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Geosciences Community Roadmap 2024

Update of Swiss Community Needs for Research Infrastructures 2029–2032

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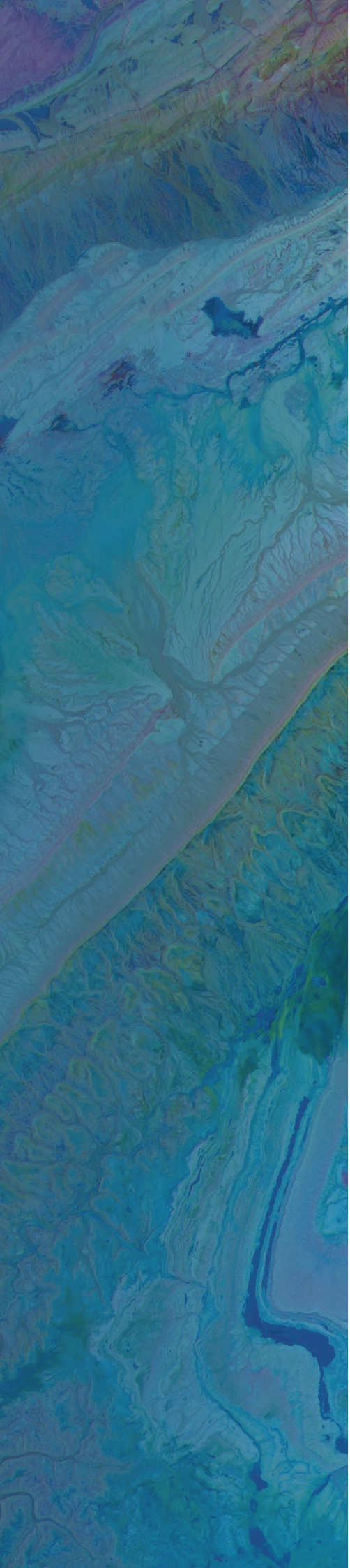

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Update of Swiss Community Needs for Research Infrastructures 2029–2032

Content

1 Executive summary

Swiss geosciences are at the heart of major national and global challenges that our society is facing, including climate change and weather extremes, long-term environmental trends, natural hazards (e.g. landslides, floods, seismic and volcanic events), the energy transition towards a green and blue economy, sustainable management of natural resources (e.g. water, soils, ecosystems, critical metals, building materials), and the increasing interest towards extra-terrestrial life and resources. In order to remain at the forefront of geosciences research and provide the fertile environment necessary for groundbreaking findings addressing these societal challenges, the Swiss Geosciences Community proposes five large infrastructures, organised into four pillars built on a common data-driven research foundation.

The four proposed pillars encompass the full breadth of geosciences from geo-observation and monitoring at and above the surface (Geo-OBSERVE and Geo-MOBILE) to sampling and analyses of geomaterials through space and time (Geo-TIME and Geo-EXPLORE). The pillars are all based on data analysis, processing and exploitation (Geo-DATA) and grouped under one roof, the 'Integrated Swiss Geosciences' as represented in Figure 1. All infrastructures are equally important, complementary, and necessary to drive Swiss geoscience research at its frontiers.

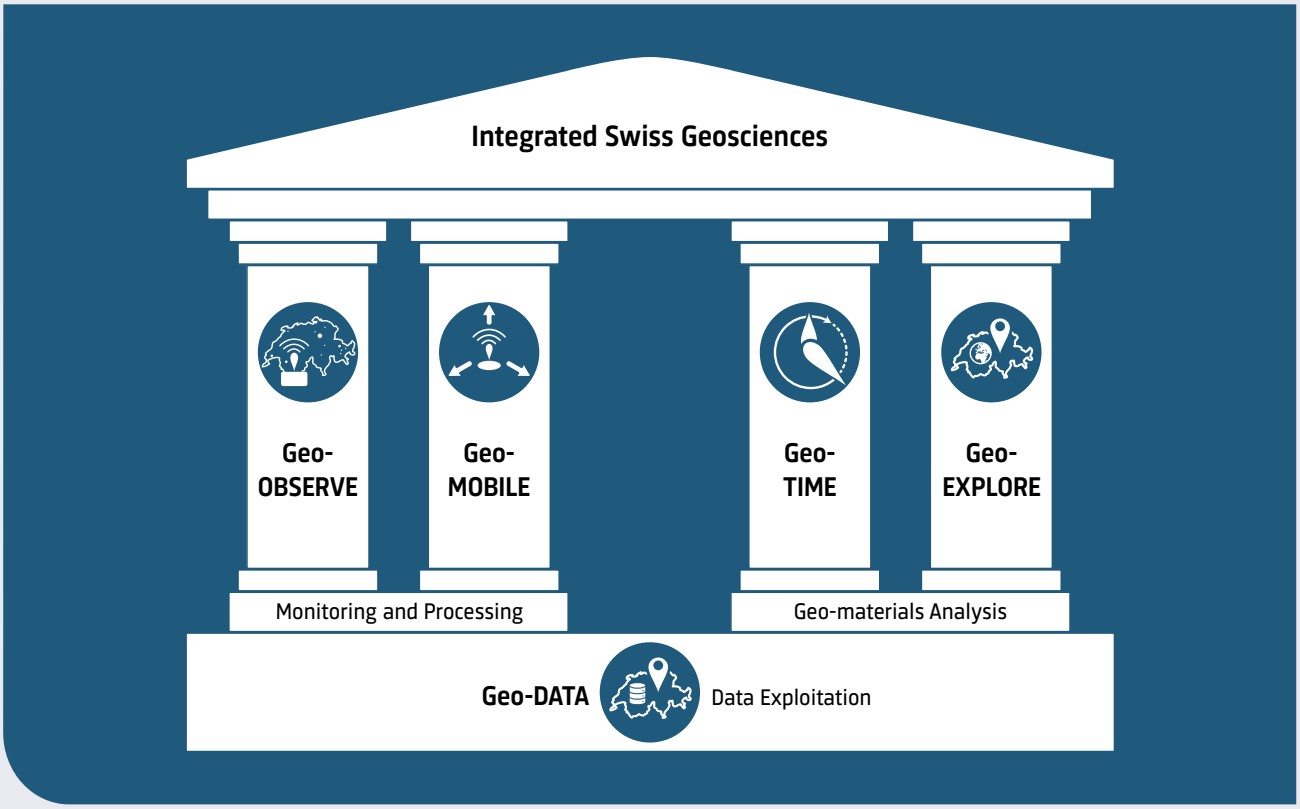


Figure 1: The 2029–2032 Integrated Swiss Geosciences is built upon four thematic pillars and a foundation that constitute the building blocks for a state-of-the-art multidisciplinary integrated and harmonised geoscientific research environment. Pillar I, Geo-OBSERVE, integrates the unique long-term observation efforts that make Switzerland one of the most data-rich areas on Earth. Pillar II, Geo-MOBILE, consists of a multifaceted mobile infrastructure that can be deployed for temporary monitoring. Pillar III, Geo-TIME, consists of a distributed network of state-of-the-art facilities for determining timescales and rates of geological events. Pillar IV, Geo-EXPLORE, consists of a federated large state-of-the-art centralised facility for the processing, storage, curation and *in situ* analysis of geomaterials. All four pillars are based on the use of data, with the distributed Geo-DATA infrastructure providing the data-driven foundation of the entire edifice.

Aletsch Sahara Dust July 2024.
Source: Modified Copernicus Sentinel-2 data

2 Foreword

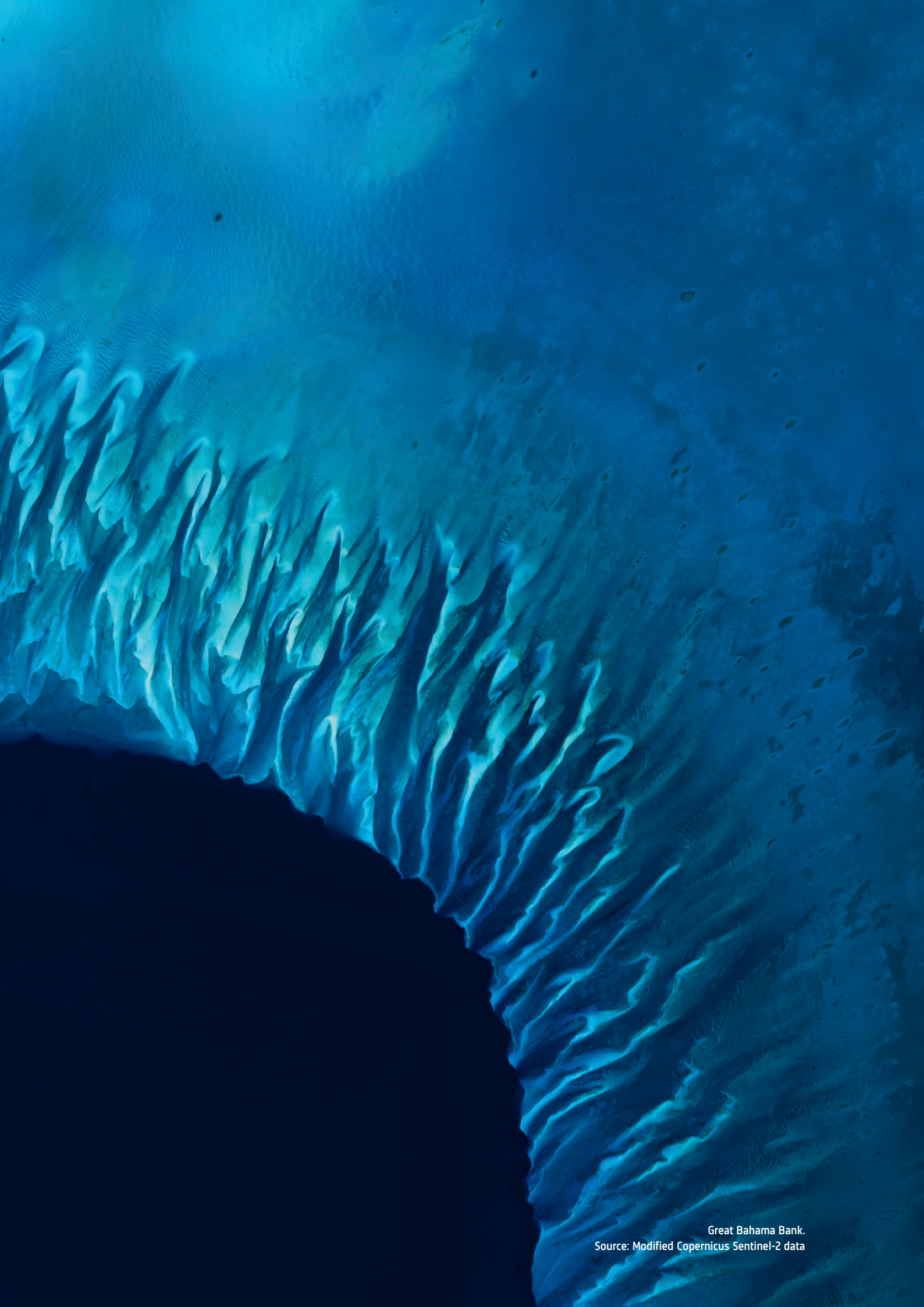
This document is an update to the Geosciences Community Roadmap published in 2021.[1] It presents the needs of the Swiss Geosciences Community in terms of future national and international research infrastructures. Together with similar community roadmaps in other disciplines, it is an important element of the four-year process leading to the development of the Swiss Roadmap for Research Infrastructures 2027 to be written by the State Secretariat for Education, Research and Innovation (SERI[2]) in view of the ERI Dispatch 2029–2032 to the Federal Council. The role of these 'bottom-up' inputs is to serve as an important basis for the strategic planning of the higher education institutions in terms of new or major upgrades to national infrastructures, as well as to inform and support SERI during its decision-making process on Swiss participation in international research infrastructure networks and organizations.

