EuroGeoSurveys
European Geoscience for Society
The Geological Surveys of Europe

EuroGeoSurveys

Strategic Research and Innovation Agenda

Building a Geological Service for Europe

MARCH 2025

Executive Summary

The EuroGeoSurveys ten-year Strategic Research and Innovation Agenda (SRIA) 2025-2034 sets out a forward-looking framework for the sustainable use and management of Europe's geological resources. Our SRIA sets targeted goals, priorities, and actions to support the energy transition while building European competitiveness. It focusses on geoscientific data, information, and knowledge of the subsurface to address European and global challenges, including climate change, energy security, and resource sustainability. Centred on research, innovation, and collaboration, our SRIA serves as the scientific foundation for our vision of a **Geological Service for Europe** – a permanent, sustainable and data-driven service that will provide critical geoscientific insights for European policymakers, industry, and citizens.

EuroGeoSurveys is a not-for-profit association representing 37 national and regional geological survey organisations, and over 10,000 European geoscientists. Fostering collaboration, EuroGeoSurveys enables harmonisation of geological data at European level, and an expert network resource for managing Europe's subsurface. This collective effort supports the EU's overarching strategic goals, including the European Green Deal and the UN Sustainable Development Goals. Our SRIA identifies research and innovation goals critical to support Europe's policy objectives and drive sustainable, data-driven approaches to manage subsurface resources, environments, and hazards.

Geoscientific And Digital Foundational Framework

- Understanding the Subsurface – Geological Data
- A Sustainable European Geological Data Infrastructure

EGS SRIA 2025

Strategic Geoscientific Focus

- Energy Transition & Decarbonization
- Responsible Raw Materials
- Sustainable Management of Groundwater in a Climate Change Context
- Managing Geohazards and Environmental Risks

Integrating Subsurface Management And Stakeholder Engagement

- Urban Geology, Geoheritage and Land Planning
- Societal and Economic Impact: Knowledge Sharing, Policy Support, and Public Engagement

Understanding the Subsurface – Geological Data: Detailed onshore and offshore geological data, maps, and models are essential for informed decision-making across sectors, supporting land-use planning, resource management, and environmental protection.

A Sustainable European Geological Data Infrastructure[1] (EGDI): Geoscientific digital infrastructure and Findable, Accessible, Interoperable, and Reusable data, delivered through EGDI, will provide policymakers, researchers, and industry with critical subsurface and offshore data, promoting transparency and informed decision-making.

Energy Transition & Decarbonisation: The subsurface is key to the energy transition: through geothermal energy deployment, and subsurface storage of carbon dioxide and hydrogen, supporting the EU's climate neutrality goals and implementation of the Net-Zero Industry Act[2].

Responsible Raw Materials: Addressing Europe's critical raw materials (CRM) dependencies, domestic production and sustainable raw materials management requires new exploration and mining models, methods, and technology, supporting implementation of the EU Critical Raw Materials Act[3], promoting circular economy, and reducing environmental impact.

Sustainable Management of Groundwater in a Climate Change Context: Improved understanding of groundwater dynamics, monitoring, sustainable management practices, and new technologies will secure long-term water availability for multiple uses.

Managing Geohazards & Environmental Risks: Geohazard monitoring technologies and data-driven strategies will contribute to risk mitigation for landslides, earthquakes, volcanic eruptions, subsidence, and floods. Standardised soil sampling, assessment, and monitoring will improve soil health.

To boost the impact of its strategic goals, EuroGeoSurveys' SRIA follows a holistic approach, targeting integrated subsurface management and inclusive stakeholder engagement. By aligning with European policy, and targeting delivery through a sustainable **Geological Service for Europe**, our SRIA will enhance Europe's environmental, social, and economic resilience[4] in the face of global challenges.

Contents

Acronyms

AI	Artificial Intelligence
API	Application programming interfaces
CCS	Carbon Capture and Storage
CRM	Critical Raw Materials
DNA	Deoxyribonucleic Acid
EGDI	European Geological Data Infrastructure
EMODnet	European Marine Observation and Data Network
EPOS	Earth Plate Observing System
ETIP	European Technology and Innovation Platform
EU	European Union
FAIR	Findable, Accessible, Interoperable and Reusable
FutuRaM	Future Availability of Secondary Raw Materials Project
GIS	Geographic Information System
GSEU	Geological Service for Europe project
INSPIRE	Infrastructure for Spatial Information in Europe
ML	Machine Learning
NGSOs	National & Regional Geological Survey Organisations
R&D	Research and Development
SRIA	Strategic Research and Innovation Agenda
UAVs	Unmanned Aerial Vehicles
UGF	Urban Geo-climate Footprint
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFC	United Nations Framework Classification for Resources
UNRMS	United Nations Resource Management System
URI	Uniform Resource Identifier
WEFE Nexus	Water-Energy-Food-Ecosystem Nexus

Introduction

Who are we?

EuroGeoSurveys is a not-for-profit member association, established in 1971, providing vital subsurface knowledge to support Europe's competitiveness, social well-being, environmental management, and international commitments. EuroGeoSurveys coordinates a network of 37 national and several regional European Geological Survey Organisations (NGSOs). The NGSOs are mandated to deliver data, information, expert knowledge and advice on the geology (surface and subsurface) and associated natural resources in their respective marine and onshore territories. The network forms a workforce of >10,000 geoscientists, data-experts, and advisors. Collaboration is governed in expert groups and strategic task forces including Earth Observation and Geohazards, Geochemistry, Geoenergy, Geoheritage, Geological Mapping and Modelling, Geophysics, Marine Geology, Mineral Resources, Spatial Information, Urban Geology, Water Resources, International Cooperation and Development, and Subsurface Integrated Spatial Planning.

What is our Mission

EuroGeoSurveys addresses European challenges in the field of geosciences and collaborates on projects that inform European and national policy for the benefit of all European citizens and stakeholders. **Our mission is to enable sustainable and responsible use of the Earth's subsurface environment and resources.** The broad fields of application include effective land-use management, environmental monitoring (e.g., groundwater, soils), infrastructure planning, exploration and development (e.g., raw materials, geoenergy, underground storage), hazard assessment, risk mitigation and more.

Our Position in the European Policy Landscape

The joint activities, projects, and networks of the NGSOs allow a bottom-up data- and expertise-based approach to accelerating the green and energy transitions[5]. Meanwhile, their embeddedness in national and EU mandates (e.g., national legislation endorsing the NGSOs, and the EU CRM Act[3] and Net-Zero Industry Act[2]) drive a parallel top-down mandate.

While the NGSOs typically have a mandate to deliver geological data, information, knowledge, and advice for their respective national or regional territories, they also deliver such services to European stakeholders through the development of integrated information services, collaboration in interregional and European projects, best practices and knowledge sharing, contributions to position papers and other strategic documents, and on-demand advice and policy support. The European position of EuroGeoSurveys and its member organisations is also strengthened by involvement in and collaboration with international networks, expert groups, and initiatives, including CO_2GeoNet, the Zero Emissions Platform, the European Energy Research Alliance Joint Programme on Geothermal and Carbon Capture and Storage, the Euro-

pean Geothermal Energy Council, UNECE (UNFC & UNRMS), EMODnet, FutuRaM, the Green Deal Data Space, SCRREEN, the Water4All European Partnership, the European Commission's DG ENV Working Group Groundwater and DG GROW Raw Materials Supply Group, the European Earthquake Geology Task Force, the European Soil Observatory, ProGEO, UNESCO, the Green Data4All Initiative, EPOS, the European Technology Platform on Sustainable Mineral Resources, International Energy Agency, and more. Thus, the NGSOs, through their collaboration under EuroGeoSurveys, lie at a crucial intersection between government, industry, and academia, and between national and European institutional level, delivering data, information, and knowledge across the spectrum from research through to knowledge implementation.

37 EuroGeoSurveys Members, >10,000 geoscientists, data-experts, and advisors.

Towards a Comprehensive Geological Service for Europe

A Vision to Capitalise Europe's Geological Information and Expertise

The NGSOs are public national and regional institutes with mandates to gather and preserve subsurface information, advance geological knowledge, and advise national stakeholders and society on subsurface use and protection. These NGSO activities cover the full scope of R&I through to implementation through delivery of advice, products, and actions relevant to securing environmental, social, and economic resilience. Such geological R&I, data, and service activities are mostly governed nationally with varying degrees of detail and quality. However, investment in harmonised transboundary geological information of appropriate scale and quality has been limited and mostly results from finite projects.

Recent legislation increasingly recognises the importance of integrating national information at trans-boundary and pan-European level, e.g., the Net-Zero Industry Act and the CRM Act, both supported by outputs of the ongoing Geological Service for Europe project (GSEU). Such knowledge-sharing is also crucial for protection of soils and groundwater, and managing and mitigating geohazards and climate impacts. Without such trans-boundary and European-scale information, there is no European overview of our collective resource potential or risks. Nor is there a framework for European-level support to building the required geoscientific expert knowledge for decision-making, resource management, and EU-level reporting – expertise and best practices that may not be otherwise available at national level.

Currently, there are no incentives for ongoing updates (through R&I) and sustainable structural maintenance (through implementation actions) of geological information at European scale, beyond project-based systems. Nor is there a framework to ensure ongoing integration, harmonisation, and dissemination of geological information and research for all European countries. Crucial information is still lacking for many European regions, hampering a comprehensive overview of resources and subsurface environments and geohazards critical for cross-border and pan-European decision making. These are the roles of a sustainably EU-resourced Geological Service for Europe.

Our **vision is to create the Geological Service for Europe** as the geoscientific reference partner of the European Commission, delivering knowledge of the Earth's subsurface environment and resources as the foundation of a sustainable future for Europe. The Geological Service for Europe will be a permanent and central source of geoscientific knowledge, information, and expert advice for European and national policies, consolidating and integrating the core activities and repositories of the NGSOs in a legally embedded Service that is founded on three strategic pillars:

- **Supporting Decision Making:** The Geological Service for Europe will enhance the capacity to draw on the existing network of experts within the Geological Surveys of Europe to provide policy support and to translate geoscience knowledge to policy challenges. We will enhance our links with the European Commission and other European stakeholders and strengthen our European and international networks and partnerships.
- **Data and Information Infrastructure:** The Geological Service for Europe will develop and manage new and existing data, information, and knowledge infrastructures, operating, maintaining, harmonising and further developing the central European Geological Data Infrastructure (EGDI), delivering harmonised, reliable, and verified pan-European geological data.
- **Applied Geoscience:** The growing demand for science-driven policy and decision-making requires increased investment in research and a more interdisciplinary approach in applied geosciences. The Geological Service for Europe will deliver joint research to support European policy goals on sustainable clean energy, secure supply of critical and strategic resources, climate change mitigation[6], and environmental protection.

Our common data infrastructure, EGDI, is well advanced, with commitment from EGS members to map national databases to European-level harmonised databases delivered through EGDI. Such EGDI databases for raw materials, carbon and hydrogen storage potential, geothermal potential, and groundwater quality and quantity are either already operational or in development through the GSEU project.

A permanent Geological Service for Europe will allow such efforts to be sustained and developed into the future. It will deliver tailored geological services suited to changing policy demands and linked with key academic, government, and industry knowledge partners. Such tailored knowledge services under a Geological Service for Europe might include, for example:

- A European atlas of carbon storage potential linked with European energy and industry data, supporting project derisking.
- State-of-the-art harmonised maps and models of Europe's CRM resources and resource potential.
- A common framework and structure for delivering geoscientific technical actions to support EU bilaterial strategic partnerships on raw materials.
- Near real-time European groundwater quality and quantity monitoring and forecasting.
- Integrated subsurface and Earth-observation models to inform geohazard early warning systems.

A Public Service Supporting Europe's Policy Agenda, Sustainable Development Goals, Strategic Autonomy and Economy

The exploration, responsible exploitation, and development of geological resources is a national concern. Regional and national authorities are responsible for permitting and monitoring mining activities while their economies benefit from the extraction of resources. The protection of environment and mitigation of hazards is often governed locally. Over the past decade, however, management and environmental protection of geological resources are increasingly recognised as key strategic aspects in European legislation, international policies, and global agendas for sustainable development and mitigating the worst effects of climate change[7]. In this respect, the European Green Deal[8–10] and the UN Sustainable Development Goals define the fundamental policy targets and principles for coordinated actions across countries and between sectors.

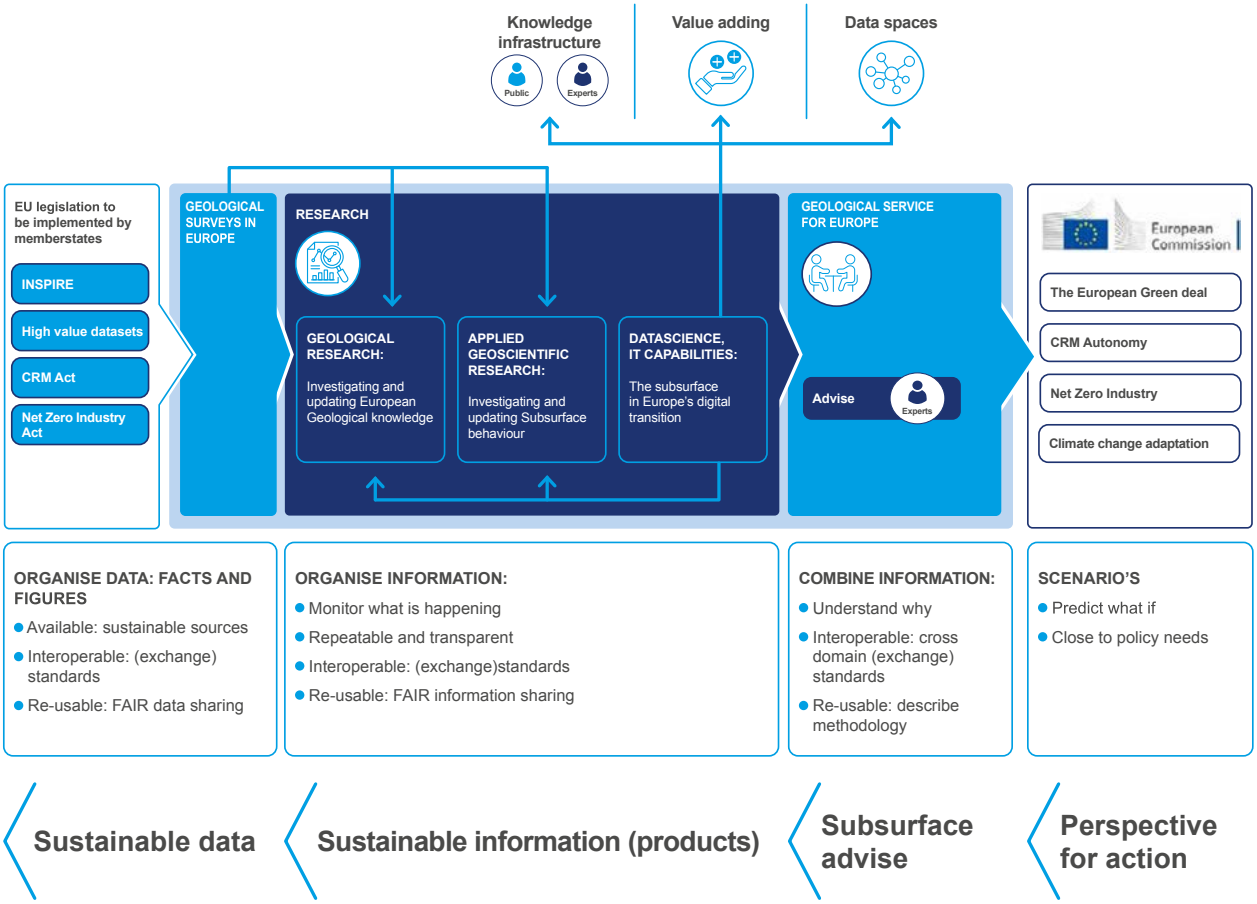
The European Green Deal sets the goal of making Europe the first climate-neutral continent by 2050, while simultaneously resetting economic policy to support competitiveness[11], sustainability, efficiency, and resilience through a coupled green and digital transition[12]. The 2030 Agenda for Sustainable Development[13], adopted by all UN Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet. At its heart are the 17 UN Sustainable Development Goals, which are an urgent call for action by all countries in global partnership, and which – to succeed – require coordinated geoscientific actions across the thematic areas outlined in this SRIA.

Horizon Europe GSEU Project: Major Steps Towards a Geological Service for Europe

The GeoERA Programme (2017–2021: Horizon 2020 co-funded ERA-Net that supported 15 projects in Geoenergy, Groundwater, Raw Materials, and Information Platform) was followed in 2022 by the 5-year Geological Service for Europe (GSEU) project (2022–2027) under Horizon Europe. The project links 49 partners from 36 countries (EuroGeoSurveys, its member NGSOs, and other national geoscientific research institutes). The objective of GSEU is to deliver key pan-European harmonised datasets and atlases informing on European groundwater, geoenergy, raw materials, coastal resilience, offshore substrate, and data structures for foundational geological maps and models needed to support all of these areas. Flagship products are being delivered through the European Geological Data Infrastructure (EGDI), developed with ongoing testing and input from diverse user groups to maximise uptake and application of the data. In parallel, through GSEU we strive to build synergies with related projects and initiatives (e.g., EMODnet, EPOS, FutuRaM, the Green Deal Data Space, SCRREEN), connecting datasets and infrastructures (e.g., EIGL, EPOS), and key partners (e.g., UNECE, JRC) for maximum uptake. We also already work actively beyond the boundaries of the GSEU project to implement needed upskilling, e.g., through a train-the-trainers programme promoting uptake of the UN Framework Classification for Resources (UNFC), mandated under the CRM Act.

The path towards a Geological Service for Europe.

Ultimately, a permanent Geological Service for Europe requires sustainable resourcing to ensure that EuroGeoSurveys and the NGSOs can continue to support the Green Deal through our actions, maintaining and improving key European datasets and knowledge, delivering geoscience-based policy support, mentoring and training geoscientists, and promoting best practices and knowledge sharing.

