

A Geological Service for Europe – building trust through interdisciplinary and intersectoral collaboration

Julie Hollis^{*1}, Philippe Calcagno², Guillaume Bertrand², Daniel de Oliveira³, Philippe Negrel², Enrique Díaz-Martínez⁴, Francesco La Vigna⁵, Eleftheria Poyiadji⁶, Nathalie Tonné⁷, Sytze van Heteren⁸, Nicola Dakin⁹, Klaus Hinsby¹⁰, Peter van der Keur¹⁰, Gunter Siddiqi¹¹, Dana Čápoová¹² and Francesco Pizzocolo⁸

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Geology encompasses all of the Earth sciences and thus is multidisciplinary. It does not respect geopolitical borders, so requires teamwork across disciplines and between nations. Applying geological solutions to climate change increasingly requires transdisciplinary teamwork. This extends well beyond the geosciences to inform on issues of universal concern, e.g., deployment of renewable energy, management of groundwater resources, mitigation of climate-induced geohazards, and more. To achieve sustainability and success in these fields, it is essential to employ knowledge of subsurface, land, and subsea geology for the discovery, tracking, preservation, regulation, and exploitation of resources. This knowledge also supports integrated and coherent surface and subsurface spatial planning and the creation of cohesive laws guided by scientific insights. This in turn requires multi-stakeholder collaboration between scientific and governmental agencies, industry, and civil society, from research design to data and knowledge application. Such a broad spectrum of engagement is at the heart of the concept of a Geological Service for Europe, founded on a long history of collaboration between the Geological Surveys of Europe –extending networks, fostering innovation, sharing knowledge, building capacity and common standards. Given the current lack of public knowledge and negative perceptions of geology, collaborative efforts based on objective science can have a significant impact on building trust. This contribution highlights the collaboration of the Geological Surveys of Europe with non-geoscientific partners in serving society, supporting nature, and delivering the Green Deal.

La géologie englobe toutes les sciences de la Terre et est donc multidisciplinaire. Elle ne respecte pas les frontières géopolitiques et nécessite, par conséquent, un travail d'équipe entre les disciplines et entre les nations. L'application de solutions géologiques au changement climatique exige de plus en plus un travail d'équipe transdisciplinaire. Cela va bien au-delà des géosciences pour informer sur des questions d'intérêt universel, telles que le déploiement des énergies renouvelables, la gestion des ressources en eaux souterraines, l'atténuation des risques géologiques induits par le climat, etc. Pour assurer la durabilité et la réussite dans ces domaines, il est essentiel d'utiliser les connaissances de la géologie souterraine, terrestre et sous-marine pour la découverte, le suivi, la préservation, la réglementation et l'exploitation des ressources. Ces connaissances permettent également une planification spatiale intégrée et cohérente de la surface et du sous-sol, ainsi que la création de lois cohérentes guidées par des connaissances scientifiques. Cela nécessite une collaboration multipartite entre les agences scientifiques et gouvernementales, l'industrie et la société civile, depuis la conception de la recherche jusqu'à l'application des données et des connaissances. Ce large éventail d'engagements est au cœur du concept d'un service géologique pour l'Europe, fondé sur une longue histoire de collaboration entre les services géologiques européens - extension des réseaux, promotion de l'innovation, partage des connaissances, renforcement des capacités et normes communes. Compte tenu du manque actuel de connaissances du public et des perceptions négatives de la géologie, les efforts de collaboration fondés sur une science objective peuvent avoir un impact significatif sur l'image de marque de l'Europe.

La geología abarca todas las ciencias de la Tierra y por lo tanto, es multidisciplinaria. No se restringe a las fronteras geopolíticas, por lo que requiere trabajo en equipo entre disciplinas y naciones. Aplicar soluciones geológicas al cambio climático cada vez más requiere trabajo transdisciplinario, que va más allá de las geociencias para informar sobre problemas de interés universal, como el despliegue de energías renovables, la gestión de recursos hídricos subterráneos, la mitigación de geopeligros inducidos por el clima, entre otros.

Para lograr la sostenibilidad y el éxito en estos campos, es esencial emplear el conocimiento de la geología del subsuelo, la tierra y el subsuelo marino para descubrir, monitorear, preservar, regular y explotar recursos. Este conocimiento también respalda la planificación espacial integrada y coherente en superficie y subsuelo, así como la creación de leyes cohesivas guiadas por conocimientos científicos. Esto, a su vez, requiere colaboración interdisciplinaria entre agencias científicas y gubernamentales, la industria y la sociedad civil, desde el diseño de investigación hasta la aplicación de datos y conocimientos.

