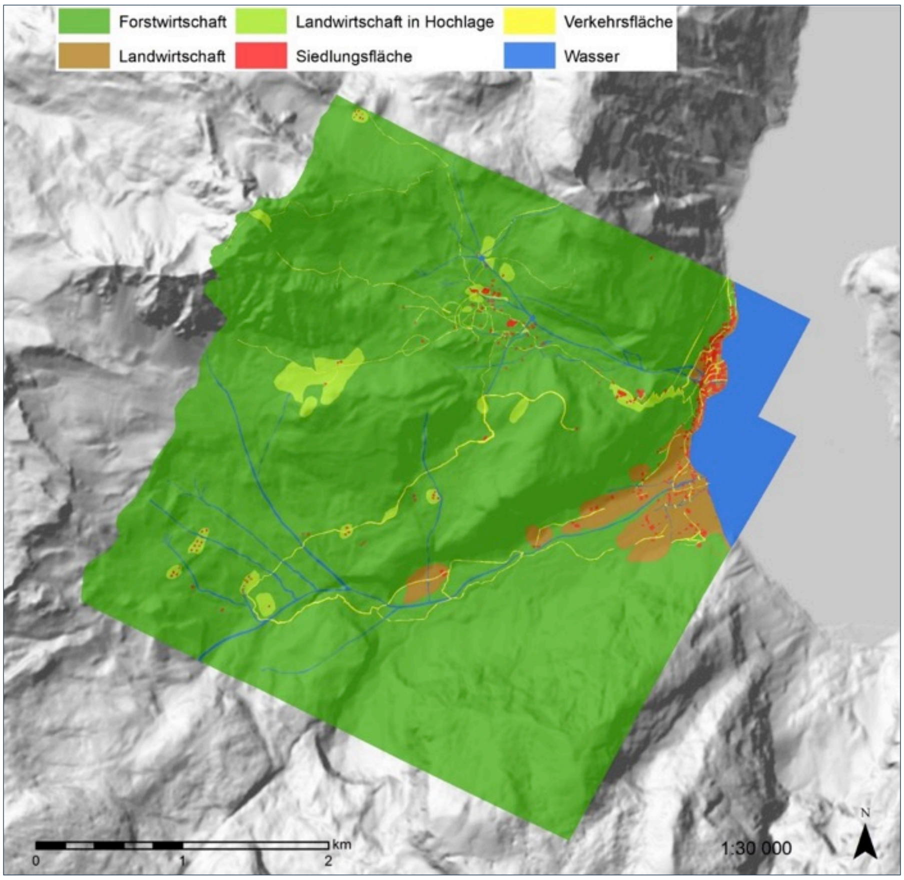


*Figure 41: Riezinger 1713 (260): Categorized representation of the polygons. Graphic: J. Klammer*

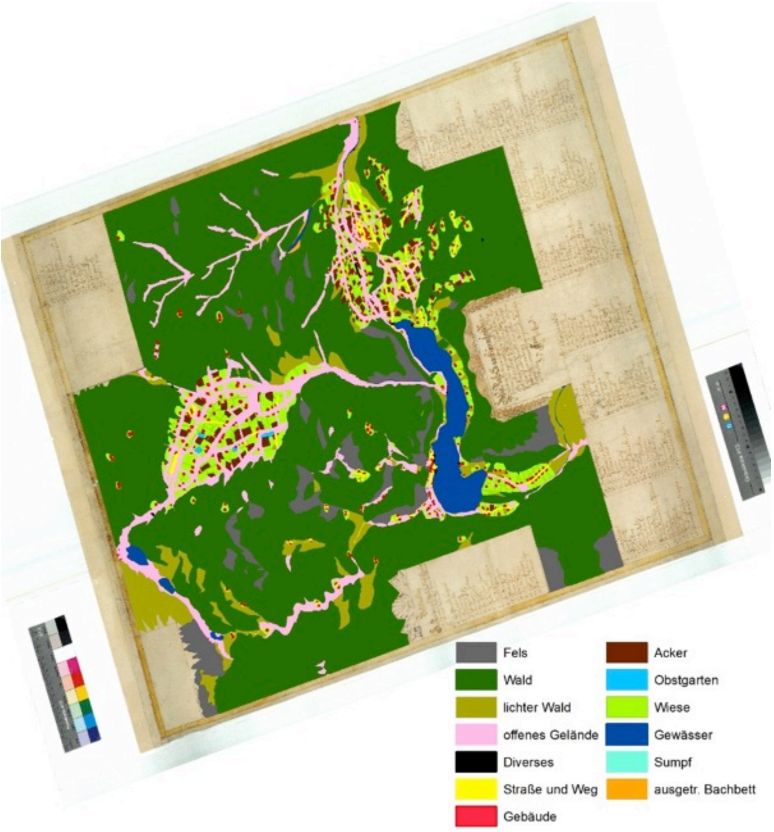


*Figure 42: Riezinger 1743 (259a): 1961drawn polygons with source specific class division. Graphic: J. Klammer*