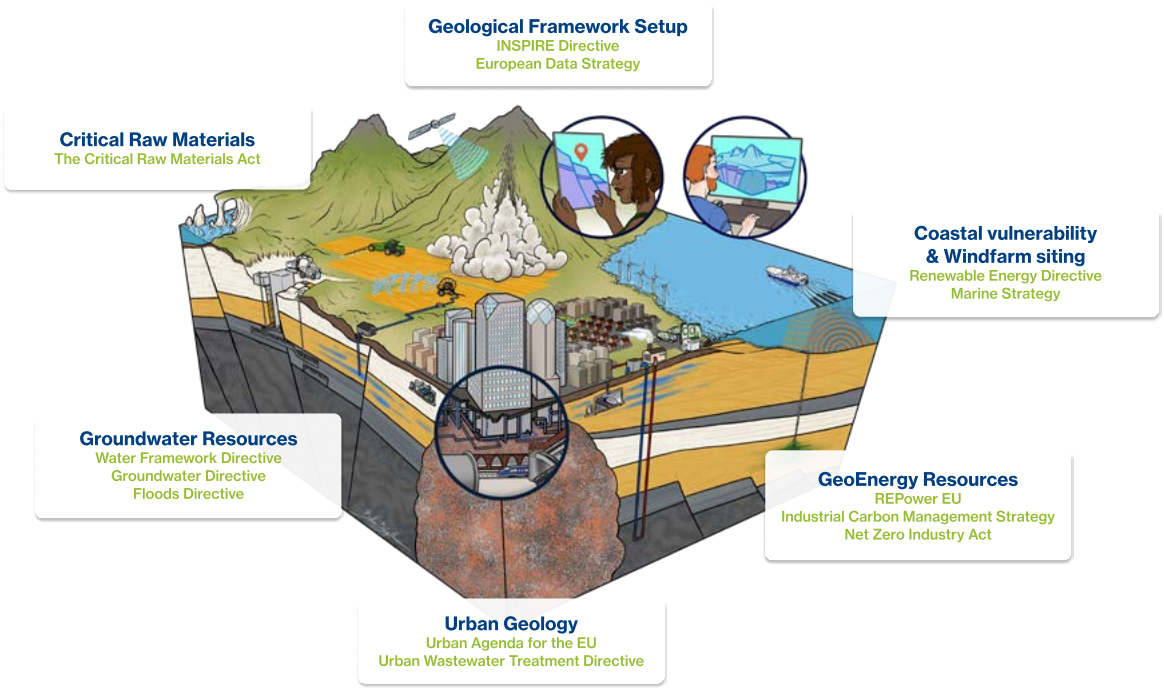


The role of the European Geological Surveys and a future Geological Service for Europe in supporting science-informed EU policy.

A Strategic Research and Innovation Agenda as the scientific foundation of the Geological Service for Europe

Research and Innovation Enables the Transition to Sustainable Use of the Subsurface

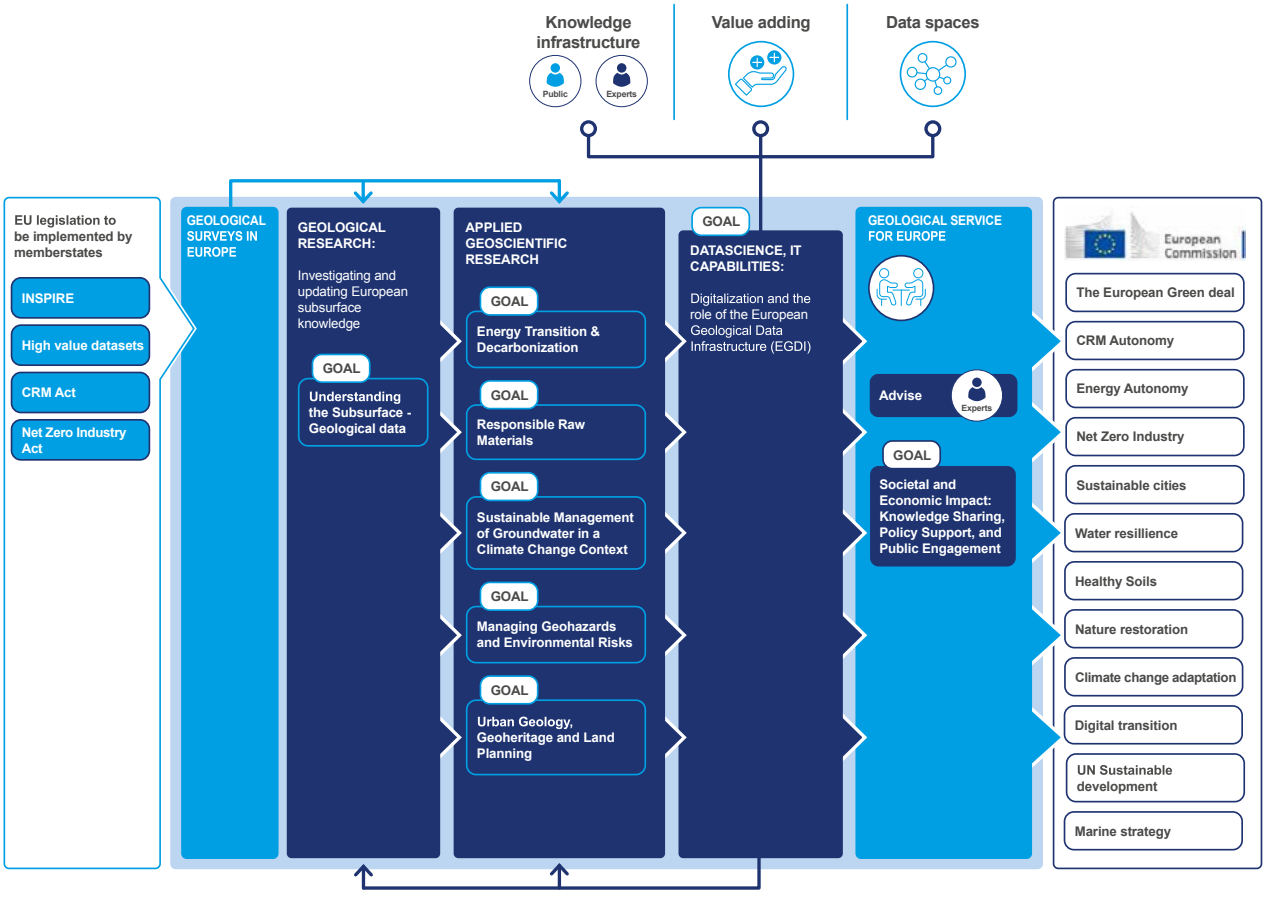
The use of the European subsurface is transitioning from predominantly economic extractive activities towards deployment of innovative, renewable technologies delivering clean and sustainable services to support the European Green Deal and the UN Sustainable Development Goals[14]. This includes geothermal heating and cooling, storage of clean energy carriers and CO_2, protection and responsible use of groundwater resources, and domestic CRM production. This changing and increased use of the European subsurface requires a stronger understanding of the subsurface in new places and depths and providing greater detail and new parameters in places that have been previously mapped and explored. Geological information and knowledge must be applied in new ways as the subsurface becomes more integrated with, e.g., new energy infrastructures and changing urban environments. The deployment of subsurface technologies comes with impacts and, concurrently, increased risks from climate-related hazards. Adequate prevention and mitigation depend on improved forecasting, reduction of uncertainties, and new monitoring techniques.



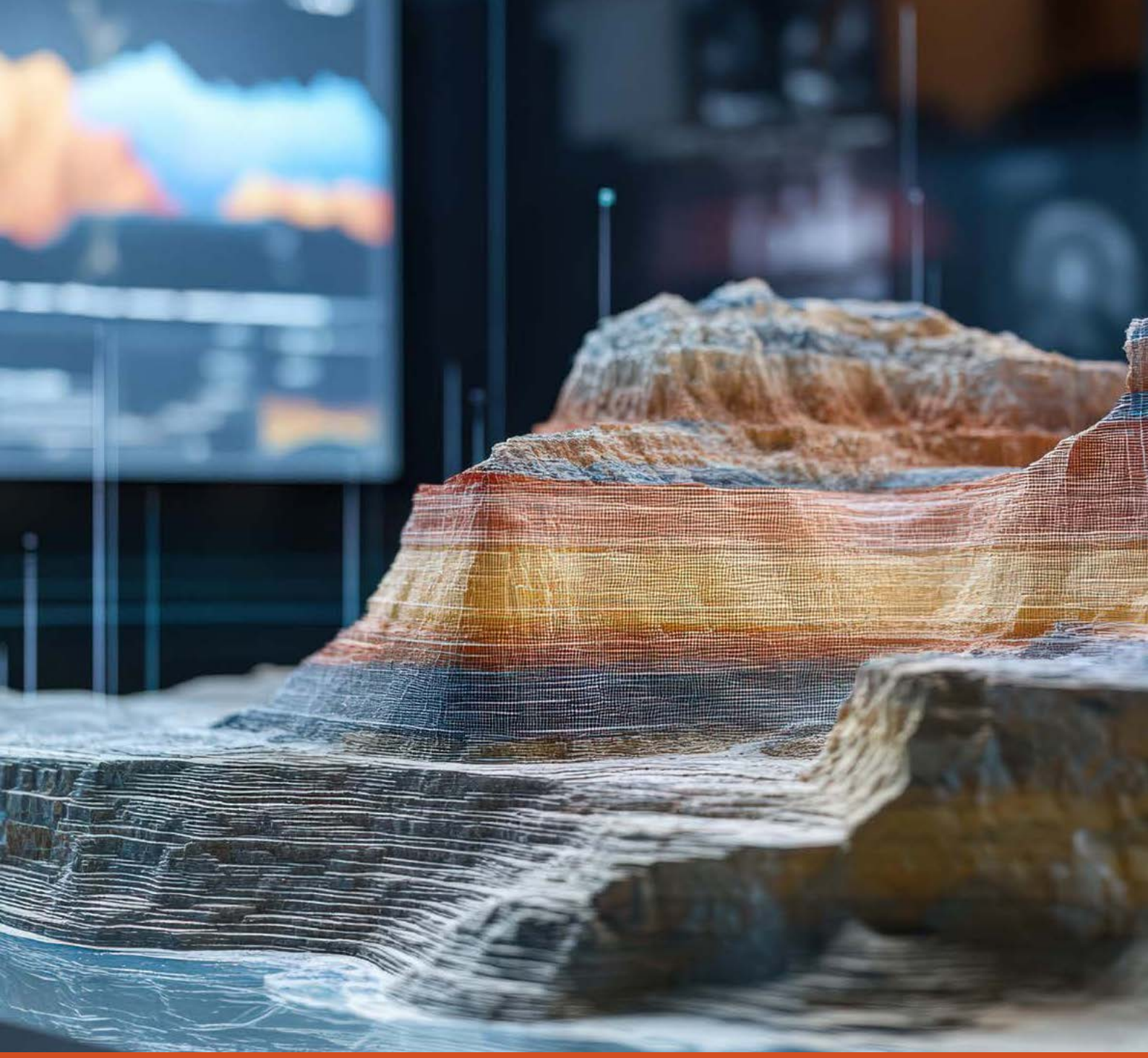
Competing subsurface uses are integrally connected with European Green Deal policy.

Research and Innovation (R&I) is a critical driver for the development of a permanent Geological Service for Europe. State-of-the-art subsurface information and geoscience knowledge are crucial to secure Europe's strategic autonomy, competitiveness, prosperity, and environmental sustainability across a diverse spectrum of sectors including construction, technology, mining, energy, agriculture, and urban development. Concomitantly, geoscience R&I is needed to enable environmental monitoring, nature restoration, and sustainable and efficient management in the face of increasing and competing surface and subsurface uses and a changing climate.

This SRIA sets out how EuroGeoSurveys aims to develop collaborative European geoscience research, building on EuroGeoSurveys' key roles connecting national and European-level geoscience with policy, industry, academia, and society. By delivering this SRIA, EuroGeoSurveys aims to contribute to the success of national-level implementation of European Green Deal policies and achieve a sustainable future through a common Geological Service for Europe.



The structural elements of the EuroGeoSurveys SRIA and connections to science-informed EU legislation and policy.



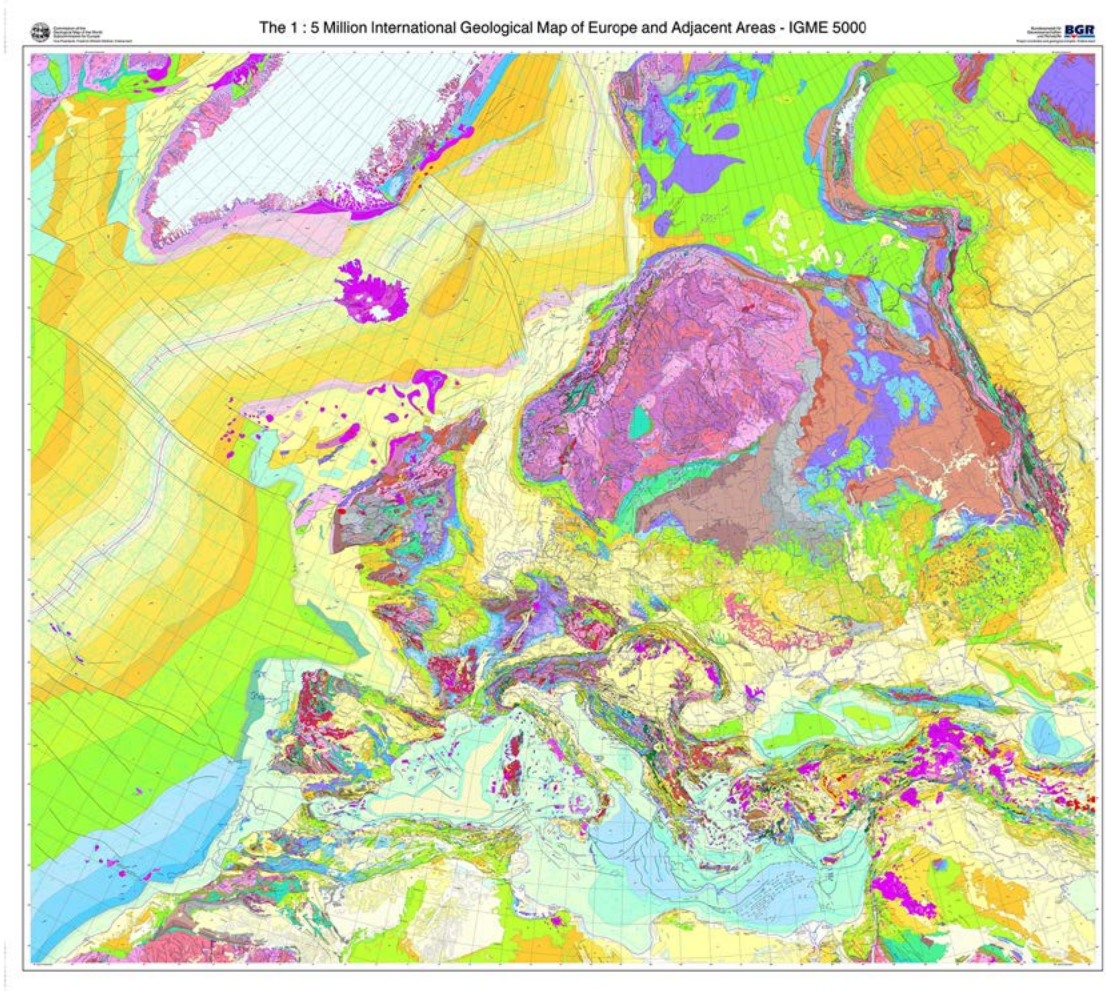
Geoscientific And Digital Foundational Framework

GOAL

Understanding the Subsurface – Geological Data

Responsible economic and environmental planning require precise geological information about the subsurface – information that constitutes the bottom-line for all applications related to subsurface use and resources. To support such planning, 2D and 3D geological mapping is necessary. These maps and models are the foundation of all geological work, allowing geologists to transform data into meaningful knowledge about the structure, composition, resource endowment, and evolution of the Earth. The practical applications of these maps and models are enormous in scope, allowing:

- access to raw materials, including CRM
- discovery and improved access and monitoring of groundwater resources
- support an improved connection between groundwater and surface water resources
- development of geoenergy potential (e.g. geothermal energy, heat and cold, energy storage)
- improved access to mineral resources, surface and subsurface
- mitigation of climate change impacts and other geohazards
- identification and preservation of geoheritage for science, education, and tourism



The 1:5 Million International Geological Map of Europe and Adjacent Areas – IGME 5000 – a collaborative effort of the European NGSOs[17]

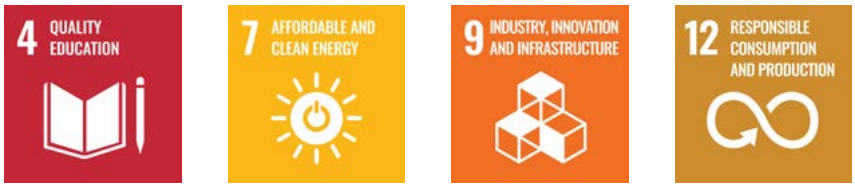
While financially resource intensive, geological mapping is a sound investment, returning a benefit-cost ratios of 4:1 to > 100:1 in terms of, e.g., exploration investment, jobs, taxes and royalties. However, investment at European scale has been limited. Transboundary, harmonised, basic geological data sets of appropriate scale and quality are still lacking for most European regions, and both the surface and subsurface knowledge of the European territory is heterogeneous in both quantity and quality. This presents major obstacles to delivering geoscience-based solutions to surface and subsurface-related enviro-economic challenges.

Effective implementation of new and anticipated European policy and legislation (e.g., CRM Act[3], Net-Zero Industry Act[2], Soil Monitoring Law[15], Renewable Energy Directive[16]), will require continuously updated, high-quality geological datasets, maps, and models. As the nationally (and in some cases European) mandated authorities to deliver this data, the NGSOs have key roles in supporting the implementation of policies comprising the European Green Deal and related industrial policies.

Within the GSEU project, EuroGeoSurveys will deliver (amongst others) basic elements of a geological mapping and modelling framework, including data models (conceptual and physical), new and improved scientific vocabularies, an open-source toolbox for 3D geomodelling, and a meta data service for geological maps, map data sets, and 3D geomodels relevant at the European level.

These GSEU project outputs need completion of the framework by then still missing vocabularies (e.g., for Quaternary, near surface deposits), a system for regional, transboundary correlation of lithostratigraphic units, and establishment of a collaborative platform for joint activities in 2D and 3D modelling. Use of this framework must urgently start by creating harmonised, transboundary datasets of European regions or at continental level in 2D and 3D at scales of 1:250.000 and beyond. Continuous updating and refining of data sets is necessary and will be possible only by embedding this activity in a stable institutional environment.

Beyond this, a modern and effective approach of (re)investing in Europe's marine and continental geological knowledge must be accompanied by innovation measures, e.g., new methods in geophysical data acquisition, exploration of AI-based tools for integration of large data volumes from different sources (geological, geophysical, geochemical) in 3D geomodelling, and development of algorithms for automated generalisation of 2D and 3D geological models. Moreover, innovative pathways of technical and organisational support of national and transboundary geological mapping initiatives should be explored.



Geological datasets, maps, and models lay the foundation for delivering on UN SDGs.

Priority USG1 – Reinvest in updating of geological information of Europe

Over the last two decades, most geological surveys have invested in digitisation and harmonisation of existing geoscientific data, information, and knowledge. The maps are now available as vector maps with attached databases showing mostly surface geology. However, detailed reconnaissance of the subsurface remains incomplete, with poor resolution, or outdated scientific concepts for many regions in Europe.

