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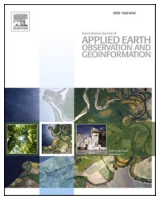

Mapping and understanding Earth: Open access to digital geoscience data and knowledge supports societal needs and UN sustainable development goals

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ABSTRACT

Open access to harmonised digital data describing Earth's surface and subsurface holds immense value for society. This paper highlights the significance of open access to digital geoscience data ranging from the shallow topsoil or seabed to depths of 5 km. Such data play a pivotal role in facilitating endeavours such as renewable geoenergy solutions, resilient urban planning, supply of critical raw materials, assessment and protection of water resources, mitigation of floods and droughts, identification of suitable locations for carbon capture and storage, development of offshore wind farms, disaster risk reduction, and conservation of ecosystems and biodiversity. EuroGeoSurveys, the Geological Surveys of Europe, have worked diligently for over a decade to ensure open access to harmonised digital European geoscience data and knowledge through the European Geological Data Infrastructure (EGDI). EGDI acts as a data and information resource for providing wide-ranging geoscience data and research, as this paper demonstrates through selected research data and information on four vital natural resources: geoenergy, critical raw materials, water, and soils. Importantly, it incorporates near real-time remote and in-situ monitoring data, thus constituting an invaluable up-to-date database that facilitates informed decision-making, policy implementation, sustainable resource management, the green transition, achieving UN Sustainable Development Goals (SDGs), and the envisioned future of digital twins in Earth sciences. EGDI and its thematic map viewer are tailored, continuously enhanced, and developed in collaboration with all relevant researchers and stakeholders. Its primary objective is to address societal needs by providing data for sustainable, secure, and integrated management of surface and subsurface resources, effectively establishing a geological service for Europe. We argue that open access to surface and subsurface geoscience data is crucial for an efficient green transition to a net-zero society, enabling integrated and coherent surface and subsurface spatial planning.

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1. Introduction

The significance of Earth's subsurface is frequently overlooked in decision-making and policymaking processes, and discussions concerning present-day societal challenges. However, it is important to acknowledge that numerous essential natural resources and processes originating from beneath the surface play a vital role in advancing "systems integration for global sustainability" often across large distances (Liu et al., 2015; Luetkemeier et al., 2021).

Richardson et al. (2023) argue that Earth is beyond six of nine planetary boundaries. Hence, tools are urgently needed for sustainable and more efficient management of Earth's resources and integrated surface and subsurface spatial planning. Given that certain limits within which humanity can thrive have already been surpassed (Rockström et al., 2009; 2023; Cousins et al., 2022; Wang-Erlandsson et al., 2022), or face significant pressure (Steffen et al., 2015; Lade et al., 2020; IPCC, 2022; United Nations, 2022) new more efficient approaches for safeguarding Earth-regulating systems are needed (Rockström et al., 2024). To achieve this, it is crucial to have easy access to digital geoscientific information adhering to the FAIR (Findable, Accessible, Interoperable, Reusable) principles (Wilkinson et al., 2016) at nested scales ranging from local to global. This accessibility is essential to enable transdisciplinary research and innovation for the green transition to a net-zero future (Ingemarsson et al., 2022).

The subsurface, including the topsoil, provides essential resources such as geothermal energy, thermal energy storage capacity, sustainable energy carriers, critical minerals, aggregates, groundwater, soils, options for nature-based solutions, groundwater ecosystems and other eco- and geosystem services (Griebler and Avramov, 2015; Limberger et al., 2018; Fleuchaus et al., 2018; Frantzeskaki et al., 2019; Franks et al., 2022; Bleischwitz et al., 2018; De Roo et al., 2021; Frisk et al., 2022). To ensure sustainability, a comprehensive understanding of geoscience data in 4D is required, including remote and in-situ near real-time observations, model projections, and assessments for natural geohazards and those induced by subsurface exploitation (van der Meer et al., 2012; van Gessel et al., 2017; Henriksen et al., 2023; Liu et al., 2016; Auflič et al., 2023; Orlecka-Sikora et al., 2020; Dinar et al., 2021). Geological, geochemical, geophysical, and (eco)hydrological data, monitoring and modelling are essential for addressing societal challenges related to resource exploration, climate change mitigation and adaptation, assessment of impacts of climate extreme events, and monitoring of geohazards and disaster risks (Arvanitidis et al., 2015; Calcagno, 2015; Middleton et al., 2020; Smelror, 2020; Turner et al., 2021; Viesi et al., 2022; Hollis et al., 2022; Quevauviller, 2022). Consequently, EGDI was launched in 2016 by the EuroGeoSurveys (EGS) as a stable framework sustaining and maintaining open access to digital geoscience data and knowledge to ensure the long-term preservation and availability of data from joint EU projects and individual regional and national surveys spanning more than a century. Today, EGDI is the only Pan-European platform for geoscience information that provides shared and free access to terrestrial and marine subsurface data from 37 geological survey organizations across Europe, including all EU member states, collaborating under EGS. Together these data support anticipated future developments of digital twins in earth sciences (Nativi et al., 2021; De Felipe et al., 2022; Rigon et al., 2022; Moigne, 2022; Henriksen et al., 2023) for sustainable resource management and the achievement of UN SDGs, the European Green Deal and the UN Resource Management System, UNRMS (EGS, 2023; European Commission, 2019; United