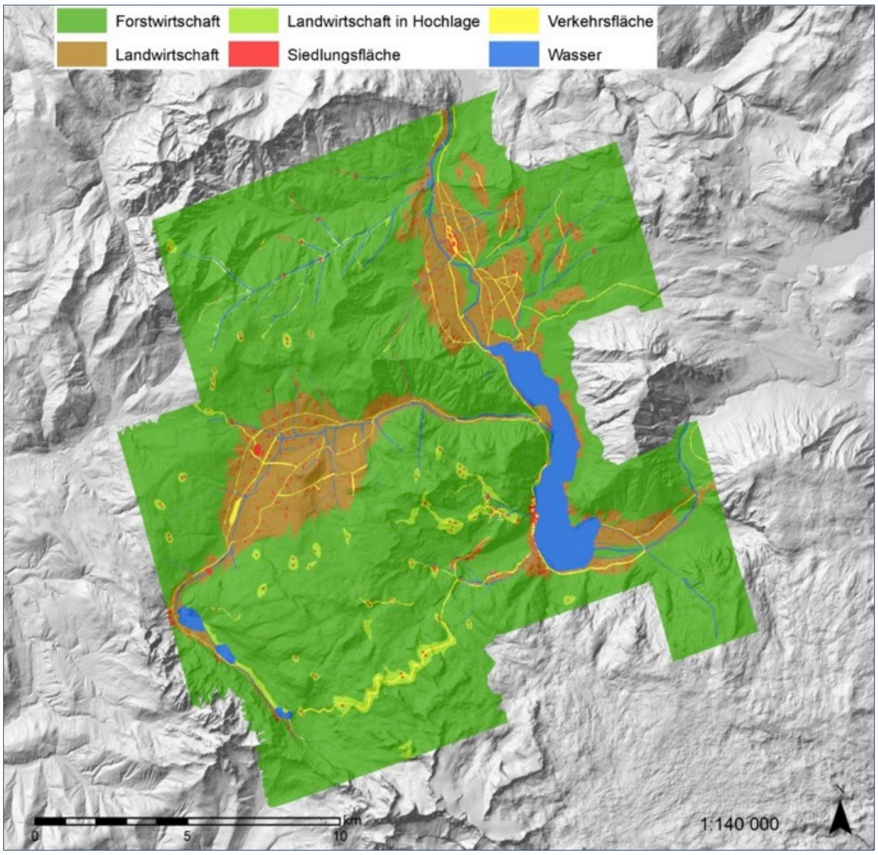


*Figure 43: Riezinger 1743 (259): Categorized representation of the polygons. Graphic: J. Klammer*