The collection and continuous update of continental and marine geological data and their interpretation, by establishing geological models (maps, sections and 3D- to 5D-models) and through expertise, is essential to update and disseminate geological information to various stakeholders.

New European legislation (e.g., the Critical Raw Materials or Net-Zero Industry Acts) will require investment to collect additional data, information, and knowledge and to produce European-scale transboundary 3D models at the resolution needed to evaluate mineral and geoenergy resources as well as CO_2 storage potential, across Europe and with common standards.

IMPLEMENTATION

Action USG1.1 – Establish a collaborative Geographic Information System platform

Expected outcomes:

- An open-source, integrated GIS-based platform, allowing for effective and transboundary collaboration of experts in the creation of new regional data sets.
- Defined workflows, training, and support for project teams.
- Guidelines include minimum requirements for geological mapping in Europe for different scales.
- A sustainable organisational structure for custodianship of the data model and vocabularies.
- A solid governance system to ensure ongoing storage, maintenance, and up-dating of the data.

RESEARCH & DEVELOPMENT

Action USG1.2 – Create scientific vocabularies for missing themes to enable data harmonisation at European level

Expected outcomes:

- Scientific vocabularies for Quaternary near surface deposits ('lithogenetic units') and landforms, structural elements of rocks, and other themes, to support an ontology for geological baseline data.
- Online vocabularies, based on Simple Knowledge Organisation System and linked data technology, available through EGDI.
- A technical and organisational framework for the governance, management, and updating of vocabularies including suitable front-ends, editorial boards, etc.
- A semantic reasoner for AI fact-checking and knowledge deduction for existing vocabularies, building on developments made in the GSEU project.

- A repository to host, update, visualise, provide, and query geoscientific vocabularies.

IMPLEMENTATION

Action USG1.3 – Create regional, harmonised transboundary datasets at a scale of 1:250.000 to 1: 1 million

Expected outcomes:

- Regional transboundary datasets, based on, e.g., lithotectonic units, as fundamental classification element of legends with further subdivision according to lithology, age, genesis (environment, process), lithostratigraphic units, and others. E.g. (1) a small-scale dataset of the European basement based on the IGME 5000 and lithotectonic map produced in the GSEU project, (2) a harmonised 1. 1 Million Geological Map of Europe using the One Geology-Europe dataset and new data, based on the data model and vocabularies developed in the GSEU project.
- A semantic web-based system to manage regional, transboundary correlation of lithostratigraphic units in Europe, including a set of rules for the harmonisation procedure.
- Multiple integration of regional geological datasets with applied geoscientific data sets in the fields of raw materials, groundwater bodies, potential geological hazards, geothermal energy, etc.

IMPLEMENTATION

Action USG1.4 – Support new, and improve existing, national geological mapping programmes

Expected outcomes:

- Documentation of best-practice examples for the organisation of mapping campaigns and multi-annual mapping programmes.
- A board of experts for trans-boundary geological mapping to advise on implementation of (transboundary) continental and marine geological mapping programmes at NGSO level.
- Recommendation of (open-source-based) digital workflows in data acquisition.
- Foster innovative incentive schemes at EU-level to support national and transboundary mapping programmes.
- Established network of highly specialised experts in the fields of e.g. biostratigraphy, geochronology, mineralogy, geochemistry or petrology at NGSO level for mutual support in sample processing from mapping campaigns.

Priority USG2 – Towards a European-scale 3D geological model

Knowledge of the European subsurface is critical to access resources and to assess and mitigate risks. A common approach at the European countries level is foreseen to achieve a coherent and multi-use description of the subsurface. However, the ways to access the underground and its parameters are often sparse and indirect. Geomodelling combines the available data and information from e.g., geology, geophysics, and geochemistry. The goal is to give a comprehensive and transboundary description of the subsurface in 3D.

The ambition is to produce a 3D crustal-scale model of the main lithotectonic units to a depth of 5–10 km. The model will be built using the main existing syntheses (1:5M European geological map[17], combined with national 3D models) and the most recent seismic profiles. The main interfaces to be incorporated include the major faults separating the main lithotectonic units, the basement-sedimentary cover boundary, and the crust-mantle boundary. However, when considering the uppermost part of the Earth's crust in urban areas, an adapted approach is required regarding spatial resolution and input data as well as processing, description, packaging, and provision of relevant geological and hydrogeological 2D and 3D specialist data.

RESEARCH & DEVELOPMENT

Action USG2.1 – Define common rules for the description of geological objects in 3D for integrating national geomodels at European scale

Expected outcome:

- Technical specifications and requirements to harmonise and make compatible 3D geological models at European scale.

RESEARCH & DEVELOPMENT

Action USG2.2 – Set up a common, integrated platform to host and query 3D geomodels in relation with EGDI

Expected outcome:

- A numerical repository to host, visualise, and query 3D geological models.

RESEARCH & DEVELOPMENT

Action USG2.3 – Develop a European-scale 3D geological model

Expected outcome:

- A pan-European 3D Geological Model to serve user needs.

IMPLEMENTATION

Action USG2.4 – Build high-resolution 3D digital geological models

Expected outcomes:

- Visualisation of complex subsurface conditions by integrating 3D geological models with existing infrastructure data, enabling clearer understanding of spatial relationships between geological formations and underground structures, building on developments from the GSEU project.
- Enhanced geological insights provided through detailed 3D models, enabling identification of key formations, rock properties, groundwater flows, and potential hazard zones.
- Optimisation of subsurface resource use through application of 3D models, allowing planners to efficiently allocate resources such as groundwater and geothermal energy, while minimising conflicting uses, e.g., tunnels, utilities, and natural resources.

Priority USG3 – New technologies for subsurface investigation and geo-modelling

3D. Modern geophysics (e.g., electromagnetic UAV surveys, quantum gravimetry, electromagnetic technologies, optical fibre monitoring, micro gravimetric, micro seismics) provide a new range of techniques to improve investigation of the subsurface. Beyond sharing common methodologies and best practices, research efforts should also focus on developing and deploying R&I using a common framework and, wherever possible, open source. A key area of development is to build up an integrated semantic model (ontology) in geological basic data (including geology, geophysics, geochemistry, seismology, etc.), to better serve applied geosciences.

RESEARCH & DEVELOPMENT

Action USG3.1 – Setup innovative ground-based and airborne geophysical methods in geological surveying and exploration

Expected outcomes:

- New investigation methods combining data acquisition from the ground to satellite.
- An 'acquisition-processing-modelling' value chain based on multi-scale geophysics, remote sensing, digital geology, Machine Learning, and big data processing.
- Geophysical methods adapted to accessibility and noise constraints of the urban environment.
- Distributed acoustic sensing solutions to survey and monitor urban events.

RESEARCH & DEVELOPMENT

Action USG3.2 – Develop new methods and tools based on geomodelling and AI to integrate data and information from different sources (e.g., geology, geophysics, geochemistry)

Expected outcome:

- Automated and semi-automated solutions to construct integrated 3D geomodels designed for specific user needs building on deliverables of the GSEU project.

IMPLEMENTATION

Action USG3.3 – Develop common 3D geomodelling methodologies and R&I framework

Expected outcomes:

- A shared R&I framework for European partners to co-construct new geomodelling solutions.
- An open-source toolbox for 3D geomodelling, to choose the most appropriate solution depending on the geological and application contexts.

Geoscientific And Digital Foundational Framework

GOAL

A Sustainable European Geological Data Infrastructure

Data and digitisation are at the heart of EU strategy. In modern society, open access to trusted data is central policy making. The INSPIRE Directive[18] covers the first level of the Data, Information, Knowledge, and Wisdom pyramid. This data value chain relies on combined data management, data science, and applied geological knowledge with Information Technology capabilities for secure data transfer and storage. NGSOs have decades of experience developing better, faster, more transparent workflows that combine geological data, information, and knowledge with applied R&I. Considering the societal challenges, digital representations of above- and below-surface interactions are necessary. The biggest challenge is having these digital representations at one's fingertips, ensuring the knowledge behind them is state-of-the-art, and that the supporting data is accurate, trusted, and up to date[19]. This value chain connects data, expertise, and models in a specific context coming from different organisations, which requires agreements on collaboration, defining who will provide which data and knowledge, and, of course, the necessary data and Information Technology infrastructure to support this.

The Geological Service for Europe will support research, policy, industry, and public stakeholders with pan-European and national geological data, information, and knowledge to enable data-based decision-making on a European scale. These elements will be captured in the evolving EGDI, which will provide access to the data used, the models created, and the tools developed from these models. This knowledge infrastructure, which includes a portal for scientific results, reports, and viewing datasets, will serve as a central hub for subsurface-related data and information to connect with other data spaces and infrastructures. The Geological Service for Europe will offer data and information across the entire Data, Information, Knowledge, and Wisdom pyramid, combining where possible the data from geological surveys, industry and research organisations into a single ecosystem. Incorporating relevant expertise from NGSOs and EuroGeoSurveys Expert Groups, the Geological Service for Europe will deliver expert geoscientific advice on diverse Green Deal policy and collaborate to create a perspective for action. EGDI is fundamental to enable this.

The European Geological Data Infrastructure lays a foundation for delivering on these UN SDGs.

Priority DIG1 – Standardisation framework for FAIR[20] Data and Metadata

Standardising geological data collection, interpretation, and dissemination is fundamental to ensuring data compatibility and usability across different platforms and among various stakeholders. INSPIRE technical rules are the basic element to ensure standardisation and interoperability of systems. Data models and appropriately extended ontologies will allow access to detailed datasets, labelling them as "High Value Datasets". It will be fundamental to ensure the maintenance of the entire standards framework to have Pan-European Findable, Accessible, Interoperable and Reusable (FAIR) datasets and metadata.

To facilitate scientific data harmonisation and support data scientists to integrate information of various resources and the concepts addressed by them, a Standardisation Framework should be set-up. This Framework aims to provide shared standards and scientific terms for a common understanding of Earth Science data among the different domains, operating in the different fields of the Earth knowledge. This necessitates active interaction with international standard bodies to foster a collaborative process that enhances knowledge and official resources through wider consensus. This collaboration will also ensure that Earth Science products are more easily understood by both humans and machines. To facilitate FAIR data sharing and reuse, a data sharing protocol is needed. This protocol should be driven by research needs while considering technological advancements and applicable regulatory constraints.

IMPLEMENTATION

Action DIG1.1 – Develop and maintain standard framework

Expected outcomes:

- A set of standardised data models that supports predictive analytics and scenario modelling across Europe, enabling better forecasting and scenario analysis on a pan-European level.
- A common scientific language adopted across NGSOs, ensuring consistent interpretation of geological data, and ensuring that all geological data is understood and modelled in a uniform way across different countries and platforms also through common semantics that facilitates its use by AI systems.
- A framework of standards developed and maintained for ensuring efficient, secure, and seamless data and metadata exchange between different stakeholders, including NGSOs and other organisations.
- Common protocols for secure data sharing to ensure the effortless exchange of data across national borders.
- A tool for evaluating and monitoring the FAIR level of each product to guarantee adequate quality for datasets and especially for the High Value Datasets (HVD).

Priority DIG2 – Transparent and Accessible Sustainable Value Chains

Trusting a value chain that covers the entire Data, Information, Knowledge, and Wisdom Pyramid in a Geological Service for Europe is only possible when transparency is in place. This will explain which data was used, how it was interpreted, by whom, how the connection was made with data and information from other domains, and which computing techniques and theories were used. This transparency can only be realised when expert users can drill down the entire value chain to the data level.

Traversing the value chain requires data about connections. Connections between datasets (thematic maps, GIS layers, 3D models) can be described using high quality INSPIRE Metadata. Connections of objects (individual boreholes, environmental monitoring stations, map data etc.) can be described either in relational databases or by using linked data techniques and standard ontologies. Value chains are usually parallel with processing chains that are well described for example by the Observations and Measurements standard. A lot of additional information collected in the inventory process do not fit into standard Metadata but can be managed in dedicated databases.

IMPLEMENTATION

Action DIG2.1 – Develop and Improve Geological Data and Information Systems

Expected outcomes:

- Enhanced transparency by adding information on connected items and the nature of their connections.
- Maintained and developed comprehensive semantic metadata system of raw geological data and processed geological information semantically linked with a source.
- Relations between metadata, data, information, and models, ensuring seamless integration between how data is received, updated, stored, and displayed.
- Search systems can drill through metadata or knowledge graphs to explore the origin or deeper context of different datasets.

IMPLEMENTATION

Action DIG2.2 – Develop User Interface Design for Geological Data Systems

Expected outcomes:

- Development of a robust and user-friendly search platform that leverages emerging trends in search solutions, such as semantic search and AI-powered tools, to improve efficiency and accuracy.
- A dynamic, user-centric interface that integrates multiple data views, contextual information, storytelling techniques, and visualisations. This interface will empower stakeholders to easily navigate and interpret geological data, enhancing their decision-making and analytical capabilities.
- Seamless incorporation of geological nomenclatures, catalogues, and classifications within the EGDI User Interface. This ensures the use of standardised terminologies and enables consistent navigation of geological data across diverse datasets and classification systems.
- A dashboard-style environment that presents clear and intuitive descriptive statistics, linked to policy-relevant key performance indicators, for streamlined analysis and reporting.

Priority DIG3 – Ensuring Up-to-date and Trusted Data

Currently added value products often are the result of a 'one-off' exercise and use a snapshot of datasets and models frozen in time. These datasets tend to change over time, the same holds for modelling concepts. This reduces the usability of the information product. Data value chains are more valuable when they are up to date, meaning that all relevant data that is available is used to (automatically) update the product within a reasonable timeframe.

IMPLEMENTATION

Action DIG3.1 – Automate Data and Access Management for Geological Systems

Expected outcomes:

- Incremental and automated updating of models and information products when new data becomes available, improving decision-making accuracy, reducing manual intervention, and ensuring that users have access to the most current data.
- Automation of versioning along the entire data value chain, providing real-time notifications and updates, ensuring transparency and traceability of changes.
- Advanced Identity and Access Management techniques used across multiple organisations. This is a secure and controlled access system that ensures only authorised individuals can make changes, providing robust protection for data integrity.
- Identity and Access Management to shield non-public data and ensure access for authorised users. This interconnected system will ensure that sensitive data is protected while maintaining seamless access for authorised users.

Priority DIG4 – EGDI: Evolution into a Pan-European Geoscience Knowledge Hub

The European Geological Data Infrastructure (EGDI), established in 2016, is a platform designed to provide free access to pan-European and national geological datasets and services from Europe's NGSOs.

By integrating diverse geoscientific datasets from multiple European countries into a unified digital infrastructure, EGDI delivers a comprehensive, pan-European perspective on geoscientific challenges and spatial areas, supporting research, policy-making, and sustainable development. The EGDI infrastructure serves as the backbone for the provision of multinational, distributed, derived, spatial and temporal datasets, considering INSPIRE and other international standards.

At the heart of the GSEU project, EGDI is evolving from a foundational data platform into a sophisticated knowledge hub, developed in the direction of European Dataspace integration[21]. This transition will provide a wide range of stakeholders with even easier access to high quality geoscience data and ability to share information that can significantly support the decision-making process and increase its efficiency.

IMPLEMENTATION

Action DIG4.1 – Develop and implement a roadmap for integrating EGDI with relevant European data spaces

Expected outcomes:

- A geological ”dataspace” that seamlessly connects to other relevant European dataspaces and enables efficient data sharing without the need for redundant API development.
- Integration with non-geological dataspaces: integrating geological data with other environmental, economic and social datasets will give stakeholders access to a more comprehensive understanding of the impact of the subsurface on wider societal and environmental issues.

IMPLEMENTATION

Action DIG4.2 – Ensure open and accessible data and tools for developers, researchers, and educators.

Expected outcomes:

- A robust and accessible EGDI knowledge hub that supports innovation and research by providing reliable access to continental and marine geological data and tools for external developers, academic communities and industry. This also includes public awareness campaigns to increase the understanding of the importance of subsurface data in energy and environmental contexts.
- A skilled data and software development workforce. Investing in education and training programmes to build a skilled workforce capable of using advanced digital tools for subsurface data analysis.

IMPLEMENTATION

Action DIG4.3 – Implement Linked Data technology within the EGDI platform to enhance data interoperability, discoverability, and reusability.

Expected outcomes:

- Adoption of semantic technologies for faster and more insightful data analysis. By applying the SKOS and RDF web standards, using triplestores and assigning URIs, we lay the groundwork for Linked Data. Implementing linked data technology then enables seamless integration and interoperability of diverse datasets by using standardised formats and ontologies.
- Option to identify and (re)use evolved ontologies to improve knowledge usability across domains. Ontologies are the foundation for sustainable knowledge graphs, providing the structured semantic framework necessary for consistent data integration, interoperability, and long-term usability. By re-using/adapt evolved ontologies, we can promote semantic interoperability among diverse datasets and applications spanning different domains.
- Implementation of knowledge graphs to foster integrated data use in the geological domain. By linking diverse pieces of information, they can represent nuanced concepts and intricate relationships between different data points. This capability is crucial for AI systems that need to “understand” and process information in a way that reflects the complexity of real-world scenarios.

Strategic Geoscientific Focus

GOAL

Energy Transition & Decarbonization

European and national legislations, policy roadmaps, and research initiatives focus on enabling and accelerating the development and upscaling of new geoenergy technologies and sustainable uses of the shallow and deep subsurface. Stakeholders in governmental and non-governmental organisations and industry require fit-for-purpose geoscientific data, information, and decision support criteria for performing techno-economic evaluation of geoenergy resources, de-risking investments, planning and permitting new sites for deployment, regulating operations, and managing environmental impacts.

There is a general need to identify and characterise investible potential for production of geothermal energy[22–24], storage of heat and cold, permanent storage of CO_2, and temporary underground storage of hydrogen and other storable energy carriers. EuroGeoSurveys has already taken major steps in delivering required subsurface information and knowledge via the GSEU project and will further support the growth of a net-zero energy industry by delivering the following R&I priorities and actions.

The main expected outcomes for the R&I actions in this goal are directed at:

- Enabling the implementation of subsurface data, information, and knowledge in national and European policy and decision-making processes.
- Establishing future-proof information platforms that serve expert and non-expert needs and allow continuous renewal and incorporation of new data and models, with innovative methods including AI-based tools.
- Investigating and leveraging new prospects that support Green Deal ambitions.

Our Energy Transition & Decarbonisation actions contribute to delivering on these UN SDGs.