SERI has formally mandated the Swiss Academy of Sciences (SCNAT) to update the seven community roadmaps[3] previously published in the disciplines of biology, chemistry, geosciences, astronomy, particle physics, photon science and neutron science. SCNAT engaged its network of member societies and commissions to reach out to the scientists willing to get involved. It encouraged diversity of the participating scientists and provided the needed support for the collaborative writing, the layout, the publication and printing of this document.

1 Geosciences Roadmap for Research Infrastructures 2025–2028 by the Swiss Geosciences Community (2021) Swiss Academies Reports 16 (4)

2 All acronyms are listed in appendix

3 https://scnat.ch/roadmaps



Great Bahama Bank.
Source: Modified Copernicus Sentinel-2 data

3 Introduction

Looking ahead at the challenges of the 21st century, geosciences are bound to play a key role. Societal issues related to global change, natural hazards, and the sustainable use of natural resources and critical materials (including the exploration beneath the surface) all need a strong input from the geosciences. Additionally, the rapid development of planetary sciences, following the discoveries of the first exoplanets three decades ago, calls for long-lasting commitment from the geosciences in this expand-ing field. Hence, having the appropriate research infrastructures in Switzerland to contribute to finding solutions for these challenges while remaining at the forefront of scientific development is of paramount importance for the years to come.

Switzerland and the rest of the world have evolved a great deal since the first Geosciences Roadmap in 2021, both on the scientific and the political level. The funding dedicated to natural sciences has slowed down, and Switzerland has moved away from some European initiatives as a result of political decisions. An example is the decision from the Federal Council to postpone negotiations to become a member of the European Union's Copernicus Earth Observation programme whose datasets and services have applications in all domains relevant to geosciences and beyond, such as atmosphere, land, climate change, marine systems. On a changing planet, this calls more than ever for joint geoscientific initiatives and secure funding in large infrastructure facilities to not lose momentum in earth observation, monitoring, sampling, analyses and data-driven science.

Hence, the scientific need for monitoring and observation, geomaterial analyses and curation, and data exploitation requires solid and state-of-the-art research infrastructure responding to fast changing technological developments.

The following update to the 2021 Geosciences Roadmap describes five large infrastructures needed by the research community, identified by a bottom-up approach involving more than hundred geoscientists from almost all universities and research institutes across Switzerland. The proposed infrastructures were identified over a six-month process beginning in spring 2024. The Swiss Geosciences Community was informed about the potential renewal of the SERI mandate in 2023 and the scientists who expressed interest were invited for a kick-off meeting in April 2024. Following this early meeting, five different working groups were created on the basis of infrastructures ('pillars') described in the first Geosciences Roadmap (2021). The main framework of the 2021 roadmap was maintained, but two major changes were proposed for 'pillar IV' called Geo-DATA. In the previous version of the roadmap, this pillar was split into two subcategories: Virtual Geo-Data and Physical Geo-Data. However, both sub-categories are two stand-alone but very complementary much needed infrastructures.

Within this perspective and to highlight the importance of both infrastructures, Physical Geo-Data is now presented as Geo-Explore which fits the scientific needs in terms of physical samples, now identified as geo-materials, curation and analyses. While Virtual Geo-Data, identified now as Geo-DATA, forms the foundation of the Integrated Swiss Geosciences initiative. It secures and enables the shared exploitation and accessibility of virtual data amongst the Swiss geoscientific community across all pillars.

The editorial board for this update of the Geosciences Community Roadmap consists of the chairs and co-chairs, elected by each of the five working groups who were responsible for editing and circulating the draft documents among their respective communities. It was decided early on to focus on the updated infrastructures' requirements and on what has changed over the last four years. Prioritisation of the different pillars is not advisable since only together do they constitute a solid edifice, with an integrated perspective for the entire Swiss geoscience community. The present document was sent for review in September 2024 to all the Swiss geoscientists who expressed their interest.

Several infrastructures described in the 2021 Geosciences Roadmap made it into the Swiss Roadmap for Research Infrastructures 2023[4] after the selection process by swissuniversities, ETH board, the Swiss National Science Foundation (SNSF) and SERI. However, as the outcome of the process and the related funding options are not yet known, and since the needs for such infrastructures remain as urgent and relevant as in 2021, the community decided to list them again in the present document.

4 Swiss roadmap for Research Infrastructures in view of the 2025–2028 ERI Dispatch (2023) State Secretariat for Education, Research and Innovation (SERI)

Richat Structure.
Source: Modified Copernicus Sentinel-2 data

4 Findings and recommendations

4.1 Federation of infrastructures, laboratory instruments and expertise

Amongst the Swiss geoscience community, there is a strong need to federate laboratories, and observatories as well as to pool instruments in order to group strengths and expertise to deliver long-term cost-efficient science. An important aspect of these geoscience pillars is that they provide both centralised and distributed facilities. Centralised facilities, such as Geo-EXPLORE, are planned to be in one specific, accessible location, ensuring open and easy access across universities and the ETH-domain. They will enable sharing and curating of geomaterials while also pooling analytical expertise and know-how. These infrastructures will rely on distributed networks (like monitoring or scientific drilling programs), in Switzerland and abroad. This also goes for Geo-MOBILE, which plans to constitute a pool of instruments available for specific research projects based on a competitive bidding process. On the other hand, distributed facilities, such as Geo-TIME, Geo-DATA and Geo-OBSERVE are envisaged to not be concentrated in one location but federated amongst research and teaching institutions around the country, thus monitoring a wide range of different parameters from various locations in Switzerland. This mix of centralised and distributed facilities would optimize the usage of the research infrastructures over the long-term, and pool expertise to run them.

4.2 Data in geosciences

In geoscience, data analysis and processing, including observational data and analytical measurements, are fundamental for enabling high-quality science. An important aspect of data is its geolocation, which allows exchange within and across communities for interdisciplinary, holistic scientific analysis and modelling of earth processes. Ideally, standardised interfaces could make data accessible from existing and, where needed, new infrastructures. These can then be linked with computational resources for modelling complex earth processes or feeding modern AI models. The recent rise of artificial intelligence (AI) has changed the geoscientific landscape, bringing new and exciting prospects for research in geosciences. AI is one key technology to cope with challenges related to big datasets and it is becoming increasingly essential for geosciences, offering powerful tools for analysing complex geoscientific data and creating earth system models. Moreover, the United Nations and its Global Geospatial Information Management (GGIM) programme recently released a position paper[5] highlighting the crucial aspects of geo-localisation and geo-referencing, for both scientists and society, as location-based positioning applications are increasingly critical.

Most research activities may benefit from transversal support for data management and curation. All pillars described in this document share the need and willingness to build on FAIR (Findable, Accessible, Interoperable and Reusable) and adequately curated data. Sharing data access, curation and exploitation would increase efficiency but also allow more complex and interdisciplinary science and make data accessible long-term for other communities.

4.3 Infrastructures needed

The Integrated Swiss Geosciences Initiative proposes five large infrastructures, identified as 4 pillars Geo-OBSERVE, Geo-MOBILE, Geo-TIME and Geo-EXPLORE, all supported by Geo-DATA for efficient storage and exploitation of data.

5 E/C.20/2021/7/Add.2 – Position Paper on Sustaining the Global Geodetic Reference Frame

Geo-OBSERVE

A Swiss-wide, coordinated long-term geosciences observational infrastructure is key to providing the backbone, testbed and user platform for the national community with an excellent basis for membership in and collaboration with internationally coordinated networks and research infrastructures (RIs). Despite their undisputed importance, the Swiss RIs are under-resourced and rely heavily on 'in-kind' contributions from universities and organizations. Recommendation 2 of the 2021 Geosciences Roadmap stating that advanced Swiss RIs should receive the required funding and coordination to sustainably contribute at the highest quality level and with the best visibility, is thus still valid. It has been recognised in the context of the revision of the Federal Act on the Promotion of Research and Innovation (RIPA) that better coordination of long-term funding of RIs is needed. Internationally, the importance of long-term sustainability of the terrestrial reference frame has been recognised in a United Nations Resolution.[6]

Recommendation: Continuous and reliable perspectives are needed to sustainably operate and further develop the long-term geosciences observational infrastructure (Geo-OBSERVE). Strengthening Geo-OBSERVE will help foster collaboration in the geoscience community and pave the way towards a more cohesive and holistic approach to research.

Geo-MOBILE

Many processes or structures can be effectively studied with data from short-term or long-term temporary deployments of mobile instruments positioned below, on and above the ground. In this context, the observational capabilities in seismology and geodesy have evolved significantly both in Switzerland and internationally: advanced technologies like Distributed Acoustic Sensing (DAS) and low-cost Global Navigation Satellite System (GNSS) have been making high-resolution, real-time monitoring more accessible and effective. Despite these technological advancements, the Swiss research approach remains fragmented, with individual projects and institutions operating independently. This lack of coordinated infrastructure has limited the scope and impact of research efforts, particularly in addressing the urgent challenges posed by climate change, such as glacier melting, permafrost thawing, and increasing natural hazards. The need for a unified, national infrastructure is further emphasized for Switzerland's participation in international collaborations, where a lack of modernised, shared equipment risks diminishing the country's leading position. A centralised mobile monitoring infrastructure could significantly enhance observational capabilities, enabling more effective responses to climate and environmental challenges as well as rapid response actions in the aftermath of natural disasters.

Recommendation: To maintain and enhance Switzerland's standing in the geosciences, it is crucial to establish a coordinated national mobile monitoring infrastructure, as proposed in the Geo-MOBILE pillar. This infrastructure will include a well-organised, modernised instrument pool that is accessible to all relevant academic institutions. By centralising resources and fostering tighter collaborations among institutions, this infrastructure will not only improve the efficiency and scope of geoscientific research but also enable Switzerland to fully participate in important international projects. The infrastructure will support the advancement of environmental monitoring capabilities essential for addressing the increasing impact of climate change and natural hazards, aligning with the growing societal need in this regard.

6 A/RES/69/266: https://ggim.un.org/documents/a_res_69_266_e.pdf

Geo-TIME

Determining timescales and process rates at the highest possible precision and accuracy, across scales from near-instantaneous to the age of the Earth and beyond, is a fundamental aspect of the geosciences. Frontier instrumentation dedicated to measuring timescales and rates are costly and time-consuming and often cannot be accommodated by single institutions. Hence, it is necessary to build a new distributed infrastructure serving the Swiss community, to expand the capabilities of dating facilities, and to incorporate emerging geochronological techniques, including those that record processes operating on short time scales near the Earth's surface. In order to better understand the timing and rates of processes that shape the Earth and other planetary bodies in the present and past, higher temporal resolution from novel instrumentation is required.