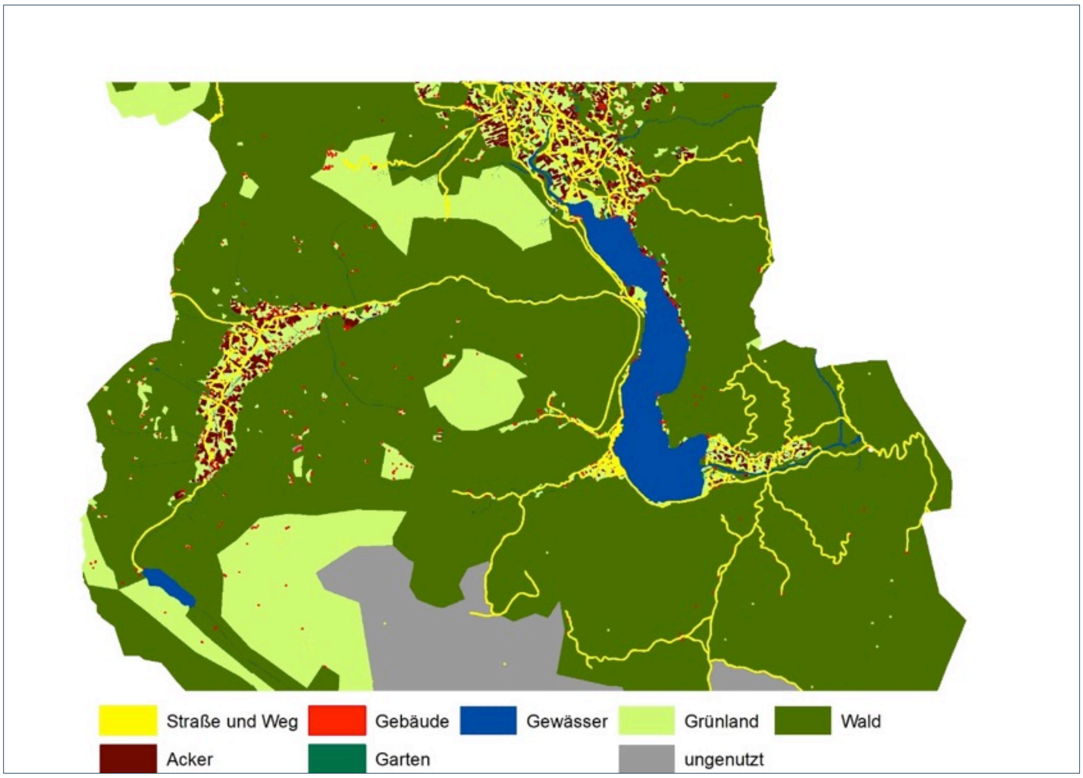


*Figure 44: Franziszeischer Kataster: 5219 drawn polygons with source specific class division. Graphic: J. Klammer*

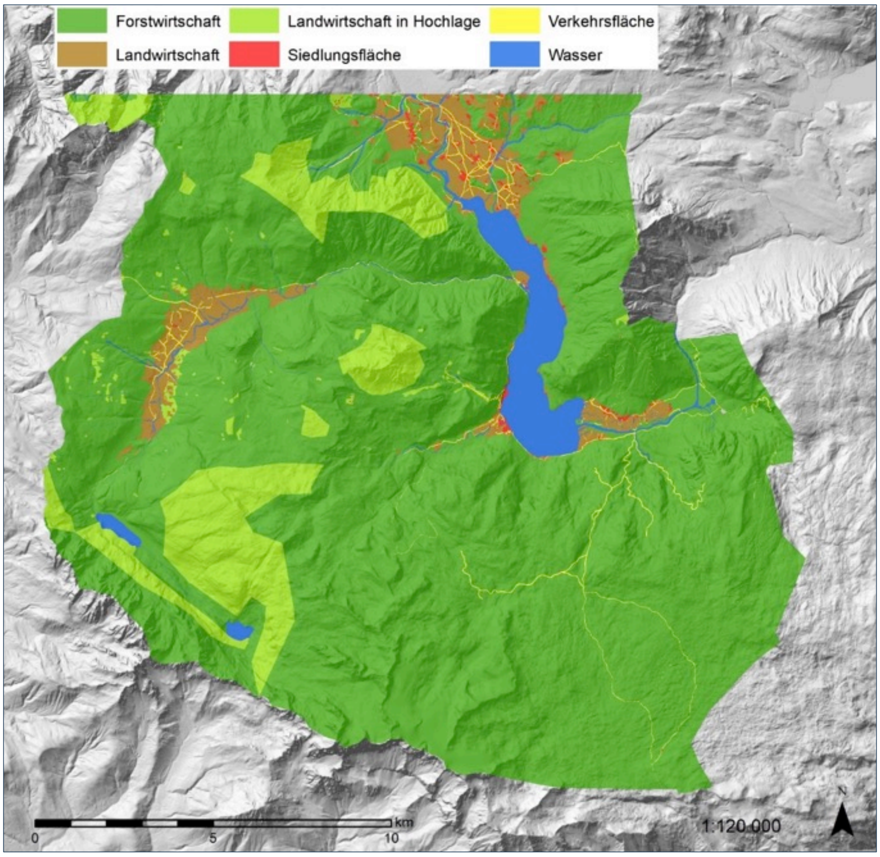


*Figure 45: Franziszeischer Kataster: Categorized representation of the polygons. Graphic: J. Klammer*