European Climate Law & Net Zero Industry Act

- **Reduce** net greenhouse gas emissions by ≥ **55% by 2030** compared with 1990 levels
- Focus on **key technologies** (incl. geothermal, hydrogen, CCS) for decarbonisation objectives
- **Improve functioning of the internal market**
- **Ensure energy supply**
- **Strengthen industrial competitiveness**
- **Accomplish net zero objectives**

CCS targets: Reach annual injection capacity of ≥ 50m tonnes CO_2 by 2030, 2-yearly analysis of planned and operational CO_2 projects and potential storage sites, and guidelines for appropriate levels of CO_2 purity and trace elements in the CO_2 stream.

NGSO actions for policy implementation

Lead the development of an investment atlas of potential CO_2 storage sites by 2026 based on a common storage readiness level format and building on the current HE GSEU project

Assist Member States to make publicly available data on areas where CO_2 storage sites could be permitted on their territory, including saline aquifers

Contribute to implementation of **Article 21** of the Net Zero Industry Act, **under national mandates to NGSOs, by collecting, archiving, and delivering required geological data, information, and knowledge relevant for the development of and investment in storage of CO_2**

Key geological information services related to the European Climate Law[25] and Net-Zero Industry Act.

Priority ETD1 – Develop and deploy pan-European information and decision support systems to accelerate deployment of geothermal systems

Geothermal is a proven and versatile renewable energy resource with vast untapped potential for dispatchable low-emissions electricity generation, heating and cooling of residential and commercial buildings, industrial processes, and agriculture. Geothermal has been a part of energy systems for more than a century but has played a limited role globally. Recent European initiatives urge its enhanced use for its increasing role in a clean energy transition. This priority specifically focuses on the following topics in the EU geothermal strategy complementing R&D priorities of the ETIP-Geothermal SRIA:

- Fit-for-purpose digital geological data for techno-economic evaluations of geothermal resources, de-risking schemes, and efficient permitting and developing of geothermal projects.
- Accelerating underground thermal energy storage.
- Improved environmental performance assessment for different use perspectives.

The expected outcome of this priority is to ensure that pan-European geothermal information systems are tailored to support and implement European policies on sustainable energy use of the subsurface, ensuring efficient and informed decision-making.

IMPLEMENTATION

Action ETD1.1 – Develop tailored information services to support and accelerate techno-economic geothermal development

Expected outcomes:

- Public state-of-the-art information systems, improving accessibility and implementation of national and regional geothermal data, information, and knowledge at European level. This will include results from previous European research projects no longer accessible online, and relevant, accessible data from academia and industry. These will deliver data and potential on geothermal production and storage to inform future business models. Such information systems should constantly incorporate measurement and monitoring data from ongoing geothermal projects and be complementary with other systems, e.g., the European Geothermal Research and Innovation Search Engine (EGRISE), to reduce geological uncertainties and expand knowledge of subsurface properties needed for (technically and financially) derisking future projects and mitigating (groundwater) impacts.
- Improved information on the state-of-play across Europe by including dedicated information in the availability, accessibility, heterogeneity, and quality of data per region. This will be an important guidance to design actions on under-explored and under-exposed potential for geothermal energy applications.
- An extended resource base and identification of untapped potential with realistic estimates of geothermal resources across Europe through incorporation of state-of-art resource assessment methods, play-based portfolio analysis, and use of AI and ML methods. This will incorporate a determination of the “Probability of Success” for geothermal projects from both an engineering and a “Levelised Cost of Energy” perspective.
- Improved derisking of technical potential at project-level and support of national derisking guarantee schemes through detailed investigations of geological uncertainties, insights in pre-drill geological

uncertainties, and guidance on resolving information and exploration gaps.

- Increased understanding of the geothermal energy associated risk and benefits to citizens through information and stories presented on EGDI, leading (with project derisking) to increased social acceptance of the utilisation of geothermal technologies.
- Improved environmental performance assessment and environmental risk assessment to enhance project sustainability and efficiency by developing advanced monitoring systems and methodologies to follow and mitigate potential environmental risks and promoting an open data policy for dissemination and reuse.

Directive ("RED III")

- **Targets >32% share of renewable energy sources** in the EU's final energy consumption by 2030 (including wind, solar, hydrogen, and geothermal)
- **Encourages integration of renewable energy sources into buildings**

The **European Parliament resolution of 18 January 2024 (2023/2111(INI))** calls for a common **European Strategy for Geothermal Energy** to:

- **Reduce administrative burdens**
- **Aid investments in buildings, industry and agricultural sectors**
- Establish a **Geothermal Industrial Alliance** to fast-track
  - **Best practices**
  - **Effective implementation** of legislation
  - **Harmonised financial risk mitigation** insurance scheme

Member States are encouraged to design national strategies that support regions in transitioning to geothermal energy.

NGSO actions for policy implementation

Develop and deliver geological data and expertise to support national authorities in transitioning from petroleum exploration and production to **deploying renewable energy** (e.g., geothermal, geological storage capacities for hydrogen, compressed air, heat and cold and CO_2)

Develop public databases and atlases indicating harmonized cross-border potential for renewable technologies at European scale. **Collaboration** under the HE GSEU project

Support capacity building, scientific networking, and joint responses to EU and interregional calls for project proposals. Collaboration through pan-European expert groups (including CO2GeoNet, ZEP, EERA CCS JP, and EuroGeoSurveys Geoenergy Expert Group)

Key geological information services related to the Renewable Energy Directive (III)[26,27]

Priority ETD2 – Establish pan-European data, information, and knowledge for the accelerated and secure deployment of CO_2 underground storage potential in both core development areas and emerging R&I areas

In Europe, Carbon Capture and Storage (CCS) is developing heterogeneously. Some countries have projects in advanced stages of permitting and financial investment decisions, while others have a far less mature view of storage opportunities. Extensive collection of primary data and analysis of raw data are still required. As the European CCS industry transforms from isolated flagship demonstration projects to a pan-European industry, requiring the development of hundreds of storage sites, there is an urgent need to optimize use of the subsurface.

The CO_2 geological storage atlas of Europe, being developed through the GSEU project, will collate available data for a harmonised pan-European view and use Storage Readiness Levels to highlight the maturity of storage site development. The need remains for significant resources to analyse data and undertake fundamental research to support delivery of tools that can inform decision makers. There is the need for R&I to tackle questions raised by the developing fleet of CO_2 storage projects in Europe including optimising use of pressure budgets, near-wellbore processes, monitoring and modelling storage sites for stakeholder assurance, site closure and abandonment processes, and innovative local storage solutions (e.g., geothermal with CO_2 and mineralisation storage).

In line with targets in the Industrial Carbon Management Strategy[28], the Net-Zero Industry Act, and the EU Communication on 'A Green Deal Industrial Plan for the Net-Zero age[8]', the main expected outcomes of this priority are to:

- Accelerate the secure and efficient deployment of underground CO_2 storage in Europe.
- Directly contribute to enabling use of information released under the Net-Zero Industry Act to create a pan-European CO_2 storage opportunities portfolio and produce a pan-European investible storage assessment.
- Facilitate and improve knowledge sharing between stakeholders to accelerate and optimise deployment of CCS. This includes the CCS knowledge-sharing platform highlighted in The Communication on Industrial Carbon Management that will facilitate the collection of information on and sharing of best practices between CCS projects in the EU. Contribute practical knowledge on CO_2 storage e.g. through the European Carbon Dioxide Capture and Storage Laboratory Infrastructure facilities.

IMPLEMENTATION

Action ETD2.1 – Contribute to closing remaining knowledge gaps through R&I and by responding to new research challenges identified by storage projects that will come online over the next few years

Expected outcomes:

- Map and parameterise saline aquifers as important targets of onshore and offshore CO_2 storage at national and pan-European scale.
- Technical recommendations for characterising and implementing a pan-European CO_2 storage network, including optimising use of pressure budget, transboundary issues, and site closure. Improve understanding of potential migration pathways to inform risk assessment.
- Technical information to support national discussion and harmonised decision making for national and European research programmes and development of CCS strategies. Continue to demonstrate the value of geoscientific knowledge to achieving Net-Zero. Assess priority actions to enable assessment of investable storage, including identifying promising geographical areas to prioritise data processing, value of reprocessing data with current approaches, areas where new data are required, regulatory issues, etc.
- Co-developed joint research in areas of common interest to NGSOs, delivering European and national opportunities for CCS. Advance innovative monitoring technologies including cost/benefit. Investigate processes supporting innovative local storage solutions.
- Up-to-date information systems providing early access to fit-for-purpose CO_2 storage-relevant data by implementing innovative solutions for processing, ingesting, and analysing large quantities of (industry/legacy) data for CO_2 assessments (e.g., ML). Improved means to share knowledge to maximise use of data released under the Net-Zero Industry Act.

Priority ETD3 – Enable secure, efficient and timely unlocking of underground hydrogen storage capacities

The EU Strategy on Hydrogen[29] put forward a vision for the creation of a European hydrogen ecosystem aligned with the European Green Deal, with ambitious hydrogen production and imports (2x10Mtons) for 2030. In this context, underground hydrogen storage can be a key factor to support European energy system decarbonisation and facilitate development of a fully integrated clean hydrogen ecosystem. The development of underground hydrogen storage across Europe depends on geological conditions and availability of storage sites, as well as (local) storage needs. Currently, planned hydrogen storage projects are insufficient to cover predicted demand. The SRIA for the Clean Hydrogen Partnership (Clean Hydrogen Joint Undertaking) mentions specific priorities relating to the expertise and research activities of NGSOs, including:

- Development of decision support and planning tools to help unlock hydrogen storage as a scalable and flexible solution in the European energy system, underpinned by assessment and demonstration of underground storage to validate the performance in different geology.
- Provision of sustainable and safe designs for underground storage including studies on lined mined caverns for storing hydrogen when neither salt caverns nor porous media are available.
- Development of tailored information to support, accelerate, and de-risk underground hydrogen storage including assessment of effects and impacts that may occur during injection and storage of hydrogen in underground reservoirs.

RESEARCH AND DEVELOPMENT

Action ETD3.1 – Develop fit-for-purpose information services to support and accelerate techno-economic development of underground storage solutions for hydrogen and other energy carriers

Expected outcomes:

- Public state-of-the-art information systems to improve European-level accessibility and implementation of national storage capacity data, information, and knowledge by integrating and unlocking data repositories.
- Accelerated commercialisation and optimised upscaling of underground hydrogen storage projects by collecting, analysing, and disseminating public information and monitoring data from pilot projects and commercial-scale demonstrators across Europe.
- Improved derisking of technical potential at project-level and support of national derisking guarantee schemes through detailed investigations of geological uncertainties, insights into pre-drill geological uncertainties, and guidance on resolving information and exploration gaps.
- Improved environmental performance assessment to enhance project sustainability and efficiency by developing advanced monitoring systems and methodologies and promoting an open data policy for dissemination and reuse.

Priority ETD4 – Maturing next-generation geoenergy technologies

There is a wide range of emerging technologies (e.g., deep geothermal closed-loop systems, recovery of critical raw materials (e.g., lithium) from geothermal brines, use of natural hydrogen) that cannot yet be mapped at pan-European scale. However, these technologies are expected to have potential economic interest and a significant role in achieving decarbonisation goals.

RESEARCH AND DEVELOPMENT

Action ETD4.1. – Facilitate the innovation and deployment of new technologies

Expected outcomes:

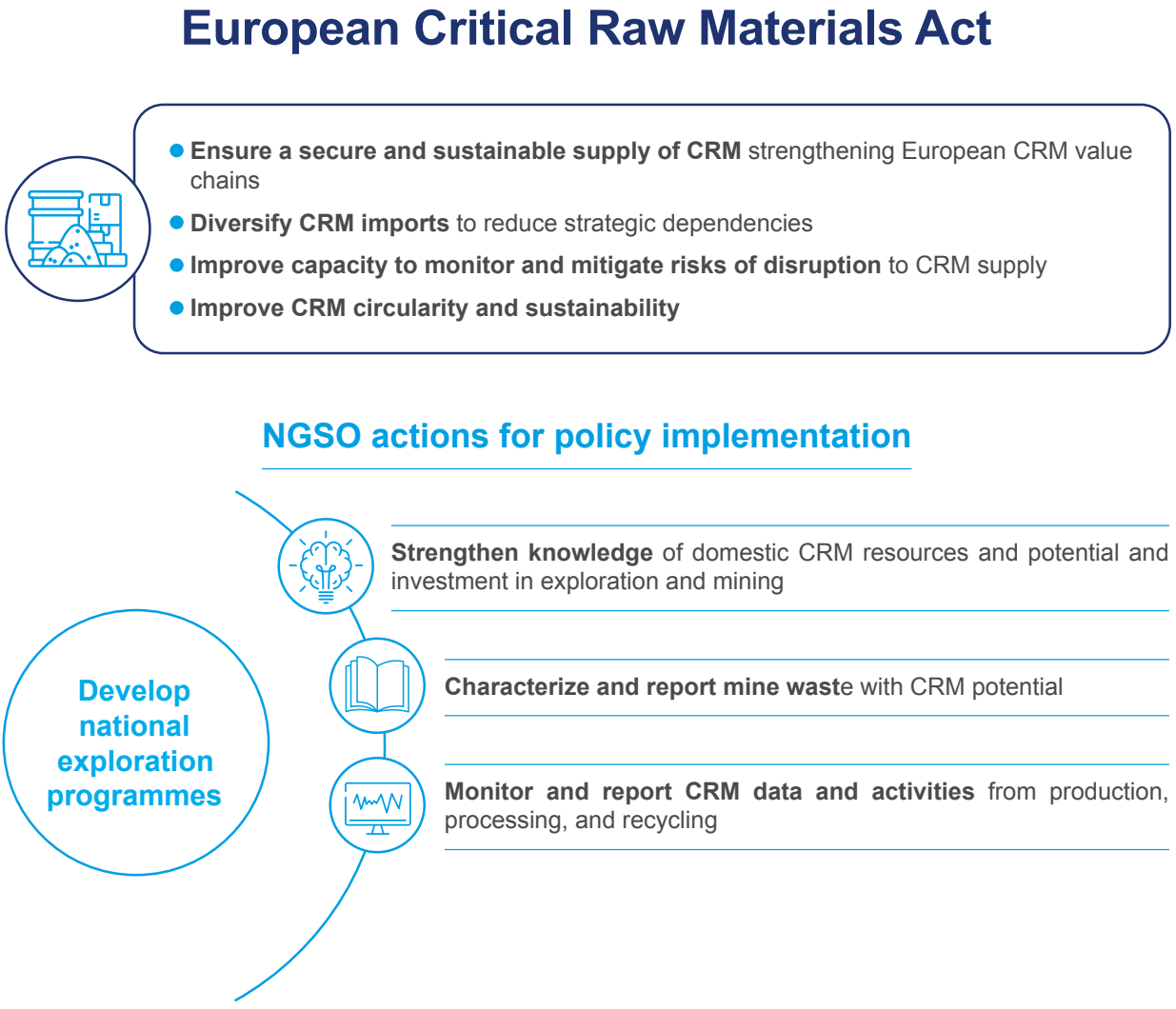
- Advanced recovery of CRM from geothermal brines as by-products by delivering tailored information and tools, including resource assessments. This will support implementation of CRM Act and Net-Zero Industry Act to maximise potential CRM sourcing and make geothermal power generation more economically favourable.
- Integration of enhanced geothermal systems, advanced geothermal systems, and closed-loop into pan-European geothermal information and decision support systems by investigating their feasibility and contributing to sustainable deployment.
- Insight on the presence of technically and economically exploitable natural hydrogen resources by modelling basins and reservoirs that could accumulate favourable natural hydrogen volumes and developing tools to characterise hydrogen-bearing rocks.
- Improved exploration and exploitation of natural hydrogen resources by developing exploration methodologies with geophysical, new gas monitoring techniques, and possibly remote sensing technologies.

Strategic Geoscientific Focus

GOAL

Responsible Raw Materials

Raw materials are essential to Europe's economic competitiveness, security, and autonomy, particularly in the context of the energy transition. Europe's heavy dependence on imports of raw materials and intermediate products from third countries[30–36] has weakened value chains in, amongst others, electronics, automotive and aerospace construction, and battery production. This dependence risks not only sovereignty and industrial opportunities, but also transfers the environmental and social costs of European consumption to other regions. This ethical dimension underlines the need to adopt responsible sourcing practices throughout the supply chain.



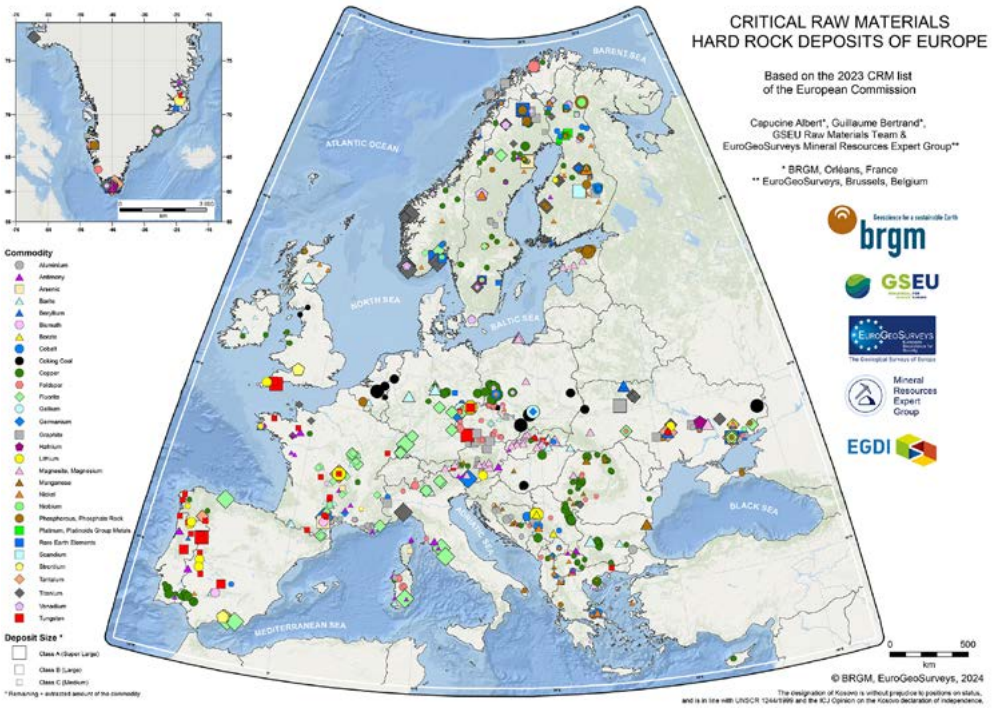
Key geological information services related to the Critical Raw Materials Act.

The CRM Act[3], in its ambitions of ensuring secure and sustainable supplies of CRM for Europe, will draw on the expertise of EuroGeoSurveys and its member NGSOs to deliver:

- Resource assessments including national exploration programmes to identify national resources and potential (primary and secondary).
- Raw materials data compiled and harmonised at European scale, onshore and offshore, primary and secondary, including supporting deployment of UNFC and promotion of the UN Resource Management System.