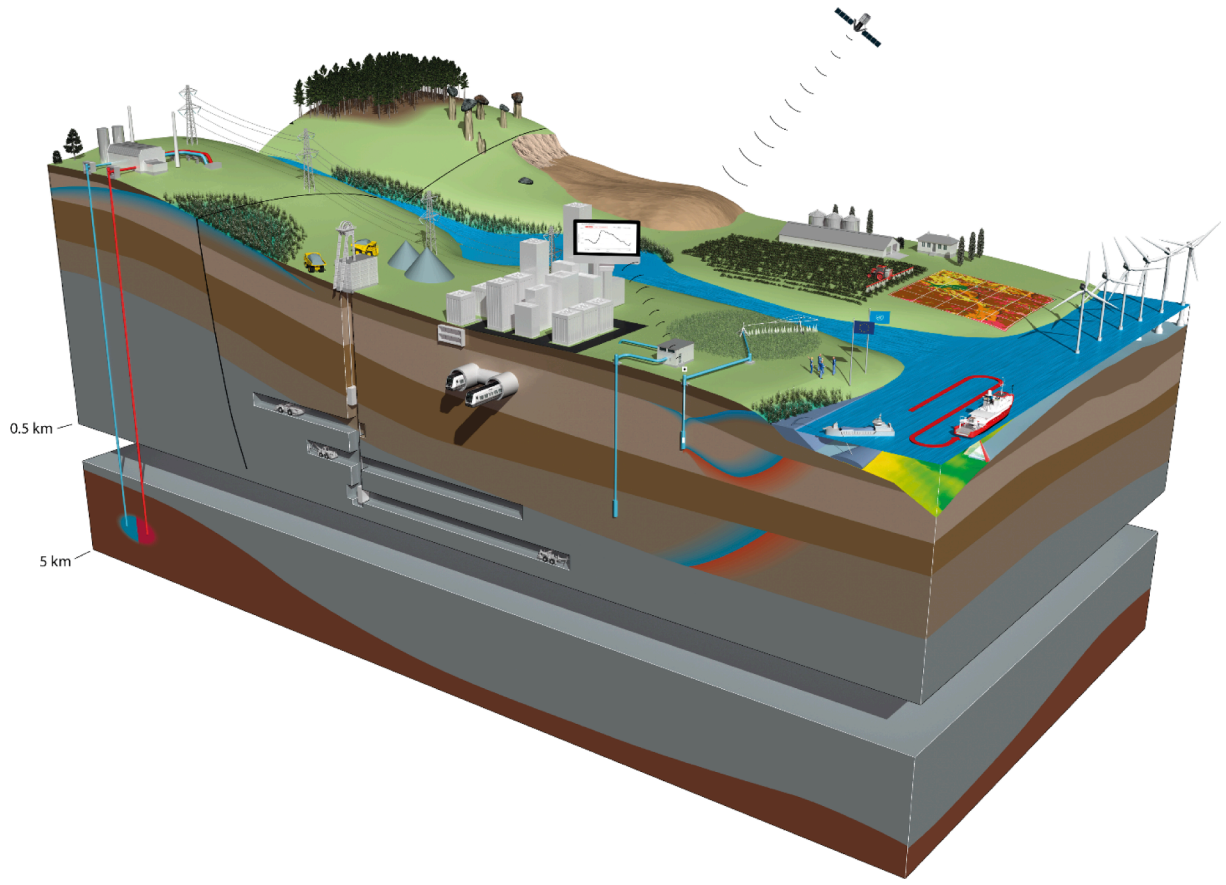

Fig. 1. Conceptual model of natural resources exploitation, remote and in-situ observations, mapping, and monitoring of Earth's natural resources, geohazards (illustrated by fault and landslide) and groundwater-dependent ecosystems. Red/Blue boundaries in the subsurface in the coastal zone are salt- (red) /freshwater (blue) boundaries, while red and blue wells to several kilometres' depth illustrate the use of deep geothermal energy. Coloured squares NW of windmills illustrate digital soil map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nations, 2021b).

EGDI offers a gateway to geoscientific data and the latest research findings aggregated and supplied by the ten expert groups of EGS (EGS, 2023, Fig. 1). Concrete examples highlighting the value of open access to digital data and knowledge compiled in EGDI include 1) Practical applications of soil geochemical data through EGDI digital map services by consulting companies assessing risks or pollution impacts associated with establishing and developing industries such as metal production and smelting or wood impregnation. Soil geochemical data is also useful in detecting nutrient deficiencies in agricultural soil, which can be addressed with additional fertilization. In this situation, assessing the potential for nitrogen (N) and phosphorus (P) contamination in groundwater and terrestrial and aquatic ecosystems is critical. This evaluation is crucial for safeguarding drinking water supplies and ecosystems from pollution that can significantly impact human health and biodiversity. It's worth noting that the biogeochemical flows of N and P are among the six planetary boundaries already transgressed, according to Richardson et al. (2023); and 2) An efficient green transition to a net-zero society and sustainable management of subsurface resources have become a growing concern, and many regions in Europe are conducting assessments and projections to determine the desired development paths of competing subsurface uses considering "Do No Significant Harm" principles. Such studies heavily rely on European geoscientific data to e.g. assess the potential for CO_2 geological storage, hydrogen storage, geothermal energy (Figs. 1 and 2a), mining for critical minerals, while still ensuring no significant harm to water resources and nature potentially crossing borders.