Recommendation: It is recommended that a large, federated RIs be established, integrating multi-user facilities in a consortium with the highest expertise, dedicated to the determination of timescales of processes in the geosciences (Geo-TIME) at the best possible quality. This requires the long-term funding of highly trained permanent staff assisting in data acquisition and analysis, which will be critical for future breakthroughs in earth and planetary sciences and for a rapid response of the geosciences to societal issues.

Geo-EXPLORE

Due to the lack of a centralised Swiss geomaterial facility, precious decadal-long sample and core collections, currently based at individual laboratories, are at risk of being lost due to local space constrains and/or lacking long-term management plans. Additionally, the accelerated Swiss geothermal energy exploration, the active search for radioactive waste disposal sites, and the urgent need for sustainable water exploitation, results in an increasing archive of newly acquired subsurface geomaterials requiring sophisticated *in situ* subsampling, analytical and curation needs. Also, in light of climate change, centralising hands-on information on climate archives, e.g. in core sections, will provide the data and tools to the government to develop future climate strategies. Finally, the analysis of geomaterials lies at the heart of many key disciplines in the domain of the geo- but also the life- and archaeological sciences. It helps to elucidate on the processes that shaped the Earth, the response to environmental and/or anthropogenic change and societal development that in turn was influenced by past climate and environmental change.

Recommendation: Geo-EXPLORE recommends the set-up of a federated large centralised geomaterial facility with provisions for state-of-the-art and cutting edge in situ analysis as well as dedicated and highly specialised subsampling capacity and curation. The facility will require space on the order of 3000 m^3, allocated to analytical instrumentation, specialised sampling laboratories and appropriate storage for samples and cores (cold room, freezers etc.). The facility will be managed by different universities and will require qualified and long-term employed academic staff specialised in sample and core curation along with operating and maintaining analytical instrumentation and IT systems.

Geo-DATA

Geodatasets are being produced at an increasing pace as part of geoscientific research. Yet these datasets are often stored in a large variety of formats and scattered among different platforms. There is also a lack of integration, coordination and harmonisation of data management on an international level. This, and the lack of trained and appointed data scientists, impedes the findability, usability and curation of digital geoscientific datasets, and, consequently, obstructs interdisciplinary and innovative Swiss geoscientific research as a whole.

Recommendation: It is recommended to develop a Geo-DATA platform to unify access to the large variety of geoscientific datasets. This platform will serve as the Swiss national hub for the management of digital geoscientific datasets and will provide capabilities for the harmonisation, dissemination, long-term archiving, and collaborative analysis of data. Tailored interfaces will allow users to carry out analyses and simulations in an integrated manner. The platform will be connected to other national and international data infrastructures thus enabling unprecedented synergies. It will fulfil the aim of the SNSF and other funding agencies to provide public access to research findings and data while guaranteeing FAIR data access.

5 Description of the needs

5.1 Pillar I — Integrated Long-term Observatory

Description

Pillar I proposes to widen and strengthen geoscientific research via an Integrated Long-term Observatory (Geo-OBSERVE) which is designed to complement monitoring networks at the regional scale, also including the existing RIs as a backbone infrastructure. Geo-OBSERVE will target Swiss Earth system interactions and human influences across all spheres from the inner Earth to space.

Vision for the future

A Swiss-wide, coordinated long-term geosciences observational infrastructure provides the backbone, testbed and user platform for the national community with an excellent basis for collaboration with international networks and RIs. It also offers enhanced opportunities for groundbreaking interdisciplinary research and ensures international competitiveness.

Continuous and reliable perspectives are needed to further develop the national RIs to 1) be able to respond efficiently and in a timely manner to environmental changes in Switzerland and 2) contribute internationally with Swiss expertise and high-end science to address global environmental issues. Moreover, initiatives like Geo-OBSERVE serve as powerful catalysts for strengthening the geosciences community. By fostering a common infrastructure, we can increasingly share best practices and methodologies, paving the way towards a more cohesive and holistic approach to research.

Recent developments

The national/international context

The number of research initiatives in Earth observation has steadily increased in response to a motivation to better understand earth structure, dynamics and processes. One key element is still the integration of existing monitoring/observation networks leveraging significant synergies and benefits because funding and coordination only partly materialised, e.g. in the context of the revision of the RIPA which strongly facilitates memberships in European Research Infrastructure Consortia (ERIC). At the national level, a consortium drafted a concept in line with Geo-OBSERVE's vision on sustainable agriculture and agroecology (Swiss Biosites for Sustainable Agriculture and Agroecology (SISAL), a joint RI within the ETH domain, not yet funded) and biogeochemical and earth material fluxes along a continuum from mountains to lowlands. A series of ETH Domain joint initiatives are funded in the strategic areas of energy, climate and environmental sustainability, which take advantage of data from observational infrastructures and networks to address cross-cutting themes of strategic importance for Switzerland. Swiss observational infrastructures also provide data to the European Open Science Cloud (EOSC), or to other international efforts aimed towards digital twins of the Earth. At the international level, the European Space Agency ESA-ministerial Conference in 2022 gave the green light for the Genesis mission that will implement a highly improved terrestrial reference frame and thus contribute to many fields such as global geodesy, metrology, natural hazard prediction, and monitoring of climate change, highlighting again the need for accurate observation. The Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald (SwissOGS) is presently one of the most productive Satellite Laser Ranging (SLR) stations worldwide and will contribute significantly to the SLR tracking of the Genesis mission and will thus be essential for determining next generation terrestrial reference frames. The SwissOGS is also highlighted in the Astronomy Roadmap and became part of the Swiss Quantum Communication Infrastructure (Swiss-QCI) project listed in the 2023 Swiss Roadmap for Research Infrastructures. In May 2024 the ESA/JAXA (Japan Aerospace Exploration Agency) mission EarthCARE, focused on remote sensing of aerosols and clouds, was launched and Swiss institutions (through a number of European Union (EU) funded initiatives and ERICs) are heavily involved in calibration/validation and integration of its data in numerous weather and climate model contexts.

Specific major successes and recent developments

Major advances in machine-learning (ML) supported processing and analysis have been achieved in recent years. To leverage its full potential, ties between observational and computational infrastructures (Geo-OBSERVE and Geo-MOBILE with Geo-DATA) need to be strengthened.

At the international level, Switzerland became a full member of the Integrated Carbon Observation System (ICOS) and the European Plate Observing System (EPOS) in 2023. That same year, the European Commission (EC) also established the Aerosol, Clouds and Trave Gases Research Infrastructure (ACTRIS) as an ERIC with Switzer-

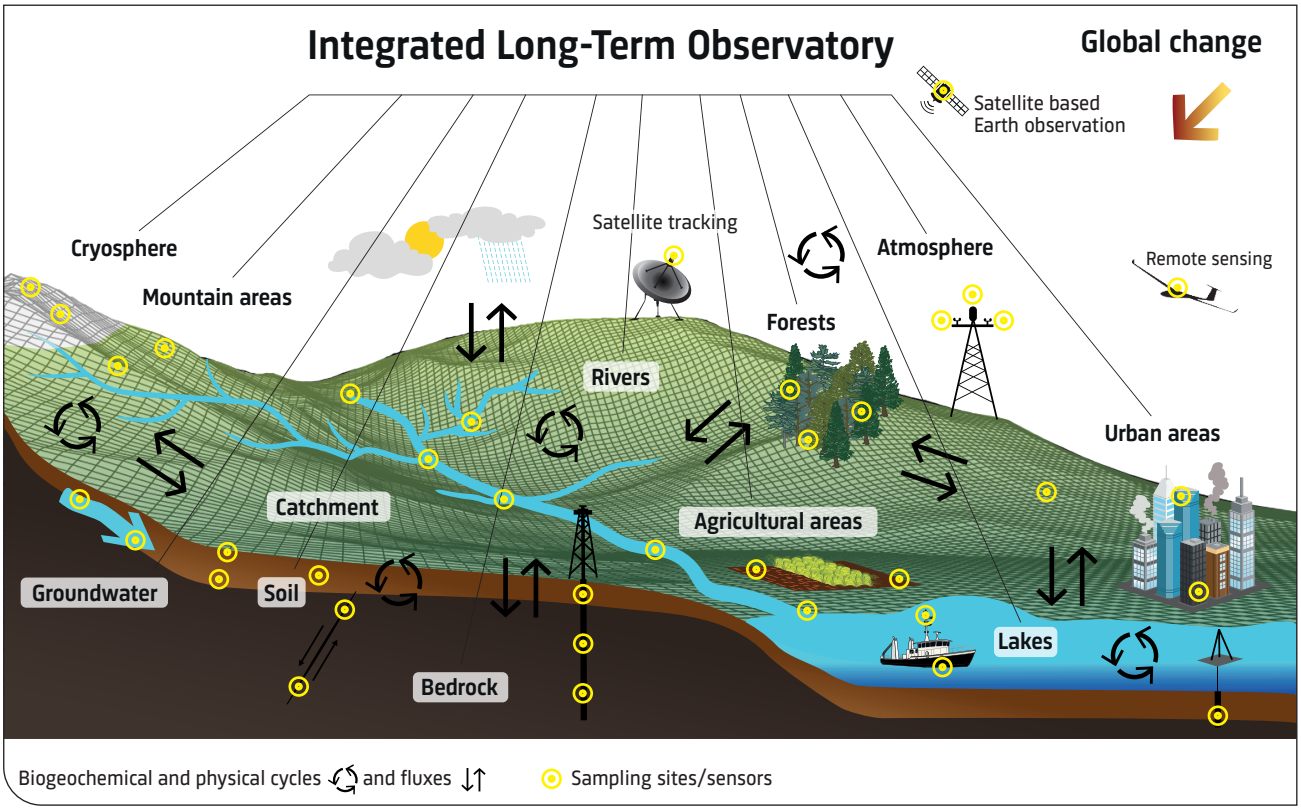


Figure 2: The Integrated Long-Term Observatory will combine highly equipped observatories and sensor networks to unravel the cycles and fluxes of water, carbon, nutrients, aerosols and trace elements across all spheres. Source: The trees, crops, urban area and research vessels illustrations are from Jane Hawkey, Ian Image Library, https://ian.umces.edu/imagelibrary; background: Dmitriy Razinkov

land being a permanent observer. It should be noted however, that none of the three (ICOS, EPOS, ACTRIS) have yet to secure long-term financial commitments. This is in contradiction to the important role the Swiss partners play in the respective ERICs and puts their successful developments and activities in danger.

At the national level, some major infrastructures were improved. The WSL Pfynwald RI as part of the Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research (eLTER) network and the Swiss Long-Term Forest Ecosystem Research (LWF) programme have been upgraded by the SNSF, WSL and EPFL for the 'VPDrought project'. The WSL Swiss Long-term Forest Monitoring RIs, LWF and TreeNet received support to make use of their 30-year-long data series to investigate the adaptive capacity of Swiss forest ecosystems under climate change thanks to the EU funded project FORWARDS. The SwissOGS RI has been upgraded with new equipment for Satellite Laser Ranging. The Bedretto Underground Laboratory for Geosciences and Geoenergies was consolidated and further developed as a long-term experimental observational facility of significant importance in the context of Switzerland's long-term climate strategy as well as a national contribution to EPOS. Discussions on creating a network of Swiss Underground Research Labs (Swiss-URL) have continued, involving the BedrettoLab, the Mont Terri Rock Laboratory and the Grimsel test site. The LéXPLORE RI on Lake Geneva has become an integral part of the Swiss aquatic research landscape and is currently strengthening connections with other geosciences observational platforms though open data pipelines.