- Standardisation including common methods and best practices, particularly targeting trans-boundary regions.
- Public knowledge and awareness. The future of the European raw materials sector depends on public understanding, education, and support.
- Raised capacity and contributions to international dialogue with partner organisations or third countries to share best practices and expertise on raw materials supply chains, contributing to raw materials diplomacy, diversification of sourcing, and strategic partnerships.

EuroGeoSurveys will support the European raw materials policy and industry in assessing Europe's raw materials potential, developing innovative and sustainable solutions for exploration, characterisation, production, and recycling.



Map of Critical Raw Materials hard rock deposits of Europe[70].

EuroGeoSurveys Responsible Raw Materials actions contribute to delivering on these UN SDGs.

Priority RRM1 – Support raw materials exploration to assess European potential

The CRM Act advocates a more global approach to securing CRM in Europe. The European NGSOs will be key players in the development of regional mineral exploration methods and programmes. Although Europe has developed substantial knowledge of its raw materials potential through its long mining history, there undoubtedly remain significant discoveries to be made, particularly of metallic deposits. Exploration for deeper, unconventional mineral deposits requires development of new metallogenic models based on comprehensive reconstructions of the geological history, reassessments of existing data using new geological concepts, and in-depth analyses of mineral systems. This involves analysing all of Europe's geological potential using centralised, standardised data. To achieve this, NGSOs and data infrastructure experts must work together through strong and active networks. Based on these considerations, EuroGeoSurveys has identified the following actions:

IMPLEMENTATION

Action RRM1.1 – Maintain a reliable and harmonised inventory of European mineral resources, accessible to multiple stakeholders

Expected outcomes:

- Further develop, maintain, and regularly update the MIN4EU database under the umbrella of the EGDI, to deliver access to current, harmonised, complete, and verified mineral resource data, in line with common European standards. This includes harmonisation of resource data using the UNFC and INSPIRE standards.
- Regular delivery of new, improved data, information, and knowledge of European mineral resources.
- Data packages, analyses, and explanatory products customised to different stakeholders, to maximise dissemination, awareness, and understanding of Europe's onshore and offshore mineral resources.

IMPLEMENTATION

Action RRM1.2 – Apply cutting-edge exploration models that integrate mapping, tectonics, mineral systems analysis, and advanced data processing techniques

Expected outcomes:

- A harmonised database of lithotectonic units of all mineral provinces in the European territory coupled with data on geochemical and geophysical characteristics. This data will be upgraded especially in connection to the national exploration programmes, based on detailed characterisation of European lithotectonic units, encompassing aspects of their geological history and mineral prospectivity. This will provide a basis for renewed assessment of mineral raw materials potential, and application to other resources such as CO_2 storage, groundwater, geothermal energy and to geohazard risk assessment and mitigation.
- Collaborative research initiatives between NGSOs and academia targeting specific European mineral provinces to re-examine ore-forming processes in key areas (e.g., Kupferschiefer, Variscan, and Alpine belts). This will contribute to deciphering complex ore minerals processes, essential to develop appropriate exploration strategies.

- A comprehensive assessment of European ore deposits areas supported by Machine Learning approaches, contributing to reassessments of mineral provinces, and requiring consistent and standardised description of lithological and geological units to generate predictive mineralisation maps. Such maps, hosted by EGDI, will enable targeted exploration of favourable regions.
- 3D predictive modelling approaches, in parallel with better knowledge of geological structures and geometries at depth, to support exploration for deep and under-cover deposits.

RESEARCH AND DEVELOPMENT

Action RRM1.3 – Spearhead collaborative R&I initiatives with industry and technology partners, to improve exploration methods from European to local scale

Expected outcomes:

- Advanced exploration technologies including innovative geophysical surveying, 3D surveys, and multidisciplinary approaches incorporating geological mapping, geochemistry, drilling, core analysis, petrophysical studies, and advanced data treatments.
- Strategic partnerships with industry stakeholders and technology providers.
- A set of pilot projects, in R&I partnership with industry, to explore the subsurface faster, deeper, and more efficiently with innovative technologies and efficient geological characterisation.

RESEARCH AND DEVELOPMENT

Action RRM1.4 – Multi-Disciplinary Approach for responsible research of unconventional ore deposits

Expected outcomes:

- Inventory of the resource potential of brines (e.g., lithium and bromine) related to geothermal systems or sedimentary basins.
- Assessment of Europe's marine mineral resources and potential using a comprehensive analysis of ore forming processes and environments. This requires research to better understand genetic processes of marine strategic raw materials deposits, map their distribution, and characterise their properties.

Priority RRM2 – Improve responsible supply of raw materials in Europe

Developing robust, scientifically based methods for assessing the economic, environmental, and social impact of supply chains will enable analysis and comparison of the environmental and societal benefits along supply chains, from exploration and mining (key areas of activity for EuroGeoSurveys member NGSOs) to the final products, supporting critical transitions in the energy, digital, and industrial sectors.

IMPLEMENTATION

Action RRM2.1 – Create and share comprehensive models to forecast the life cycle of mineral resources

Expected outcomes:

- Forecasts of future material flows and stocks, leveraging established tools like Material Flow Analysis and Input-Output Tables.
- Supply risk and criticality analyses carried out in relationship to different prospective scenarios of demand evolution, achieved through collaboration between NGSOs and organisations such as national mineral raw material observatories and industry.
- Prevent sterilisation of mineral resources through responsible land-use planning.

IMPLEMENTATION

Action RRM2.2 – Maintain up-to-date criticality assessments for raw materials (Critical Raw Materials and Strategic Raw Materials) to support public authorities and industry

Expected outcome:

- Updated and integrated models and methods to assess key parameters, e.g., reserves, production, consumption, recycling, and geopolitical factors that could impact supply risk, providing public authorities and industrial sectors access to the latest information needed to make informed decisions.

IMPLEMENTATION

Action RRM2.3 – Build collaboration between EuroGeoSurveys and other stakeholders in the raw materials sector, particularly with national raw materials observatories

Expected outcomes:

- A European-level holistic approach to EuroGeoSurveys collaboration with raw materials stakeholders, including government, academia, policy- and decision-makers, and industry.
- An organised network accessible to R&I teams and national raw materials observatories, able to provide consolidated data to inform raw materials value chain analysis.
- Improved data integrity and reliability, and efficiency of collaboration in the raw materials R&I sector, including structured connections to stakeholders in exploration, mining, and processing, to ensure uptake of R&I.

IMPLEMENTATION

Action RRM2.4 – Develop international collaborations to support European raw materials resilience

Expected outcomes:

- Support for implementation of EU bilateral strategic partnerships on raw materials, including technical

actions, cooperation on R&I, capacity building, and knowledge sharing.

- Strengthened organisational-level international geoscience diplomacy in raw materials, contributing to raised awareness of the relevance of geoscience for policy at international level.
- Strengthened international geoscientific expert networks in raw materials.

RESEARCH AND DEVELOPMENT

Action RRM2.5 – Develop data, tools, and methods to assess the environmental and societal impacts of supply chains, using a stakeholder co-designed and multi-disciplinary approach

Expected outcomes:

- Ongoing development of Life Cycle Assessment data and methods adapted to mining and quarry sector needs. This includes creating new indicators, improving database reliability, and managing uncertainties within supply chain analysis.
- Local environmental impact assessment approaches integrating social science perspectives. This combined approach is needed to address the challenges and drivers impacting the mining sector's social license to operate, particularly in a context of public distrust.

Priority RRM3 – Support the development of responsible mining and a circular economy

Minimising the environmental impact of the mining sector requires developing and promoting responsible methods across the entire mining life cycle, from exploration and extraction to processing, refining, mine closure, and recycling. While the primary focus of NGSOs lies in exploration and post-mining activities, their expertise plays a vital role in environmental and impact assessments of these activities. Also, unlocking the vast potential of Europe's existing mining waste – abandoned sites, current waste rock, tailings, and metallurgical residues – is crucial to sourcing 10% of the EU's annual production from within the Union, as required by the CRM Act. These secondary sources represent a valuable resource of critical and strategic raw materials. By first characterising these potential secondary resources and using optimised reprocessing and environmentally friendly techniques, Europe can significantly reduce its reliance on external resources and move closer to achieving the targets set by the European Commission.

RESEARCH AND DEVELOPMENT

Action RRM3.1 – Through co-design with industry and policymakers, develop innovative and non-invasive observation, data acquisition, and data processing tools (multiscale and multisource) to support the full mine life cycle

Expected outcomes:

- Innovative exploration, mining, and processing techniques that minimise environmental impacts, and automised monitoring of mining activities and environmental impacts (e.g., Earth observation tools, UAVs, contributing to e.g., water treatment, tailings management, dust prevention, improved biodiversity and geoconservation, mine site remediation, etc.).

- Technical tools and expert decision-support structures to support data-informed interaction between operators and policymakers.

IMPLEMENTATION

Action RRM3.2 – Using stakeholder engagement, assess local socio-environmental-economic ecosystems of abandoned and existing mines

Expected outcome:

- Applied tools and methods to maximise resource efficiency and economic benefits, while minimising environmental impact.

IMPLEMENTATION

Action RRM3.3 – Update knowledge of the raw materials potential of European mine waste

Expected outcomes:

- Ongoing maintenance and update of a database of European mine waste delivering (through EGDI) access to up-to-date secondary raw materials data, with common EU standards, building on the GSEU project. This includes data harmonisation using UNFC and INSPIRE standards.
- Methods and workflows for systematic physical and chemical characterisation and assessment of mining wastes (including tailings and processing wastes) to optimise recovery and minimise environmental impact. This will draw on data from all available sources, including industry, and will support application of UNFC to characterise and map mine dumps and other potential secondary mineral resources. Methods will combine observation techniques (aerial to field mapping), volume calculations, and geochemical analyses to quantify resource potential, focussing also on risk assessment.

RESEARCH AND DEVELOPMENT

Action RRM3.4 – Promote innovation and new technologies for abandoned mining wastes recycling to allow economically viable mineral extraction

Expected outcomes:

- Innovative processing technologies for economic extraction of raw materials from mining wastes. New approaches will address challenges inherent in low grade deposits, e.g., increasing processing volumes, improving separation efficiency, and minimising environmental footprint.
- Pilot R&I projects in partnership with industry, focussing on innovative recycling concepts and technologies adapted to tailings and mining wastes.

Strategic Geoscientific Focus

GOAL

Sustainable Management of Groundwater in a Climate Change Context

Groundwater is essential for drinking water, economic development, and the functioning of ecosystems. Climate change is impacting this precious resource and adaptation strategies must take account of groundwater systems, which can be part of the solution but also a vulnerable end-member. Climate change is a key issue when tackling the overarching challenges for water resources, including the restoration of a good quantitative and chemical status for all groundwater and a good ecological status of surface water bodies in Europe, as required by the Water Framework[37] and Groundwater[38] Directives and related guidances[39] the assessment of status (both quantitative and chemical).

Achieving these goals requires transdisciplinary research and sound understanding of interactions between groundwater and surface water status and uses, and between on- and offshore groundwater and groundwater-dependent terrestrial and associated aquatic ecosystems. Integrated use of groundwater and surface water is imperative to ensure good quantitative and chemical status of both, sustain legitimate and sustainable uses (drinking water, agriculture, industry) and ecosystems, and bring freshwater use back within planetary boundaries[40]. Pressures on quantity and quality of groundwater and surface water include climate- and land-use changes, contamination from industrial, agricultural and urban sources, and freshwater abstraction for competing uses[40–45] in connection with the green transition.

Water Framework and Groundwater Directives

- **Achieve good quantitative and chemical water status for all water bodies in the EU** (rivers, lakes, groundwater)
- **Promote sustainable water management and protection from pollution**, laying the groundwork for water resilience

Associated policies include the **Nitrates Directive**, the **EU Farm to Fork Strategy**, the **Urban Waste Water Treatment Directive**, the **Drinking Water Directive**, the **Floods Directive**, and the **Zero Pollution Action Plan**

NGSO actions for policy implementation

Deliver pan-European harmonized datasets, methods, and expert knowledge of European groundwater quality and quantity through HE GSEU project and EuroGeoSurveys Water Resources Expert Group

Create synergies with other research and policy organisations and initiatives, e. g. EEA, Water4All Partnership, the EC's DG ENV Working Group Groundwater, IAH, IGRAC, UNECE

Key geological information services related to the Water Framework and Groundwater Directives[46–53].

The R&I actions in this goal aim to deliver a sound geoscientific background, supporting society to sustainably manage groundwater resources and providing good groundwater chemical and quantitative status and to concretely realise the following outcomes:

- Dedicated geoinformation products, such as map viewers, databases, and integrative IT platforms hosting data and information about groundwater quantity and quality monitoring, including cutting-edge near real-time measurements and advanced interpretation techniques.
- Advanced modelling and visualisation tools to inform water authorities and the public about the projected effects of human actions, impacts of land-use changes, and climate change mitigation and adaptation measures. This includes development of integrated groundwater-surface water models to quantify effects of hydroclimatic changes, extreme events and temporal trends.
- Up-to-date methodologies to integrate groundwater flow, reactive transport, and travel time modelling of pollutants that can describe the functioning of groundwater systems related to the protection of drinking water and the restoration of groundwater-dependent terrestrial and -associated aquatic ecosystems.
- Improved integrated groundwater-surface water hydro(geo)logical modelling tools, with better geological delineation, enabling simulations of continuity of the water cycle, from precipitation, surface flow, unsaturated flow to the groundwater table, to groundwater flow in and between aquifers, including aquitards, and the outflow to springs and receiving surface waters.
- Methods to derive groundwater residence-time distributions which empower the assessment of groundwater resource vulnerabilities and inform about realistic timelines for reaching remediation targets, given the history and fate of contaminants in groundwater bodies in current and changing climate.
- Tools and models to identify vulnerable areas and improve groundwater monitoring to support targeted water conservation strategies and assessment of the impact and efficiency of mitigation solutions on groundwater, including nature-based solutions.
- Forecasting approaches to quantify the evolution of water tables, short and long-term risk of floods and droughts, and evolution of contamination in reaction to contamination pulses and source measures that aim to reduce further contamination.
- Improved understanding of the relation between elevated concentrations of geogenic elements and contaminants in groundwater and their impact on human and environmental health.
- Integrative approaches based on sound geoscientific knowledge and 4D geocharacterisation to evaluate and balance competing subsurface uses in relation to drinking water, storage of heat, gases and solutes, exploration of geothermal energy including the effects on temperature, salinity, cross-contamination and water use.

Global Biodiversity Framework & 2030 EU Biodiversity Strategy

- **Restore, maintain, and enhance nature's contributions** to society, including ecosystem functions and services (e.g., regulation of air, water and climate, soil health, pollination and reduction of disease risk, protection from natural hazards and disasters) through nature-based solutions or ecosystem-based approaches

NGSO actions for policy implementation

Develop and deliver groundwater monitoring data on fluxes and chemical status and relate them to biodiversity indicators

Establish common access to groundwater data

Contribute to preservation and restoration of nature by modelling the contribution of groundwater to surface waters and related biodiversity

Key geological information services related to the Global Biodiversity Framework and 2030 EU Biodiversity Strategy[54,55].

EuroGeoSurveys Sustainable Management of Groundwater actions contribute to delivering on these UN SDGs.

Priority GW1 – Groundwater resources in a changing climate: impact assessment, mitigation and adaptation

Effective management approaches are required to develop sustainable groundwater management strategies in response to changing hydrological conditions and climate scenarios. These management approaches rely on sound geoscientific understanding of groundwater systems and their hydrogeological and hydrogeochemical interactions with surface water and meteorological and climatic conditions. Floods and droughts will have huge economic effects on society by damaging infrastructure, the built environment in general, and ecosystems. Hence, monitoring of water tables to forecast floods and droughts is needed to protect society and nature and minimise the costs of extreme climate events. We argue that integrated (coupled or hybrid) hydroclimatic, groundwater-surface water, and coastal-marine water interaction modelling (calibrated using near real-time monitoring data) will help identify vulnerable and resilient groundwater bodies and groundwater-dependent terrestrial and aquatic ecosystems, prioritise adaptation and mitigation measures, and develop sustainable water management strategies. There is a need to reconcile differences in spatial and temporal scales, incorporate uncertainties in climate projections and hydrological parameters, and account for complex feedback mechanisms between surface water and groundwater systems. Using large scales and transboundary settings is necessary, as is sharing scenarios, parameters, and model outputs, requiring collaboration between NGSOs and other organisations, ensuring trans-disciplinarity. Groundwater models and related data should support increased understanding of the complex interaction of subsurface urban infrastructure and aquifers. They should also provide data, information, and knowledge to support development of the upcoming IPCC Special Report on Climate Change and Cities[54].

IMPLEMENTATION

Action GW1.1 – Improve data availability at different spatial scales, from local to global

Expected outcomes:

- Dedicated geoinformation products, such as map viewers, databases and integrative IT platforms hosting information about groundwater quantity and quality monitoring data, including cutting-edge near real-time measurements and advanced interpretation techniques.
- Methods to integrate past and current monitoring data, focusing on trend detection, forecasting and optimisation of data flows, developing state-of-art databases and information and communication technology tools.
- Advanced modelling and visualisation tools to inform the public of projected effects of human actions and impacts of land-use changes and climate change mitigation and adaptation measures, including the further development and enhancement of integrated groundwater-surface water models, to quantify the effects of hydroclimatic changes and temporal trends.
- Further implementation and application of field sensors and information and communication technology tools (e.g., real-time sensors, smart meters, smart phone applications).
- Increased information density and transparency over water use and availability to raise societal awareness (e.g., using citizen science supported techniques).
- ML-aided techniques applied to extend the available information to data-scarce areas (e.g., in combination with hydrological modelling and satellite data).
- City-scale groundwater monitoring networks implemented to support urban climate change mitiga-

tion and adaptation[54] and water security and safety in urban areas.

RESEARCH AND DEVELOPMENT

Action GW1.2 – Develop scientifically sound hydrogeological models integrating climate, surface, and marine water interactions

Expected outcomes:

- Improved, integrated modelling frameworks, accounting for uncertainty and variability.
- Multi-scale modelling frameworks that capture interactions between local-scale hydrological processes and regional-scale climate patterns, and account for spatial heterogeneity in hydrogeological properties, land-use, and topography that affect risk of floods and drought.
- Up-to-date methodologies to integrate groundwater flow, reactive transport, and travel time modelling of pollutants that can describe the functioning of groundwater systems related to the protection and restoration of associated ecosystems (e.g., tools to quantify microbial activity, which is beneficial for groundwater quality).
- Improved hydrogeological modelling tools, with better geological delineation, enabling simulations of continuity of the water cycle, from precipitation, surface flow, unsaturated flow to the groundwater table, to groundwater flow in aquifers and the outflow to springs and receiving surface waters.