The value of the data and knowledge compiled in EGDI is further depicted and demonstrated in the following four sections: section 2) Renewable energy and carbon capture and storage in rural and urban environments, section 3) Raw materials, minerals, and aggregates for the green transition, section 4) Water security in a changing climate and section 5) Geochemical mapping of soils for sustainable societies: from urban to continental scale. The four sections briefly summarize recent research and data collection by EuroGeoSurveys regarding or related to the exploitation of the four vital natural resources: geoenergy, critical raw materials, water, and soils. Sustainable management of the four natural resources representing a wide range of "sub-resources" (e.g., the critical minerals Li, Ni, Cu etc.) is indispensable in achieving the intricately linked UN Sustainable Development Goals. Open data access to surface and subsurface geoscience data is crucial to support efficient global and multi-stakeholder partnerships for sustainable development (SDG17).

2. Renewable energy and carbon capture and storage in rural and urban environments

Reducing anthropogenic CO_2 emissions is crucial and requires significant decarbonisation of the energy sector. This involves shifting from a fossil-based energy system to a zero-carbon, renewable energy system that strains essential resources such as critical raw materials and freshwater (European Commission, 2023a, b; United Nations, 2021a; Ingemarsson et al., 2022). As a result, we are seeing significant changes in resource production and increased use of subsurface resources, which also needs to consider climate change projections and impacts, and the Water-Energy-Food-Ecosystem (WEFE) nexus (de Roo et al., 2021).

Increasing urban populations are placing extreme pressure on natural resources and the environment. Urban areas are a major contributor to global greenhouse gas emissions (Smith and Bricker, 2021), and they are the areas most significantly affected by hydroclimatic extreme events, especially in coastal zones (Elmqvist et al., 2019). The relationship between population growth, urban expansion and resource use is non-linear, meaning that the impacts of urbanisation on the environment are difficult to predict and increasingly unfavourable (Harte, 2007). For example, the increasing rate of water demand has been twice the rate of population growth in recent decades (United Nations, 2015) and while urban centres only cover approximately 3 % of the land surface, they account for more than 70 % of energy consumption and 75 % of carbon emissions (Smith and Bricker, 2021; note the central location of the city in Fig. 1), challenging resource distribution networks.

Even though the importance of the geological environment and the urban subsurface to delivering the UN SDG have been recognised (Volchko et al., 2020), geoscience information has traditionally been under-utilised in planning and development. The significance of geoscience information is often misunderstood or underappreciated (Royse et al., 2013). To address this, we need to assess the intimate links between the geological environment, climate, urban development, and societal needs, where a region's geology directly influences the availability of natural resources, urban hazards, and the extent to which urbanisation causes environmental degradation.

Within urban areas, shallow subsurface services are already extensively utilised. Sewer systems, crucial for sanitation purposes, are among the earliest examples. The storage of goods and cars, transportation networks, groundwater, and shallow geothermal energy for space cooling or heating represent more recent additions. In general, the shallow subsurface is almost as crowded as the surface. Since the subsurface infrastructure is not readily observable, spatial documentation of its location, use and relation to geology is essential (Volchko et al., 2020).

The growing use of renewable shallow geothermal energy (SGE) in urban areas may threaten valuable groundwater resources (Fig. 2). Geothermal heat pump technology uses the shallow (typically up to 400 m deep) subsurface as an energy source and sink, efficiently transferring thermal energy directly from the heat stored in rocks, soils, and groundwater to human infrastructures, and vice versa. Although this technology is generally regarded as environmentally friendly, it inevitably produces a temperature change in the subsurface (Rivera et al., 2017). Hence, it may result in significant physical, chemical, and biological effects and threats to groundwater quality. In urban environments (smart cities), any change is anticipated to be increasingly controlled and monitored in near real-time (Kitchin, 2014), e.g., as part of digital twins that control and ensure the long-term technical and environmental sustainability of SGE systems. This monitoring relies on integrated geoscientific data, e.g., digital twins operating and optimising city SGE systems. The development of an SGE decision-support and information tool led by EuroGeoSurveys was an essential first step in support of the upscaling of decarbonisation of the energy sector in urban areas. Data such as groundwater temperature and level, thermal conductivity, and hydraulic properties have been collected and harmonised throughout 14 urban pilot areas in Europe within the MUSE project of the GeoERA program (GeoERA, 2022). These geoscientific data are fundamental to unravelling the complexity of thermal regimes in the shallow subsurface of cities (Fig. 2). Moreover, coupled with the analyses of existing legal frameworks, they provide sound thresholds for SGE governance (García-Gil et al., 2020).

However, a single solution such as SGE will not suffice to reach the sustainable energy transition goals. Energy systems will have to be more flexible to account for the variable nature of growing renewable energy resource portfolios, and transmission and distribution networks will need to be expanded to accommodate the electrification of end-use sectors (United Nations, 2021). Moreover, the introduction or expansion of other renewable energy techniques, such as the exploitation of deep geothermal energy (Limberger et al., 2018; Weibel et al., 2020), carbon capture and storage (Olivarius et al., 2019; Bredesen et al., 2023), offshore wind farms and efficient battery technologies must also be supported with interoperable geological data to realize the green transition and a carbon–neutral society. Many of these deeper or offshore applications are developed outside the urban context, e.g., in rural areas (Fig. 1), but are driven by urban needs. From a broader perspective, this leads to an increase in both on and offshore surface and subsurface use for, e.g., the construction of infrastructure and the extraction of raw materials from the subsurface. This intricate and far-