Este amplio espectro de compromiso es el corazón del concepto de un Servicio Geológico para Europa, basado en una larga historia de colaboración entre los servicios geológicos de Europa: extensión de redes, fomento de la innovación, intercambio de conocimientos, desarrollo de capacidades y estándares comunes. Dada la falta actual de conocimiento público y las percepciones negativas sobre la geología, los esfuerzos colaborativos basados en la ciencia objetiva, pueden tener un impacto significativo en la construcción de confianza. Esta contribución destaca la colaboración de los servicios geológicos de Europa con socios no geocientíficos en el servicio a la sociedad, apoyo a la naturaleza y cumplimiento del Pacto Verde.

1. Introduction

The European Green Deal is a broad suite of European Union (EU) proposals to mainstream climate issues across all sectors of the EU economy to ultimately achieve the ambition of making Europe the first climate neutral continent by 2050. The sustainable use and management of the Earth beneath our feet is crucial to this goal. To achieve such sustainable use and management of the Earth, we must understand the intersectional effects of the processes operating in Earth systems – processes within the lithosphere, hydrosphere, atmosphere, biosphere, and cryosphere. The study of these interacting

- ¹ EuroGeoSurveys
- ² BRGM – Service Géologique National,
- ³ Laboratório Nacional de Energia e Geologia,
- ⁴ Instituto Geológico y Minero de España (IGME-CSIC),
- ⁵ ISPRA - National Institute for Environmental Protection and Research, Geological Survey of Italy,
- ⁶ Hellenic Survey of Geology and Mineral Exploration,
- ⁷ European Marine Observation and Data Network (EMODnet) Secretariat,
- ⁸ TNO – Geological Survey of the Netherlands,
- ⁹ British Geological Survey,
- ¹⁰ Geological Survey of Denmark and Greenland,
- ¹¹ Conim ag, Zurich
- ¹² Czech Geological Survey,
- * julie.hollis@eurogeosurveys.org

processes is called geology. Geologists are crucial for achieving the Green Deal [1] – through provision of data, information, and knowledge of e.g., geothermal energy, groundwater dynamics including quantity and quality, mineral raw materials for green technologies, achieving sustainable urban environments, and locating geological storage capacity for heat and cold energy, alternative fuels, and sequestration of carbon dioxide. Unfortunately, the importance of this geological knowledge is little known to most people, and geology is suffering from an almost global negative perception that is driving down geoscience university student enrolments, compounding the problem [e.g. 2]. So, while collaboration has always been an important element of geoscientific work – given the diverse nature of geology as a science – in the context of mitigating climate change, collaboration outside the geosciences has become more important than ever. This is necessary to develop the trust required to tackle climate change by building relationships and a common vision between geoscience, industry, government, and the broader public [e.g., 3].

As a starting point, knowledge of the Earth structure and processes is needed to optimise benefits from our natural resources and to mitigate risks. Analytical geology involves detection and measurement of scientific variables, such as chemistry, structure, and morphology. These and other analytical data are gathered by geologists to construct geological maps of various kinds. Accurate geological maps are the basis of all geological work. In essence, they are the language

of geologists, allowing data to be transformed into meaningful knowledge about the structure, composition, and evolution of the Earth. However, while surface data is relatively easy to access, available subsurface data is often sparse and indirect. Geological modelling combines the available multi-source data and information via computer-aided processes to give a comprehensive picture of the geology in the three (space), or four (including time), dimensions [4–8]. Geomodelling is based on multiple geoscientific fields such as geology, hydrogeology, geophysics and geochemistry, and for many geoscientific applications [e.g., 9–13]. Consequently, building a geomodel is an interdisciplinary and collaborative task where scientists share their knowledge and work together to combine their data. Moreover, by integrating geomodels with infrastructure development, geologists and engineers can create models that not only depict geological features, but also existing infrastructure. These approaches strengthen a co-constructed representation of the underground that can be shared among the scientific community. Geomodelling is also a way to engage non-scientific partners: visualising a 3D geomodel, e.g., flying over geological objects or slicing them in cross-sections (Fig. 1), is a powerful and natural common language for sharing knowledge of the subsurface with stakeholders such as decision makers and the public.