IMPLEMENTATION

Action GW1.3 – Understand groundwater residence/travel time distributions as key factors for vulnerability assessment to global change impacts on groundwater systems

Expected outcomes:

- An environmental tracer database for assessing groundwater vulnerability across Europe, based on tritium and other age tracers, and extending information from tracers using ML methods.
- Methods to derive groundwater residence-time distributions which empower assessment of groundwater resource vulnerabilities and inform on timelines for reaching remediation targets, given the history and fate of contaminants in groundwater bodies in a changing climate.
- Innovative tracer-assisted and -calibrated groundwater modelling approaches.

Priority GW2 – Nature-based solutions for sustainable groundwater management and resilient groundwater resources

In recent year, nature-based solutions (sometimes in combination with engineered solutions, i.e. hybrid), have become important in climate change adaptation and water conservation strategies supporting sustainable water management. In urban contexts, nature-based solutions (often implemented as, e.g., green spaces, bioswales to retain excess subsurface water) have contributed to mitigating risks for urban flooding and damage to housing and infrastructure while harvesting co-benefits including more attractive urban environments and benefits to public health. In rural contexts, nature-based solutions are implemented to retain and store surface water by primarily river, lake, and floodplain restoration and from runoff events. Nature-based solutions can utilise the buffer capacity of subsurface shallow groundwater to store retained water, notably by means of Managed Aquifer Recharge (MAR) to deal with both increased flood and drought risk. Nature-based solutions provide multiple benefits besides flood and drought mitigation, including enhancement of biodiversity and carbon sequestration (particularly in the case of peatlands and wet forests).

RESEARCH AND DEVELOPMENT

Action GW 2.1 – Assess and deliver nature-based solutions for integrated quality and quantity groundwater management

Expected outcomes:

- Tools and models to identify vulnerable areas and improve groundwater monitoring to support targeted water conservation strategies, including using nature-based solutions. This will ensure more resilient and sustainable water supply. Sustainable water management is essential to mitigate flood and drought risk, ensure safety of citizens, and urban water security.
- Assessment of the impact and efficiency of mitigation solutions on groundwater, including nature-based[55] (or hybrid) strategies, urban and industrial wastewater reuse, nature-based water treatment systems (e.g., soil-aquifer treatment), and managed-aquifer recharge to promote the increase of mitigation options in Europe.
- New, improved, and integrated surface and subsurface monitoring tools for management and protection of water resources and impact assessment and design of climate change mitigation and adaptation solutions. Advanced monitoring systems for emerging pollutants are proposed and tested in pilot areas and on operational scale for managed-aquifer recharge, and soil-aquifer treatment systems. For managed-aquifer recharge, special focus is placed on efficient screening tools for emerging pollutants such as human and veterinary pharmaceuticals, personal care products and their metabolites, and persistent compounds such as Per- and polyfluoroalkyl substances (PFAS). Improved tools and methodologies to characterise aquitards, which function as important barriers to groundwater contamination of deep (paleo)water and which determine the interactions between renewable groundwater and paleo groundwater resources.

Priority GW3 – Protecting Groundwater in relation to drinking water, ecosystems, and public health

The need to revise the Water Framework Directive[37], Groundwater Directive[38], Environmental Quality Standards Directive[56], and Drinking Water Directive[50] has led to numerous discussions on the need for, and means of, monitoring chemical substances in groundwater. The sheer number of chemical compounds (listed under the REACH regulation[57]) and their metabolites and complex interactions is a major challenge for water quality assessment and mitigation. Basic questions, e.g., how to efficiently monitor all parameters affecting the chemical and ecological status of groundwater and associated ecosystems, require further development and standardisation of new monitoring techniques. The ecological status of dependent ecosystems is strongly related to groundwater quantity and quality. Water quality monitoring needs further development of non-target analyses towards standardisation and combination with quantitative assessment. There is a need for time-integrated measurements of pollutants in groundwater (e.g., passive sampling) and other 'omics' technologies (e.g., environmental DNA indicators), for a first step toward the assessment of the ecological status of groundwater itself (microbial communities).

IMPLEMENTATION

Action GW 3.1 – Tools to address groundwater contamination in relation to public health

Expected outcomes:

- Up-to-date methodologies to relate groundwater contamination patterns to historic and current emissions, accounting for the reactivity of the subsurface and travel times through unsaturated and saturated zones.
- Forecasting approaches to quantify evolution of groundwater contamination in abstraction wells, natural springs, and receiving surface waters in reaction to contamination pulses and source measures that aim to reduce further contamination, with special attention to time lags between measures and resulting breakthrough of solutes in relation to contamination legacies.
- Methodologies to quantify the buffer capacity of the subsurface in relation to prolonged diffuse contamination of shallow groundwater, including reactivity of subsurface sediments and turnover times and renewal times of groundwater within aquifers and aquitards.
- Expanded and curated non-target analyses reference databases for European main groundwater bodies to facilitate compound identification and classification, and standardised protocols and quality assurance procedures to improve reliability of non-target analysis results.

RESEARCH AND DEVELOPMENT

Action GW 3.2 – Improve tools for assessing groundwater chemical and quantitative impacts on ecosystems

Expected outcomes:

- Increased number and quality of monitoring data on surface-water/groundwater interaction using (near) real-time monitoring sensors for both quantity and water quality (e.g., physical and chemical parameters), combined with remote-sensing technologies.
- First steps towards impact-based monitoring, e.g., integration of non-target analysis with other omics-approaches to elucidate complex interactions between pollutants, organisms, and ecosystems and understand effects of chemical exposure on environmental and human health.
- Improved water table measurements at important and sensitive groundwater-dependent terrestrial and dependent or associated aquatic ecosystems (rivers, lakes).

Priority GW4 – Groundwater and the green transition

The green transition requires protection of groundwater quality and sufficient quantity in the process of extracting and managing natural resources, including (critical) mineral resources, CO_2 capture and storage, and geothermal energy. Geosciences, and in particular water resources, research must further contribute to understanding interconnectedness, interdependencies, and trade-offs between management of groundwater and the green transition. Addressing this requires innovative modelling approaches. As climate change and other global change drivers (e.g., population growth, urbanisation, and land-use change) exacerbate pressures on water resources and affect the green transition, integrated climate-surface water-groundwater models are required to understand the role of those drivers and develop adaptive water management strategies and resilience measures. For an effective green transition, "strategies are also needed to mitigate potential water risks for energy storage solutions, including pumped hydropower, as well as mining..."[34]. Although most solutions towards a net-zero society involve freshwater, "low emission energy scenarios often lack quantification of impacts on water quality and ecosystems, which must be incorporated into national and regional planning." The cross-disciplinary nature of the NGSOs, particularly in relation to urban geology (priority URB1), geothermal energy (priority ETD1), and environmental risk or the resources-society-nature system in general (priorities MGER2, MGER3), provides a strategic position from which to approach adaptation solutions, accounting for multiple aspects of the subsurface and enabling subsurface spatial planning.

IMPLEMENTATION

Action GW 4.1 – Dealing with competing uses in a busy subsurface environment

Expected outcomes:

- Integrative approaches based on sound geoscientific knowledge and 4D geocharacterisation to evaluate and balance competing subsurface uses in relation to drinking water, storage of heat, gases and solutes, exploration of geothermal energy including the effects on temperature, salinity, cross-contamination, and water use.
- Advanced modelling tools to study interactions between drinking water storage and abstractions, heat production and storage, and cross-contamination between subsurface compartments.

Strategic Geoscientific Focus

GOAL

Managing Geohazards and Environmental Risks

Geohazards (e.g., earthquakes, volcanic eruptions, tsunamis, sinkholes, landslides, soil erosion, radon emissions, among others) pose growing challenges as populations increase and become more urbanised, while suffering increasing climate-related pressures. Weather- and climate-related extremes caused economic losses estimated at EUR 738 billion from 1980–2023 in the EU[58]. Critical infrastructure (nuclear facilities, dams, etc.), urban and coastal environments, and cultural heritage are especially vulnerable, potentially leading to cascading disasters (e.g., flooding in Slovenia and Greece causing landslides, 2023; La Palma eruption, 2021). Although some natural geohazards are beyond human control (e.g., earthquakes, volcanoes), governments, communities, and individuals can implement measures to mitigate risks and enhance resilience. Human-induced hazards (triggered or exacerbated by human activities, e.g., land-use changes, industrial activities, mining, excessive groundwater pumping, intensive agriculture, and resource extraction) are often more predictable and preventable through careful management, spatial planning, regulations, and mitigation strategies.

The EU has several regulations and initiatives related to geological hazards, primarily under the broader framework of disaster risk management and environmental protection, which are at the heart of international agreements, including the Treaty of Lisbon[59] and the Sendai Framework[60]:

- **EU Civil Protection Mechanism**: This mechanism facilitates cooperation among EU Member States in disaster prevention, preparedness, and response. It includes measures for dealing with natural and human-induced hazards, including geological hazards.
- **European Disaster Risk Management**: The EU has policies aimed at reducing disaster risks through preventive, preparedness, response, and recovery actions. These policies address various natural hazards, including earthquakes, landslides, and volcanic eruptions.
- **EU Thematic Strategy for Soil Protection[61]**: This strategy includes measures to address soil threats (e.g., landslides and erosion), emphasising national mitigation and remediation.
- **EN Eurocodes[62]**: These are a series of 10 European Standards, EN 1990–EN 1999, providing a common approach for the design of buildings and other civil engineering works and construction products. They are the recommended reference for technical specifications in public contracts, integrating seismic hazard. The Second Generation EN Eurocode parts will be distributed by CEN to the National Standards Bodies no later than 30th March 2026.

The main expected outcomes for the R&I actions in this goal are directed at:

- Improving understanding of geohazard events, onshore and offshore, including human-induced and multi-hazard approaches.
- Delivering better quantification of geohazard processes and related impacts by integrating subsurface data, cutting-edge earth-observation monitoring, and high-performance models.
- Establishing coherent European common data management and risk mapping approaches.
- Improving risk assessment and mitigation using more detailed mapping of susceptibility, hazards, vulnerabilities, and risks adapted to decision making. Advising for European legislation. Improving early-warning systems.
- Improving soil health by delivering methods for monitoring and assessing soil quality[63–65].

Treaty of Lisbon & Sendai Framework

- **Treaty of Lisbon** (2007) **guarantees equal civil protection from natural hazards**
- **Sendai Framework** (2015) advocates for disaster risk reduction through understanding, governance, investment, and preparedness.

The **2024 report of the European Commission, '*Preventing and managing disaster risk in Europe*'**, is dedicated to implementing the EU Civil Protection Mechanism, which aims to:

- **Strength cooperation** on civil protection
- **Improve prevention, preparedness**, and **response** to disasters
- Exchange of **best practices**

NGSO actions for policy implementation

Serve data and expertise relevant to civil protection and emergency response related to geohazards (e.g., earthquakes, volcanic eruptions, flooding, and land instability / landslides)

Share best practices, developed through the actions of the EuroGeoSurveys Earth Observation and Geohazards Expert Group

Provide geological data for assessment and mitigation of geohazards

Collaborate through EuQuaGe, a volunteer organization of geologists from European governmental and academic institutions from 18 countries, for **rapid, effective, and coordinated assistance to national scientific organizations in the event of earthquake, sharing standardized methodologies and tools**

Key geological information services related to the Treaty of Lisbon[59] and Sendai Framework[60].

EuroGeoSurveys Managing Geohazards and Environmental Risks actions contribute to delivering on these UN SDGs.

Priority MGER1 – Improve understanding of natural and human-induced geohazard events: towards forecasting

Understanding geohazard events is essential for assessing and mitigating associated risks. Research should address the most common hazard-related questions: what? why? how? where? when? employing a wide range of methods and techniques (e.g., geological and geophysical surveys, remote sensing, in-situ testing, big data analytics, AI including ML, stochastic and multiphysics modelling). These approaches enable more accurate mapping, monitoring, analysis, and forecasting of geohazard events, informing effective risk reduction strategies and enhancing community resilience.

Field observations and advanced technologies such as satellite imagery, aerial surveys, and ground sensors (e.g., optical fibre) are revolutionising understanding of geohazards. This surge in data enables extensive area mapping, real-time information collection, and deeper insights. The recent European Ground Motion Service from Copernicus provides consistent and reliable information regarding natural and anthropogenic ground motion across Europe by analysing long time-series of radar data.

Although Earth observation data makes major contributions to addressing relevant issues, knowledge of the geological structure and the hydrogeological conditions of the subsurface are essential both for understanding the phenomena detected and for developing targeted solutions.

The development of new stochastic and multiphysics models able to numerically simulate reality is a multifaceted process that involves a variety of activities tailored to the type of model. Models provide tools to understand, define, quantify, visualise, or simulate how a phenomenon or geo-system behaves. If the proposed model can reproduce past and present behaviour, it could be used for forecasting the future (4D modelling). A challenge lies in developing realistic models able to consider the complexity of processes involved, working on multiple scales and timeframes, and managing uncertainties.

RESEARCH AND DEVELOPMENT

Action MGER1.1 – Innovate mapping and monitoring of geohazards by increasing the use of Earth observation through new technologies and advanced sensors

Expected outcomes:

- Integration of diverse data sources to create methods for combining data from spaceborne, aerial, and ground-based sources to gain a comprehensive view of geohazards.
- Implementation of advanced data analysis techniques using AI, to identify patterns and insights from Earth observation data, leading to a more comprehensive understanding of geohazards.

RESEARCH AND DEVELOPMENT

Action MGER1.2 – Develop new stochastic, multiphysics, or mixed models: towards Digital Twins and forecasting

Expected outcomes:

- Stochastic models, using Earth observation data and AI, to identify dependencies, cause-effect relationships, and empirical geohazard forecasting.

- Multiphysics models calibrated using Earth observation data, to identify realistic numerical simulations and quantitative geohazard forecasting.
- Mixed models, combining stochastic and multiphysics approaches, to smooth uncertainties.

Priority MGER2 – Risk assessment and mitigation

Risk is a function of how a hazard combines with vulnerability and exposure. Understanding these relationships makes it possible to identify ways to reduce risks, either by reducing hazard intensities or frequencies, or by decreasing exposure and/or vulnerability. From an operational viewpoint, identifying areas prone to hazards enables authorities to implement spatial planning measures to reduce their impact on communities and infrastructure. Conversely, infrastructure development and construction standards must account for likely geological hazard event magnitudes to ensure longevity and resilience.

To effectively manage risks and disasters, national and civil protection authorities require spatial data depicting the potential impacts of geohazards in their continental and marine territories. When disasters transcend borders, inconsistencies in decision-making processes (e.g., scale, hazard zoning, impact representation) can create challenges in transboundary collaboration. A homogeneous understanding of geohazards at the European scale fosters more effective risk reduction strategies and preparedness efforts. At the same time, close co-operation with local authorities and institutions is required as geological-induced risk is heavily dependent on the area under consideration (e.g., higher resolution is required for urban areas).

Knowledge of past events is crucial for understanding the spatial distribution, frequency, and severity of geohazards. Standardising data collection ensures consistent information quality, which facilitates transparent data sharing and collaborative analysis.

IMPLEMENTATION

Action MGER2.1 – Continuous updating of inventory and geohazards database

Expected outcomes:

- Improved standardisation of geohazard event data collection and management practices.
- Robust system for maintaining a continuous inventory and updating a geohazards database.

IMPLEMENTATION

Action MGER2.2 – Establish coherent and common risk mapping approaches across Europe

Expected outcome:

- Unified system for risk representation. This standardisation should encompass Mapping Levels, ensuring consistent maps across regions, and Numerical Web Services, enabling seamless data exchange and collaboration through standardised web services.

IMPLEMENTATION

Action MGER2.3 – Improvement of susceptibility, hazard, and risk maps

Expected outcomes:

- New susceptibility and hazard models and maps across different spatial scales and timeframes.
- New quantitative vulnerability models and maps across various scales, from individual buildings to entire regions. These tools should consider both physical infrastructure (structural vulnerabilities) and social, economic, and environmental factors (systemic vulnerabilities).
- New quantitative risk models and maps across different spatial scales and timeframes. Considering factors such as structural integrity (building level) and systemic weaknesses (territory level) will allow more precise risk maps, risk assessments, and prioritization.

IMPLEMENTATION

Action MGER2.4 – Improvement of early-warning systems

Expected outcome:

- New early-warning systems for geohazards, including multihazards approaches, integrating sub-surface data, real-time cutting-edge Earth-observation monitoring, and high-performance models.

Priority MGER3 – Reduce pollution and improve soil health

Healthy soil is a fundamental prerequisite for human existence. Many NGSOs in Europe contribute to the monitoring of soil quality and properties, mostly for urban and industrial soils, but also for land management purposes. That mission is complementary to soil quality for agricultural uses, which is usually handled by other organisations. Due to lack of soil protection policies, soils have been overexploited globally and are now under threat from degradation (e.g., erosion, contamination, sealing). Soils play a vital role not only for food production but also indirectly for water storage and groundwater recharge and purification. Regarding climate change adaptation, soil management will play a major role in mitigating drought, floods, and extreme weather events. Anthropogenic pressure on soil is steadily growing; in the EU alone, approximately two-thirds of soils face degradation risk because of inadequate management practices. The EU's 2050 Zero Pollution Ambition[52], encompassing clean air, water, and soil, entails reducing pollution to levels that no longer pose a threat to human health and natural ecosystems, creating a near-pollution-free environment. Achieving this ambitious objective necessitates swift and coordinated action throughout Europe.

This priority focusses on delivering data, geological expertise, and methodologies for monitoring and assessing soil quality to make informed decisions related to land-use dependent developments.

EU Soil Monitoring Law

- **Establish a comprehensive and consistent monitoring** framework allowing regular and accurate assessment of soil health
- **Long-term objective of all EU soils in a healthy condition by 2050.**

NGSO actions for policy implementation

Provide a common definition and benchmarking of healthy soil using geochemical baselines

Establish a monitoring framework with standardized soil health indicators

Enable sustainable soil management

Recommend action plans for contaminated sites

Key geological information services related to the EU Soil Monitoring Law[15].

IMPLEMENTATION

Action MGER3.1 – Establish Natural Background Levels for soil chemical and physical properties

Expected outcomes:

- Definition of natural chemical background for European soil at various scales, to identify areas suffering from pollution or nutrient deficiency. Both can be remediated by successful soil management practices, once recognised.
- Geochemical background and threshold values are established for potentially toxic elements (PTEs) in soil. Their sources are identified and described, considering soil type, climate, and land-use, and adapted to the regional and local scale.