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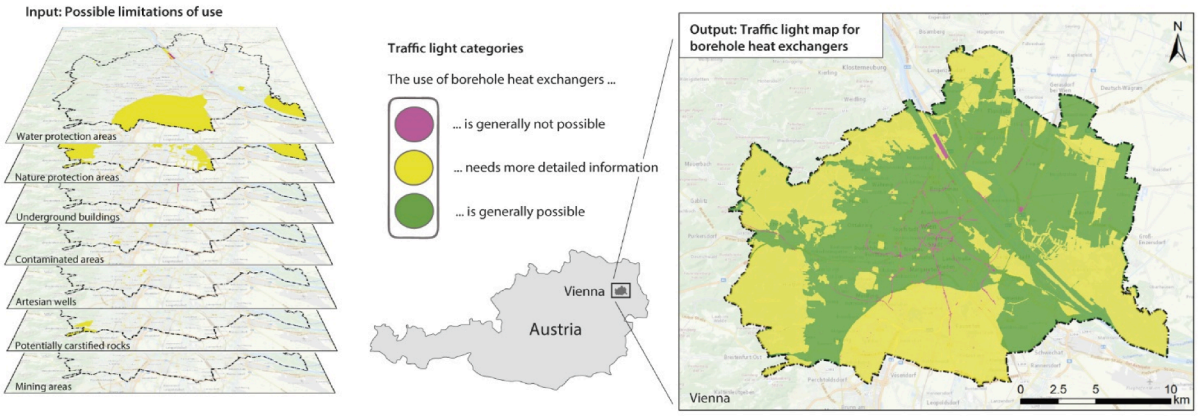

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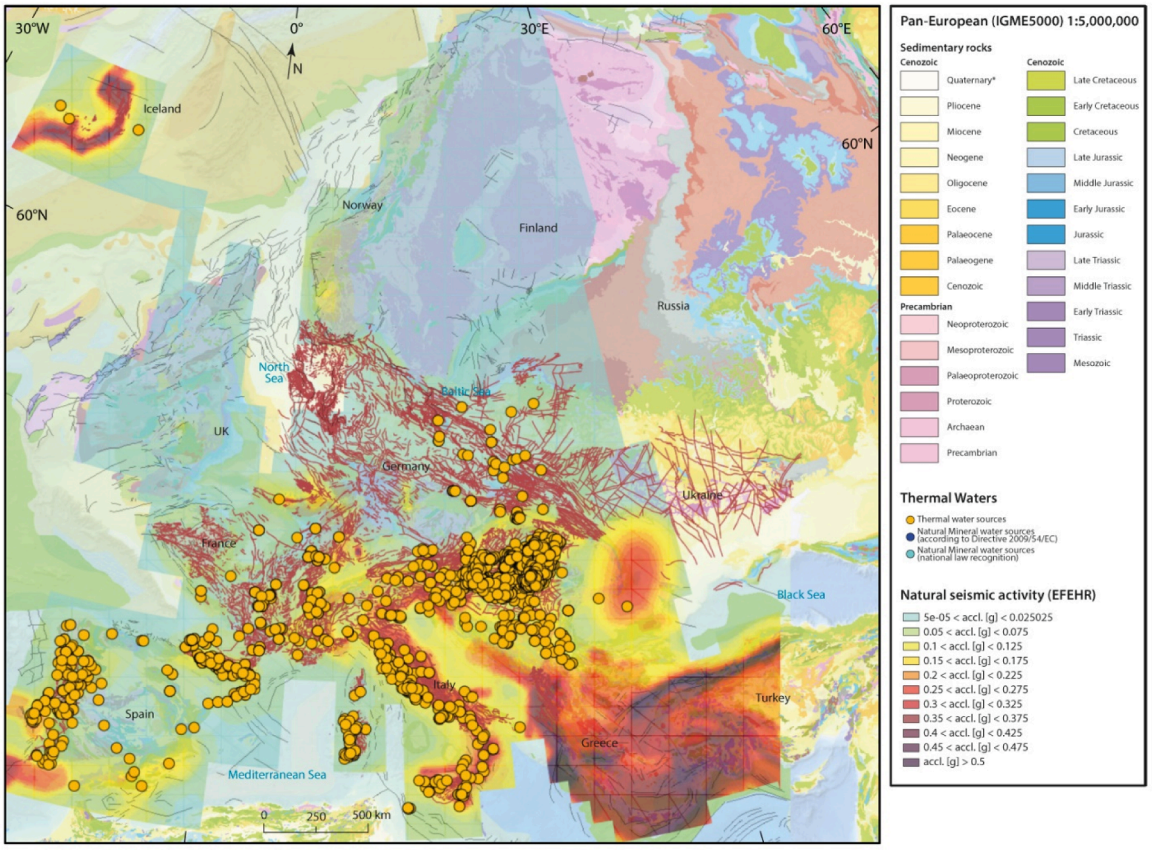

