Permafrost Monitoring through Reprocessing and Repetition of Geophysical Measurements (REP-ERT)

September 01, 2019 – October 31, 2022

Final Report

Prof. Christian Hauck | Department of Geosciences, University of Fribourg, Switzerland

Dr. Coline Mollaret| Department of Geosciences, University of Fribourg, Switzerland

Dr. Christin Hilbich| Department of Geosciences, University of Fribourg, Switzerland

with the support of the Federal Office of Meteorology and Climatology MeteoSwiss, in the framework of GCOS Switzerland

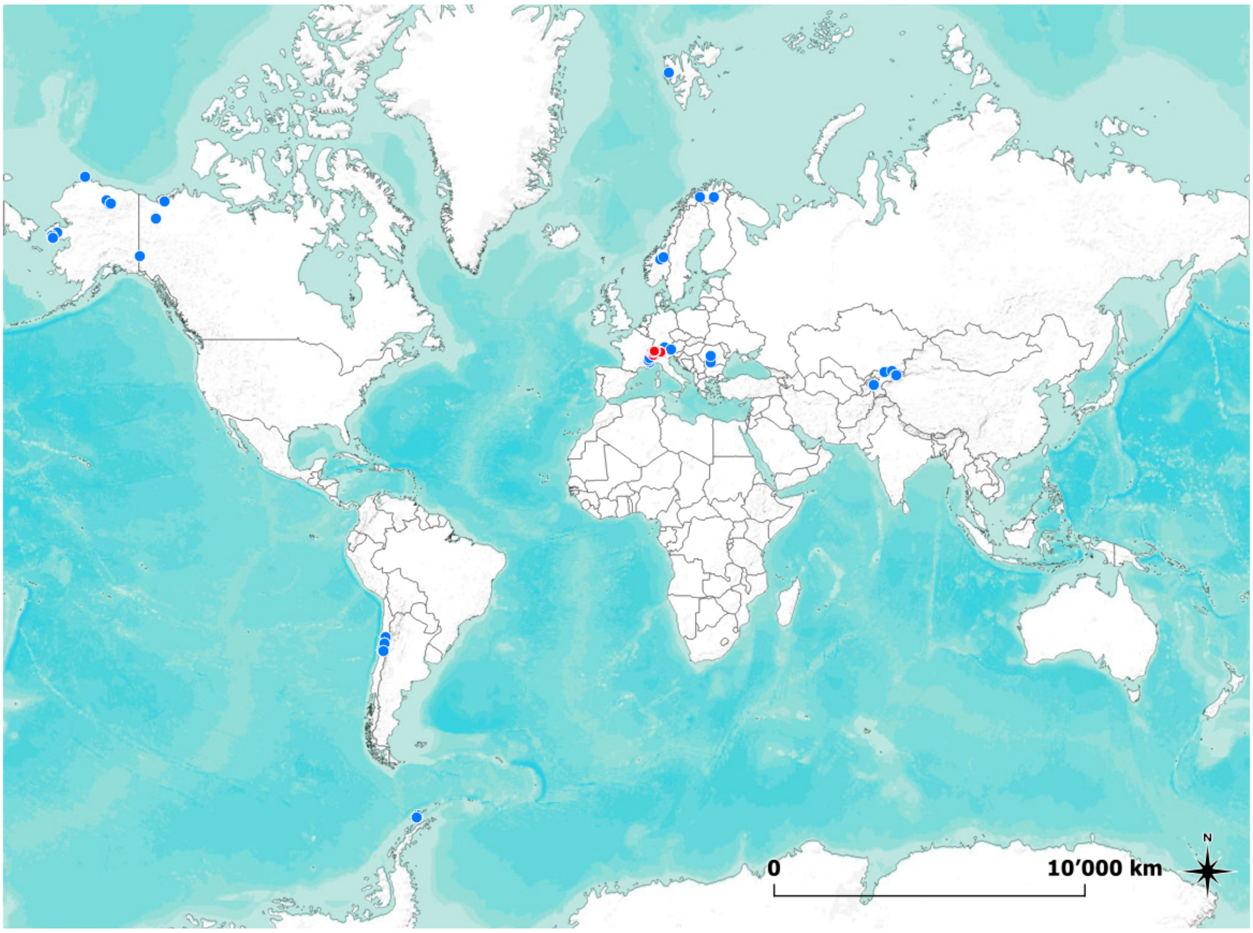


Figure 1: Current extension of the database to the global scale. The map shows only locations of ERT surveys on permafrost (Red: Swiss sites, Blue: international sites), which are currently contained in the IDGSP data base.

1 Summary

Permafrost is currently warming on a global scale including not only polar but also mountain permafrost occurrences; many of these changes are operationally documented in national permafrost networks such as the Swiss permafrost monitoring network PERMOS. However, the warming trend is not uniformly distributed, as permafrost occurs in a large variety of complex landforms with different ground ice contents, surface material and therefore different thermal regimes (e.g. Etzelmüller et al. 2020).

Geophysical techniques are used since a long time to spatially extend singular borehole data and add quantitative information about important permafrost properties other than temperature, such as ground ice content. From the large variety of geophysical properties, especially electrical resistivity has been proven capable of accurately distinguishing between frozen and unfrozen soil due to its particular sensitivity to the presence of liquid water content. The so-called Electrical Resistivity Tomography (ERT) method has therefore become a standard technique to spatially characterise and visualise permafrost occurrences over profiles of typically a few 100m length and 20-50m depth. In a monitoring setup, repeated ERT measurements allow detecting and quantifying freeze and thaw processes over seasonal and interannual time-scales (Hauck 2002, Hilbich et al. 2011, Mollaret et al. 2019).

Currently, only very few permafrost sites worldwide are continuously monitored with ERT as part of national monitoring programmes (~10). A much larger number of individual ERT surveys from the past exist (estimated to be > 200 alone in the Swiss Alps), which have not yet been part of national or international databases. Within the MeteoSwiss funded project "Permafrost monitoring through reprocessing and repetition of geophysical measurements (REP-ERT)", a focus is laid on the systematic archiving and reprocessing of historical geoelectrical measurements in permafrost regions and develop guidelines for measurement repetitions after long time periods. The project had the overall objective to highlight the potential of repeating these historical ERT measurements for permafrost monitoring in the context of climate change at low costs. Hereby, permafrost occurrences do not have to be monitored continuously, because the non-invasive ERT measurements can be repeated after long time spans (e.g. 5 or 10 years) if profile coordinates are known, and resulting differences between historical and repeated electrical resistivities can be attributed to changes in ice content. To be able to do so, the historical ERT surveys and their metadata have to be preserved in an open-access data base, the data sets have to be re-processed and measurement and processing protocols had to be jointly developed within the permafrost and geophysical scientific communities.

Within the REP-ERT project we were able to (a) compile and initiate an international database for historical ERT data on permafrost, (b) develop and apply suitable QA/QC criteria for data filtering and inversion, (c) develop a protocol for regular ERT repetitions on time scales of ~10 years and (d) conducted a first analysis of ~300 data sets, which are already included in the new data base, with ~50 repetition data sets. First results indicate a strong decreasing trend of electrical resistivities (and therefore ice content) in Europe with only very few exceptions.

The project addresses the following elements of the GCOS implementation plan 2016, i.e. improved data management, stewardship and access (part II, chapter 2.3: Data access, Metadata, Quality control, Preservation, Discoverability) as well as the focus "Recovery of instrumental in-situ data" for the ECV Permafrost ((part II, chapter 2.4.2 and chapter 5.4).