IMPLEMENTATION

Action MGER3.2 – Develop standard methodologies for soil mapping and monitoring

Expected outcomes:

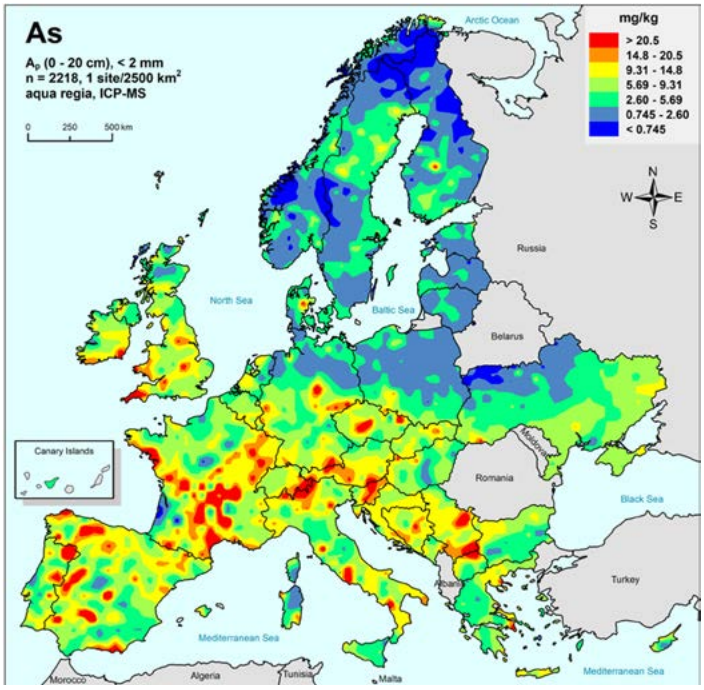
- Definition and validation of standardised, common methods of sampling, analytical protocols, data management, and visualisation, for mapping all parameters that define soil health status.
- Improved standardisation of soil quality assessment protocols, which guarantee the broad use of soil data in the transnational environment.
- Definition of parameters best characterising the chemical status of soil in relation to geographic location, climate, precipitation conditions, and land-use specifications. This will allow efficient planning of soil monitoring campaigns, considering region-specific features.

IMPLEMENTATION

Action MGER3.3 – Monitor soil erosion and contamination

Expected outcomes:

- Ongoing monitoring of soil erosion processes, including natural and anthropogenic erosion and related to geological parent materials. Notwithstanding, soil erosion is a long-term, large-scale process that requires systems-level management.
- Integrated understanding of soil erosion and contamination (e.g., potentially toxic metals, micro-plastics, pesticides), carbon losses, nutrient excess or loss, land degradation in the frame of climate change, and food security.



Pan-European arsenic concentration in agricultural soil: an example of soil data delivered by the EuroGeoSurveys Geochemistry Expert Group[63,64].

Integrating subsurface management and stakeholder engagement

GOAL

Urban Geology, Geoheritage and Land Planning

Land management and urban planning strongly depend on subsurface conditions, properties, and resources. NGSOs have significant roles to play in identifying solutions for safe and sustainable use of the urban subsurface in relation to responsible, long-term spatial planning.

Many subsurface-related policies and legislation have a siloed approach, targeting improvements within policy domains or sectors[54]. On the other hand, urban and spatial planning practices have a more holistic approach, dealing with a variety of competing spatial and societal functions. The subsurface must be brought into the scope of spatial planning to improve integration of subsurface-related policies and legislation in spatial and urban planning. Thus, the challenges (geohazards) and opportunities (resources) of the urban subsurface can be optimally addressed. The main challenge is seamless integration with above-ground sciences, practices, and standards.

Target groups are spatial and urban planning representatives at local, regional, and national levels. Additionally, preserving geoheritage and geodiversity as part of natural heritage is essential for ensuring that urban growth respects both natural resources and environmental sustainability.

Urban Agenda for the EU

- **Foster collaboration between cities** to tackle shared challenges in the fields of **clean energy, circular economy**, and **climate adaptation**

The agenda is strongly interconnected with the **Renewable Energy Directive** (encouraging integration of renewables into urban energy systems), the **Urban Wastewater Treatment Directive** (ensuring cleaner water discharge and supporting protection of public health and ecosystems), and the **Nitrates Directive** (controlling nitrate pollution from agricultural sources).

NGSO actions for policy implementation

Improve management of the urban subsurface and support planning and decision-making via activities of the EuroGeoSurveys Urban Geology Expert Group initiated as a COST Action linking NGSOs, city councils, research partners, and the private sector

Deliver networking, knowledge sharing, and develop common projects and campaigns

Make data available for understanding, planning, and development of urban underground resources (e.g., groundwater, geothermal energy) and to assess and mitigate geohazards, enable early warning systems, and raise awareness

Key geological information services related to the EU Urban Agenda[16,47,66].

This goal relies on 4 components:

- **Modelling**: to understand, visualise, and resolve competing user needs of the subsurface, addressing both resources and threats with a knowledge-based approach.
- **Integration**: to foster better use of knowledge and models to produce sound spatial planning.
- **Regulation**: a framework to inform decisions and sustainable development of urban areas.
- **Social engagement**: public awareness is crucial to develop good practices for appropriate, safe, and well-balanced land-use.

EuroGeoSurveys Integrating Subsurface Management and Stakeholder Engagement actions contribute to delivering on these UN SDGs.

Priority URB1 – Urban Geology: A Crucial Asset for Sustainable Cities

Geology is the 'primary infrastructure' of cities, playing a critical role in the development, sustainability, and resilience of modern cities: geological information supports safe urban planning and infrastructure. As cities expand and become more complex and populated, integrating the subsurface into above-ground agendas is vital to ensure the stability and sustainability of key systems. In line with the EU's ambition for a sustainable urban future, the urban subsurface is recognised as a multi-use 3D space where public transport, water, electricity, gas, heat, and telecom networks coexist. This space provides critical resources such as water and geothermal energy but also delivers vital geological system services such as water infiltration and heat regulation, essential for both the economy and environment. Subsurface characterisation, considering anthropogenic (man-made) deposits and subsurface objects, is crucial for identifying and mitigating ground risks in land-use planning and construction, as well as implementing net-zero technologies and nature-based solutions.

As cities face risks of natural and climate-related hazards (e.g., flood, landslide, subsidence, seismic activity, volcanic activity, sinkholes, drought) and urbanization grows, the urban subsurface must be considered in tandem with urban expansion, whether for industrial or tertiary development, using responsible, balanced land-use planning. Subsurface space can play an increasing role in decarbonising cities through technological solutions such as geothermal energy, seasonal heat and cold storage, stormwater banking, and local shallow groundwater use for irrigation, while also mitigating urban heat island effects.

Integrating geological, hydrogeological, resource, and environmental data with built environment models is essential to prevent conflicts of use, manage risks, and develop innovative solutions to harness the properties of the urban subsurface. Key stakeholders—city managers, urban planners, the construction

sector, and infrastructure owners—rely on this information for robust spatial planning, design of new infrastructure, and risk management and reduction. R&I is crucial for shaping future sustainable cities. The complex and diverse tasks in urban areas require close cooperation with the relevant specialist disciplines (e.g. hydrogeology, geohazards, etc.).

IMPLEMENTATION

Action URB1.1 – Develop urban subsurface ontologies and standards compatible with Building Information Modelling standards

Expected outcomes:

- Common ontologies for urban subsurface mapping and 3D modelling, including terminology for anthropogenic deposits (connected to USG 1.2).
- Aligning subsurface data (geology, hydrogeology, geomechanics, geophysics) with Building Information Modelling EU standards to integrate, view, and analyse above-ground and below-ground data in a single, standardised digital environment.
- Setting Building Information Modelling-compatible subsurface standards to make data functionally and dynamically available in third-party 3D working environments, using open, interoperable interfaces (e.g., OGC API 3D GeoVolumes) and similar exchange formats (e.g., 3D tiles, I3S).
- A platform for use cases and best practises methods for geological mapping adapted to urban environments.
- Seamless integration with above-ground infrastructure. By aligning subsurface data with Building Information Modelling standards, professionals (e.g., engineers, architects, geologists) can integrate, view, and analyse above- and below-ground data in a standardised digital environment.
- Cross-disciplinary collaboration. Strengthened collaboration and networking between civil engineers, urban planners, geoscientists, and utility company personnel, improves project coordination and reduces conflicts during construction and maintenance.

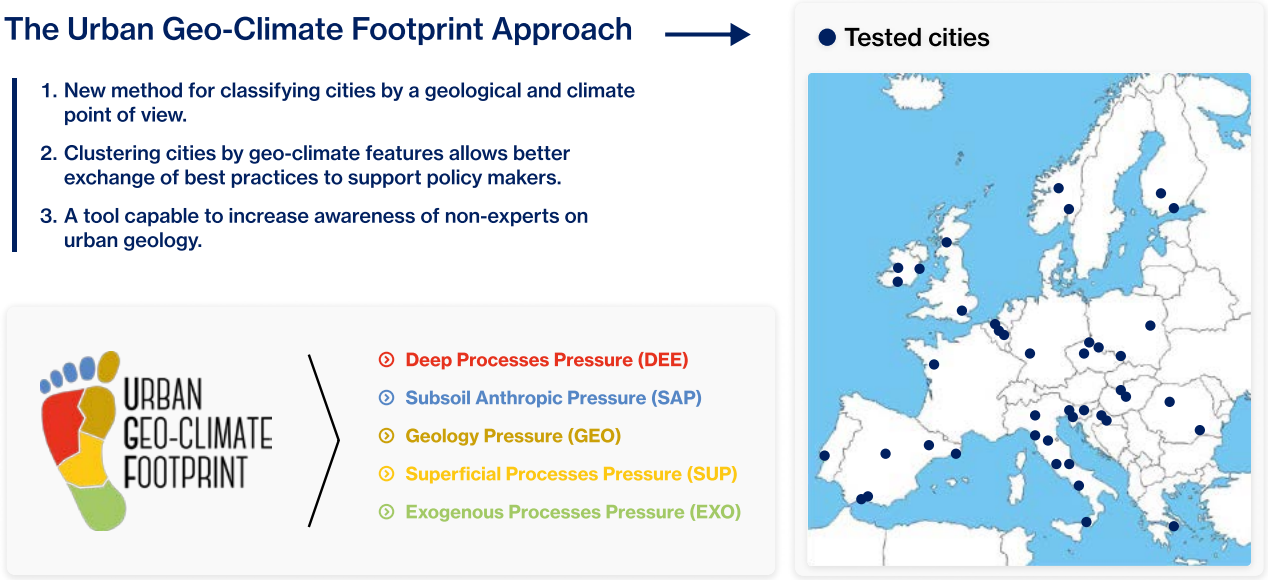
IMPLEMENTATION

Action URB1.2 – Analyse the geological and climate footprint of cities

Classifying cities based on their geological and climatic makeup is crucial for understanding their vulnerabilities and developing risk mitigation strategies. This approach, exemplified by the Urban Geo-climate Footprint tool[67], helps assess urban challenges through the lens of both geology and climate. The underlying principle is that cities with similar geological and geographical settings will likely face comparable challenges due to shared geological hazards and climate change impacts. This classification fosters awareness among non-experts and decision-makers of the complex interplay between geological conditions, climate change pressures, and human activities in cities. The Urban Geo-climate Footprint tool also provides basic information on existing resources in the cities' subsurface. The aim of this action is to classify European cities using the Urban Geo-climate Footprint method.

Expected outcomes:

- Knowledge exchange, empowering city planners to share best practices for building urban resilience.
- Increased awareness of non-experts on the urban subsurface and relative preparedness about issues and hazards but also on existing geological resources.
- Knowledge-based decision-making for actions and policies that enhance geoscience-informed climate justice.



The Urban Geo-climate Footprint Approach[67].

IMPLEMENTATION

Action URB1.3 – 3D models to manage competing use and support urban subsurface spatial planning and decision-making

Expected outcomes:

- High-resolution, evidence-based, digitally driven geological 3D models for urban experts to inform decision-making, incorporating key disciplines (e.g., geohazards, geotechnics, hydrogeology, geology, geophysics). Expanded urban 3D geology models (beyond environmental quality and geohazards) to include climate adaptation scenarios and sustainable energy use (connected to, e.g., GW 1.2).
- 3D models as tools for subsurface visualisation and knowledge transfer across disciplines, improving communication with urban communities and stakeholders.
- Selected cities implement 3D models as Digital Twins, serving as case studies to explore the full potential of urban geology models for planning and climate resilience. A co-design approach ensures Digital Twin models meet stakeholder needs and are accessible and understandable to non-experts, fostering community engagement.

Priority LUP1 – Land-use Planning

Land-use planning is essential for responsible and sustainable exploitation of resources. As natural resource potential often lies in the subsurface, strategic planning is needed to ensure that these resources can be accessed to avoid conflict of uses and without compromising environmental integrity and community development. Effective land-use planning, such as for mineral exploitation, use of groundwater for various purposes, use of subsurface space, subsurface storage, etc., involves balancing economic growth opportunities with long-term environmental stewardship, integrating geological data, and working in coordination with local communities, local authorities, industrial or agricultural users, and national policymakers.

By identifying areas with subsurface strategic uses (e.g., raw materials, geothermal energy, groundwater) and aligning with land access and usage regulations, governments and industries can optimize a responsible use of the subsurface and its resources while minimising disruption to ecosystems, urban development, and other uses. This requires handling various interests both at national (potentially also transnational) and local levels and to involve stakeholders of these two categories. Careful planning can also mitigate land use conflicts, ensuring that subsurface use is compatible with activities such as agriculture, conservation, cultural and social habits, and urban expansion.

RESEARCH AND DEVELOPMENT

Action LUP1.1 – Strategic Land-use Planning for Sustainable Resource Exploitation

Expected outcomes:

- Identification of areas high subsurface potential, integrated with land access and usage regulations, optimising resource extraction while preserving environmental integrity and promoting sustainable economic growth.
- Development of strategic land-use tools adapted to decision-making processes, communication with stakeholders, that balance subsurface use with competing land uses, ensuring minimal disruption to ecosystems and local communities.
- Development socio-economic tools combining land management and subsurface use.

Priority HER1 – Geoheritage

Geoheritage refers to natural geological features that have significant characteristics including:

- **Scientific Value**: Sites that provide key insights into Earth's history, e.g., locations with rare fossils or unique rock formations.
- **Educational Value**: Places that can be used to educate the public about geological processes, natural history, or environmental conservation.
- **Cultural and Aesthetic Value**: Locations that have cultural significance or that people consider visually stunning, contributing to a region's identity or spiritual significance.

Geoheritage sites are often preserved for their importance in understanding Earth's history and can represent a significant component of tourism activities throughout Europe. Geoheritage represents the geological history of our planet, encapsulating records of climate changes, the evolution of life, and major geological events that have shaped today's natural resources. These unique sites are not only scientifically significant but also integral to preserving Europe's natural heritage. Geodiversity, which refers to the variety of geological environments, materials, and processes, also underpins biodiversity, emphasising the close relationship between life and geology.

The most representative sites, holding unique geological records, must be documented, protected, and designated as part of European natural heritage, ensuring their legal conservation. Geoconservation must also be integrated into European environmental policies, recognising the importance of geological factors in the sustainable use of nature and in the conservation of natural heritage .

IMPLEMENTATION

Action HER1.1 – Identify and Preserve Geoheritage Sites

Expected outcomes:

- Enhanced public and policymaker understanding of natural history, promotion of geosites for science, education and tourism, and contribution to sustainable land management.
- Protection of Europe's geological treasures as part of its broader natural heritage.

IMPLEMENTATION

Action HER1.2 – Integrate Geoconservation into Environmental Policies

Expected outcomes:

- Support to environmental policies, strengthened nature conservation programmes, and promotion of public awareness about the importance of geoheritage.
- A greater alignment between geodiversity and biodiversity in conservation efforts, leading to more comprehensive, integrated continental and marine environmental protection strategies.
- Geoheritage is considered in land-use planning and environmental assessments, reducing risks associated with geological hazards and improving sustainable development.

IMPLEMENTATION

Action HER1.3 – Education and Public Engagement

Expected outcomes:

- Increased public knowledge and appreciation of geoheritage through educational programmes and geotourism initiatives, fostering stewardship of geological and natural heritage.
- Communities are empowered to engage in preservation of local geoheritage sites through targeted outreach and interactive learning experiences.
- A stronger connection between citizens and geological heritage, contributing to broader environmental consciousness and advocacy for conservation.

IMPLEMENTATION

Action HER1.4 – Research and Interdisciplinary Collaboration

Expected outcome:

- Better understanding of the interplay between geodiversity and biodiversity both onshore and offshore, particularly for biodiversity mapping, informing more effective environmental management and conservation policies.

Integrating subsurface management and stakeholder engagement

GOAL

Societal and Economic Impact: Knowledge Sharing, Policy Support, and Public Engagement

It is essential to harness and enhance Europe's geoscientific knowledge and expertise to address pressing challenges of the energy transition, environmental sustainability, geohazard risk mitigation and preparedness, and economic resilience, and to boost the impact of our SRIA Goals. This requires concerted efforts to share knowledge and best practices across borders, engage the public, and ensure policies are supported by scientific data. By building a network that connects geoscientific and communication experts, educates the public, and informs policy, the Geological Service for Europe will be pivotal in supporting Europe's Clean Industrial Deal[8]. This goal highlights critical areas of knowledge sharing, public engagement, and policy support to deliver societal and economic impact.

Priority SEI1 – A Network for Knowledge Sharing and Best Practices

NGSOs connect centuries of cumulative national data, information, and expert knowledge at continental scale – including through EuroGeoSurveys' 11 Expert Groups and 2 Task Forces – to deliver a common pan-European geoscientific data and expert knowledge base. This includes the collaborative human network of thematic experts to inform consistent, holistic, science-informed policy across multiple sectors and policy areas. Relationships, communication, and best practices are central to accelerating the Clean Industrial Deal[68]. Thus, it is crucial to strengthen our expert network, foster dialogue, and connect with communications specialists and ambassadors for geoscience with strong access points to stakeholder groups including academia, decision- and policymakers, industry, and the public.

RESEARCH AND DEVELOPMENT

Action SEI1.1 – Fostering Collaboration, Knowledge Sharing, and Geoscience Innovation to Support Europe's Industrial and Policy Efforts

Expected outcomes:

- An organised network connecting geoscientific experts with key stakeholder access points (e.g., ambassadors for geoscience, the media, educators, and public decision-makers).
- Accelerated Energy Transition and Industrial Projects: faster adoption of geoscientific data will reduce costs, improve resource efficiency, and minimise environmental impact.
- Standardised Practices and Improved Data Sharing: the creation of common standards for geological data management, subsurface exploration, and reporting ensures consistency across borders, fosters cooperation between nations and creates a unified approach.
- Improved Global Competitiveness and Capacity Building: Strengthened global geoscience partnerships, participation in international initiatives, support to capacity building in third countries, and an established knowledge-sharing network to ensure sustainable resource management and competitiveness and geohazard risk mitigation.