Fig. 2. (a) Example of a "Traffic-light" model delineating where subsurface geothermal energy is possible in Vienna, Austria. The example not exhibited in EGDI shows subsurface information supporting knowledge-based decision-making for shallow geothermal energy (SGE). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
adapted from Steiner et al. (2021). Left: layers of geological subsurface data simplified into "No-go, maybe and yes" classes (middle) to a potential SGE map to the right. (b) Example of map combinations in EGDI – the map shows a combination of six different map layers 1) onshore geology (1:5.000.000), 2) offshore (seabed) geology (1:5.000.000), 3) on-shore fault systems (dark red and grey lines), 4) off-shore fault systems (greyish lines) 5) Natural Seismic activity (e.g., dark red areas around Iceland in the North-West and Italy, Greece and Turkey in the South-East) and 6) Geothermal waters reported by the GeoERA HOVER project (yellow circles), (EGDI 2023a). To get the exact same map display as in Fig. 2b the user must modify the transparency of the shown layers manually in EGDI (2023a).

reaching chain underscores our reliance on the subsurface. It necessitates a vast amount of subsurface data related to the accessibility of resources, the subsurface capacity for infrastructure developments, and the sustainable management of competing subsurface uses. These initiatives should also be closely associated with other vital principles, such as urban policy development, disaster risk reduction, and the communication and dissemination of geoscience knowledge (Hollis et al., 2022).

This demonstrates the importance of treating the sustainable energy transition as a complex multi-disciplinary challenge within the resources-society-nature nexus. A first but essential step in this direction taken by EGS, related to competing subsurface uses, is the development of traffic-light models (Fig. 2a) to assess the risk of legal conflicts. These models are designed to bring together data on geological potential (i.e., resource occurrence) and policies related to the use of the subsurface use (i.e., 3D subsurface concession blocks or nature reserves at the surface), providing a comprehensive view of opportunities and limitations for current and future subsurface use.

Fig. 2b shows an example of the combination of six different maps available in EGDI. The information underlying the maps can be consulted interactively via the EGDI map viewer and metadata catalogue. The map features can be made transparent or brought to the front to focus on specific elements. In this case, onshore fault systems (red lines), geothermal waters (yellow circles) and natural seismic activity (dark red colours etc.) are brought to the front. At the same time, the geological maps are made more transparent. The map shows potential relationships between the location of faults, geothermal energy (e.g., Portugal, Italy, and Hungary), and the high risk of natural seismic activity (e.g., Iceland in the northwest, Greece and Turkey in the southeast).

3. Raw materials, minerals, and aggregates for the green transition

Ambitious climate action, through the required energy transition described above, brings significant demand for mineral resources, e.g., for the rapidly growing use of clean energy technologies (European Commission, 2023a, b; Wittenberg et al., 2022). The production of solar panels, wind turbines, and batteries depends strongly on available supplies of critical minerals (Wittenberg et al., 2022; Pickens et al., 2022), and there is a looming mismatch between the ambition to limit global warming and the accessibility of critical and strategic minerals necessary to bring this ambition to fruition.

Criticality is a measure of two main parameters: 1) economic importance and 2) supply risk (European Commission, 2017), and it is determined based on thresholds set for both parameters (European Commission, 2018). Some critical raw materials, such as graphite, lithium, nickel, and cobalt, are needed only for one or two technologies, primarily related to energy storage. These have higher demand uncertainty as technological disruption, and deployment could significantly impact their use. The most significant share of demand for copper comes from solar PV and wind. However, demand may be underestimated as it does not include the transmission infrastructure to connect these new technologies to electricity grids. Additional minerals are likely to become scarcer and have future supply risks. Current rates of consumption and emerging value chains for these strategic minerals that are not yet critical also need to be addressed. The pandemic and the geopolitical situation of countries with volatile government policies have highlighted the need for integrated and transparent value chains from mines to consumers (European Commission, 2011). The energy transition depends on the ability to source all critical and strategic minerals from reliable, sustainable, and dependable sources. Cost-effectiveness requires quantitative geological information that is accessible, adaptable, and comparable. In short: we need to know how much of what is where (Fig. 3) and if the extraction is feasible.

Accelerated mineral exploration is, therefore, an indispensable step in the EU's strategy for securing raw material supply. Exploration must be undertaken on land and subsea (Fig. 3, Hein et al., 2020). While the mineral potential of the continents has been recognised since prehistoric times, the subsea environment is a promising frontier for mineral exploration (Vallius et al., 2022; González et al., 2023). With a large diversity of environments and resource types, including high- and low-temperature hydrothermal deposits (massive seafloor sulphides), sedimentary exhalative lead–zinc deposits (SEDEX), phosphorites, cobalt-rich ferromanganese crusts, and manganese nodules, the deep-sea deposits are desirable targets for their polymetallic nature with potentially high contents of rare earth elements and other critical metals. Marine placer deposits are another potential source for many industrial materials, critical metals, and gemstones. Seabed mineral deposits host the most significant resources on Earth for some critical metals like cobalt (Fig. 3), tellurium, manganese, and rare earth elements (Wittenberg et al., 2022). From a DNSH (do no significant harm) perspective, the environmental aspects of their extraction should be compared to those on land.

Aside from critical and strategic minerals, the assessment must also include bulk materials needed in the energy transition and in mitigating the effects of global warming. Sand and other aggregates are easily overlooked as strategic bulk minerals, which are not renewable (United Nations Environment Programme, 2014). The spatial distribution and varying quality (related to grain size, mineralogy, and shape) play an essential role in the economic and environmental feasibility of offshore energy islands (hubs) for storing and distributing wind energy and of area-specific coastline stabilisation efforts using shoreface nourishment by offshore sediments ("Building with Nature", Fig. 1) rather than rigid structures.