In this contribution, we highlight examples of collaborative activities in

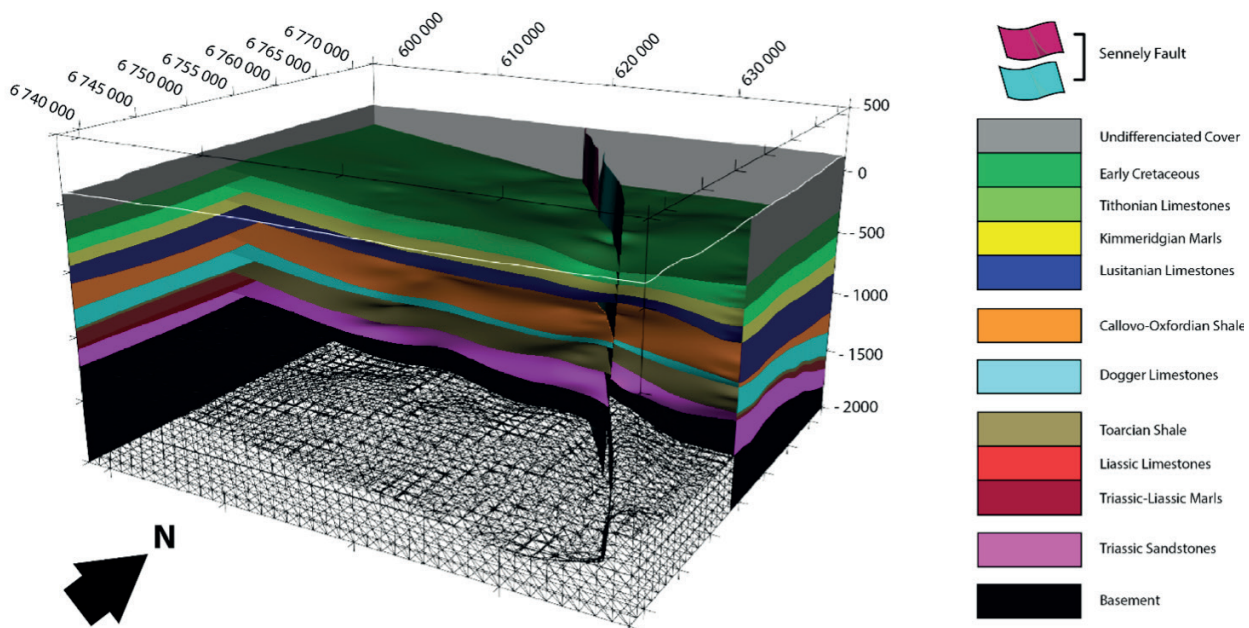


Figure 1: 3D Geomodel of the Orléans Métropole (France) constructed mainly from geological and geophysical data and information [12].

the context of a Geological Service for Europe. Focusing on these three methodological approaches – analytical, mapping, and modelling – to illustrate, across diverse branches of geoscience, that a common focus on interdisciplinary and intersectoral collaboration is crucial to achieving European climate goals.

2. Analytical geology

2.1. An example of mineral resources

In the context of increasing pressure on raw materials supply to satisfy surging demand, largely driven by the energy and digital transitions [e.g., 14], geology has reached the top of the policy and media agenda. While understanding the genetic processes of mineral deposit formation depends on geologists, modern mineral exploration largely relies on trans-disciplinary collaborations that are not limited to geosciences. The very notion of “ore deposit” itself is, by essence, not restricted to geosciences as it is largely based on economic criteria (i.e., a volume of material containing the targeted elements in sufficient concentration and quantity that extraction is economically viable). The acquisition of analytical data, from microscopic observation of minerals to large scale satellite remote sensing, requires multidisciplinary collaborations. These collaborations enable, e.g., development of modern mineral prospectivity mapping methods that help target exploration and thus optimise cost/efficiency ratio and minimise environmental impact. Such compilation, harmonisation, and processing of diverse and ever-increasing volumes of data require the support of various disciplines of data sciences and increasingly include the use of artificial intelligence. Beyond scientific collaboration, prospecting, to exploration and development, as well as mine closure and rehabilitation, all require collaboration between geologists and experts in fields such as legislation, economics, engineering, and mineral processing. Additionally, collaboration with the diverse stakeholders involved in complex and intricate value chains that impact national economies and geopolitical interactions is essential.