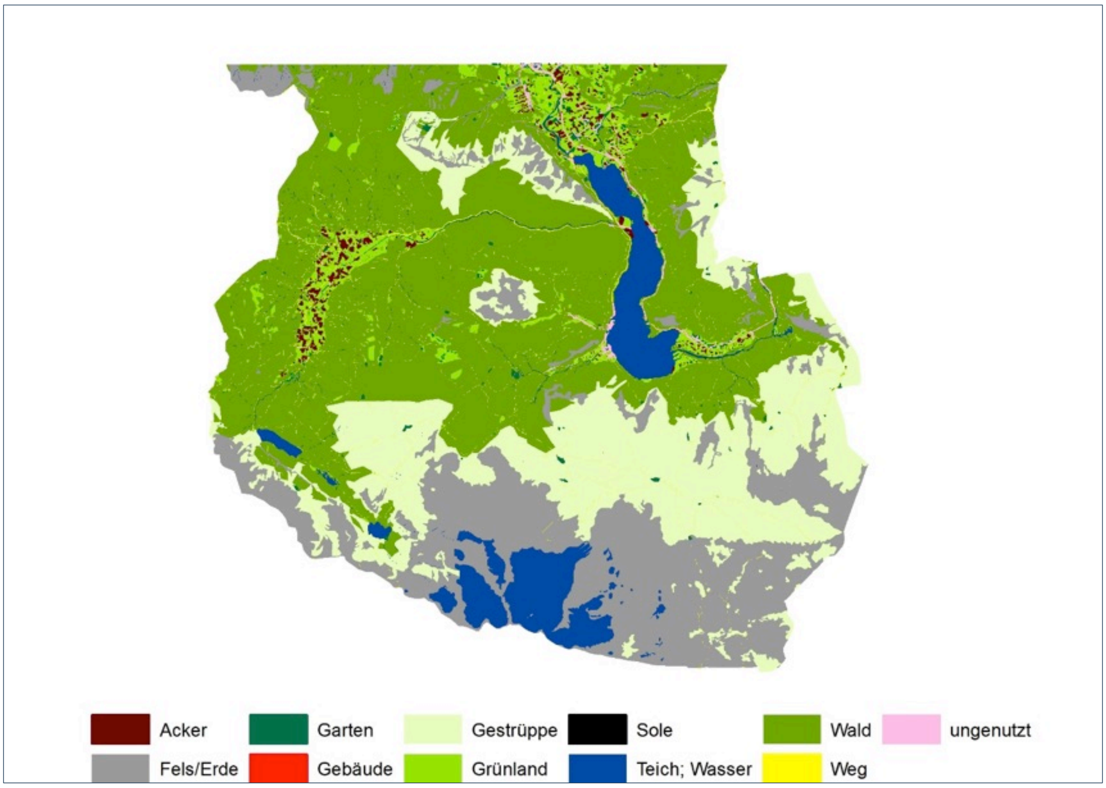


*Figure 46: Dritte Landesaufnahme 1873/74: 6026 drawn polygons with source specific class division. Graphic: J. Klammer*

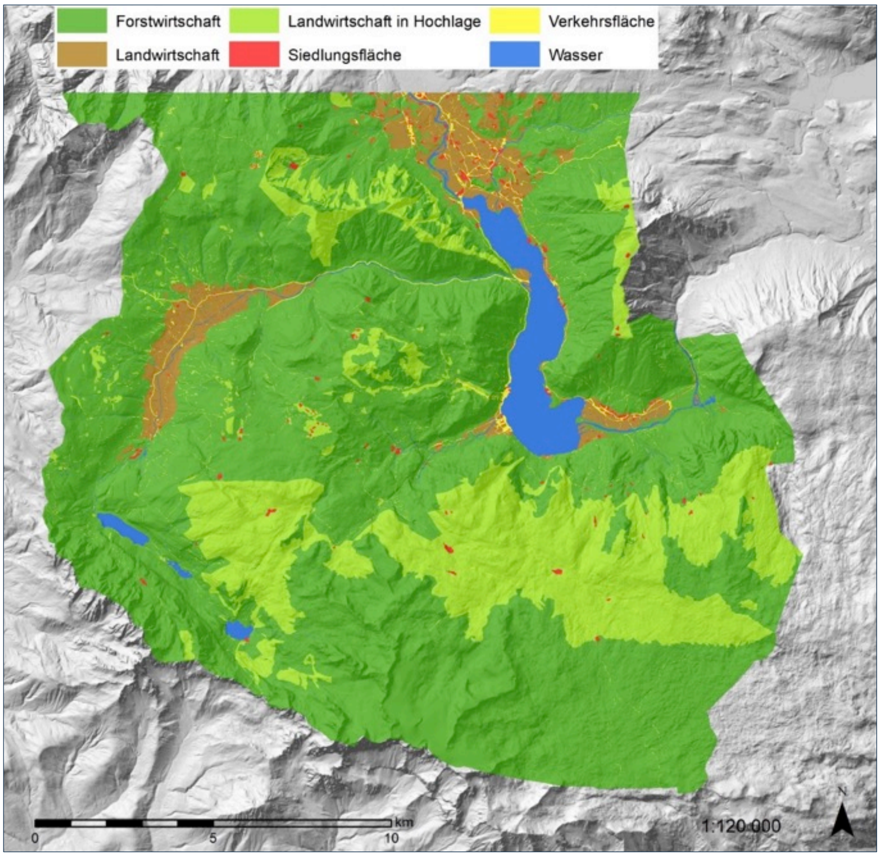


*Figure 47: Dritte Landesaufnahme 1873/74: Categorized representation of the polygons. Graphic: J. Klammer*