2 Scientific report

2.1 Introduction

BACKGROUND

Permafrost, defined as lithospheric material with temperatures below 0 °C for at least 2 years, exhibits currently significant thawing on a global scale (Gudmundsson et al. 2022, Smith et al. 2022). Permafrost degradation can lead to potentially severe impacts such as CO_2 and CH_4 release from formerly frozen arctic soils to atmosphere, by this increasing greenhouse gas concentrations (Schuur et al. 2015), but also soil destabilization upon thawing. Slope instability is especially dangerous in mountainous regions in the form of rock falls and debris flows, and poses an increased risk to infrastructures and villages, especially in densely populated regions such as the European Alps (e.g. Ravanel et al. 2017, Haeberli et al. 2017, Chiarle et al. 2021).

Changes in permafrost conditions are usually detected and monitored through continuous temperature measurements in boreholes (e.g. Biskaborn et al. 2019, Noetzli et al. 2022). However, due to logistic and financial constraints, boreholes are scarce and furthermore provide only point information without possibility to assess the spatial representativity of the obtained data. Many operational permafrost networks therefore combine borehole temperature data with spatially distributed ground surface temperature data and/or geophysical surveying (e.g. PERMOS 2022, Isaksen et al. 2022, Etzelmüller et al. 2020). Geophysical surveys can furthermore be used to determine various physical properties of the permafrost occurrences and their changes with time. Among those, especially subsurface ice and liquid water contents are calculated from geophysical surveys (e.g. Hauck et al. 2011, Mollaret et al. 2020, Halla et al. 2021), ice content being one of the most important parameters in permafrost-related climate, hydrological and geotechnical modelling studies.

Among the geophysical surveying techniques, Electrical Resistivity Tomography (ERT) is used most frequently, and for the largest variety of applications, including continuous monitoring (Hilbich et al. 2011, Farzamian et al. 2020), landform characterization (Kneisel and Schwindt 2008), subsea permafrost (Arboleda-Zapata et al. 2022), influence of vegetation on permafrost (Uhlemann et al. 2021), rock glaciers (Emmert and Kneisel 2017), large-scale ecosystem analysis (Dafflon et al. 2017), hydrological significance (Langston et al. 2011), frozen rock faces (Magnin et al. 2017, Krautblatter et al. 2010), geothermal impacts on permafrost (Goyanes et al. 2014) and many more. ERT determines the electrical resistivity of the subsurface, which is extremely high for ground ice occurrences (ice being considered an electrical insulator) and very low for liquid water. ERT therefore allows the mapping of permafrost extent (horizontally and vertically) where no borehole information is available, as well as to monitor changes in ice-water ratio accompanying temporal variations (e.g., Hauck 2002; Scandroglio et al. 2021; Supper et al. 2014). However, due to financial and logistic reasons only very few continuous ERT monitoring installations on permafrost exist worldwide (Hilbich et al. 2011, Farzamian et al. 2020). An alternative to such automated systems are manually, but regularly (e.g. yearly) repeated ERT surveys such as the six permafrost sites in the Swiss Alps that have been constantly monitored with ERT in the context of the Swiss Permafrost Monitoring Network (PERMOS) since 2005 (Mollaret et al. 2019) and similar setups in Norway (Etzelmüller et al. 2020) and Canada (Lewkowicz et al. 2011). ERT surveys can also be singularly repeated over a long time period and interpreted in the context of climate change by relating them to air or ground temperature data from nearby monitoring stations (Etzelmüller et al. 2020). However, although hundreds to thousands of ERT surveys on permafrost must exist, almost none of them have been systematically archived or are accessible to the scientific community or the general public.

OBJECTIVES AND GOALS

The project "Permafrost monitoring through reprocessing and repetition of geophysical measurements (REP-ERT)" had the overall objective to highlight the potential of repeated ERT measurements for permafrost monitoring in the context of climate change at low costs. Hereby, permafrost occurrences do not have to be monitored continuously, because the non-invasive ERT measurements can be repeated after long time spans (e.g. 5 or 10 years) and differences in the resulting electrical resistivities can be attributed to changes in ice content. To be able to do so, historical ERT surveys and their metadata have to be archived in an open-access data base, the data sets have to be re-processed systematically and measurement and processing protocols have to be jointly developed within the permafrost and geophysical scientific communities.

The goals of the REP-ERT project were therefore to (a) compile a database for historical ERT data on permafrost, (b) to develop and apply suitable QA/QC criteria for data filtering and inversion, (c) develop a protocol for the regular ERT repetitions on time scales of ~10 years and (d) initiate first steps to include electrical resistivities as ice content proxies and permafrost ECV's on an international level.

The project addressed the following elements of the GCOS implementation plan 2016, i.e. improved data management, stewardship and access (part II, chapter 2.3: Data access, Metadata, Quality control, Preservation, Discoverability) as well as the focus "Recovery of instrumental in-situ data" (part II, chapter 2.4.2) for the ECV Permafrost (part II, chapter 5.4). The first stage of the project focused on ERT surveys and permafrost occurrences in the (Swiss) Alps; in the second year we were able to extend the initiative to a worldwide database (the International Database of Geoelectrical Surveys on Permafrost, IDGSP) by initiating a new Action Group within the International Permafrost Association (IPA).

2.2 Methods and activities

2.2.1 Collecting and archiving historical ERT data on permafrost terrain

COLLECTION OF METADATA

In a first step, resistivity metadata of permafrost surveys were collected within our and other Swiss research groups working on permafrost terrain, resulting in ~200 individual metadata sets from various field sites within Switzerland (Fig. 2). In a second step, this "call-for-metadata" has been extended to anyone interested to contribute to the database (through the IPA Action Group IDGSP, see below). The call is still open and advertised at national and international conferences (such as the Swiss Geoscience Meeting, the EGU General Assembly, the EUCOP/ICOP conferences of the IPA, and the GELMON workshop) and aims at continuously collecting and archiving ERT data on permafrost.

As a prerequisite for the homogenization of the historical data from a large variety of sources, joint naming conventions had to be developed and the precision of the metadata (e.g. regarding the approximate location of the measurement, especially for old measurement when GNSS was not standardly used) had to be improved in many cases. Subsequently, a standardized metadata form was developed and published on the project website, which needs to be filled by data contributors. We choose to create this metadata form as an Excel file to be user-friendly enough to attract as many contributors as possible. The metadata form contains six small sections with ~50 fields (half of them obligatory, and the other half optional), including details on e.g. survey date, geometry, coordinates, landform, substrate and data source.

The details of the metadata form and homogenization procedures were discussed and jointly decided within several workshops of international colleagues working on geoelectrical surveying on permafrost. Due to the Corona crisis, these meetings had to be held in virtual mode. A major outcome was the extension of the project to a fully international initiative and database (see Fig. 1) with an explicit connection to the International Permafrost Association (IPA) (task T10 of the original proposal). Based on the positive feedback of the community, we decided to apply for a so-called IPA Action Group (2021-23) with the name "Towards an International Database of Geoelectrical Surveys on Permafrost (IDGSP)" (IDGSP). This Action Group was officially accepted by the IPA in January 2021 and is led by the Cryosphere and Geophysics Research Group, University of Fribourg (https://www.unifr.ch/geo/cryosphere/en/projects/permafrost-monitoring-and-dynamics/idgsp.html). Actions Groups are international networks to foster scientific discussions with a specific aim and outcome, but without explicit funding.