Future needs

Scientific need, impact and urgency

The need for a long-term observatory has steadily increased in the past four years. The interoperability and integration envisioned for the Geo-OBSERVE infrastructures will enhance the compatibility among the various research disciplines and address topics of high societal relevance related to climate change (ecology, energy, well-being and health). The use of synergies will have positive impacts on budget efficiency. These efforts align with European and global efforts and regulations.

The environmental aspects addressed by the components of the Geo-OBSERVE RIs have become all the more relevant given the accelerating pace of climate change and its impact on society, in Switzerland and elsewhere. The

observations will be used to monitor, model and refine predictions, and may in particular focus on the water cycle, the cycles of chemical elements or compounds, pollutants and nutrients, as well as contribute to sustainable support for the exploitation of geo-resources, geo-energy, carbon capture and storage, supporting Switzerland's 2050 Net Zero target.

The events of massive flooding and landslides in summer 2024 in Valais, Ticino, and Bernese Oberland serve as a reminder of the importance of permanent infrastructures for real-time observation of the geosphere in order to provide a rapid and effective response for the public and institutions (e.g. rapid mapping). Geo-OBSERVE thus complements the Geo-MOBILE infrastructure which may collect further data in case of hazards.

The contribution of geodetic and geophysical techniques to monitor climate change and natural hazards is of increasing importance and has a strong societal impact, along with geothermal exploration and monitoring, which are essential for the energy transition. The geodetic satellites GRACE and GRACE-FO are among the most frequently cited missions in the reports of the Intergovernmental Panel on Climate Change (IPCC), underlying the importance to continue and enhance the spatial and temporal resolution of terrestrial water storage (adopted as an Essential Climate Variable by the Global Climate Observing System (GCOS) in 2022) by the planned joint ESA/NASA Mass-change And Geosciences International Constellation (MAGIC).

Far from stopping at the Earth's surface, Geo-OBSERVE's infrastructures will encompass the fields of space research and security. Switzerland is currently developing and installing a space law that requires very specific capabilities and expertise that stations such as SwissOGS can offer, particularly on the subject of space debris.

Community

Beyond the Swiss research community and its hosting research institutions, the population will benefit greatly from better information on climate change adaptation and mitigation, natural hazard response, and improved agriculture, forest management and farming practices.

By tailoring highly-specialized instruments, industries affected by (dynamic) changes in the earth system, companies dealing with natural hazards and industries interested in energy, resources, or water and carbon management will be potential users/partners of the long-term geo-observatory.

Many national and international programmes will benefit and/or provide important information from/to Geo-OBSERVE. The programmes listed below build the foundation of Geo-OBSERVE or profit from the Swiss-wide coordination of the monitoring actions. Furthermore, the High Altitude Research Station Jungfraujoch and Gornergrat (HFSJG) provides a worldwide unique infrastructure that is key to all the listed programmes that are focusing on atmospheric observations.

Programmes

ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure
Copernicus	EU Satellite-based Earth observation program
ECCSEL	European Carbon Dioxide Capture and Storage Laboratory Infrastructure ERIC
eLTER	Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research
EOSC	European Open Science Cloud
EPOS	European Plate Observing System
ESA	European Space Agency
Eumetsat	European Organisation for the Exploitation of Meteorological Satellites
G3W	Global Greenhouse Gas Watch
GAW	Global Atmosphere Watch Programme
GCOS	Global Climate Observing System
GEO	Group on Earth Observation
GGOS	Global Geodetic Observing System
GGRF	Global Geodetic Reference Frame
GNSS	Global Navigation Satellite System: such as Galileo (with IGS, EUREF, etc.)
IAG	International Association of Geodesy: with services like IERS, IGFS, IGS, ILRS, IVS, ISG, COST-G
IAU	International Astronomical Union
ICOS	Integrated Carbon Observation System
IUGG	International Union of Geodesy and Geophysics
Swiss FluxNet	Network of six long-term ecosystem greenhouse gas flux measurement sites in Switzerland
UN-GGIM	United Nations Committee of Experts on Global Geospatial Information Management
UNECE-WGE	UNECE Working Group on Effects
WMO	World Meteorological Organization

5.2 Pillar II — The Mobile Monitoring Infrastructure

Description

Geo-MOBILE refers to a proposed Mobile Monitoring Infrastructure designed to significantly enhance the spatial and temporal resolution of geoscientific observations across Switzerland. This infrastructure aims to address the limitations of permanent monitoring systems by providing versatile, mobile, and rapid-response solutions equipped with a wide array of high-precision and cost-effective sensors for temporary deployments. Geo-MOBILE will facilitate in-depth monitoring and analysis of poorly characterised processes and natural hazards such as earthquakes, landslides, glacial floods, and extreme weather events, as well as contribute to understanding geothermal systems. The infrastructure will consist of two primary pools of instruments: one focused on above-ground monitoring (including GNSS, atmospheric sensors, and drones) and another on below-ground processes (such as seismometers, fibre-optic sensors, and borehole instrumentation). These mobile platforms will support interdisciplinary research, improve hazard rapid-response capabilities, and contribute to understanding environmental changes driven by climate impacts, ensuring Switzerland remains at the forefront of geoscientific research.

Vision for the future

The establishment of a common, collaborative and well-organised instrument pool in the context of Geo-MOBILE will make Swiss academia benefit from the recent advancements in technologies. It will enable Swiss participation in important international endeavours, such as the joint measurement campaign TEAMx or Adria Array and similar future projects. Switzerland will slide behind other countries without a national large research infrastructure (LRI) that can focus efforts and allow for better coordination. As such, an efficient Geo-MOBILE pillar will ensure that Swiss research continues to lead in the development of observational, methodological, and data-driven innovations. Furthermore, modernising geodetic equipment to support the latest GNSS signals will drive advancements in monitoring capabilities, enabling more precise and reliable geospatial measurements.

Recent developments

The national/international context

In seismology, DAS has further revolutionised the observational capabilities in the field. DAS turns existing or new fibre optic communication cables into a seismic antenna enabling unprecedented spatial and temporal resolution. DAS is now being deployed routinely in various contexts; however, the fields of applications and the related processing techniques are still in the blossoming phase, while partly limited by the availability of the interrogators (data acquisition systems for DAS data). Likewise, the use of geodetic instruments has become more prevalent than ever. For instance, the use of GNSS for monitoring ground deformation has been made more accessible by advancements in low-cost hardware, supporting signals from multiple satellite constellations and frequencies and thus reaching similar precision as high-grade GNSS hardware. Technological advancements in terrestrial radar, laser scanning, and drones equipped with cameras and scanners have further contributed to high-resolution mapping and flexible, cost-effective data collection. Novel applications of GNSS include the monitoring of biomass and vegetation water content and thus contribute to monitoring plant health and biodiversity. Also, GNSS reflectometry is of increased importance for monitoring snow height and snow water equivalent. Undoubtedly, in the coming years GNSS monitoring capabilities will experience significant advances. This is seen with the Galileo High-Accuracy Service (HAS) that has been rolled out recently and is being adopted for improved real-time positioning and monitoring. Additionally, the ESA-funded LEO-PNT satellites, to be launched between 2025 and 2027, will bring GNSS signals from low Earth orbit, with higher signal strength, better geometry, and reduced vulnerabilities.

In general, natural hazards are only rarely analysed jointly by geodetic and seismological tools, although it has been demonstrated that joint inversions based on the two types of datasets provide more robust results and a better understanding of processes. A joint national LRI would better connect the scientists in the respective fields, and lead to more and stronger cooperations with high impact in the research field.

Specific major successes and recent developments

Geodetic equipment has been successfully used in various monitoring tasks, including the Brienz landslide, which has been prominently featured in the news. Swiss scientific institutions have pursued field studies of ground deformation in several locations, although these have been rather individual efforts due to a lack of joint instrument pools. The Swiss Geodetic Commission (SGC) has initiated a project focused on the mapping and monitoring of deformations of the Matterhorn. CERN has required geodetic and seismological expertise and measurement campaigns in feasibility studies for the ‘Future Circular Collider’. Through a collaboration between MeteoSuisse and ETH Zurich, low-cost GNSS receivers have been deployed at ten meteorological sites

for atmospheric and environmental monitoring, demonstrating the interdisciplinary aspect of space geodesy. The Expertise Center for Climate Extremes (ECCE) has recently been established at the University of Lausanne. All research teams in the domain of Geo-MOBILE continue to participate in international collaborative projects, such as the AdriaArray effort in seismology. Some of the research teams carry out geothermal project preparation and monitoring, for both fundamental- and applied-science aspects.

Description and development prospects

The growing impact of climate change on Switzerland over the last years has increased the need for geodetic and seismological measurements. The unprecedented melting of the glaciers, losing 10% mass in just two years, has drastically altered the environment, creating glacier lakes that pose flash flood risks. Additionally, the melting of permafrost has significantly increased slope instabilities. The more frequent occurrence of long-lasting severe weather periods has led to a multitude of costly flooding and landslide events. More than ever, a mobile infrastructure is needed to monitor and study such hazards, as most of them cause signals visible by seismology and/or geodesy, and the respective research fields in interpreting such signals evolve rapidly. With the continued coverage of such events in the news, the political interest has significantly increased. The events of summer 2024 in Valais and Ticino and Bernese Oberland (massive flooding and landslides) served as a reminder of the importance of real-time observation of the geosphere in order to provide a rapid and effective response for the public and institutions (e.g. rapid post-disaster mapping). Similarly, as Switzerland is still in the exploratory phase of harvesting geothermal energy, surveying and monitoring efforts are foreseeable for a better understanding of such systems.

Future needs

Scientific need, impact and urgency

In the field of application of Geo-MOBILE, the interest and spectrum of tools have both increased since the publication of the previous roadmap. Despite this, the status quo prevails in the research approach: individual projects, teams and institutions govern the evolution of research and related science. The community agrees that a shared national infrastructure will boost the observational capacities and the research impact of Switzerland. To keep Switzerland at the fore-front of geoscience, tighter links and even better international visibility will be realised with a national LRI. Since no joint mobile infrastructure is available, monitoring efforts rely on individual institutions or smaller collaborations, limiting their scope and reactivity, and highlighting again the need for the Geo-MOBILE infrastructure The contribution of methods from geodetic and geophysical techniques to monitor natural hazards and the impacts of climate change is of increasing importance and has a strong societal impact, along with geothermal explo-ration and geothermal monitoring, which are essential for the energy transition. These provide obvious links for academia to implement joint projects with industry and administrative bodies.

Figure 3: The Brienz rockslide, monitored by seismic and geodetic equipment, stopped just in front of the village.
Source: Simon Löw

Community

Beyond the directly involved Geo-MOBILE core group in academia, a large group of academic researchers from other disciplines in combination with an even larger user base from administrative institutions and industry will benefit from the Geo-MOBILE data and infrastructure on a collaborative basis. The fields of application of these methods encompass geothermal energy, nuclear waste storage, seismic site characterization, scientific drilling, volcanology, meteorology, forestry, hydrology, glaciology, georeferencing, tectonics, geomatics, planetary and space sciences. Most of the administrative institutions and companies have ties to academia, which is mutually beneficial but often relies on prior connections. Ultimately, Swiss society will benefit from an efficient national infrastructure that allows better early warning of natural hazards and better guidance for political decisions concerning the impact of climate change.