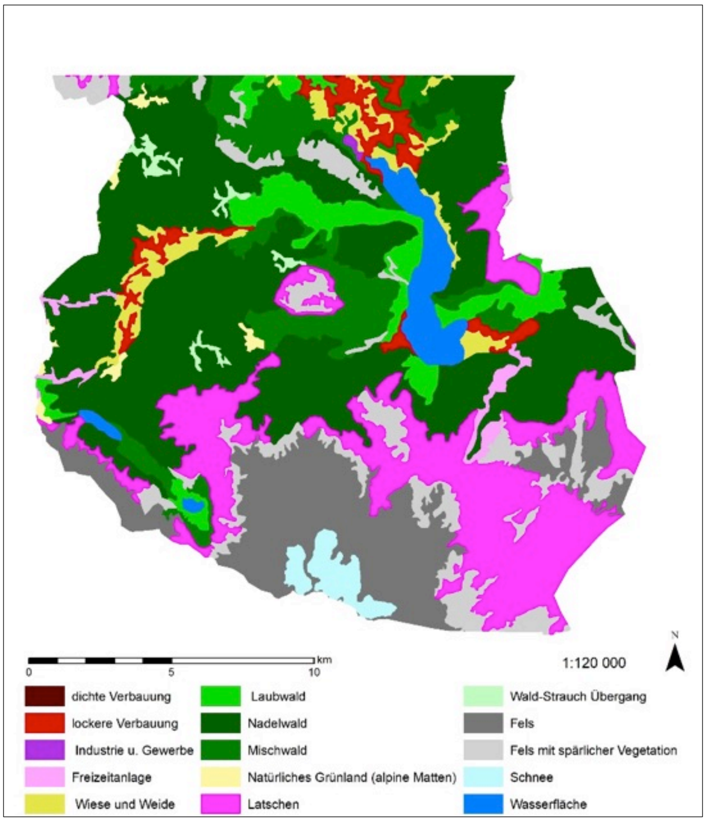


*Figure 48: Corine Land Cover 2018: 116 drawn polygons with source specific class division. Graphic: J. Klammer*

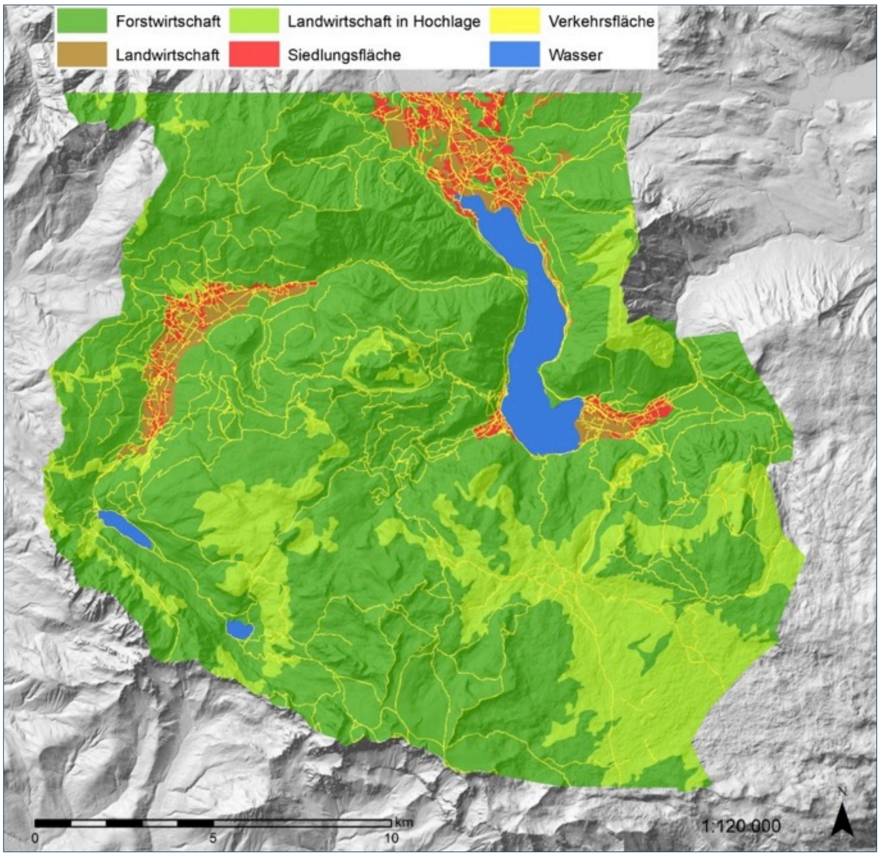


*Figure 49: Corine Land Cover 2018: Categorized representation of the polygons. Graphic: J. Klammer*