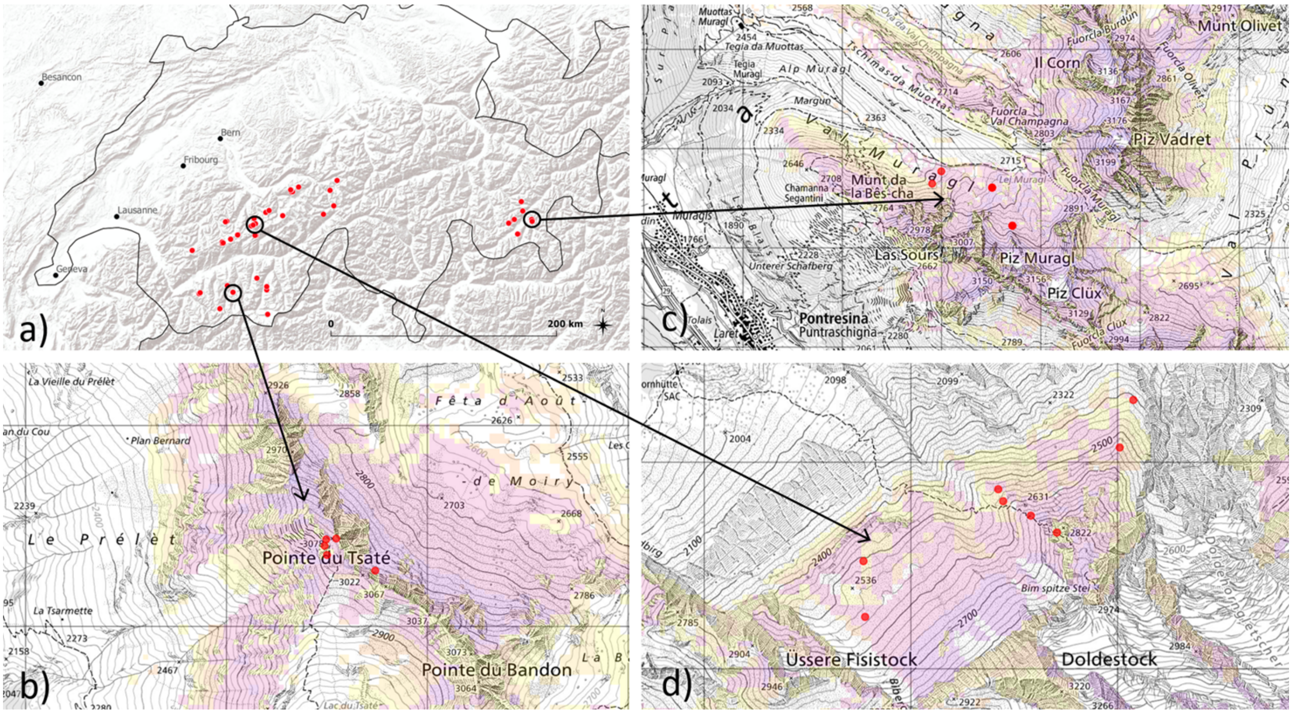


Figure 2: (a) Map with location of 200 single ERT surveys on permafrost in Switzerland, which have been compiled in the REP-ERT project and which are already contained in the IDGSP data base. (b)-(d): close-ups of specific regions in the Valais Alps, Engadine and Bernese Alps for illustration. The maps are underlain with the colour-coded modelled permafrost distribution currently available under map.geo.admin.ch. The database is constantly updated by adding further survey locations and their metadata.

DATABASE DEVELOPMENT

We distinguish between the metadata base described above and the full database, the latter containing also the actual resistivity data. A server hosted at the University of Fribourg has been dedicated to the database (called "Resibase", maintained by the IT service of the University allowing for a long-term archive). We used the open-source relational database management system PostgreSQL (together with Psycopg2 - a PostgreSQL database adapter for Python). To develop the structure of the database we compiled a list of all necessary and optional content, which was subsequently translated into the different tables for data and metadata. Finally, the relations between the tables were defined. The database is constructed in an adaptive way, so that new tables (or new fields in existing tables) can be added in future if needed. Figure 3 shows the resulting structure of the database and how the 17 main tables are related to each other. 11 secondary tables are not represented in Figure 3 for better readability. The secondary tables are used to reduce the storage needs on the server, by linking certain type of fields to a unique numeric id. In Fig. 3, the metadata tables are shown in blue, while the data themselves (raw and inverted) are shown in green. Filtering parameters are shown in yellow, inversion parameters such as the mesh are shown in orange, and data quality information is shown in red.

Note, that the "borehole" table including the GTNP-code (Global Terrestrial Network of Permafrost, IPA) allows a future direct connection with the GTN-P database (tasks T10/T11 of the project proposal).

COLLECTION OF RESISTIVITY DATA

Collecting the actual resistivity data has been initiated through a separate call for data in 2022. Before doing so, a community discussion was started in 2021 (via several online meetings) to harmonize and standardize the raw data format as well as find suitable guidelines for data inversion. For all datasets, the so-called *unified data format* (http://resistivity.net/bert/data_format.html) was finally chosen, which is a transparent and transportable data format used in many geophysical inversion algorithms. As most historical ERT datasets (the earliest stem from the late 1990's) have been archived individually and with specific data formats linked to either the acquisition device (raw data) or the inversion software (inverted data), ERT data collection into the database is a cumbersome task, as it involves (i) contacting the original PI, (ii) verifying and complementing missing metadata (e.g. coordinates, topography) and (iii) converting all data to the unified data format. Data are now being continuously added by scientists of the Cryosphere and Geophysics Research Group, University of Fribourg.

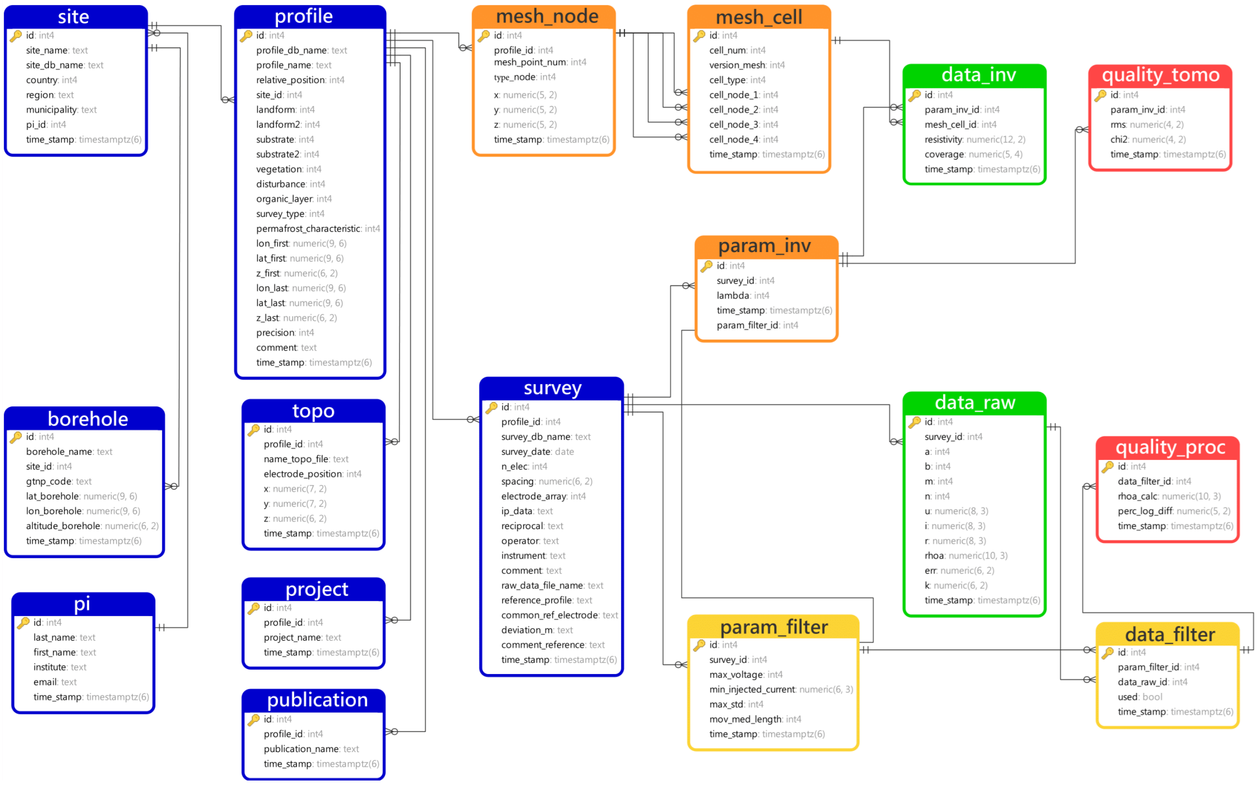


Figure 3: Structure of the database Resibase including 17 related main tables categorized in 5 groups: metadata (blue), raw and inverted resistivity data (green), filtering parameter (yellow), inversion parameter (orange) and data quality (red) (taken from Mollaret et al., in preparation).