2.2. An example of cultural heritage preservation

After several decades of successful application in earth sciences and environmental research to elucidate the sources of water, solutes, minerals, and

pollutants [15, 16], analytical geoscience has recently played a linking role between art, culture, science, and technology. It has bridged into understanding and protecting cultural heritage, using isotopic fingerprinting. A first example is the discrimination of the sources of polluting sulphate neoformation causing degradational weathering of building stones. Investigation of sulphur and oxygen isotopes can constrain the sources, origin, and processes involved in the causes of different types of cultural stone damage [17], discriminating between extrinsic and intrinsic pollution sources and assessing their respective roles in the degradation of historical monuments [18]. This process can distinguish and quantify contributions from different sources, e.g., natural and internal to building stones, with pyrite playing a major role; natural and external, via marine aerosols; anthropogenic, from urban air pollution and, e.g., addition of plaster and cement, often from the Roman period [19].

A second example concerns traceability of stone materials used in medieval and renaissance sculptures. Traceability means tracking and recording the origin, route, and destination of products, materials, and information from the manufacturer or its supplier to the consumer [20]. Gypsum alabaster in medieval artwork equalled or even surpassed the importance of marble for religious sculptures and effigies. However, because few written records remain, neither the reconstruction of the medieval trade, nor the identification of artists, workshop locations, and trade routes can be easily constrained. Nonetheless, determining the origin of raw materials used for sculpture is crucial for art historians and museums. The first attempts to trace raw materials for gypsum alabaster artworks were made using mineralogical studies and trace elements, with unconvincing results. More successful was the use of multi-isotope fingerprinting of alabaster provenance, using sulphur, oxygen, and strontium isotopes [21, 22]. With isotopic fingerprints, a large corpus of European alabaster sculptures was connected to historical quarries and trades in the Middle Ages and Renaissance period. For example, a 2017 study [22] showed that English alabaster was exported over the continent by the Spanish and by particularly by long-lived (>500 y) French Alpine trades. This also revealed historical trade routes, the diversity of supply of medieval artists and workshops, and the presence and provenance of restoration materials.

3. Geological mapping

3.1. An example of sustainable urban planning

Urban environments are laboratories where geological knowledge must serve city managers, politicians, and citizens. Moreover, the citizens can sometimes be directly involved through citizen-science using a “social geology” approach. An important way to increase the citizens and city administrators’ awareness and engagement on the urban underground, what is usually considered “out of sight, out of mind,” is using maps. Everything starts from maps. In modern urban settlements city development is based on planning procedures that extract necessary basic information from maps. Detailed geological and thematic mapping is needed in urbanised areas to reduce uncertainties, to enable optimal ground usage and sustainable management, and to make what is under the ground (in the subsurface) more visible for non-experts [23]. Thematic geological, hydrogeological, and instability maps, e.g., are usually (or should be) considered in a city masterplan and in a city civil protection plan for several reasons:

- i. They provide crucial information about the subsurface setting beneath a city, fundamental for understanding the distribution of different kind of rocks;
- ii. They delineate areas with specific geological characteristics, such as stable ground for construction or areas prone to subsidence or flooding, or to amplify seismic waves, informing on land use zoning;
- iii. They contribute to city sustainability by highlighting zones with potential subsurface resources (minerals, building stones, geothermal energy, groundwater, etc.) or, e.g., where to favour stormwater infiltration via nature-based or hybrid solutions to mitigate urban flooding based on local hydrogeology [24].

Greece, e.g., has introduced geological maps into urban planning [25]. Here, the “geological housing suitability studies” are by law, necessary for development of new urban areas. These are used to:

- a. Identify geological hazards; prefer low level hazards or take mitigation measures,