The community of data or data product users is even larger. Administrative bodies across the country, at all levels, benefit from the collected data and derived data products. As an example: considering the users of earthquake catalogues, hazard maps, risk models, felt report forms, the entire population of Switzerland (and beyond) is a user. Geophysical data also plays a key role in scientific drilling projects of the International Continental Scientific Drilling Programme (ICDP) such as the Drilling the Ivrea-Verbano zonE (DIVE) project, and it creates national and international collaborations with scientists in other disciplines, including those in Geo-TIME and Geo-EXPLORE.

Switzerland is linked/bound to many international programmes in seismology and geodesy in the broader frame of mobile observations. They are listed alphabetically as acronyms in the box to your right.

Programmes

AdriaArray	Dense regional array of seismic stations covering the region of the Adriatic Plate
AlpArray	Assessing Alpine Orogeny in 4D-space-time Frame
EIDA	European Integrated Data Archive infrastructure within ORFEUS
ESA	European Space Agency
Eumetsat	European Organisation for the Exploitation of Meteorological Satellites
FDSN	Federation of Digital Seismograph Networks
GEO	Group on Earth Observation
GGOS	Global Geodetic Observing System
GGRF	Global Geodetic Reference Frame
IGS	International GNSS Service
EUREF	IAG Reference Frame Sub-Commission for Europe
IAG	International Association of Geodesy and services like IERS, ILRS, IVS, IGFS, ISG, COST-G
IASPEI	International Association of Seismology and Physics of the Earth's Interior
IAU	International Astronomical Union
ICDP	International Continental Scientific Drilling Program
ILP	International Lithosphere Programme
ITU	International Communication Union
IUGG	International Union of Geodesy and Geophysics
ORFEUS	Observatories & Research Facilities for European Seismology
UN-GGIM	United Nations Committee of Experts on Global Geospatial Information Management

5.3 Pillar III — The Swiss Geo-TIME facility

Description

Pillar III proposes to build a new research infrastructure related to the determination of timescales and rates of geological processes at the highest possible precision and accuracy (Geo-TIME). This infrastructure is developing new technologies and coordinates national facilities fully open to Swiss geoscientists. This will revolutionise our capabilities to quantify rates of geoscientific processes from the Anthropocene to deep time. This requires novel infrastructures (instrumentations) and highly qualified staff for operation, development and maintenance. The Geo-TIME facility provides the services to geoscientists to fully benefit from such state-of-the-art technology.

Vision for the future

The proposed infrastructure is dedicated to the determination of timescales and rates of processes operating from seconds to billions of years. The vision for the future is to develop innovative analytical, geochronological and geochemical approaches at various scales that will keep the Swiss geoscience community at the forefront of international research and education. Such a distributed facility will be unique in its ability to train future students from different Swiss universities in the latest methods to characterise, date or assess the formation mechanisms of various geological samples.

The long-term vision is to expand this national infrastructure to include instrumentation addressing time scales of environmental and climate change topics such as quaternary sedimentation, ^{14}C, luminescence dating and other cosmogenic nuclide dating, groundwater transport and dating of glacial samples on decadal to millennial timescales, but also planetary and space topics.

Recent developments

The national/international context

The Geo-TIME proposal was submitted and prioritised by swissuniversities and the ETH-Board Committee as one of the top proposals for funding listed in the 2023 Swiss Roadmap of Research Infrastructure. It has attracted considerable interest from national and international geoscience communities and institutions interested in establishing absolute and precise time markers. This interest has recently expanded beyond the geosciences, through a renewed emphasis on planetary science. The ongoing discovery of exoplanets, the joint NASA-ESA Mars Sample-Return Mission, the NASA and JAXA asteroids sample return missions, and new expeditions to the Moon are some of the events that underscore this renewed interest. These missions will provide scientists with key samples to answer pressing questions about the formation and evolution of the Solar System, including its chronology. In addition, new multidisciplinary centres have recently opened to pursue research on topics, such as the Life in the Universe Centre at the University of Geneva and the Centre for the Origin and the Prevalence of Life at ETH-Zurich. These centres were established to conduct cutting-edge research at the interface of earth sciences with biology, astronomy, chemistry, physics, and climate sciences.

Specific major successes and recent developments

As previously stated, following the 2021 Geoscience Roadmap document, a Geo-TIME proposal was evaluated by SNSF as one of the top proposals for funding in the 2023 Swiss Research Infrastructure Roadmap. Important milestones have already been successfully implemented: 1) two latest-generation Electron Probe Micro Analyzers (EPMA) equipped with a soft X-ray emission spectrometer have been installed at the Universities of Geneva and Bern placing Switzerland in a world-leading position for the analysis of minerals and other solid materials, with exciting applications for the study of geological and environmental processes; 2) a team from the Swiss Plasma Centre at EPFL, in collaboration with the University of Lausanne, has made significant progress in the construction and development of a new ion source for generating a high-density negative ion beam with applications to the Secondary Ion Mass Spectrometers, a priority in the Geo-TIME project; and 3) the ability of femtosecond lasers to improve *in situ* dating techniques in minerals using LA-ICPMS is being tested at ETHZ.

Description and development prospects

The current geopolitical context requires additional attention to nuclear safety and the measurement of radiogenic nuclides, which uses some of the technologies of geochronological research defined in the Geo-TIME project. The Secondary-Ion Mass Spectrometry (SIMS) laboratory at the University of Lausanne has been discussing with the International Atomic Energy Agency (IAEA) the establishment of such analytical procedures in Switzerland.

The development of new technologies applicable to the determination of timescales of processes in the geosciences, such as femtosecond lasers, new detector systems (e.g. Zeptona Faraday detector) and novel mass spectrometer geometries (e.g. LA-ICPMS-TOF and MS-MS-ICPMS) is also relevant to Geo-TIME. These instruments evolve on an annual basis and any modern infrastructure hosting them must be able to renew and update them within an adequate time frame.

Future needs

Scientific need, impact and urgency

The main narrative of the 2021 Geoscience Roadmap project Geo-TIME remains relevant, that is, determining timescales and process rates with the highest possible precision and accuracy across a range of scales for Earth, environmental and planetary sciences. Fundamental processes to be addressed include the rate of plate tectonics, the emergence of continents, timescales of volcanic eruptions, the diffusion of elements through solid materials, the rates of weathering and erosion, the formation of planets, and climatic variability. There are also pressing societal demands to better understand strategic metal deposits for the energy transition, volcanic hazards, and the impact of climate change, while clear strategies are needed for fundamental geoscientific themes such as carbon capture, long-term safe waste disposal, paleoseismicity and nuclear safety. In the international context, there is a renewed emphasis on planet formation, the evolution of life, and nuclear safety.

The Geo-TIME infrastructure draws on the strengths of an internationally recognised, Swiss-based research community that has further grown since 2021. The new federated and coordinated infrastructure will fill a gap in terms of the latest generation of instrumentation and improve the efficient use of costly instrumentation at the national level. In addition, Switzerland leading research in *in situ* geochronology has contributed several reference materials and novel protocols to the global scientific community and this role will be strengthened with the new instruments and novel analytical developments.

Community

The beneficiaries of this infrastructure are scientists of national universities and research institutes in the ETH domain, new research centres on the origins of life, and the international geoscience community. The infrastructure is also attractive for potential future National Centres of Competence in Research (NCCRs) combining geosciences, biology, chemistry and astrophysics. Time-resolved geodata are also crucial for the Swiss geological community in the compilation of geological maps. This infrastructure will foster short- and medium-term scientific exchanges within the international geoscience community, making it attractive for sample return missions beyond Earth.

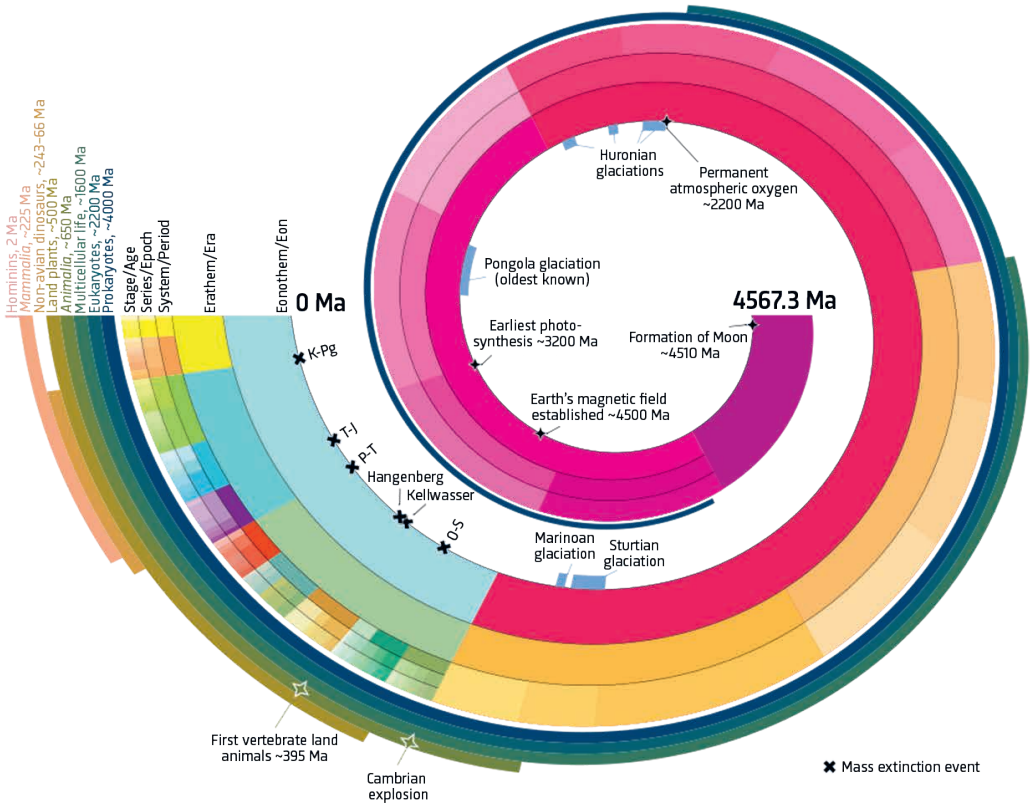


Figure 4: Geological time scale, representing the evolution of the planet based on the chronological dating of the rock record. This evolution is defined by events on all time scales, which the Swiss Geo-Time facility aims to study in detail using the most advanced instrumentation.
Source: Wikimedia Commons/Jarred C. Lloyd

The geoscience pillars Geo-EXPLORE and Geo-OBSERVE are particularly linked to the Geo-TIME research infrastructure to characterise the collected or observed material. Collaborations with the material science community, which is at the forefront of developing innovative materials for solar panels and semiconductors, will be enhanced by the Geo-TIME facility as some of the instruments are also widely used to characterise material surfaces. This infrastructure will also be attractive to companies working on sustainable materials in the construction and energy sector.

Researchers involved in Geo-TIME participate in the international drilling programmes, International Ocean Discovery Programme (IODP) and ICDP, and some of the research carried out will involve samples from these programmes. Through the two centres for the Origin of Life, several researchers are involved either in sample-return missions (NASA, ESA or JAXA) or in large research consortia such as the Origins Federation. The new infrastructure will also support collaborations with the IAEA.