Table 1 presents the current number of data and metadata, which are fully integrated in the database. As becomes obvious from Table 1, there is currently a much higher number of metadata than full resistivity data sets in the database, which is due to the much earlier call-for-metadata (in 2021) compared to the call-for-data (in 2022). This discrepancy will automatically balance in the coming year.

Table 1: Comparison of data base entries on national (Swiss) and international level

	Switzerland	European Alps	International Database
Principal Investigators	6	12	21
Countries	1	5	14
Sites	38	47	75
Profiles (metadata)	117	136	294
Surveys (metadata)	200	244	405
Projects	10	22	35
Linked Publications	15	33	43
Data sets & topo	30	31	36
Topography points	1620	1668	2 029
Apparent resistivity values (quadrupoles)	20513	21042	23 310

VISUALISATION

For database robustness and security reasons, the database itself cannot be directly accessed by anyone outside the University of Fribourg. However, our goal is to provide a user-friendly public web interface to visualize the content of the database (including metadata and data) and eventually allowing data download (as for the PERMOS data browser).

A first attempt of data visualization was done through QGIS-Cloud, but after initial tests, we realized that the existing functions of QGIS-Cloud were too limited and would not satisfy our wishes of data visualization in a long-term perspective. In collaboration with Dr. Teddi Herring (Ottawa University, Canada, member of the steering committee of the IPA Action Group), we changed the visualization tool to a dash app, dash being an open-source framework for building data apps. Heroku cloud application platform will then be used to deploy the data app. This visualization framework is still under development and is foreseen to be operational in 2023 (an example is shown in Fig. 4).

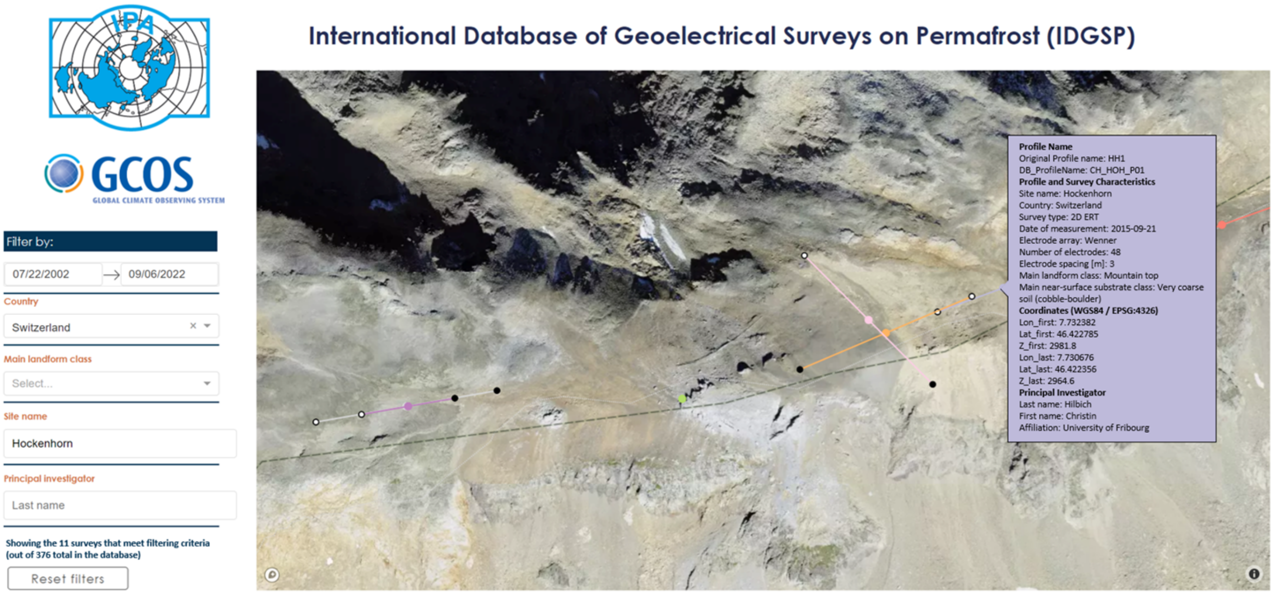


Figure 4: Example of the dash app under development showing the visualization of ERT surveys with their selected associated metadata on a map. The example shows various ERT profiles at the Hockenhorn site in the Bernese Alps.

2.2.2 Quality control

FILTERING AND PROCESSING WORKFLOW

During the virtual project workshops with the geophysical and permafrost community it was decided to use a continuous online discussion via slack channel and the community developer platform Github to develop joint QA/QC criteria for processing and repeating of ERT data on permafrost. To cover a broad range of permafrost occurrences, data sets from several research groups were uploaded covering the European Alps, Alaska and Antarctica to test the various existing strategies. Main challenges for unified guidelines and recommendations were defined as follows: (i) the large variety of permafrost occurrences with many different individual obstacles for high quality ERT data, (ii) the availability of various data inversion schemes with different quality control procedures within the geophysical community. Recommendations include therefore data filtering schemes that take into account the different data quality for repeated surveys over a long time period as well as the use of common inversion schemes that are freely available. An analysis of the challenges for unified QC criteria were presented at several conferences (Herring et al. 2021, Mollaret et al. 2022). A joint paper with recommendations for the permafrost community is currently in preparation (Herring et al., in preparation).

Quality control is strictly speaking needed for the whole measurement and processing chain of ERT data including (a) the measurements, (b) data filtering, (c) data inversion and (d) data interpretation. The recommendations will address all four steps, whereas the joint processing guidelines focus on steps (b) and (c) (Figure 5) - especially as measurement quality of historical data cannot be changed retrospectively.

A specific characteristic of permafrost is its extremely large variability – compared to e.g. glaciers or snow. Permafrost substrates can vary from frozen sands, silts or clays, with sometimes significant salinity due to proximity to the sea, to vegetated substrates with high organic content, coarse-grained frozen debris and low-porosity bedrock in mountainous regions. They can be completely saturated or extremely dry and ice contents can vary between 0-100 %. Consequently, resistivity values of permafrost occurrences can show a huge range between several 10s of Ohm.m and several MOhm.m. Filtering and inversion procedures (Fig. 5) must be able to address these large differences in absolute values and contrasts between frozen and unfrozen parts of a profile. Similarly, repeated data sets over long periods must be filtered and inverted consistently to avoid misinterpreting changes in data quality, filtering characteristics or inversion artefacts as climate related resistivity changes.