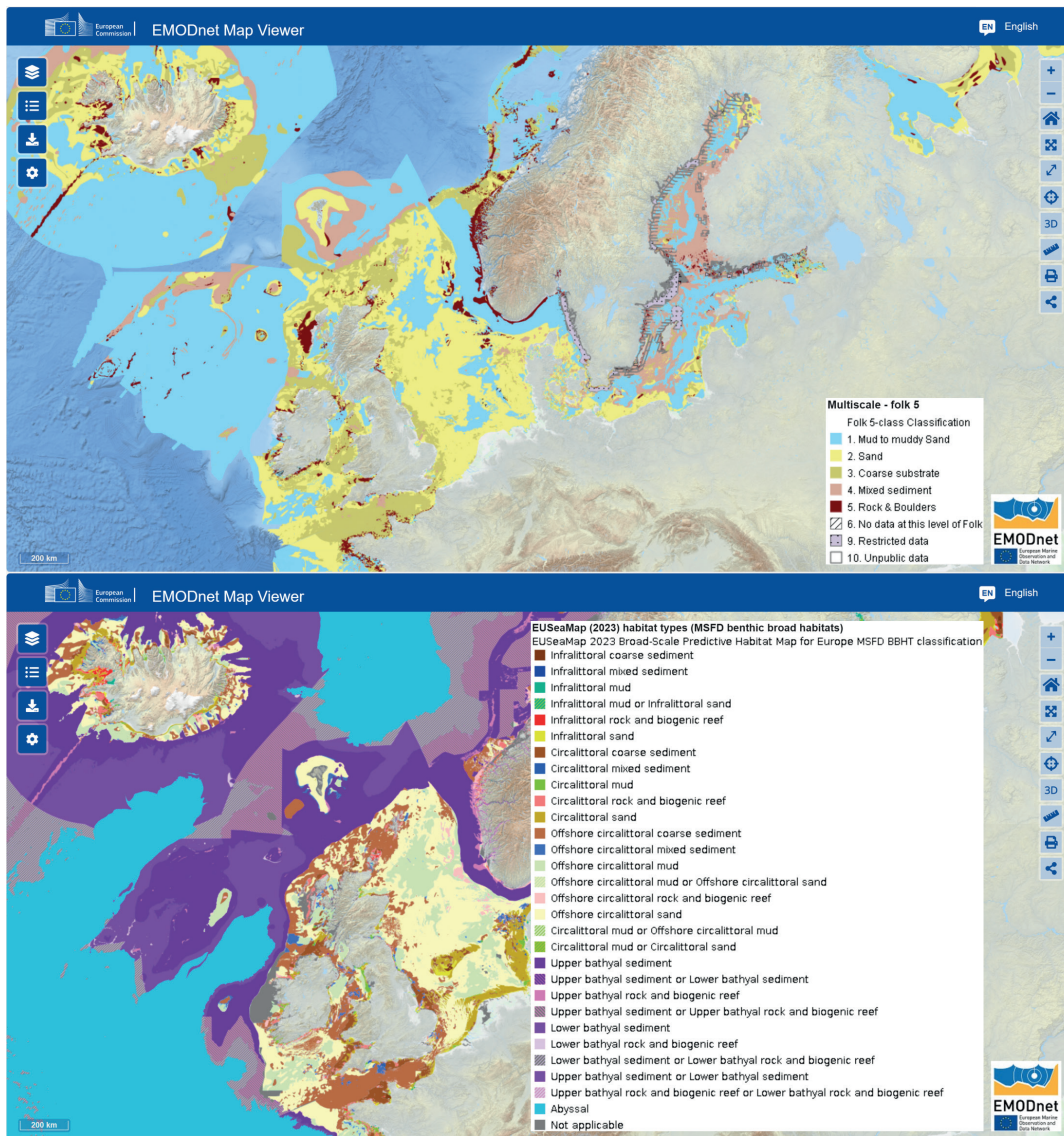


Figure 2: The seabed-substrate map of EMODnet Geology (upper panel) is clearly reflected in the cross-thematic EUSeaMap (lower panel).

- b. Assess geotechnical parameters of foundation formations; giving instruction for safe building,
- c. Identify areas that must be protected; areas with valuable resources like mineral deposits or groundwater resources, in urban areas or the surrounding catchment in which the urban area is located and affected by downstream groundwater flow.

Using such information, delivered through urban maps, it is also possible to identify urban areas that are distant but have similar subsurface structure and characteristics, and thus similar issues. This is the focus of the Urban Geo-climate Footprint (UGF) [26, 27], a new methodology and tool developed for urban areas, developed through the

EuroGeoSurveys network. By making use of available maps and datasets at European level, this tool allows homogeneous semi-quantitative evaluation of city geological complexity by calculating scores and indexes. This tool helps in sharing geological knowledge with citizens and city practitioners, giving a general overview of the geological setting and geology-related issues of urban areas, but also a cross-city comparison and best practices exchange in climate change adaptation.

3.2. An example of shallow marine mapping

EMODnet – the European Marine Observation and Data Network – is an EU marine data service that has been operational since 2009. The recent cen-

tralisation of the data services from the seven thematic data portals under a single umbrella – the EMODnet Portal (emodnet.ec.europa.eu) – has made it easier than ever for users to combine data and data products from bathymetry, biology, chemistry, human activities, physics, and seabed habitats with those from geology. One of the most well-known examples of cross-thematic work in EMODnet is EUSeaMap (Fig. 2) [28, 29], a data product which uses seabed substrate as a predictive surrogate for seabed habitats. Geological input is combined with information on bathymetry (depth), biology (biological zone), and physics (hydrodynamic energy) to map seabed habitats according to the European Nature Information System (EUNIS). The physical substrate is divided into five classes: rock and boul-