5.4 Pillar IV — The Swiss Geo-EXPLORE facility

Description infrastructure

The Swiss Geo-EXPLORE facility is aimed at providing access to 1) novel cutting-edge *in situ* analytical infrastructure and 2) professional and targeted curation of geoscientific samples such as drill cores as well as surface terrestrial and extraterrestrial samples. It is envisioned to establish a centralised hub where geomaterial processing (e.g. drill cores and related samples, other terrestrial and extraterrestrial samples) can be performed according to international standards using proper sampling environments coupled with highly sophisticated *in situ* analytical equipment. This includes specialised laboratory infrastructure for the combined sampling of geomaterials and sensitive organic molecules (e.g. DNA). The infrastructure will be openly accessible to the Swiss and international research community as well as industry (e.g. Nagra) and public sector entities (e.g. Swisstopo). The infrastructure will also form the Swiss hub of the international continental and ocean scientific drilling programmes ICDP and IODP – both organisations highly support such an infrastructure in Switzerland through officially declaring it an 'entrusted' facility once established.

State-of-the-art *in situ* analytics and long-term, curated geomaterial storage are an important pre-condition to conduct qualitative and innovative geoscientific research at the highest international standards. From an infrastructure perspective, the facility should at least feature the following: 1) geomaterial cutting, *in situ* sampling and description facilities under specific environmental (e.g. anoxic conditions) and contaminant-free/sterile conditions; 2) analytical technologies for *in situ* element and high-resolution organic molecule analysis; 3) core-scanning facilities for petrophysical properties, 4D X-ray CT visualization, visible and near infrared imaging, and element composition of rock, sediment and other geomaterials; 4) sufficient capacity for professional long-term sample curation and storage under appropriate conditions for optimal sample preservation (e.g. cold storage, freezer storage, discrete sample storage); and 5) qualified and long-term employed professional staff. Possible Infrastructure building designs have already been projected in preparation for the previous roadmap stage. This is an advanced infrastructure concept.

Vision for the future

A Swiss Geo-EXPLORE facility is required to continue exploring and probing Earth's interconnected lithosphere-hydrosphere-amosphere-biosphere systems through scientific drilling, and more importantly, contain cutting-edge analytical, sampling and storage facilities. It will continue to strengthen Switzerland's leading role in international scientific sampling programmes (e.g. IODP, ICDP, joint NASA-ESA Mars Sample-Return Mission) and interdisciplinary research, from the exploration of the deep subsurface to the analyses of extra-terrestrial materials. It will equip the Swiss research community with novel, next-generation *in situ* analytical technology currently unavailable in Switzerland and scarce internationally, enabling sophisticated analyses of geomaterials. Additionally, through coordinated and centralised long-term curation efforts under specific environmental storage conditions, the facility will prevent the loss of invaluable cores and samples currently stored at local research laboratories, where they are at high risk of being discarded due to the lack of space and poor conservation conditions. Furthermore, the facility will support the training of undergraduate and early-career researchers in Switzerland and abroad, including the development of active collaboration with geoscientists from the Global South.

Recent developments

The national/international context

Many ongoing (e.g. NamCORE, DOVE, DIVE, WBDP, ADD-ON, etc.) and future (e.g. Sunda Shelf, Poso, Belize Barrier Reef, etc.) projects under the umbrella of the inter-national scientific drilling programmes (IODP, ICDP) have been initiated and are being led by Swiss researchers. The organisation of the IODP and ICDP which are both aimed at exploring Earth's interconnected lithosphere-hydrosphere-atmosphere-biosphere systems, has changed towards a more integrated land-to-sea approach. The reorganisation of the IODP (IODP^3) has emphasized the role of Europe in international scientific drilling and with that, amplified the role of Switzerland as one of the leading nations. Swiss leadership in scientific drilling builds on long-term expertise and is a recognised precondition for the continuous education of the next generation of scientists and active involvement in forthcoming programmes. As a result of Switzerland's active and successful involvement in these programmes and its role in shaping their scientific planning, SNF has renewed memberships to scientific drilling programmes on land (ICDP) and sea (IODP^3) for the period 2025–2028. Switzerland has been heavily invested in realising past large-scale scientific drilling projects but is lacking the facilities necessary to also become a leader in the downstream core analytical part of these projects. Swiss researchers are currently heavily dependent on facilities abroad to reach Swiss-funded project goals. The demand and access needs for geo-analytical facilities specifically designed for drill-core

and sensitive geomaterial analysis as well as for expertise in sample curation and storage is constantly high and expected to increase both nationally and internationally.

Existing international infrastructures have reached their capacity limits and are not easily accessible (overseas locations) to the Swiss research community. Suitable facilities providing and centralising *in situ* state-of-the-art analytical equipment in Switzerland are not in place. New cutting-edge analytical equipment is rare and spread out amongst various Swiss institutions and so, are cumbersome to access. Dedicated facilities to properly sample, analyse, store and curate core archives and sensitive (extraterrestrial) samples under specific environmental conditions (e.g. T-control, relative humidity-control, contamination-free, anoxic) are lacking. This is particularly a problem for recently developed approaches such as sedimentary (ancient) DNA, where the development and application of these methods is expected to dramatically accelerate in the near future as emphasized by a recent noble prize award in the field of ancient DNA analysis. Appropriate characterisation and storage of valuable drill core and extraterrestrial samples is an important precondition for subsequent targeted analytical approaches using sophisticated mass spectrometry techniques available at universities in Switzerland and abroad and as envisioned for the Geo-TIME network.

Specific major successes and recent developments

Owing to the growing societal, industry and fundamental research demands, the field of *in situ* sampling and analysis has recently made major technological advances. Analytical methodology has advanced substantially allowing for much more sophisticated and novel applications especially regarding the *in situ* analysis of elements and organic molecules at the µm scale and in 4D. New core analytical technologies, such as spectral CT (computed tomography) scanning technologies combined with geochemical and geophysical logging, allow for detailed insights into the cycling of elements through rock-fluid interactions in the lithosphere which is necessary for a better understanding of geodynamics and novel carbon capture, and storage technologies. High-precision characterisation of subsurface core data with *in situ* high-resolution laser ablation MALDI XR FT-ICR-MS analysis of organic molecules directly on clean drill core surfaces allow for novel insights into sub-seasonal-scale reconstructions of temperature that will aid future predictions of climate variability in a warming world while also allowing to grasp the composition and stability of organic

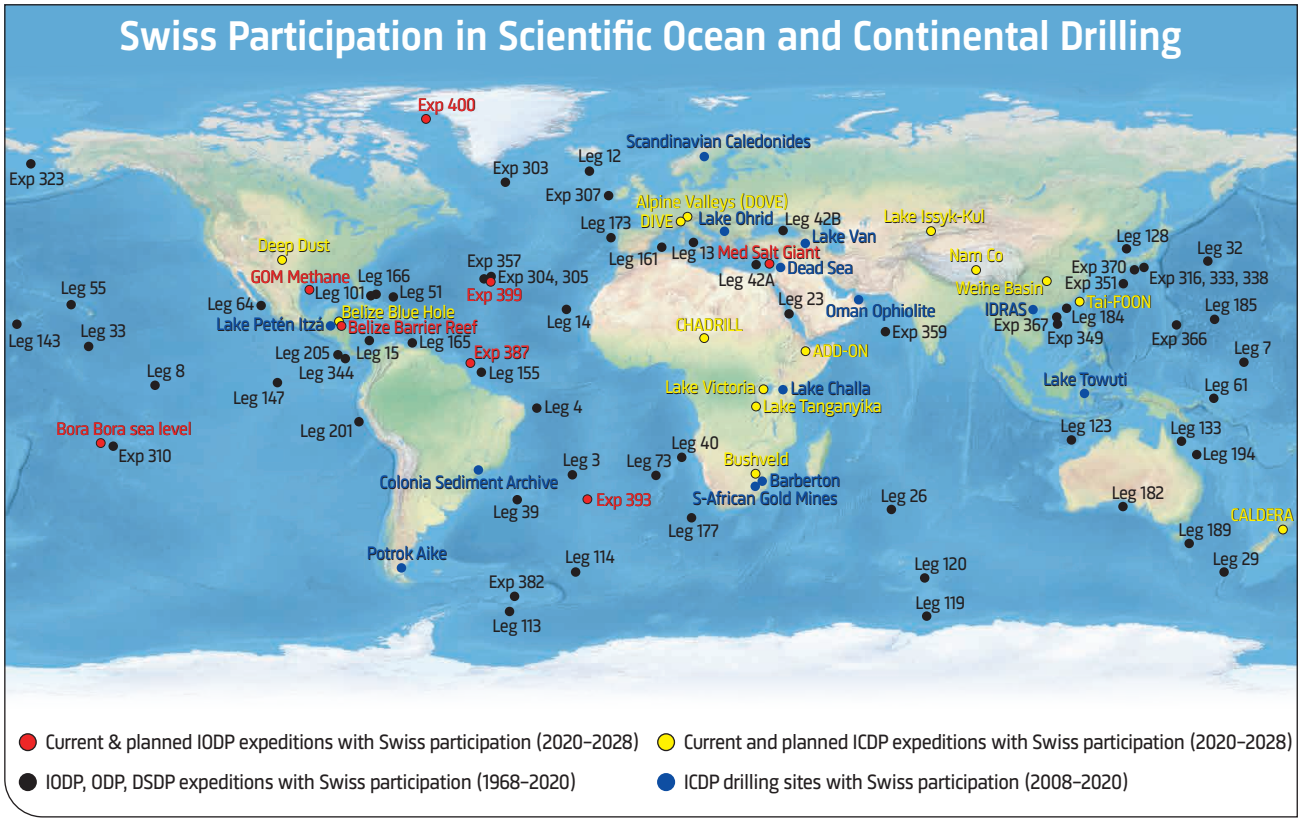


Figure 5: World map showing past and current Swiss participation and leadership in international ocean and continental scientific drilling programmes since 1968 (IODP) and 2008 (ICDP), respectively. Continued SNF funding (2025–2028) of ICDP and IODP3 memberships allows the advancing of projects currently in their initial stages of planning and workshop phase. Source: Miriam Andres, UNIBE

molecules at unprecedented resolution and detail. Existing analytical equipment in Switzerland is outdated and distributed at individual institutions and not broadly accessible for the user community to date. Geo-EXPLORE is aimed at filling this technology gap by creating a cost-efficient and shared infrastructure.

A centralised Swiss-community-based geoanalytical infrastructure bid from the last roadmap process for such an analytical and storage facility has received excellent evaluations by international expert reviewers and written confirmation by the IODP and ICDP to be labelled as entrusted facility/laboratory for future projects under the umbrella of these international programmes.

Future needs

Scientific need, impact and urgency

The relevance of a Geo-EXPLORE facility remains as high as already expressed in the previous roadmap (referred as P-DIG Physical Data Infrastructure for the Geosciences). There is still an urgent need for the application of advanced analytics on newly acquired core and sample (terrestrial and extra-terrestrial) material as well as sample curation and storage similar to the last thematic roadmap stage. Probing Earth's lithosphere is essential for understanding Earth's interconnected systems from the surface to the mantle. International scientific programmes also highlight the urgency and potential of re-studying archived cores and geomaterials with novel cutting-edge techniques for higher resolution analysis. Unique geomaterials have significantly contributed to formulating hypotheses and advancing research on Earth's past, present, and future. Core material analysis is expected to drive breakthrough discoveries in geosciences, with societal relevance in coming decades.