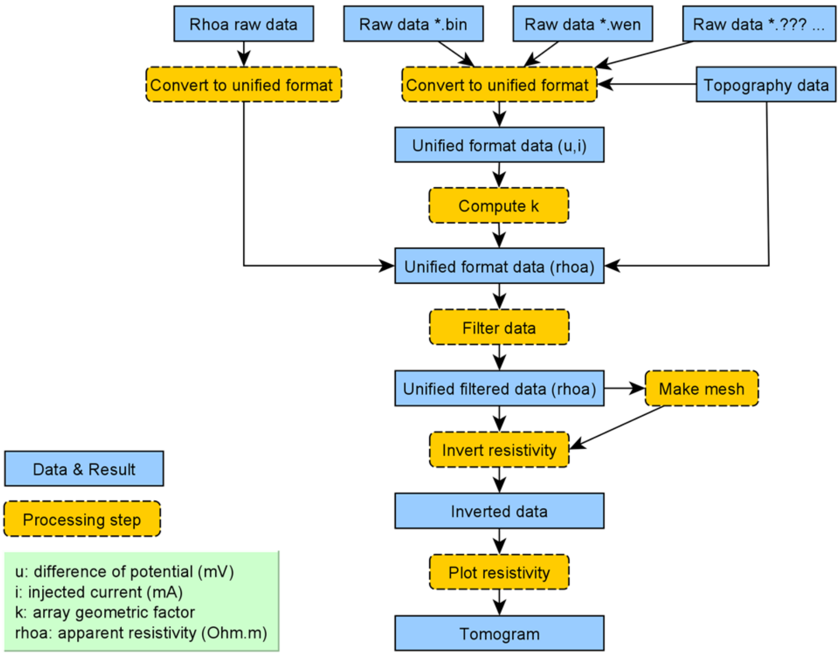


Figure 5: Workflow of the processing steps for resistivity data in the IDGSP database.

2.2.3 Repetition of ERT measurements

REPETITION PROTOCOL

The oldest ERT surveys on permafrost stem from the late 1990's, when the ERT technique became feasible due to multi-electrode instruments and suitable inversion software. Before that time, Vertical Electrical Soundings (VES) have been conducted, which can also be repeated (e.g. Wee and Delaloye 2022), but lack the spatial resolution and data density of ERT surveys, the latter having typically ~20 to 50 times the amount of data. We propose to repeat these old surveys as quickly as possible, and focus for the less recent ones on repetitions every 10 years. If accessibility and logistics are favorable also repetitions every 5 years are recommended.

Care has to be taken regarding the recovering of the coordinates and configurations of the historical profiles – experience within the project has shown that these are often less well documented (and accurate!) than expected. A specific case is moving permafrost bodies such as rock glaciers. Here, remeasuring at the historical coordinates will lead to errors, as the substrate will have moved according to the flow velocity of the landform. An additional challenge is the question whether the whole landform has moved or whether the movement is restricted to a surficial layer, as for example the material above a shear horizon of a rock glacier. We propose to repeat ERT surveys on rock glaciers according to the moving coordinates of the surface, but assessing these uncertainties upon processing and interpretation. An example is given in Buckel et al. (submitted), who used historical orthophotos to locate the start and end points of the historical ERT profiles based on visual markers such as large boulders, which helped to define the (shifted) location of the profile in the field.

RE-MEASUREMENT OF HISTORICAL ERT PROFILES

Within the project we focused on two aspects: (i) collecting existing repetitions of historical ERT profiles and interpreting them jointly in the context of climate change and (ii) repeating additionally historical ERT profiles over different substrates to identify challenges for the repetition protocol.

2.3 Results

The new database allows a multitude of analyses, both, regarding the electrical properties of permafrost in general and their temporal changes in the context of climate change. Figure 6 shows an example of an analysis of typical resistivity values in unfrozen (active layer) and frozen (permafrost) state. As expected, resistivity strongly increases upon freezing, it is nevertheless intriguing that most data lie on a straight line on a log-log scale suggesting that the data adhere to a common power law, independent of their very different landforms, substrates and therefore absolute resistivity values. The observed ratio between active layer and permafrost resistivity can hereby be similarly well explained by three different petrophysical models (Fig. 6a-c), confirming that inter-site comparisons can be made even if different conduction mechanisms take place. Fig. 6d shows in addition that for a specific region, resistivity values differ significantly between different landforms.

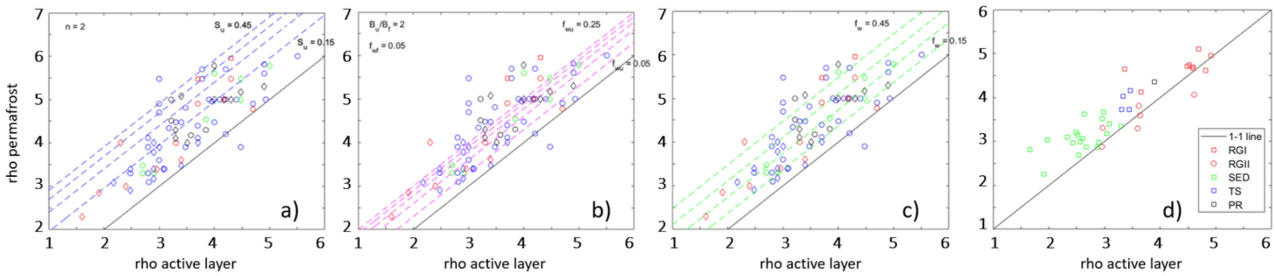
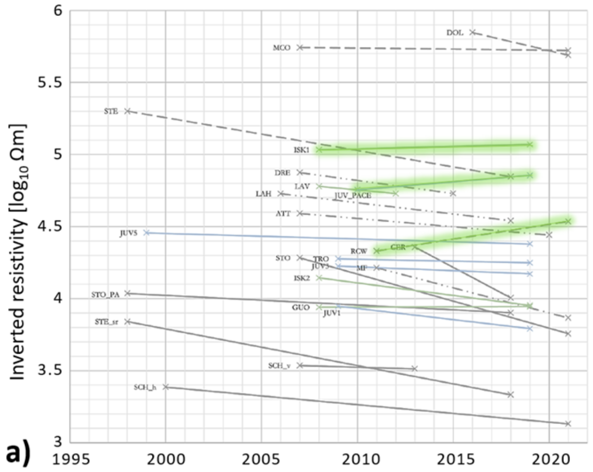


Figure 6: Relationship between the resistivity [$\log_{10}$ Ωm] of the active layer and permafrost for 94 profiles from the new database. The black line marks the 1-1 relationship. Permafrost resistivity (y axis) is 10 to 100 times larger than active layer resistivity (x axis), independent of absolute value and electrical conduction mechanism. Different petrophysical models were tested: (a) blue dashed lines are derived from Archie's Law (electrolytic conduction, Archie 1942), (b) pink dashed lines mark a surface conduction model (Duvillard et al. 2021) and (c) green dashed lines are derived from the geometric mean model (Mollaret et al. 2020). All models are shown for different unfrozen water contents. (d) Subset of the full Central Andean dataset, classified according to landforms (Hilbich et al. 2022). RGI: intact rock glaciers, RGII: degrading rock glaciers, SED: sediment slopes, TS: talus slopes, PR: protalus ramparts.

REPETITION OF ERT SURVEYS

The main objective of the project was addressed by (i) analysing the existing ERT survey repetitions and (ii) initiating large-spread ERT repetition campaigns to determine the climate-induced resistivity change in permafrost regions and address the question of possible permafrost degradation. Figure 7 shows a first analysis of existing ERT repetitions at 22 permafrost sites in the European Alps and Norway (Stalder 2022). Within the last two decades 19 out of 22 sites show a resistivity decrease in the permafrost layer corresponding to ground ice loss. This analysis is independent of the deepening of the active layer by defining a so-called zone-of-interest (ZOI, the part of the tomogram which is averaged for the analysis) limited to the permafrost layer (Etzelmüller et al. 2020).