Priority SEI2 – Public Awareness, Engagement, Education, and Policy Support

EuroGeoSurveys and the NGSOs can further contribute to building public engagement and acceptance of controversial sectors, including mining and carbon storage, and underestimated sectors such as geohazards and geothermal. NGSOs have important roles to play in addressing social equity concerns, particularly in communities affected by resource extraction or land and subsurface use changes, by engaging early and using tailored communication and knowledge co-creation. They can contribute to closing skills gaps in many geoscientific areas of expertise, notably critical raw materials, by supporting development and implementation of geoscience education programmes[69]. These programmes should encompass a wide range of stakeholders including geologists, but also other sector-relevant professions, regulatory bodies, the media, and the public. By prioritising national training of geoscientists and associated professions, Europe can foster the emergence of a skilled workforce capable of meeting challenges and seising opportunities presented by Europe's net-zero industrial ambitions.

RESEARCH AND DEVELOPMENT

Action SEI2.1 – Revitalizing Geoscientific Expertise in Europe

Expected outcomes:

- Initiatives for engagement with educators and existing education initiatives to boost youth awareness of and engagement with geoscience education.
- Increased collaboration among geoscientific stakeholders.
- Stronger geoscientific competence in Europe.

RESEARCH AND DEVELOPMENT

Action SEI2.2 – Improved Geoscience Communication to Diverse Stakeholders

Expected outcomes:

- New and innovative mechanisms for engaging with stakeholders, with a focus on co-design.
- Audience-specific terminologies for improved communication outcomes.
- Translation of key documents for improved stakeholder dissemination.

RESEARCH AND DEVELOPMENT

Action SEI2.3 – Building Public Engagement for Sustainable Development

Expected outcomes:

- Public geoscience engagement at local to European scale, with direct stakeholder impact, particularly regarding resource extraction and changes in land and subsurface use.
- Improved public perception of geosciences and its application in diverse fields.
- Enhanced public engagement with key issues related to the energy transition.

RESEARCH AND DEVELOPMENT

Action SEI2.4 – Building Urban Resilience and Risk Awareness through Geoscience and Collaboration

Expected outcomes:

- Urban planners and communities will be better equipped to tackle geohazard and climate challenges, fostering resilience through knowledge-based decision-making.
- Enhanced risk awareness and collaboration between various stakeholders will ensure more effective risk management strategies.

Priority SEI3 – Policy Support Advice and Services

The Geological Service for Europe will improve pan-European harmonisation, standardisation, and knowledge sharing within and beyond the geoscientific community to underpin policy that will deliver resilient value chains[3], Net-Zero industries[2], and a sustainable environment and society. Increased availability, connectivity, and use of subsurface data are needed to inform the Clean Industrial Deal[69] and related policy, serving as a basis for the expert services required to support policy implementation.

RESEARCH AND DEVELOPMENT

Action SEI3.1 – Advance Policy Support, Risk Assessment, and Sustainable Management through Geoscientific Expertise and Collaborative Tools, Developed in Dialogue with Policy- and Decision-Makers

Expected outcomes:

- Informed policy decisions through enhanced data integration: policymakers will have access to harmonised, high-quality geoscientific data and models, enabling evidence-based decisions.
- Standardised frameworks for consistent policy application: the development of unified European standards will provide policy- and decision-makers with the tools to implement cohesive policies, reducing discrepancies and fostering cross-border cooperation.
- Real-time decision support for crisis and risk management: policymakers and civil protection authorities, will benefit from predictive models to optimise government responses, minimise geohazard risks, and improve resilience.
- Accelerated implementation of strategic initiatives: streamlined processes and decision-support tools will enable policymakers to fast-track the development and implementation of projects, ensuring quicker regulatory approval and infrastructure development.
- Data-driven solutions for long-term sustainability and resilience: by leveraging comprehensive data platforms, policymakers will be better equipped to design and implement policies that ensure sustainable management of natural resources, urban development, and environmental protection.

Conclusions

The EuroGeoSurveys ten-year Strategic Research and Innovation Agenda (2025–2034) provides the geoscientific foundation required to support Europe's strategic autonomy and competitiveness, environmental management, and sustainable development. Through this SRIA, we target our vision of a Geological Service for Europe – a permanent, sustainable, reliable source of high-quality geoscientific data, information, and knowledge of Europe's subsurface, drawing on the data and expertise of the National Geological Survey Organisations – a strategic and scientific partner to policymakers, industry, and civil society. A Geological Service for Europe will fill the need at European-level for coordinated, data-driven, and integrated sustainable use and management of geological resources (on and offshore) – energy, raw materials, groundwater, soils – environment management and protection, and geohazard mitigation and adaptation. It will ensure that Europe's subsurface is not only optimised for economic benefit but also responsibly managed and protected for future generations.

Our SRIA presents EuroGeoSurveys' roadmap – supported by member NGSOs – for achieving this vision by aligning geoscientific R&I with Europe's most pressing strategic goals, including decarbonisation, resource management, and climate resilience. It recognises that Europe's transition to a sustainable and green economy will depend heavily on our expert understanding of the subsurface, and on management and prioritization of its increasing and competing uses – for clean energy production, responsible raw material sourcing, groundwater and soil management, and geohazard mitigation.

The strategic geoscientific goals of our SRIA – energy transition and decarbonisation, responsible raw materials, sustainable groundwater management, environmental hazard and risk management – are integral components in delivering the comprehensive Geological Service for Europe. They must be supported by a sound foundation for understanding the subsurface through harmonised geological data, mapping, and modelling, and an evolving digital framework for delivering harmonised subsurface data – the European Geological Data Infrastructure. These priorities will not only support the green and digital transition but also contribute to securing Europe's strategic autonomy in key sectors, while preserving the environment and ensuring public trust through transparency and societal engagement.

Collaboration is central to our SRIA: not only within Europe but with international partners both within and beyond the geoscientific research community, to pool expertise and knowledge, strengthen strategic partnerships, and share knowledge and best practices. Coupled with this collaborative spirit, the commitment of EuroGeoSurveys' expert community to FAIR data, and interdisciplinary R&I will accelerate the application of geoscientific knowledge to tools for evidence-based decision-making.

Our SRIA is a blueprint for the sustainable and responsible use and management of Europe's marine and continental surface and subsurface. It translates our expert understanding of geoscience and the key areas for future R&I into concrete and impactful actions to address the interconnected challenges of energy and resource security, climate change, and environmental protection. Through the implementation of our SRIA, whether through current and future EU R&I funding programmes or national joint undertakings, EuroGeoSurveys will ensure that Europe's subsurface continues to be a cornerstone of its resilience and prosperity, contributing to a more sustainable future for all Europeans.

Acknowledgements

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Glossary

Acoustic sensing solutions uses sound waves to gather information about the subsurface (e.g. structure, properties, and dynamics of the Earth's subsurface).

Anthropogenic deposit is a material derived from human activities, including repurposed natural sediments (e.g., sand fill, soil enrichment) and newly formed substances.

Aquifer is a body of rock and/or sediment that holds groundwater.

Biostratigraphy is the branch of stratigraphy that uses fossils to establish relative ages of rock and correlate successions of sedimentary rocks within and between depositional basins.

Brine is a highly saline aqueous solution, often containing minerals and other dissolved substances, typically found in underground reservoirs.

Building information modelling standard states that building information modelling is a digital representation of physical and functional characteristics of a facility.

Carbon Capture and Storage (CCS) is a three-step process, involving: capturing the CO_2 produced by industrial activity or power generation; transporting it; and then permanently storing it deep underground.

CO2GeoNet is the European network of excellence on the geological storage of CO2 that is working on enabling the safe and efficient deployment of the CO2 Capture and Storage (CCS) technology (https://co2geonet.com/home/).

Critical Raw Material (CRM) is a raw material that is essential for the economy but has a high risk of supply disruption. These are integrated in a list created by the European Commission of raw materials that are essential to the EU economy but have high supply risks (https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en).

Critical Raw Material Act (CRM Act) is a legislative act of the European Union aimed at ensuring a secure, sustainable, and resilient supply of critical raw materials necessary for Europe's economic and industrial needs. Its objective is to ensure that the EU can rely on strong, resilient, and sustainable value chains for critical raw materials enabling Europe to meet its 2030 climate and digital objectives (https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en).

Digital Twins are virtual representations of a physical object, system, or process that is continuously updated with real-time data. This digital model is designed to accurately reflect the state, behaviour, and performance of its real-world counterpart. These can be used to aid in understanding and forecasting geological events.

EC's DG ENV Working Group Groundwater is a technical group established by the European Commission's Directorate-General for the Environment (DG ENV) to support the implementation of the Water Framework Directive (WFD) and the Groundwater Directive (GWD) (https://environment.ec.europa.eu/topics/water/groundwater_en).

European Energy Research Alliance Joint Programme on Carbon Capture and Storage (EERA JP CCS) is a collaborative initiative aimed at accelerating the development and deployment of carbon capture and storage (CCS) technologies in Europe (https://eera-ccs.eu/).

European Geothermal Energy Council (EGEC) is a non-profit organisation dedicated to promoting the development and use of geothermal energy in Europe (https://www.egec.org/).

Electromagnetics surveys are techniques used to measure and analyse electromagnetic fields to identify and characterise subsurface features.

EMODnet is a European marine data infrastructure that provides free and open access to marine data and information collected by various European institutions and organisations. It aims to support sustainable marine management, research, and innovation by integrating data from different sources and making it easily accessible to users (https://emodnet.ec.europa.eu/en).

Environmental DNA (eDNA) is defined as the genetic material left by organisms in the environment.

Earth Plate Observation System European Research Infrastructure Consortium (EPOS) is a pan-European research infrastructure that provides open access to integrated scientific data and products for studying the Earth's solid interior, helping to understand and mitigate natural hazards like earthquakes, volcanic eruptions, and tsunamis (https://www.epos-eu.org/).

EU Blue Deal is a comprehensive strategy to address Europe's water challenges by promoting sustainable water management, protecting aquatic ecosystems, and ensuring water security for future generations (https://www.eesc.europa.eu/en/initiatives/eu-blue-deal).

European Green Deal sets the goal of making Europe the first climate-neutral continent by 2050, while simultaneously resetting economic policy to support competitiveness, sustainability, efficiency, and resilience through a coupled green and digital transition (https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en).

European Earthquake Geology Task Force (EuQuaGe) is a group of experts that studies the geological factors contributing to earthquakes in Europe, aiming to improve earthquake risk assessment and mitigation.

European Soil Observatory (EUSO) is a platform that provides comprehensive data, knowledge, and tools to support EU policies related to soil health and sustainability. It aims to safeguard soils, promote sustainable land management, and contribute to the European Green Deal (https://joint-research-centre.ec.europa.eu/eu-soil-observatory-euso/eu-soil-observatory-policy_en).

FutuRaM is a project that is developing a knowledge base on the availability and recoverability of secondary raw materials within the EU, with a special focus on critical raw materials (https://futuram.eu/).

Geochemistry is the study of the chemical composition of the Earth and its materials, including rocks, minerals, water, and the atmosphere.

Geochronology is the study of the absolute age of geological materials and events, providing a timeline for the Earth's history.

Geoconservation refers to the actions taken to identify, protect, and sustainably manage geological sites, landscapes, and specimens with significant value for science, education, or tourism.

Geodiversity refers to the natural range (variety) of geological features, processes, and materials found in a given region.

Geoenergy refers to the use of heat and green energy, extracted from the Earth's subsurface, as well as CO_2 storage and clean energy carrier storage (e.g. hydrogen storage).

GeoERA was a European research project aimed at establishing a Geological Service for Europe. It focused on improving the understanding and management of the Earth's subsurface, particularly in relation to resources like geoenergy, groundwater, and raw materials. The project involved collaboration between various European geological surveys and research institutions (https://geoera.eu/).

Geohazards are natural processes or events that pose a threat to human life, property, or infrastructure due to their geological characteristics (e.g. earthquakes, volcanic eruptions, landslides, floods).

Geoheritage refers to geological features, landscapes, and sites that have significant scientific, educational, cultural, aesthetic, or historical value.

Geomechanics is the study of the mechanical behaviour of earth materials, such as rocks and soils, under various conditions.

Geomodelling is the process of creating and manipulating digital representations of the Earth's surface, including its features and processes.

Geophysical methods are techniques used to study the Earth's interior and its physical properties by analysing the behaviour of natural or artificially induced physical fields.

Geotechnical is a geoscientific domain that deals with the engineering behaviour of earth materials, such as soil and rock.

Geothermal refers to the heat stored in the Earth's crust, which can be extracted and used to generate electricity or provide direct heat.

Green Data4All Initiative aims to enhance environmental data sharing and public access to environmental information in the EU through updated regulations, promoting data-driven innovation and evidence-based decisions (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13170-GreenData4All-updated-rules-on-geospatial-environmental-data-and-access-to-environmental-information_en).

Green Deal Data Space is a federated ecosystem that provides access to projects and services related to resilience and sustainability, supporting the European Green Deal's goals (https://green-deal-dataspace.eu/).

Greenfield areas in mining refer to undeveloped land that is being considered or prepared for mining operations (started by a mineral exploration phase), often characterised by pristine natural landscapes and minimal existing infrastructure.

Groundwater defines the precipitation that has infiltrated the soil beyond the surface and collected in empty spaces underground.

Groundwater table is the upper boundary of the saturated zone in the subsurface where the pressure of the water is equal to atmospheric pressure.

Heat islands effects are urban areas that experience significantly higher temperatures than surrounding rural areas due to factors such as increased heat absorption from dark surfaces, reduced vegetation, and dense building structures.

Hydroclimatic refers to the interaction between hydrological processes and climate factors, encompassing the study of water cycle components (e.g., precipitation, runoff, evaporation) within a changing climate.

Hydrogeology is the scientific study of the distribution, movement, and quality of groundwater in the subsurface.

Lithogenetic units are fundamental rock bodies divisions based on their lithological characteristics, reflecting the depositional environments and geological processes involved in their formation.

Lithology refers to the physical characteristics of a rock, including its composition, texture, and structure.

Lithotectonic units are discrete, interconnected rock bodies that form the structural framework of the Earth's crust, defined by their lithological characteristics and tectonic history.

Metadata is structured information that describes, manages, and locates data, enabling its efficient access, use, and preservation.

Metallurgy is a scientific domain that study the structures and uses of metals.

Microgravimetric refers to the measurement of extremely small gravitational forces, often in environments where the Earth's gravity is significantly reduced or absent, such as space or deep underground.

MIN4EU is a European initiative that aims to provide a comprehensive database of mineral resources and information for decision-making in government and industry (https://egdi.geology.cz/record/basic/5f8008e9-7928-4ef3-a0d2-42e70a010833).

Mine dump is a large mound or hill of mining waste at the surface of a mine.

Mineral deposit is a naturally occurring concentration of a specific mineral or group of minerals in the Earth's crust that can be economically extracted.

Mineralogy is the scientific study of minerals, their composition, structure, properties, occurrence, and their formation.

Mining waste are the waste that occurs at several stages of the mining process and throughout all the life of the mine, from exploration (drilling) to mine closure.

Natural heritage refers to the biological and physical elements of the Earth, including ecosystems, landscapes, geological features, and species, that have significant ecological, scientific, or cultural value.

Net-Zero Industry Act aims to boost the EU's manufacturing capacity for net-zero technologies and their key components, addressing barriers to scaling up production in Europe and increasing CO_2 storage.

Ontologies represents the common scientific language that will be developed and adopted across geological surveys, ensuring consistent interpretation of geological data (https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en).

Pan-European of or relating to all European countries or the advocacy of political or economic unity among European countries.

Petrographic refers to the study of the microscopic composition and structure of rocks to identify minerals and their relationships within a rock.

Petrology is the scientific study of rocks and their formation, composition, and texture.

ProGEO is an international non-profit organisation dedicated to conserving Earth's geological heritage and promoting its importance for society (http://www.progeo.ngo/).

Quantum gravimetry is a method of measuring the acceleration of gravity using quantum mechanical principles, such as atom interferometry, to achieve unprecedented precision.

Quaternary is the current geological period, characterised by significant climatic fluctuations, the evolution of modern humans, and the development of complex societies.

Radiometric is a scientific field that measures and analyses the properties of radioactive materials, including their decay rates, radiation types, and energy levels.

Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is an EU regulation that sets rules for the production, placement on the market, and use of chemicals in the EU.

Remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation from a distance (usually from a satellite, aircraft and UAVs).

Renewable Energy Directive is an EU law that sets targets for the use of renewable energy sources across all sectors of the EU economy (https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en).

Reservoirs in geology are porous rock formations that store and transmit fluids, such as oil, gas, or groundwater.

Resource Description Framework (RDF) is a standard model for data interchange on the Web (https://www.w3.org/RDF/).

SCRREEN is a project that aims to strengthen Europe's critical raw materials strategy by establishing an expert network to address issues related to mining, processing, recycling, substitution, and applications of these materials (https://scrreen.eu/the-project/).

Simple Knowledge Organisation System (SKOS) is an area of work developing specifications and standards to support the use of knowledge organization systems (KOS) such as thesauri, classification schemes, subject heading lists and taxonomies within the framework of the Semantic Web (https://www.w3.org/2004/02/skos/).

Soil Monitoring Law establishes a framework for monitoring and improving soil health across the European Union to ensure it can provide essential ecosystem services and contribute to climate change mitigation and biodiversity conservation (https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_3637).

Subsurface in geology refers to the layers of the Earth beneath the surface, encompassing rocks, minerals, and fluids that are not directly visible or accessible.

Unconventional deposits in mining in mining refer to mineral resources that require specialised extraction techniques due to their unique geological characteristics, such as low-grade ores, difficult-to-access locations, or unconventional mineral forms.

Under-cover deposits in mining refer to mineral deposits that are located beneath a layer of overburden, often requiring advance exploration tools to be detected and significant excavation or mining techniques to access.

United Nations Sustainable Development Goals (SDGs) define the fundamental policy targets and principles for coordinated actions across countries and between sectors (https://sdgs.un.org/goals).

Urban geology is the study of geological processes and materials within urban environments, focusing on their impact on infrastructure, land-use planning, and hazard mitigation.

Urban spatial planning is the strategic process of designing and managing the physical arrangement of land uses, infrastructure, and facilities within urban areas to achieve desired social, economic, and environmental outcomes.

Water Framework - Groundwater Directives aim to achieve good quantitative and chemical status of European water bodies through targeted measures including pollution prevention, monitoring, action programmes, and measurable objectives.

Water4All Partnership is a European initiative dedicated to ensuring water security for all through research and innovation (https://www.water4all-partnership.eu/).
WEFE Nexus approach highlights the interdependence of water, energy and food security and ecosystems.

Zero Emissions Platform (ZEP) is an advisor to the EU on industrial carbon management and aims to speed up the use of carbon capture and storage technologies in line with Europe's climate goals (https://zeroemissionsplatform.eu/).

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