# 5. Outputs

## 5.1 Establishment of an inter- and transdisciplinary network and new initiatives

This objective was implemented very successfully. Interdisciplinary research partnerships with the Federal Geological Survey, the University of Natural Resources and Applied Life Sciences and the University of Innsbruck, among others, led to a close and productive networking of researchers from science and humanities. This materializes in a substantial interdisciplinary publication corpus and also enabled the successful implementation of new innovative projects such as the drilling project in Lake Hallstatt (Hallstatt-Hipercorig-History: https://www.uibk.ac.at/geologie/sediment/research/projects/h3-project.html.en) and the subsequent "S4LIDE - Hallstatt: Studying the Significance of Subaqueous Slides in Lake Hallstatt project (PI Michael Strasser, funding ESS-ÖAW) (https://www.uibk.ac.at/geologie/sediment/research/projects/s4lide-hallstatt.html.en) or the research on the human-environment relationship on the Dachstein plateau within a project collaboration between the German Archaeological Institute and the Natural History Museum Vienna (Kowarik et al. 2022; https://www.dainst.blog/crossing-borders/2021/10/29/zu-besuch-in-der-salzlandschaft-hallstatt/). Finally, further applications for project funding are in preparation within the framework of this research network.

Transdisciplinary partnerships with local actors such as the municipality of Hallstatt, Salinen Austria AG, nature conservation agencies, the Reinhalteverband Hallstätter See and various agricultural communities on the Dachstein plateau have been expanded or newly established. These partnerships materialize, among other things, in the holding of joint press conferences as well as the development and implementation of educational concepts (e.g. educational parcours Hallstatt High Valley together with Salzwelten Gsmbh).

## 5.2 Publications

The interdisciplinary nature of the project is reflected in the publication program. Project results were published in peer-reviewed journals in the fields of archaeology, geosciences, heritage protection, forest science and vegetation history. Results from the spatial analysis of past land use dynamics were published in a monograph.

### Peer-reviewed journals

2022

Lauterbach, S., Strasser, M., Kowarik, K., Reschreiter, H., Mandl, G., Spöttl, C., Plessen, B., Brauer, A. (2022). Large‐scale mass movements recorded in the sediments of Lake Hallstatt (Austria)‐evidence for recurrent natural hazards at a UNESCO World Heritage site. Journal of Quaternary Science. https://doi.org/10.1002/jqs.3472.

Kowarik, K., Brandner, D., Hofmann, K., Strasser, M. and Reschreiter, H. (2022). Researching Change - Understanding Change - Facing Change. 3500 years of human-environment relations in the Hallstatt/Dachstein region, Internet Archaeology 60. https://doi.org/10.11141/ia.60.7

2021

Festi, D., Grabner, M., Knierzinger, W., Reschreiter, H., Wächter, E., Kofler, W., Winner, G., Kowarik, K. (2021). 3500 years of environmental sustainability in the large scale Alpine mining district. Journal of Archaeological Science: Reports 37(4):102670, February 2021. https://doi.org/10.1016/j.jasrep.2020.102670

Grabner, M., Wächter, E., Nicolussi, K., Bolka, M., Sormaz, T., Steier, P., Wild, E.M., Barth, F.E., Kern, A., Rudorfer, J., Kowarik, K., Stöllner, T., Reschreiter, H. (2021). Prehistoric salt mining in Hallstatt, Austria. New chronologies out of small wooden fragments. Dendrochronologia 66(2):125814, February 2021. https://doi.org/10.1016/j.dendro.2021.125814

Grabner, M., Wächter, E., Mayer, K., Weber, A., Reschreiter, H., Kowarik, K. (2021b). Forest management activity in prehistoric Hallstatt, Austria. In: Johann, E., Kusmin, J., Woitsch, J. (eds.): European Forests, Our Cultural Heritage. Proceedings of the International Conference European Forests - Our Cultural Heritage, 4.-7. December 2018, St. Georgen am Längsee, Carinthia, Austria. Prague 2021, 231-252. Download: http://shop.eu.avcr.cz/en/domu/193-european-forests-our-cultural-heritage.html

Knierzinger, W., Festi, D., Limbeck, A., Horak, F., Brunnbauer, L., Drollinger S., Wagreich, M., Huang, J., Strasser, M., Knorr, K., Reschreiter, H., Gier S., Kofler, W., Herzig, C., Kowarik, K. (2021). Multi-proxy analyses of a minerotrophic fen to reconstruct prehistoric periods of human activity associated with salt mining in the Hallstatt region (Austria). Journal of Archaeological Science: Reports 36:102813, April 2021. https://doi.org/10.1016/j.jasrep.2021.102813

2020

Kowarik, K. and Reschreiter, H. (2020). Anthropogene Einflüsse auf die Hochgebirgsumwelt im Anthropozän: Einblicke aus einer alpinen Bergbaulandschaft. In: J. L. Lozán, S.-W. Breckle, H. Escher-Vetter, H. Grassl, D. Kasang, F. Paul, U. Schickhoff (Hrsg.). Wissenschaftliche Fakten. Warnsignal Klima: Hochgebirge im Wandel. Wissenschaftliche Auswertungen GEO, 109-114.