Switzerland has established leadership in both continental and ocean scientific drilling and hosts the Global Research Project (GRP) Past Global Changes (PAGES), combining sediment and ice records with modelling to assess future global change. Establishing a Swiss-based integrative geomaterial analytical facility, such as Geo-EXPLORE, will enhance this expertise and address analytical capacity gaps nationally and internationally which will also enable cross-linkage with other fields of research that have not been realised to date.

Scientific drill cores, related samples and datasets address societal needs by providing data for predictive models of global warming, research into metal resources, geothermal energy, nuclear waste storage and underground carbon capture and storage sites, as well as understanding natural hazards such as earthquakes, landslides, floods, droughts, storms and tsunamis. This research informs disaster prediction, resource sustainability, and environmental impact strategies. Additionally, studying biodiversity through drill cores has led to hypotheses about speciation, extinctions, and ecosystem resilience, offering insights into the effects of human activity on biodiversity. Scientific drill cores have shown to provide pieces of information about early life and early environments on Earth. Sediment core analysis has also shown to provide insight into Earth's critical zone processes necessary to better understand factors governing soil health and recharge of contaminant-free groundwater resources.

With advanced technology for high-resolution geomaterial measurements, subsampling, and storage, the Geo-EXPLORE infrastructure is crucial for Swiss researchers to stay at the forefront of technological advancements, sustain world-class research, and enhance Swiss-led international collaborations. It will serve as an interdisciplinary science hub addressing key scientific questions and societal challenges.

Community

The Swiss Geo-EXPLORE facility aims to be a globally recognised platform, allowing Swiss scientists to join the international effort to understand earth processes via *in situ* geomaterial analysis. This initiative is supported by Swiss cantonal universities, ETH institutions, and federal agencies which will form the core group of the infrastructure users. The infrastructure will benefit a large interdisciplinary community, train future researchers, and foster international research partnerships, including those with countries in the Global South. Close analytical liaisons are envisioned with the life sciences in the field of DNA sequencing and bioinformatics. The envisioned infrastructure is tightly linked to major international programmes such as PAGES. The international drilling programmes (IODP and ICDP) officially highly endorse Switzerland's vision for such a facility. The planned analytical platform will also be beneficial for federal agencies (e.g. Swisstopo) and industry (e.g. Nagra) entities (geothermal energy exploration, CO_2 sequestration, geohydrology, nuclear waste storage) promoting intersectoral and public-private partnerships. Geo-EXPLORE will tightly relate to Geo-DATA for the exploitation and archiving of meta- and analytical data, as well as with Geo-TIME for sample characterisation and dating of samples acquired at the Geo-EXPLORE facility.

5.5 Foundation — The virtual Geo-DATA infrastructure

Description

Geo-DATA proposes to establish an integrated digital data infrastructure for the geosciences, including *in situ* observations and remote observations (e.g. satellite data) connected through the geographic coordinates of each observation. This infrastructure would allow for comprehensive data management, harmonisation, access, storage and curation as well as support sophisticated analyses, visualisation, modelling and simulation tasks. This would serve as a virtual laboratory environment that is required for holistic, groundbreaking research in the community.

Vision for the future

Switzerland's key competences are in education, expert knowledge in both geosciences and data science, data sampling, and technology development. There is a strong foundation to produce world-leading scientific knowledge and innovation. However, to safeguard this standing for the years to come, an easily accessible data and processing infrastructure is needed, such that researchers can focus on their core competency and create knowledge from data. Switzerland should provide this capability in an independent, trustworthy and functional manner. We advocate for a decentralised, but connected and standardised infrastructure, while maintaining sovereignty in terms of data management & processing/analysis.

Recent developments

The national/international context

As mentioned in the finding and recommendations, the challenges brought up by the recently growing use of AI are clearly pivotal for the envisioned Geo-DATA infrastructure. Next to the availability of AI for data processing, there is an increase in the variety of the data being used. This is explained by the emergence of new(er) data sources including Citizen Science (i.e. also due to portable digital devices), the availability of satellite-based or airborne remote sensing data and the complementary data available from tracking systems such as Internet of Things (IoT). In particular, the growth of both openly accessible and commercially distributed remote sensing data unlocks unprecedented data volumes and global observation capabilities. The main distributors of openly and freely available data sets are commercial cloud platforms, although some national initiatives outside of Switzerland, like the French PEPS server, also provide data.

Switzerland was a pioneer in the field of georeferenced Earth Observation (EO)-data, as seen with the Swiss Data Cube (SDC), but has now been overtaken by other countries. Although, there is still a variety of different local initiatives within Switzerland, we witness a certain lack of coordination across the research and user communities due to the absence of an agreed strategy and a driving entity. Internationally, the EU Copernicus programme (as a service and infrastructure), fed by governmental needs, startups, research and a variety of business opportunities, is a main driver for environmental monitoring and the EO-based service economy that is growing quickly. Switzerland fell behind in this context, by continuously postponing discussion about its affiliation with Copernicus missing out on accessing data from the programme. For example, the newly developed CDSE which allows access to Copernicus satellite data including a standardised interface for easy access and processing of earth observation data.

Specific major successes and recent developments

In general, many initiatives were started and continue to be developed by Swiss researchers, be it efforts to capture new forms of data (e.g. new satellite missions, Aerosol Remote Sensing Data Centre Unit – ARES) or infrastructures at individual institutes. The ARES infrastructure as an example has been taking up its operations, however, the digital data portal for this RI is not yet clear. Only with a dedicated infrastructure for data access and processing, can such valuable data generators be used and optimally combined with other complementary data types.

The concept of Digital Twins is a newly emerged topic that is being implemented, for instance by Agroscope for the Swiss agricultural landscape. This infrastructure merges several types of data streams (satellite, meteorology, soil and *in situ* data) for near real-time as well as long-term analysis of the agroecosystem for agricultural applications. The swissEO project within swisstopo is making progress towards a drought warning system for Switzerland, and additionally making analysis-ready, free satellite data available from the Copernicus Sentinel-2 satellites. This initiative is also aligned with the Swiss Geoinformation Strategy. Furthermore, istSOS is an example of a software, developed by SUPSI, to easily manage sensor networks and distribute their data in a standard way.

Switzerland recently played a pioneering role by generating EO-data with the COST-G initiative that emerged from the former Horizon 2020 project EGSIEM (European Gravity Service for Improved Emergency Management). Based on these two projects, combined and unified products for Terrestrial Water Storage (TWS) as measured by satellite gravimetry were developed. These initiatives significantly

contributed to TWS being adopted as a new Essential Climate Variable (ECV) in 2022 by the GCOS as well as TWS being now very close to becoming a part of the inventory of Copernicus data. The significance of TWS and the future vision about operationally measuring TWS from space was also just recently underlined by a resolution of the IUGG that was submitted and approved at the IUGG 2023 General Assembly.

At the international level, services like the WMO Global Greenhouse Gas Watch (G3W), the Copernicus CO_2 Monitoring and Verification Support (CO_2MVS), the ICOS Carbon Portal, and the world glacier monitoring service are examples of international infrastructures for specific topics that have high importance and significant contributions from Switzerland. The ICOS is arguably one of the most advanced and established data portals, featuring nearly 500,000 datasets and on average approximately 8000 downloads per week. It illustrates the value and efficiency of a federated and FAIR structure that can be accessed machine-to-machine and referenced at the national level. Furthermore, the EC has recognised the need for research data management and initiated the EOSC to guarantee scientists' access to data-driven science. They have also established flagship initiatives in the domain of geoscience such as Destination Earth Initiative (DestinE, Digital Europe Programme DIGITAL).

Future need

Scientific need, impact and urgency

A modern, performant, integrated and interoperable geosciences data infrastructure is the backbone of almost any scientific activity. Not only will it provide data to work with (including ML/AI workflows), but also storage and archive space for data with relevant access services (including search and discovery) for mainstream as well as long-tail data which is the foundation of FAIR, reproducible and open science.

The envisioned Geo-DATA infrastructure will be key to answering a wide range of societally relevant questions. A concrete example is seen in the agricultural landscape that is being impacted by climate change, threatening agricultural production and accelerating land degradation. Geodata plays an essential role in achieving sustainability and resilience since it a) allows one to identify areas that are under threat or endangered and b) provides the basis for informed decision making. The same is true for the monitoring of further environmental parameters (e.g. atmospheric composition, biodiversity, forest monitoring, land use change, climate change effects, natural hazards, natural fluxes and greenhouse gases) that are crucial in understanding the underlying environmental processes and supporting the mitigation of economically or societally undesired developments.

With AI now being a part of our daily life, and the climate crisis and biodiversity decline becoming major threats to human well-being, the need for such an infrastructure has tremendously increased. As such, standardised procedures to easily and efficiently access and process data is key as this ensures reliable and comprehensive research and a better understanding of our Earth system to mitigate the challenges we are facing.

Community

Due to the comprehensive and interdisciplinary characteristics of such an infrastructure, it would be used by a majority of the geoscience community and beyond. Establishing it as a properly maintained and governed community infrastructure is crucial for success because data management and curation, despite their recognised benefit, are usually not a core interest for individual researchers. The infrastructure would strengthen the ability to carry out high-quality research by reducing efforts on gathering and pre-processing data and enhancing the quantity and quality of research output such that more comprehensive approaches can be employed. In addition, the fluid boundaries with other disciplines allows exchanging data through the unifying element - the geolocation - thus making more diverse data broadly available. Complementing geosciences with observations from for example biology, chemistry and vice versa will be key to obtaining a complete image of earth processes. Standardised interfaces and data access are thus crucial to connect available infrastructures and build up new ones where needed.

This integrative Geo-DATA infrastructure would provide more relevant and structured data, while also serving as an information repository for decision support at the level of municipalities, cantons and the federal government, for example in the context of climate change adaptation. The private sector (primarily small and medium-sized enterprises) would also benefit from a shared, structured Geo-DATA infrastructure, in particular by making data access more efficient and enabling higher-quality services related to the environment and earth processes.

Furthermore, we stress the importance of a full affiliation with Copernicus and Horizon Europe, and also welcome increased participation in initiatives such as the EOSC (e.g. Swiss entry node), the NFDI4Earth initiative and the GEO.

6 Conclusions

In this update to the 2021 Geosciences Roadmap, we emphasize the need to maintain a long-term vision and an integrated view within the broad geoscience community, as was already laid-out in the 2021 Geoscience Roadmap. Our recommendation to policy makers is to retain this concept of an Integrated Swiss Geoscience community, supported by five building blocks, the four pillars (Geo-OBSERVE, Geo-MOBILE, Geo-TIME, Geo-EXPLORE) and a strong foundation dealing with data management (Geo-DATA). For such a scientific community to remain competitive at global scale, it is fundamental that the research infrastructures, on which it depends, are sufficiently funded and managed by dedicated and expert staff members with long-term perspectives.

Within the pillars of an Integrated Swiss Geoscience community, Geo-OBSERVE and Geo-MOBILE ensure the necessary operation of observations and monitoring the state of our planet, while Geo-TIME and Geo-EXPLORE, focus on analysing and storing physical samples using a broad array of geochemical and geophysical techniques. Finally, Geo-DATA provide a platform for data archiving and sharing, following the FAIR principles. This integrative construction is what the scientific community needs to produce the state-of-the-art science that our society expects.