Much of Europe's terrestrial mineral potential and source locations are well known. Accurate and state-of-the-art, georeferenced base maps and thematic maps are the basis of strategic planning. However, while this makes good sense on a national, regional, or even local scale, it provides challenges when comparing the availability, accessibility, quality and quantities of mineral occurrences and deposits across borders and on a continental scale. To meet the need for mineral resources, EuroGeoSurveys has for decades worked on pan-European mapping that is now available in EGDI (EGDI, 2023, Fig. 3). Further goals are to have a fully automated central data set that is collected electronically, regularly harvested from each data provider, stored in the central EGDI database, and made available through EGDI. The next step will be constraining available resource volumes using different accessibility conditions. Volumes versus accessibility will support decision-making for different geopolitically or global-market-driven scenarios, helping us roll out the green transition in a future full of uncertainty.

Fig. 3 (upper panel) focuses on the occurrence of on and offshore cobalt mineralisations on a basic map just indicating relative depths of seabeds and land elevations making the locations of known co-mineralisations in Europe clearly visible. Fig. 3 (lower panel) zooms in on an area northeast of Athens, Greece, showing the location of cobalt mineralisations within an area of elevated cobalt concentrations measured in agricultural soils (see also Fig. 5b with copper concentrations in the same soils across all of Europe).

Apart from the previously mentioned maps, the "Geochemical Mapping of Agricultural and Grazing Land Soil" project, also known as "GEMAS" (Négrel et al., 2019), created maps of critical elements present in soils. These maps cover crucial ore provinces across Europe and highlight irregularities of elements like Pb, Sb, W, Li, In, Co, and rare earth elements that coincide with known mineral deposits and mining districts. The geochemical characteristics of the soils can assist in exploring Europe's critical mineral potential by utilising standardised pan-European data.

4. Water security in a changing climate

Groundwater, which makes up approximately 99 % of Earth's liquid freshwater, is a primary source for water supply, irrigation, industry,