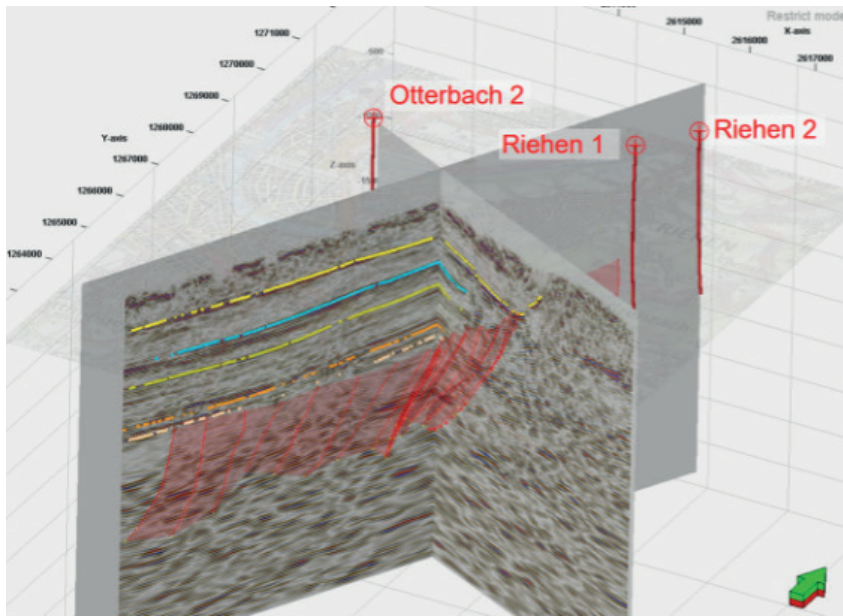


Figure 3: Modelling the stratigraphy at Riehen based on a conventional 3D seismic survey acquired in 2022, as presented to the local citizens [44].

ders, coarse substrate, mixed sediment, sand, and mud to muddy sand. To create a pan-European map, nationally used substrate classes were harmonised by a number of Geological Survey Organisations which are a partner of EMODnet [30]. Along with biogenic habitats, these substrate types are a key component of the European benthic-habitat classification [31, 32]. Another linking role that geology plays in EMODnet is in the use of bathymetry to map geomorphology.

Where the bathymetry shows only water depth, through EMODnet Geology, geologists have been able to interpret spatial patterns in water depth to explain the processes by which these patterns were formed. This increases the value of a harmonised EMODnet Bathymetry Digital Terrain Model (DTM). Underwater landforms as mapped by geologists include not just marine features, but also terrestrial lowstand (low sea level) evidence of (now subsea) rivers, polar deserts, and

ice sheets. It is even possible to recognise sedimentary, igneous, and metamorphic rock in EMODnet's Bathymetry's DTM, from recently formed Icelandic lava flows to folded and faulted Mesozoic strata offshore Southern England.

4. Geomodelling

4.1. An example of geothermal energy development

Since 1996, the geothermal energy project Riehen, in the Canton of Basel-City, has been an important supplier of geothermal heat from a reservoir at a depth of 1500 m into the communal heat distribution network. The communal utility company, Wärmeverbund Riehen AG, has a net-zero greenhouse gas emissions target and thus intends to grow the geothermal energy share at the expense of fossil fuel-derived heat by growing the geothermal reserve base and energy supply from its reservoir. In 2022, the company undertook a 3D-seismic campaign covering an area of 50 km² to identify an optimal well trajectory from surface to depth for an additional production well. In 2006, however, Basel experienced damaging induced seismicity in response to a hydraulic stimulation associated with an Engineered Geothermal System project. This occurred some 3 km deeper and miles from the currently producing reservoir. Nonetheless, the damage impacted public confidence