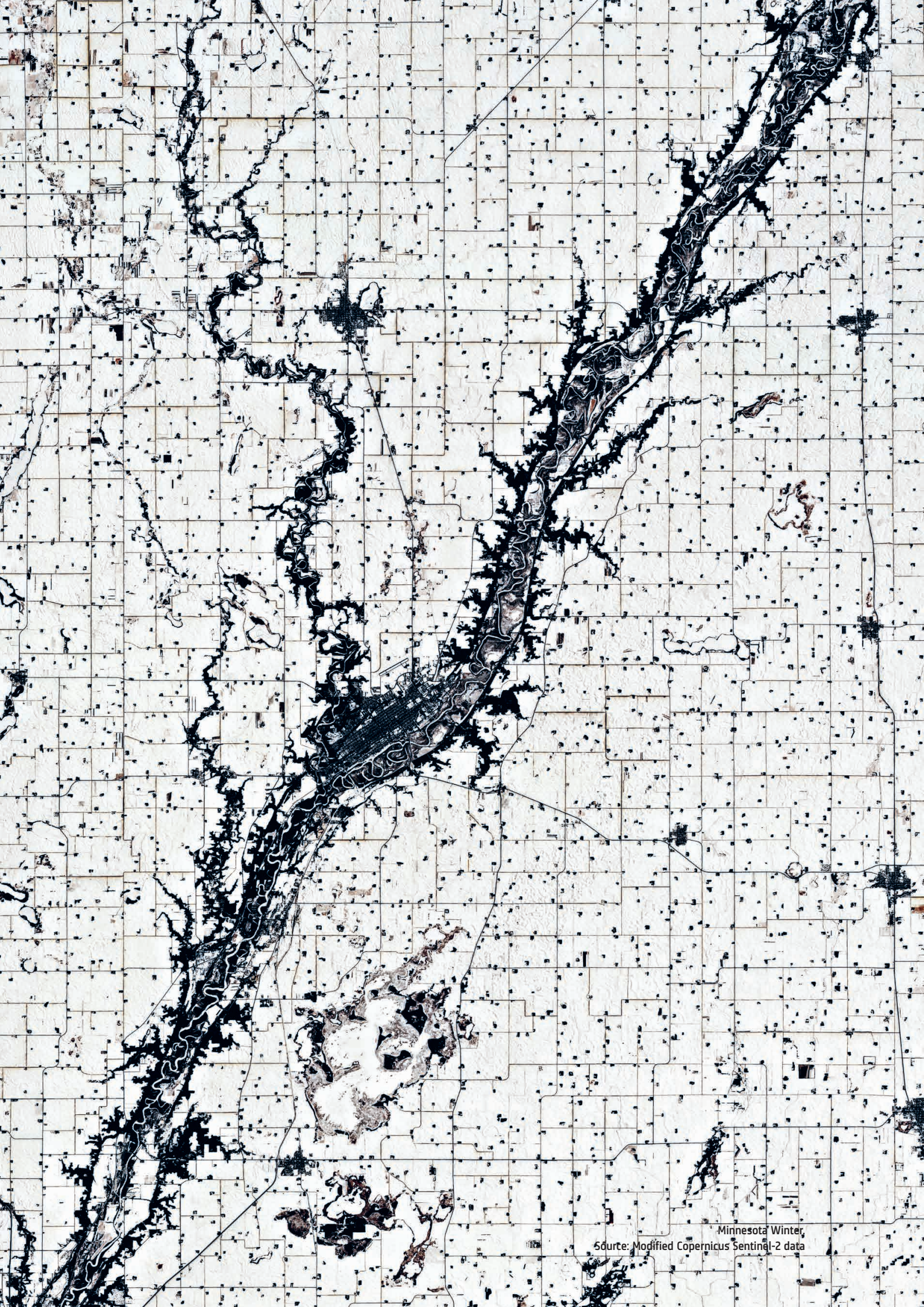
This coherent, integrated framework of the Swiss geoscience community comes from a grass-root consultation process, which involved a large number of scientists in Switzerland, and broadly reflects the most pressing needs and goals of the community. Hence, we believe that the recommendations expressed in this update have a large buy-in and would provide a rational and optimised organisation towards maximum efficiency in the future.

Star Dunes Grand Erg.
Source: Modified Copernicus Sentinel-2 data

7 Abbreviations

ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure
ADD-ON	Afar Dallol Drilling – ONset of sedimentary processes in active rift basin
AdriaArray	Dense regional array of seismic stations covering the region of the Adriatic Plate
Agroscope	Swiss centre of excellence for agricultural research
AI	Artificial Intelligence
AlpArray	Assessing Alpine Orogeny in 4D-space-time Frame
ARES	Aerosol Remote Sensing Data Centre Unit
CERN	European Organization for Nuclear Research
CO2MVS	Copernicus CO2 Monitoring and Verification Support
Copernicus	EU Satellite-based Earth observation program
COST-G	The International Combination Service for Time-variable Gravity Fields
CT	Computed Tomography
DAS	Distributed Acoustic Sensing
DestinE	Destination Earth – flagship initiative of the EC to develop a highly-accurate digital model of the Earth
DIGITAL	EU funding programme focused on bringing digital technology to businesses, citizens and public administrations
DIVE	Drilling the Ivrea-Verbano zonE
DNA	Deoxyribonucleic acid
DOVE	Drilling Overdeepened Alpine Valleys
DSDP	Deep Sea Drilling Programme (1968–1983)
EarthCare	Earth Cloud, Aerosol and Radiation Explorer. Joint JAXA/ESA satellite
Eawag	Swiss Federal Institute of Aquatic Science and Technology
EC	European Commission
ECCE	Expertise Center for Climate Extremes
ECCSEL	European Carbon Dioxide Capture and Storage Laboratory Infrastructure ERIC
ECV	Essential Climate Variable
EGSIEM	European Gravity Service for Improved Emergency Management
EIDA	European Integrated Data Archive infrastructure within ORFEUS
eLTER	Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research
Empa	Swiss Federal Laboratories for Materials Science and Technology
EO	Earth Observation
EOSC	European Open Science Cloud
EPFL	Federal Institute of Technology Lausanne
EPMA	Electron Probe Micro Analyzers
EPOS	European Plate Observing System
ERI	Education, Reasearch and Innovation
ERIC	European Research Infrastructure Consortia
ESA	European Space Agency
ETH	Federal Institute of Technology
ETHZ	Federal Institute of Technology Zurich
EU	European Union
Eumetsat	European Organisation for the Exploitation of Meteorological Satellites
EUREF	IAG Reference Frame Sub-Commission for Europe
FAIR	Findable, Accessible, Interoperable and Reusable
FDSN	Federation of Digital Seismograph Networks
FluxNet	A global network of micrometeorological tower sites
FORWARDS	The ForestWard Observatory to Secure Resilience of European Forests
G3W	Global Greenhouse Gas Watch
Galileo	EU global navigation satellite system (GNSS)
GAW	Global Atmosphere Watch Programme
GCOS	Global Climate Observing System
GEO	Group on Earth Observation
GGIM	Global Geospatial Information Management
GGOS	Global Geodetic Observing System
GGRF	Global Geodetic Reference Frame
GNSS	Global Navigation Satellite System
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	GRACE Follow-On
GRP	Global Research Project
HAS	High-Accuracy Service
HFSJG	High Altitude Research Stations Jungfraujoch and Gornergrat
IAEA	International Atomic Energy Agency
IAG	International Association of Geodesy
IASPEI	International Association of Seismology and Physics of the Earth's Interior
IAU	International Astronomical Union
ICDP	International Continental Scientific Drilling Program
ICOS	Integrated Carbon Observation System
IERS	International Earth Rotation and Reference Systems Service
IGFS	International Gravity Field Service

IGS	International GNSS Service
ILP	International Lithosphere Programme
ILRS	International Laser Ranging Service
IODP	International Ocean Discovery Programme (2013–2024)
IODP	International Ocean Drilling Programme (2003–2013)
IODP³	IODP-Cube: International drilling programme set up by ECORD and Japan.
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
ISG	International Service for the Geoid
IstSOS	Free and Open Source Sensor Observation Service Data Management System
IT	Information Technology
ITU	International Communication Union
IUGG	International Union of Geodesy and Geophysics
IVS	International VLBI Service for Geodesy and Astrometry
JAXA	Japan Aerospace Exploration Agency
LA-ICPMS	Laser ablation inductively coupled mass spectrometry
LA-ICPMS-TOF	Laser Ablation Inductively Coupled Plasma Time of Flight Mass Spectrometr
LEO-PNT	Low Earth orbit positioning, navigation and timing
LéXPLORE	A high-tech floating laboratory on Lake Leman
LRI	Large Research Infrastructure
LWF	The Long-Term Forest Ecosystem Research (LWF) programme
MAGIC	Mass-change And Geosciences International Constellation
MALDI	Matrix-assisted laser desorption/ionization (mass spectroscopy)
ML	Machine-learning
MS-MS-ICPMS	Mass Spectrometry-Mass Spectrometry Inductively Coupled Plasma Mass Spectrometry
Nagra	National Cooperative for the Disposal of Radioactive Waste
NamCORE	The Nam Co Drilling Project
NASA	National Aeronautics and Space Administration
NFDI4Earth	German national research infrastructure for the Earth system sciences
NCCR	National Centre of Competence in Research
ODP	Ocean Drilling Programme (1983–2003)
ORFEUS	Observatories & Research Facilities for European Seismology
PAGES	Past Global Change Project
PEPS	Plateforme d'Exploitation des Produits Sentinels
PSI	Paul Scherrer Institute
RI(s)	Research Infrastructure(s)
RIPA	The Swiss Federal Act on the Promotion of Research and Innovation
SCNAT	Swiss Academy of Sciences
SDC	Swiss Data Cube
SERI	Swiss State Secretariat for Education, Research and Innovation
SGC	Swiss Geodetic Commission
SIMS	Secondary-ion mass spectrometry
SISAL	Swiss Biosites for Sustainable Agriculture and Agroecology
SLR	Satellite Laser Ranging
SNSF	The Swiss National Science Foundation
SUPSI	Scuola universitaria professionale della Svizzera italiana
SwissEO	Swiss Earth Observation
Swiss Fluxnet	Network of six long-term ecosystem greenhouse gas flux measurement sites in Switzerland
Swiss OGS	The Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald
Swiss-QCI	Swiss Quantum Communication Infrastructure
TEAMx	Multi-scale transport and exchange processes in the atmosphere over mountains — programme and experiment
TreeNet	International biological drought and growth indicator network
TWS	Terrestrial Water Storage
UN-GGIM	United Nations Committee of Experts on Global Geospatial Information Management
UNECE	United Nations Economic Commission for Europe
UNECE-WEG	UNECE Working Group on Effects
UNIBAS	University of Basel
UNIBE	University of Bern
UNIFR	University of Fribourg
UNIGE	University of Geneva
UNIL	University of Lausanne
UZH	University of Zurich
VPDrought	Novel approach to disentangle air dryness and soil drought. SNSF-WSL-EPFL project
WBDP	Weihe Basin Drilling Project
WMO	World Meteorological Organization
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research
XR FT-ICR-MS	X-ray Fourier-transform ion cyclotron resonance



Minnesota Winter,
Source: Modified Copernicus Sentinel-2 data

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