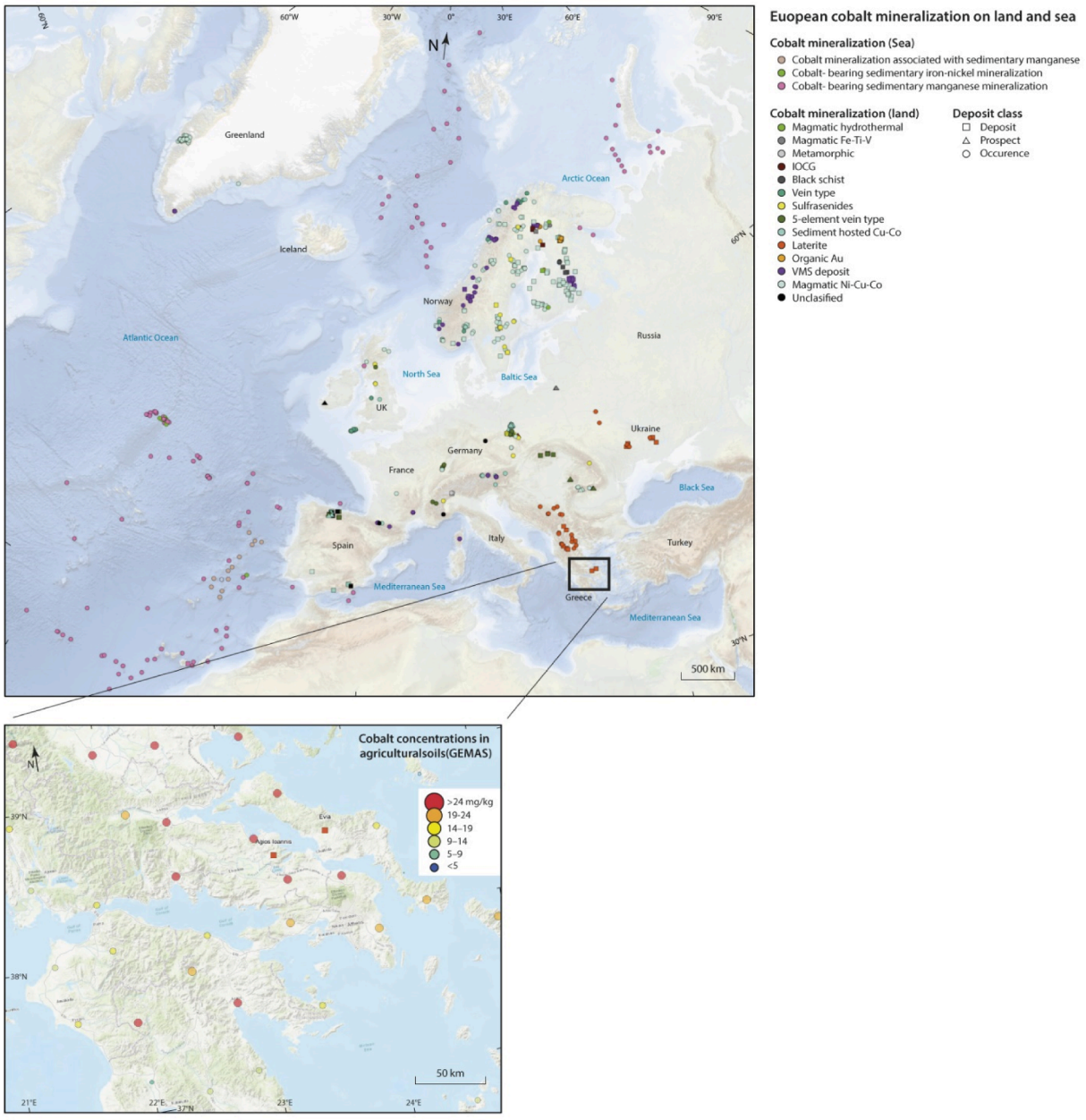

Fig. 3. a (upper panel) Europe's On – and offshore cobalt mineral resources (EGDI 2023b) and 3b (lower panel) Cobalt mineralisations (orange squares) and cobalt contents in soils above 24 mg/kg (red circles) in an area around Athens, Greece (EGDI 2023c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) To get the map view shown in Fig. 3b, the user must manually choose the "Co_Cobalt_GR_XRF" WMS layer in the Geochemistry/Grazing and agricultural land (GEMAS) dropdown menu in EGDI (2023c).

terrestrial and many aquatic ecosystems, and renewable energy solutions. Therefore, managing both the quality and quantity of groundwater sustainably is crucial to facilitating an efficient transition towards a greener future and climate change mitigation and adaptation (Ingemarsson et al., 2022; United Nations, 2022). Advanced water resources management, assessment of climate change impacts, and efficient disaster risk reduction measures responding to hydroclimatic extreme events require near real-time observations as well as integrated and dynamic groundwater-surface water models calibrated using near real-time monitoring data. These models are increasingly essential and pave the way for future hydrological digital twins at various scales, ranging from local well-fields to continental scales (Henriksen et al., 2023; Rigon et al., 2022).

Groundwater quality is facing mounting pressure from various human activities (Bunting et al., 2021; Kivits et al., 2018; Lapworth et al., 2022; Bech et al., 2022), which can potentially affect drinking water quality and human health (Schullehner et al., 2018; Thygesen et al., 2021). Additionally, natural processes may result in elevated concentrations of harmful elements or substances and can lead to cancer and other serious diseases (Smedley and Kinniburgh, 2002, 2017; Giménez-Forcada et al., 2022). For instance, arsenic originating from natural geological sources (Postma et al., 2012) has caused the most significant mass poisoning in history in Asia (Sen and Biswas, 2013), and concerns about arsenic concentrations exceeding drinking water standards extend globally, including many areas in Europe (Giménez-Forcada et al., 2022; Fig. 4a). The "health" or the ecological status and biodiversity of groundwater-dependent terrestrial or associated aquatic ecosystems are also affected negatively by contaminant loads from human activities, e.g., to lakes (Cui et al., 2023), marine and coastal waters (Hinsby et al., 2012) that ultimately result in harmful algal