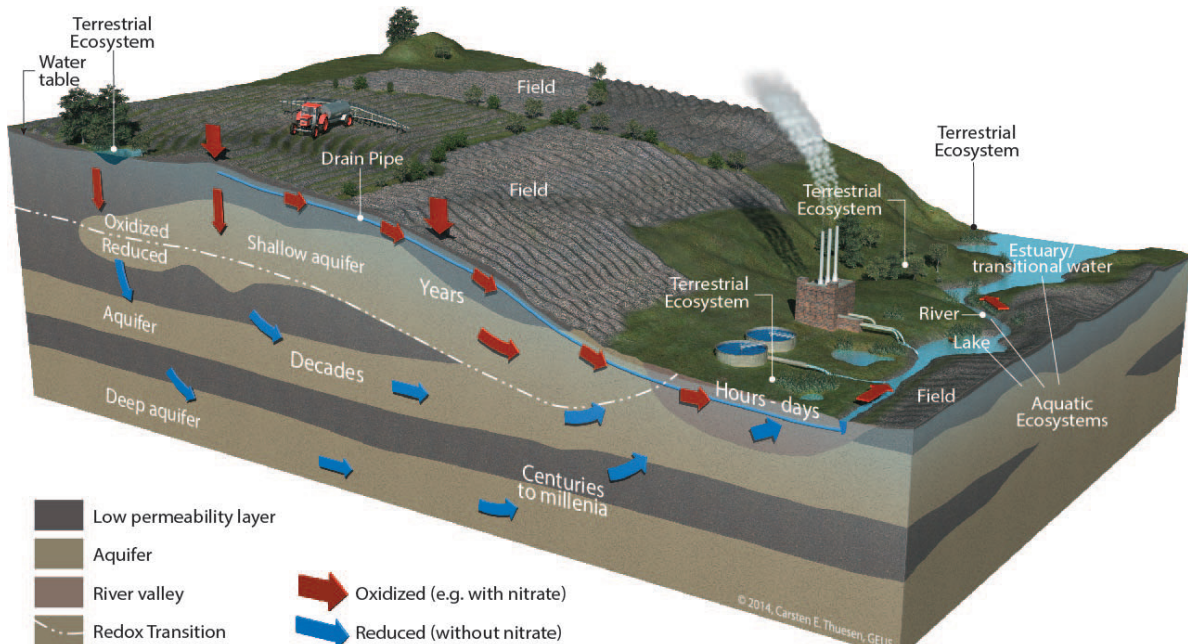


Figure 4: Hydrogeological conceptual model of a system that requires numerical modelling of the hydrological cycle using a fully integrated geological and physically-based and distributed groundwater-surface water model. This is to assess land use and climate change impacts on water resources and ecosystems at various spatial and temporal scales [43].

in geothermal energy production in the region. To maintain the high quality of its social license-to-operate and to counter fear of the unknown, the company invested extensively in communicating to its stakeholders, the local population, communal, cantonal, and federal permitting, regulatory oversight, and subsidy-granting authorities. Using 3D geological models, underpinned by data from its 3D seismic campaign and augmented by existing subsurface data, novel ambient noise tomography exploration data, and other potential field methods (gravity, electromagnetics), the company managed to further reduce exploration risk (Fig. 3). Doing so allowed the company to successfully demonstrate to its stakeholders that it is developing a sound understanding of the subsurface architecture and mitigating a fear of the unknown.

4.2. An example of integrated groundwater-surface water modelling

The complex and interconnected nature of groundwater and surface water systems and groundwater-dependent terrestrial and aquatic ecosystems [33–38] (Fig. 4) requires an approach that transcends traditional, compartmentalised views of water in the environment. Integrated dynamic and physically distributed groundwater-surface water monitoring and modelling based on geological models at varying scale [39] has allowed critical advances in our approach to understanding and managing water resources in four dimensions (space and time). By integrating dynamic, including near-real time data collection with physically distributed geological and hydrological models, scientists and water managers can better understand and project the time scales of water movement, quality, and availability (Fig. 4).

This integrated approach is crucial for integrated surface and subsurface spatial planning and climate change mitigation and adaptation [38, 40, 41]. Firstly, it allows accurate forecast of water flows and storage in response to natural and human-induced changes, including climate variability and land-use changes [34]. Such forecasting is essential for developing effective strategies for water allocation, flood management, and drought mitigation, including use of nature-based solutions to store groundwater for use during drought, increasing water security [42]. Secondly, this dynamic approach allows models to be

updated with real-time data, improving forecast precision and enabling timely decision-making in response to water management challenges such as extreme events [40].