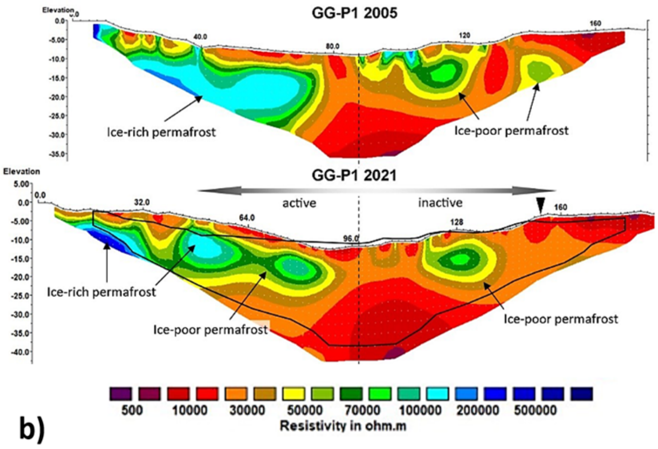


Figure 8: The evolution of mean inverted resistivities within the permafrost (so called Zone of Interest, ZOI) at 22 profiles (from A. Stalder, BSC thesis University of Fribourg, 2022). Out of these, all but three sites (highlighted in green) show a decrease in resistivity corresponding to a reduction in ground ice content.

Figure 9: Tomograms of the historical (2005) and the repeated (2021) profile GG-P1 on an active (left) and inactive (right) part of the Gianda Grischa rock glacier. The dashed line indicates the common centre point. The black line indicates the outline of the historical tomogram. (taken from Buckel et al. submitted).

Dedicated field campaigns were organized to repeat old profiles during the 3 field summers of the project, according to the repetition strategy developed within the project. In total, around 35 surveys were repeated, almost half of them in Switzerland. Figure 8 shows an example from the Gianda Grischa rock glacier complex (Buckel et al., submitted). The study on the one side confirmed the decreasing resistivity trend (corresponding to a decrease of the ice-rich part in the active part of the rock glacier) seen also in most datasets in the database so far, but provided also additional information and sensitivity analyses about potential challenges when comparing ERT results over long time spans. For example, strategies for repetitions on moving permafrost bodies were tested and analyzed in detail (Buckel et al. submitted).

Further analyses were conducted in the framework of the European PACE transect including the Swiss PERMOS sites (Etzelmüller et al. 2020, PERMOS 2022), regional studies in the Upper Engadine region (Berchtold 2021) and the Berner Oberland (Gardeweg, in prep.) as well as a first assessment of global changes (Hauck et al. 2021).

2.4 Conclusions and limitations

To conclude, we are very satisfied that we were able to set up the new database of ERT surveys on permafrost in a safe manner to achieve the main objective of the project, the generation of a sustained long-term archive. Currently, the database is still mainly filled with metadata, and fewer complete resistivity data sets, as the call for resistivity data was launched more recently (a year later than the call for metadata). Also, the database is not yet freely accessible on the web, but data can be obtained by email by making contact via the project website.

The number of datasets in the database is limited by the willingness of principal investigators to provide their data to the database. Sorting out old data may be very time consuming and may postpone or prevent PI's to send their data to the database. However, as soon as the user-friendly access to the content of the database is operational it will most probably lead to new persons contributing to the database.

The large amount of metadata and data available already allowed numerous regional and methodological studies, including, but not restricted to, the detection and analysis of climate change induced permafrost degradation with a focus on ice content changes.

The envisaged international collaboration was highly successful with the extension of the project to a fully international database with a direct connection to the International Permafrost Association (IPA). On the other hand, this extension also slowed down the project in the short-term (as decisions had to be taken with more people), but it strongly increased the value of the project in the long-term by the many inputs from the international geophysical and permafrost community, but also by the global scope of this unique geophysical database of ERT surveys on permafrost.

2.5 Outreach work, publication of data and results

The REP-ERT project as well as the associated IDGSP initiative are presented on webpages hosted by the Department of Geosciences, University of Fribourg:

https://www.unifr.ch/geo/cryosphere/en/projects/permafrost-monitoring-and-dynamics/rep-ert.html

https://www.unifr.ch/geo/cryosphere/en/projects/permafrost-monitoring-and-dynamics/idgsp.html

Together with the core members of the IDGSP initiative, processing algorithms have been set up to promote transparency and reproducibility. They are freely accessible on the github platform.

https://github.com/teddiherring/permafrost-data-processing.

Papers:

Etzelmüller, B., Guglielmin, M., Hauck, C., Hilbich, C., Hölzle, M., Isaksen, K., Noetzli, J., Oliva, M., Ramos, M. (2020). Twenty years of European Mountain Permafrost dynamics – the PACE Legacy. Environmental Research Letters, 15(10), 104070, https://doi.org/10.1088/1748-9326/abae9d

Buckel J., Mudler J., Gardeweg R., Hauck C., Hilbich C., Frauenfelder R., Kneisel C., Buchelt S., Blöthe J.-H., Hördt A., Bücker, M. (***submitted***). Identifying mountain permafrost degradation by repeating historical ERT-measurements. Submitted to The Cryosphere, 20 Oct 2022.

Herring T., Lewkowicz A., Oldenborger G., Calmels F., Mollaret C., Uhlemann S., Hilbich C., Hauck C., Farzamian M. (***in preparation***). Best practices for electrical resistivity tomography data acquisition and processing for permafrost studies. To be submitted to Permafrost and Periglacial Processes.

Mollaret, Hilbich C., Herring, T., Hauck C., Farzamian M. Uhlemann S., Pellet C, Hördt A., Dafflon B. Lewkowicz., Scandroglio R., Buckel J., Kneisel C. (***in preparation***). Initiating an international database for electrical resistivity data on permafrost. To be submitted to Earth System Science Data.

Hauck C. & the IDGSP author team (***in preparation***). Repeated electrical resistivity tomography surveys confirm ground ice loss from permafrost areas on a global scale. To be submitted to The Cryosphere

Conference Presentations:

Buckel J., Gardeweg R., Mudler J., Hauck C., Hilbich C. (2022). Repeating historical ERT campaigns highlights alpine permafrost degradation. Mid-European Geomorphology Meeting and Arbeitskreis Permafrost 2022, Kaprun, Austria, 24-27 Nov. 2022.

Mollaret, C., Hilbich, C. Pellet, Hauck, C. (2022). Permafrost monitoring through reprocessing and repetition of geophysical measurements: a GCOS-Switzerland project. The Cryosphere in a changing climate - A scientific symposium in memory of Koni Steffen, 23-24 June 2022, Davos, Switzerland.

Mollaret C., Hilbich C., Herring T., Farzamian M., Buckel J., Dafflon B., Draebing D., Fossaert H., Gugerli R., Hauck C., Kunz J., Lewkowicz A., Limbrock J.K., Maierhofer T., Magnin F., Pellet C., Pfaehler S., Scandroglio R., Uhlemann S. and the IDGSP IPA Action Group (2022). Initiation of an international database of geoelectrical surveys on permafrost to promote data sharing, survey repetition and standardized data reprocessing, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-10565, https://doi.org/10.5194/egusphere-egu22-10565.

Morard, S., Hilbich, C., Mollaret, C., Pellet, C., Wagner, F., Westermann, S., and Hauck, C. (2022). Analysis of the 20-year long permafrost evolution at the long-term monitoring site Stockhorn, Swiss Alps, by applying a petrophysical joint inversion and a thermal model (Cryogrid3). EGU General Assembly 23–27 May 2022, Vienna, Austria.

Mollaret C., Farzamian M., Gugerli R., Hauck C., Herring T., Hilbich C., Hördt A., Kneisel C., Pellet C., Scandroglio R., Uhlemann S., & Draebing D. (2021). International database of geoelectrical surveys on permafrost: a new IPA Action group. Online, October 24-29, 2021. Regional Conference on Permafrost (RCOP), Boulder, USA.

Hauck C., Mollaret C., Morard S., Hilbich C. (2021). Ground ice content loss in different mountain permafrost environments inferred from repeated and re-processed geophysical measurements data. Online, October 24-29, 2021. Regional Conference on Permafrost (RCOP), Boulder, USA.24-29, 2021. Regional Conference on Permafrost (RCOP).