Strasser, M., Berberich, T., Fabbri, S., Hilbe, M., Huang, J-J. S., Lauterbach, S., Ortler, M., Rechschreiter, H., Brauer, A., Anselmetti, F., Kowarik, K. (2020). Geomorphology and event-stratigraphy of recent mass-movement processes in Lake Hallstatt (UNESCO World Heritage Cultural Landscape, Austria). Geological Society, London, Special Publications, 500, 31 March 2020. https://doi.org/10.1144/SP500-2019-178

2018

Reschreiter, H. and Kowarik, K. (2018). 7000 Jahre Kultur- und Industrielandschaft rund ums Salz. Österreichische Zeitschrift für Kunst- und Denkmalpflege 2018/4, 437-453.

2017

Reschreiter, H. and Kowarik, K. (2017): Viele Archive - ein Ziel: 7000 Jahre Salz. Vorträge der montangeschichtlichen Tagung "Salz und Archive" Bad Ischl 2016. res montanarum 57/2017, 4-15.

**Monographs**

Kowarik, K. (2019). Hallstätter Beziehungsgeschichten. Wirtschaftsstrukturen und Umfeldbeziehungen der bronze- und ältereisenzeitlichen Salzbergbaue von Hallstatt/OÖ. (Mit Beiträgen von Michael Grabner, Julia Klammer, Konrad Mayer, Hans Reschreiter, Elisabeth Wächter und Georg Winner). Studien zur Kulturgeschichte von Oberösterreich 50.

**Project reports**

Drescher-Schneider, R. (project report). Ergebnisse der Pollenanalyse an den Seekernen 2021/1 und HAS 2016 aus dem Hallstättersee.

Klammer, J. (project report). Dynamik der Landschaft – Räumliche Untersuchungen zur menschlichen Landnutzung vom Neolithikum bis heute.

Ottowitz, D., Ita, A., Jochum, B., Pfeiler, S., Römer, A., Peresson, M., Mandl, G. W. (project report). Geoelektrische Messungen und Bohrlochuntersuchungen im Rahmen des FaceAlps Projektes 2017, 2018 und 2019.

## 5.3 Public Outreach

Public outreach played an important role in the project activities. In addition to communicating the specific questions, motivations and research results of the project, the objective was also to convey the topic of the change of the Earth System and the necessity of targeted action to a broad public. Thanks to the strong network of partners (e.g. research partners, the municipality of Hallstatt, Salzwelten GmbH and Salinen Austria AG), it was possible to implement outreach activities within the framework of the project with great success and to generate a corresponding media echo. The outreach activities consisted of organizing and participating in science fairs, public lectures, popular scientific publications in print and online (text and video contributions), the conception and implementation of an educational parcours in the Hallstatt High Valley and media work.

### *5.3.1 Popular science publications: journals and magazines (selection)*

Kowarik, K., Reschreiter, H., Strasser, M. (2021). 7000 Jahre Salz - oder noch mehr? Horizont, Mitarbeiterzeitung der Salinen Austria AG, 2021/02, 10-11.

Kowarik, K., Reschreiter, H., Strasser, M. (2021). „Neues vom Hallstätter See“. Natur historisches. Magazin des Naturhistorischen Museums, 20-21. Herbst 2021.

Kowarik, K., Brandner, D., Grabner, M., Ita, A., Jochum, B., Mandl, G., Ottowitz, D., Peresson, M., Römer, A., Reschreiter, H. (2019). Oft unterbrochen, immer wieder neu begonnen, Der prähistorische Salzbergbau in Hallstatt. Das Naturhistorische im Universum Magazin, 12/2019, 6-7.

Kowarik, K., Reschreiter, H., Anselmetti, F., Barth, F.E., Berberich, T., Brauer, A., Drescher-Schneider, R., Festi, D., Grabner, M., Ita, A., Jochum, B., Kern, A., Lauterbach, S., Oeggl, K., Ottowitz, D., Römer, A., Strasser, M. (2018). From salt mines to lake sediments. Investigating human-environment relations in the Hallstatt region, Austria. PAST. The Newsletter of the Prehistoric Society, 89/Summer 2018, 11-13.

Reschreiter, H. and Kowarik, K. (2017). Salz in Hallstatt - einmalige Einblicke in eine besondere Landschaft. Bayerische Archäologie, 2017/4, 14-19.