Instead of lumped or otherwise simplified models, integrated hydrological models based on geological models offer detailed spatial information about water processes and interactions, provided detailed data for running such models is available and can be sustained. This granularity allows identification of areas at risk of pollution, over-extraction, or other environmental stresses, and supports targeted, efficient conservation measures and spatial infrastructure investments, supporting sustainable water management and spatial planning. Furthermore, integrated groundwater-surface water monitoring and modelling allow an understanding of complex hydrological feedback mechanisms, such as the impact of groundwater abstraction on river flows or the influence of land cover changes on aquifer recharge, aggravated under effects of climate change. This comprehensive perspective can support protection and restoration of aquatic ecosystems, ensuring long-term resilience and health of groundwater and surface water resources. Integrating dynamic and physically-based distributed groundwater-surface water monitoring and modelling is foundational in sustainable management of water resources to the benefit of society and nature. It supports informed policymaking, promotes adaptive management practices, and enhances our capacity to protect water resources, society and nature in an increasingly uncertain and changing world with more frequent hydroclimatic extreme events increasing the risk of groundwater over-abstraction during droughts and flooding during torrential rain events.

5. Discussion

Geology is, by nature, multidisciplinary, making it relevant to an almost limitless spectrum of human endeavours and to the health and sustainability of the natural (and increasingly anthropogenic) environment in which we live and on which we rely. In the context of a greater reliance on subsurface resources and processes, influenced by human-induced climate change, geologists and non-geologists increasingly find it necessary to engage, co-design, and collaborate in understanding and managing our inter-

actions with the Earth, in sustainable urban development, in moving from fossil-fuels to renewable energies, in modern mineral exploration and mining (targeting efficiency, minimal environmental impact, responsible social engagement), in environmental management (water, oceans, soils, biodiversity, geodiversity), in protecting our cultural heritage. From a geological perspective, and particularly from the perspective of geological survey organisations (where most authors of this contribution are based) that are mandated to collect, archive, and distribute geoscientific knowledge, and to provide expert advice based on this knowledge, these wide-reaching ambitions to effectively collaborate across disciplines and sectors [38] must be based – first and foremost – on sound data. This data can then be built into maps, and further into 3D or 4D models.

The strategic ambition of EuroGeo-Surveys (a not-for-profit organisation of which most authors are members) is to create a Geological Service for Europe that is founded on up-to-date geological data, harmonised at European scale (the European Geological Data Infrastructure, <https://www.europe-geology.eu/>). Given the diverse social, economic, and environmental applications of geology, and the increasing need to use and manage the subsurface to mitigate climate change and land use impacts, a Geological Service is necessary to deliver Green Deal policy and support net zero. While we envisage this Service as grounded in the FAIR delivery of harmonised subsurface data, the data – and the resulting information and knowledge – is only the foundation. A Geological Service to support the Green Deal requires much more – the development and application of common approaches, standards, and reporting frameworks; cooperation on cross-border projects; Europe-wide knowledge sharing and capacity building across the multiple geoscientific areas of expertise required to support rapid science- and technology-supported societal changes. Fortunately, these crucial elements of a Geological Service already have a strong base in the more than 50-year collaboration between the Geological Surveys of Europe. This collaboration is extended by the existing broad governmental, academic, and industrial networks in the European geoscience community, which continue to grow through the activities of the 5-year EU-funded Geological Service for Europe project (GSEU). GSEU itself builds on the finished project GeoERA

Horizon 2020 Eranet (<http://geoera.eu/>), which crucially broadened and accelerated development of the European Geological Data Infrastructure that is central to a future Geological Service. The ultimate goal of GSEU is to frame the organisational and financial model to build this collaboration into a sustainable Service that is able to deliver and translate knowledge of the European subsurface to tackle the multiple intersecting challenges to becoming the first net zero continent.

Our efforts to build this Service, hand-in-hand with our pan-European expert network, continue to highlight the crucial importance of engagement, co-design,

and ongoing collaboration with stakeholders who range from policy makers across multiple sectors (minerals, energy, environment, trade, civil protection, climate action and digital transition), civil society, industry, academia, education, and publics. Such collaboration to combine data types, expertise, and different perspectives reveals – again and again – new synergies and opportunities in applying geological knowledge to support applications and users of that knowledge. These applications and users can be difficult to even identify before the process of interdisciplinary and intersectoral collaboration is initiated. Furthermore, those users may hold key information,

influence, or resources that will make the application of geological knowledge more effective and widespread. For these reasons, in environmental management (water, soils, urban environments and mines), renewable industries and energies, preservation of cultural, bio-, and geodiversity, mitigation of hazards, and in cross-cutting areas addressing sustainable development, our interdisciplinary and intersectoral collaboration efforts continue to grow.

Conflicts of Interest: The authors declare no conflict of interest.

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Dr. F. Krantz
Rheinisches Mineralien-Kontor
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Fraunhoferstraße 7
53121 Bonn / Germany
info@krantz-online.de
www.krantz-online.com