Herring, T. Farzamian, M., Gugerli, R., Hauck, C., Hilbich, C., Hördt, A., Kemna, A., Kneisel, C., Lewkowicz, A., Limbrock, J., Mollaret, C., Pellet, C., Scandroglio, R., Uhlemann, S. (2021). Standardized processing of geoelectrical data for permafrost applications: Initial findings from a new IPA action group. Online, October 24-29, 2021. Regional Conference on Permafrost (RCOP), Boulder, USA.

Morard, S., Hilbich, C., Mollaret, C., Pellet, C., and Hauck, C. (2021). 20-year long permafrost evolution at the long-term monitoring site Stockhorn, Swiss Alps by combining borehole temperature, electrical and seismic monitoring data. Online, October 24-29, 2021. Regional Conference on Permafrost (RCOP), Boulder, USA.

Hauck, C. (2021). Electrical resistivity contrast between active layer and frozen ground: why is it similar for different sites over many order of magnitudes? EGU General Assembly 2021, online, 19–30 April 2021, EGU21-15414, https://doi.org/10.5194/egusphere-egu21-15414.

Hilbich, C., Mathys, T., Hauck, C., and Arenson, L. (2021). Towards accurate quantification of ground ice content in permafrost of the Central Andes: geophysics-based estimates from three different regions, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-12553, https://doi.org/10.5194/egusphere-egu21-12553, 2021.

Hilbich, C., Pellet, C., Mollaret, C., Staub, B., Noetzli, J., Hauck, C. (2020). Permafrost monitoring through resistivity time-series analysis: the PERMOS ERT Database. Berichte Geol. B.-A., 139. 5th Internat. Workshop on Geoelectric Monitoring GELMON 2020, 18.–19.11.2020, Vienna, Austria.

Hilbich, C., Pellet, C., Mollaret, C., Staub, B., Noetzli, J., Hauck, C. (2020). Permafrost monitoring through resistivity time-series analysis: the PERMOS ERT Database. Jahrestreffen Arbeitskreis Permafrost, online, 11. 12. 2020.

Mollaret, C., Hilbich, C., Pellet, C., Hauck, C. (2020). Towards a geoelectrical database for permafrost monitoring to enable the processing and repetition of historical measurements. Berichte Geol. B.-A., 139. 5th International Workshop on Geoelectric Monitoring GELMON 2020, 18–19 November 2020, Vienna, Austria.

Hauck, C., Hilbich, C. Mollaret, C., Pellet, C. (2020). Permafrost monitoring by reprocessing and repeating historical geoelectrical measurements. EGU General Assembly, online, 4-8 May 2020, EGU20-14047, https://doi.org/10.5194/egusphere-egu2020-14047.

Hauck C., Hilbich C., Mollaret C., Pellet C. (2019). Permafrost monitoring by reprocessing and repeating historical geophysical measurements. Fribourg, Switzerland, Swiss Geoscience Meeting, Nov. 22-23 2019.

BSc theses within the project:

Berchtold, E. 2021. Change of the ice content in Alpine permafrost areas: repeated geoelectrical measurements in the Murtèl-Corvatsch area. Bachelor thesis, Department of Geosciences, University of Fribourg.

Boschung, M. 2022. Analyse des internen Aufbaus von Blockhalden mittels geoelektrischer Auswertungen von Widerstandstomogrammen. Bachelorarbeit, Department of Geosciences, University of Fribourg.

Stalder, A. 2022. Auswertung von Wiederholungsmessungen als Indikator für Permafrostveränderungen. Bachelorarbeit, Department of Geosciences, University of Fribourg.

2.6 Outlook

The project continues in the form of the international IPA Action Group IDGSP (formed until end of 2023). The IDGSP group will have an official meeting at the 6th European Conference on Permafrost (Puigcerdà, Spain, June 2023), where we co-organized two sessions that explicitly include the database developed within this project. Future organizational steps regarding long-term operational management of the database will be discussed at this conference. As permafrost is an ECV, a future involvement of GCOS would be highly appreciated. Until then, the database will continue to be hosted at the University of Fribourg within the Cryosphere and Geophysics Research Group.

A future objective of enlarging the database would be the integration of other types of geophysical data (such as seismic, GPR or IP/SIP data), which are co-located with resistivity data (similar to borehole information which is already included in the database). The structure of the database is set up to allow an easy add-on of related tables.

2.7 Acknowledgements

We would like to thank MeteoSwiss in the framework of GCOS Switzerland for providing the funding for this project. The support was first of all used to collect the historical ERT data on permafrost, construct and launch the database and develop the processing workflows continue to fill the database in the future. Many individuals contributed with their data, their advice and their help during field work of the repetition measurements and the subsequent data analysis. Without these data and help, all our efforts would have been useless. Special thanks to Dr. Cécile Pellet (PERMOS office) who supported the project with her experience with the PERMOS database. We would like to thank all IPA Action group members for all the online meetings and discussions concerning the database development, especially Dr. Teddi Herring (University of Ottawa, Canada) for the discussion and collaboration on the processing and on the dash app development.

2.8 References

Arboleda-Zapata, M., Angelopoulos, M., Overduin, P. P., Grosse, G., Jones, B. M., and Tronicke, J.: Exploring the capabilities of electrical resistivity tomography to study subsea permafrost, The Cryosphere, 16, 4423–4445, https://doi.org/10.5194/tc-16-4423-2022, 2022.

Archie, G.E. (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions of the AIME, 146(01), pp.54-62.

Biskaborn, B.K., Smith, S.L., Noetzli, J. et al. (2019). Permafrost is warming at a global scale. Nat Commun **10**, 264. https://doi.org/10.1038/s41467-018-08240-4

Chiarle, M., Geertsema, M., Mortara, G. and Clague, J. J. (2021). Relations between climate change and mass movement: Perspectives from the Canadian Cordillera and the European Alps, Glob. Planet. Change, 202, 103499, doi:https://doi.org/10.1016/j.gloplacha.2021.103499.

Dafflon, B., Oktem, R., Peterson, J., Ulrich, C., Tran, A.P., Romanovsky, V. and Hubbard, S.S., 2017. Coincident aboveground and belowground autonomous monitoring to quantify covariability in permafrost, soil, and vegetation properties in Arctic tundra. *Journal of Geophysical Research: Biogeosciences*, *122*(6), pp.1321-1342

Duvillard, P.A., Magnin, F., Revil, A., Legay, A., Ravanel, L., Abdulsamad, F. and Coperey, A. (2021). Temperature distribution in a permafrost-affected rock ridge from conductivity and induced polarization tomography. Geophysical Journal International, 225(2), pp.1207-1221.

Emmert, A. and Kneisel, C.: Internal structure of two alpine rock glaciers investigated by quasi-3-D electrical resistivity imaging, The Cryosphere, 11, 841–855, https://doi.org/10.5194/tc-11-841-2017, 2017.

Etzelmüller, B., Guglielmin, M., Hauck, C., Hilbich, C., Hölzle, M., Isaksen, K., Noetzli, J., Oliva, M., Ramos, M. (2020). Twenty years of European Mountain Permafrost dynamics – the PACE Legacy. Environmental Research Letters, 15(10), 104070, https://doi.org/10.1088/1748-9326/abae9d.

Farzamian, M., Vieira, G., Monteiro Santos, F. A., Yaghoobi Tabar, B., Hauck, C., Paz, M. C., Bernardo, I., Ramos, M., and de Pablo, M. A. (2020): Detailed detection of active layer freeze–thaw dynamics using quasi-continuous electrical resistivity tomography (Deception Island, Antarctica), The Cryosphere, 14, 1105–1120, https://doi.org/10.5194/tc-14-1105-2020.