### *5.3.2 Popular science publications: online (selection)*

Poppenwimmer, F. and Reschreiter, H. (Okt. 2020), Krisenresistent und nachhaltig: Hallstatt in der Bronze- und Eisenzeit. Wie die Hallstatt-Forschung urgeschichtliches Krisen- und Ressourcenmanagement erforscht und was das mit der heutigen Zeit zu tun hat. https://www.derstandard.at/story/2000120369157/krisenresistent-und-nachhaltig-hallstatt-in-der-bronze-und-eisenzeit

Poppenwimmer, F. and Reschreiter, H. (März 2018), Das Hallstätter Salzbergtal: Die 7.000 Jahre alte Industrielandschaft. Wie war es möglich, in dem unwirtlichen Tal ohne Strom und Straßen zu leben? Ein Oral-History-Projekt sammelt Geschichten von Zeitzeugen. https://www.derstandard.at/story/2000076074980/das-hallstaetter-salzbergtal-die-7000-jahre-alte-industrielandschaft

Kowarik, K., Anselmetti, F., Berberich, T., Fabbri, S., Hilbe, M., Lauterbach, S., Reschreiter, H., Strasser, M. (Nov. 2017), Vermessung des Hallstätter Sees: Beziehungskiste am Seegrund. Das erste Jahr des Facealps-Projekts am Hallstätter See.

https://www.derstandard.at/story/2000068746956/vermessung-des-hallstaetter-sees-beziehungskiste-am-seegrund

Kowarik, K., Reschreiter, H., Strasser, M., Lauterbach, S., Berberich, T., Kioka, A., Wrozyna, C. (Juli 2017), Ran an den Schlamm des Hallstätter Sees! Das Facealps-Team sammelt wieder Schlamm vom Seeboden. Warum immer neue Bohrungen notwendig sind. https://www.derstandard.at/story/2000061215972/ran-an-den-schlamm-des-hallstaetter-see

Kowarik, K., Reschreiter, H. (Mai 2017), 3.500 Jahre Mensch-Umwelt-Beziehung: Neue Forschungen rund um Hallstatt. Das Projekt Facealps beschäftigt sich mit der Frage ob und wie natürliche Extremereignisse die Menschen in der Region beeinflussten. https://www.derstandard.at/story/2000057814971/3500-jahre-mensch-umweltbeziehung-neue-forschungen-rund-um-hallstatt

### *5.3.3 Video contributions*

Kowarik, K., Reschreiter, H. (2021). „Woher kommt unser Salz“. Land Schafft Leben-Plattform, https://www.youtube.com/watch?v=NQqOe9ibz7Y&t=14s

Kowarik, K. (2021). „Beziehungsgeschichten Mensch-Umwelt“. Science Talks NHM Wien, https://www.youtube.com/watch?v=qiZtpY7z6Tk&list=PLYINmExqlS5oBo5xcNsZj1MrX7IRdu1l1&index=20

### *5.3.3 Media work (selection)*

**Ö1-Dimensionen**: Forschung an Seesedimenten: Facealps research featured in science show “Dimensionen” on national radio Ö1 (Nov. 2021)

Turning Salt into Gold: Facealps project prominently featured in the prestigious US popular science magazine “**Archaeology Magazine**” (Jan/Feb 2022)

Coring lake Hallstatt – Hipercorig-Hallstatt-History: **National media coverage** of Hipercorig-Hallstatt-History, e.g.:

- Salzburger Nachrichten, https://www.sn.at/panorama/oesterreich/tiefbohrung-im-hallstaetter-see-ermoeglicht-zeitreise-103967149
- ORF Science, https://science.orf.at/stories/3206645
- TV Oberösterreich Heute, - 18.05

**Universum History Documentary**: „Hallstatt und das weiße Gold die Salz-Saga": Facealps project prominently featured in international ORF-ARTE-ZDF documentary on Hallstatt (2020)

Multibeam survey on Lake Hallstatt: Reports on national television in “**Zeit im Bild 1 (19:30)**” and **ZIB 24** (23.10.2017) and on national radio in **Ö1-Journal** (24.10.2017), https://science.orf.at/v2/stories/2873976/

Palynological analysis indicates sustained human presence in Hallstatt already in the Neolithic period: Report on national television “**Zeit im Bild 1 (19:30)**” and on national radio Ö1 “**Mittagsjournal**” and “**Wissen aktuell**” (19.05.2017), https://science.orf.at/v2/stories/2844226/

The Facealps project regularly contributed to Science Fair such as “Lange Nacht der Forschung”, “Lange Nacht der Museen”, Archäologie am Berg (annual NHMW science Fair in Hallstatt) and the Austrian UNESCO World Heritage days (2020 online event: https://www.youtube.com/watch?v=Z1-AVV6XGxE)

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