Goyanes, G., Vieira, G., Caselli, A., Cardoso, M., Marmy, A., Santos, F., Bernardo, I. and Hauck, C. (2014): Local influences of geothermal anomalies on permafrost distribution in an active volcanic island (Deception Island, Antarctica). Geomorphology. 225. 10.1016/j.geomorph.2014.04.010.

Gudmundsson, L., Kirchner, J., Gädeke, A., Noetzli, J. and Biskaborn, B.K. (2022). Attributing observed permafrost warming in the northern hemisphere to anthropogenic climate change. Environmental Research Letters 17(9), DOI: 10.1088/1748-9326/ac8ec2.

Haeberli, W., Schaub, Y. and Huggel, C. (2017). Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges, Geomorphology, 293, 405–417, doi:10.1016/j.geomorph.2016.02.009.

Halla, C., Blöthe, J. H., Tapia Baldis, C., Trombotto Liaudat, D., Hilbich, C., Hauck, C., and Schrott, L. (2021). Ice content and interannual water storage changes of an active rock glacier in the dry Andes of Argentina, The Cryosphere, 15, 1187–1213, https://doi.org/10.5194/tc-15-1187-2021.

Hauck, C., (2002). Frozen ground monitoring using DC resistivity tomography. Geophysical research letters, 29(21), pp.12-1.

Hauck, C., Böttcher, M., and Maurer, H. (2011). A new model for estimating subsurface ice content based on combined electrical and seismic data sets: The Cryosphere **5**(2), 453–468

Hilbich, C., Fuss, C., and Hauck, C. (2011). Automated Time-lapse ERT for Improved Process Analysis and Monitoring of Frozen Ground: Permafrost and Periglac. Process. 22(4), 306–319

Hilbich, C., Hauck, C., Mollaret, C., Wainstein, P., and Arenson, L.U. (2022). Towards accurate quantification of ice content in permafrost of the Central Andes – Part 1: Geophysics-based estimates from three different regions, The Cryosphere, 16, 1845–1872, https://doi.org/10.5194/tc-16-1845-2022.

Isaksen, K., Lutz, J., Sørensen, A., Godøy, Ø., Ferrighi, L., Eastwood, S. and Aaboe, S. (2022). Advances in operational permafrost monitoring on Svalbard and in Norway. Environ. Res. Lett. 17 095012.

Kneisel C, Schwindt D. 2008. Geophysical mapping of isolated permafrost lenses at a sporadic permafrost site at low altitude in the Swiss Alps. In Proceedings of the 9th International Conference on Permafrost, Fairbanks, Alaska, DL Kane, KM Hinkel (eds). Institute of Northern Engineering, University of Alaska Fairbanks: Fairbanks, Alaska, USA; 959– 964.

Krautblatter, M., Verleysdonk, S., Flores-Orozco, A. and Kemna, A., (2010). Temperature-calibrated imaging of seasonal changes in permafrost rock walls by quantitative electrical resistivity tomography (Zugspitze, German/Austrian Alps). Journal of Geophysical Research: Earth Surface, 115(F2).

Langston, G., Bentley, L.R., Hayashi, M., McClymont, A. and Pidlisecky, A. (2011), Internal structure and hydrological functions of an alpine proglacial moraine. Hydrol. Process., 25: 2967-2982. https://doi.org/10.1002/hyp.8144

Lewkowicz, A.G., Etzelmüller, B. and Smith, S.L., 2011. Characteristics of discontinuous permafrost based on ground temperature measurements and electrical resistivity tomography, southern Yukon, Canada. *Permafrost and Periglacial Processes*, *22*(4), pp.320-342.

Magnin, F., Josnin, J.-Y., Ravanel, L., Pergaud, J., Pohl, B., and Deline, P.: Modelling rock wall permafrost degradation in the Mont Blanc massif from the LIA to the end of the 21st century, The Cryosphere, 11, 1813–1834, https://doi.org/10.5194/tc-11-1813-2017, 2017.

Mollaret, C., Hilbich, C., Pellet, C., Flores-Orozco, A., Delaloye, R. and Hauck, C. (2019): Mountain permafrost degradation documented through a network of permanent electrical resistivity tomography sites. *The Cryosphere*, *13* (10), 2557-2578.

Mollaret, C., Wagner, F.M., Hilbich, C., Scapozza, C. and Hauck, C. (2020): Petrophysical joint inversion applied to alpine permafrost field sites to image subsurface ice, water, air and rock contents. Front. Earth Sci. 8:85.doi: 10.3389/feart.2020.00085.

Mollaret, C., Hilbich, C., Herring, T., Farzamian, M., Buckel, J., Dafflon, B., Draebing, D., Fossaert, H., Gugerli, R., Hauck, C., Kunz, J., Lewkowicz, A., Limbrock, J. K., Maierhofer, T., Magnin, F., Pellet, C., Pfaehler, S., Scandroglio, R., and Uhlemann, S. and the IDGSP IPA Action Group (2022): Initiation of an international database of geoelectrical surveys on permafrost to promote data sharing, survey repetition and standardized data reprocessing , EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-10565, https://doi.org/10.5194/egusphere-egu22-10565.

Noetzli, J., Arenson, L., Bast, A., Beutel, J., Delaloye, R., Farinotti, D., Gruber, S., Gubler, H., Haeberli, W., Hasler, A., Hauck, C., Hiller, M., Hoelzle, M., Lambiel, C., Pellet, C., Springman, S., Vonder Muehll D., Phillips M. (2021). Best Practice for Measuring Permafrost Temperature in Boreholes Based on the Experience in the Swiss Alps. Front. Earth Sci., 9, doi: 10.3389/feart.2021.607875.

PERMOS Database. Swiss Permafrost Monitoring Network, Fribourg, Switzerland, doi:10.13093/permos-2016-01, 2016. http://dx.doi.org/10.13093/permos-2016-01.

PERMOS 2022. Swiss Permafrost Bulletin 2021. Noetzli, J. and Pellet, C. (eds.) 22 pp, doi:10.13093/permos-bull-2022.

Ravanel, L., Magnin, F. and Deline, P., (2017). Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif. Science of the Total Environment, 609, pp.132-143.

Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D., Kuhry, P., Lawrence, D.M. and Natali, S.M., (2015). Climate change and the permafrost carbon feedback. Nature, 520(7546), pp.171-179.

Smith, S. L., O'Neill, H. B., Isaksen, K., Noetzli, J. and Romanovsky, V.E. (2022). The changing thermal state of permafrost, Nat. Rev. Earth Environ., 3(1), 10–23, doi:10.1038/s43017-021-00240-1.

Stalder, A. (2022). Auswertung von Wiederholungsmessungen als Indikator für Permafrostveränderungen. BSc thesis, Department of Geosciences, Université de Fribourg.

Supper, R., Ottowitz, D., Jochum, B., Roemer, A., Pfeiler, S., Kauer, S., Keusching, M., and Ita, A. (2014). Geoelectrical monitoring of frozen ground and permafrost in alpine areas: field studies and considerations towards an improved measuring technology: Near Surface Geophysics, 12(1), 93-115.

Uhlemann, S., Dafflon, B., Peterson, J., Ulrich, C., Shirley, I., Michail, S., & Hubbard, S. S. (2021). Geophysical monitoring shows that spatial heterogeneity in thermohydrological dynamics reshapes a transitional permafrost system. Geophysical Research Letters, 48, e2020GL091149. https://doi.org/10.1029/2020GL091149

Wee, J. and Delaloye, R., 2022. Post-glacial dynamics of an alpine Little Ice Age glacitectonized frozen landform (Aget, western Swiss Alps). Permafrost and Periglacial Processes. https://doi.org/10.1002/ppp.2158.