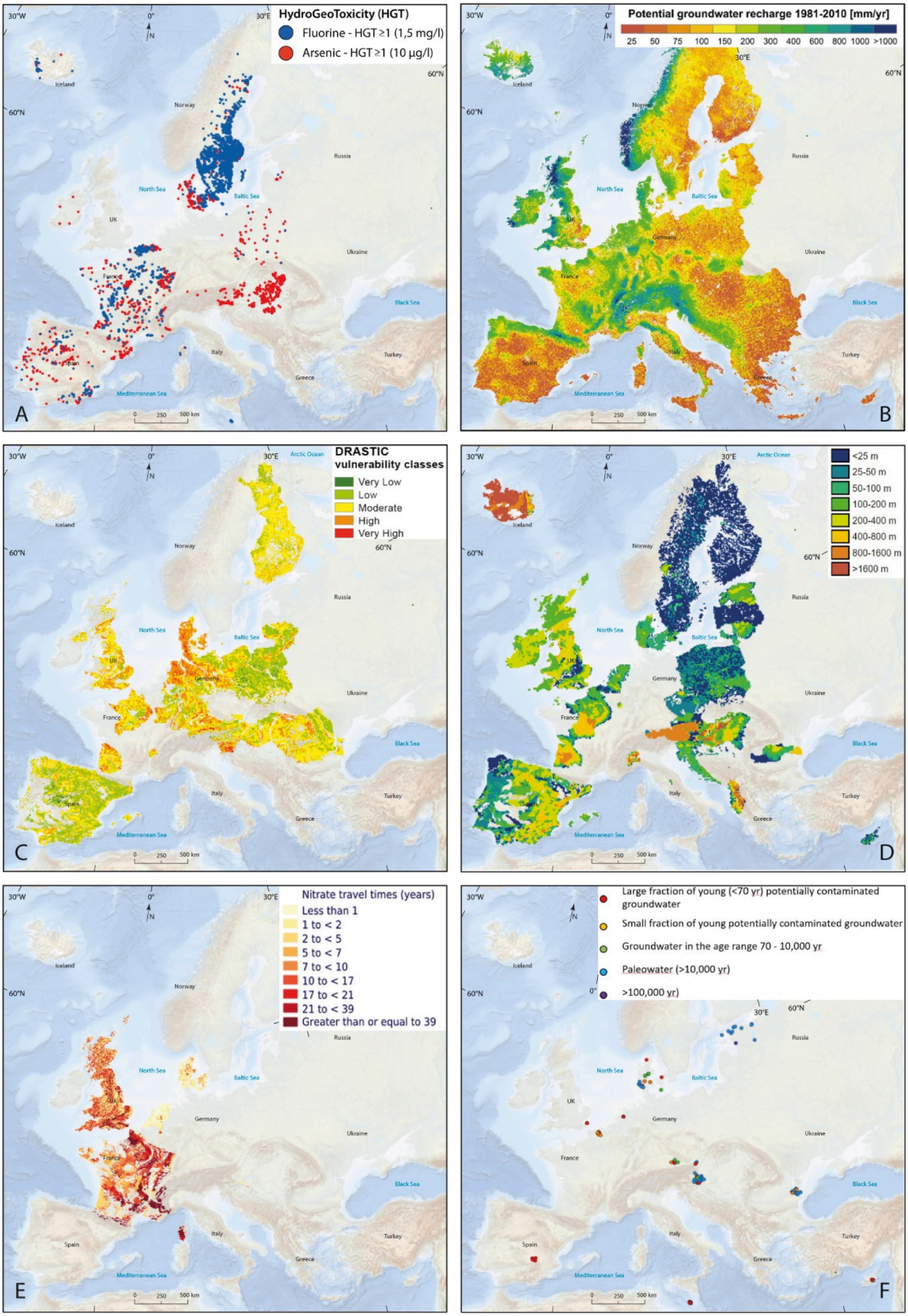

Fig. 4. Examples of groundwater quality and quantity data available in the EGDI map viewer. (a) Groundwater As (red) and F (blue) concentrations above EU drinking water standards (Gímenez-Forcada et al., 2022, EGDI, 2023d), (b) Annual potential groundwater recharge as averaged for the period 1981–2010 (Martinsen et al., 2022, EGDI, 2023e), (c) Groundwater vulnerability to pollution from the surface (DRASTIC Index, EGDI, 2023f), (d) Thickness of exploitable aquifers (EGDI, 2023g, Andersen et al., 2023), (e) Nitrate travel time through the unsaturated zone (EGDI, 2023h) and (f) Groundwater age indicators in European aquifers – examples (EGDI, 2023i). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) Note! The user is able to choose from four different base maps as background layers in EGDI. Here we have used the "EMODNet Bathymetri Basemap" as background.

blooms, hypoxia, and reduced biodiversity (Reusch et al., 2018). Over the past 50 years, nitrate, and pesticides, primarily from agricultural sources (Hansen et al., 2017; Mcknight et al., 2015), have been the most common contaminants contributing to the poor status of European groundwater resources. This has resulted in the closure of water supply wells and biodiversity loss. However, there is increasing concern about new emerging organic contaminants, including pharmaceuticals, PFAS, and other endocrine disruptors, which pose risks to both water supply and ecosystems (Bunting et al., 2021; Cousins et al., 2022).

Seawater intrusion into coastal aquifers is a global issue intricately connected to climate change, rising sea levels, and the excessive exploitation of groundwater in coastal regions causing water table decline (Hinsby et al., 2011; Ferguson and Gleeson, 2012; Werner et al., 2013; King et al., 2022; Jasechko et al., 2024). Recent studies on the Greenland ice sheet suggest that sea levels will inevitably rise by at least 27 cm, possibly reaching up to 78 cm, throughout the 21st century (Box et al., 2022). This places coastal cities and groundwater resources under significant strain. Seawater intrusion into subterranean estuaries, i.e., the part of coastal aquifers where freshwater and seawater mix, leads to profound changes in biogeochemical processes that can have both positive and negative impacts on coastal ecosystems, e.g., by enhancing biological productivity or harmful algal blooms (Moore and Joye, 2021). Moreover, the downward movement of contaminated groundwater, caused by excessive pumping and poorly designed wells, poses a risk to the integrity of deeper aquifers that supply pristine, high-quality drinking water to European populations (Broers et al., 2021; Raidla et al., 2019).

Therefore, carefully mapping and monitoring groundwater quality is essential to safeguard this vital resource. Assessing natural background levels (Hinsby et al., 2008; Preziosi et al., 2021), redox conditions (Koch et al., 2021), groundwater travel time distributions (Jakobsen et al., 2019; Broers et al., 2021), and vulnerability (Voutchkova et al., 2021) are crucial for identifying areas of groundwater contamination, understanding migration patterns, and determining the sources and history of pollutants and toxic geogenic elements (Jakobsen et al., 2019; Giménez-Forcada et al., 2022). It is necessary to thoroughly understand the biogeochemical and physical parameters and processes that influence groundwater quality to effectively assess pollutant pathways and travel times through models. It is essential to recognise that groundwater systems have a slow response rate, which must be considered in their management. The transport times through the unsaturated zone, and consequently, the time lag for measures aimed at improving groundwater chemical status, such as reducing nitrate leaching from agricultural areas, exhibit significant variations across Europe (EGDI, 2023, Fig. 4e). Such information is vital for evaluating the effectiveness and timing of policy measures aimed at improving groundwater chemical status.

The availability of groundwater and access to an adequate water supply of good quality pose growing challenges in a changing climate characterised by frequent droughts (Brauns et al., 2020) and floods (Henriksen et al., 2018), impacting water resources for agriculture (Gomez-Gomez et al., 2022), the built environment (He et al., 2016), and ecosystems (Kløve et al., 2014). Across Europe, precipitation, water resources, groundwater storage (EGDI, 2023; Fig. 4d), and recharge (Martinsen et al., 2022; EGDI, 2023) vary significantly. The projected climate changes will affect groundwater and the availability of water resources for soil and food production in different ways (Cuthbert et al., 2019; Taylor et al., 2013; Pinke et al., 2022). Excessive water can increase the risk of flooding from groundwater or streams, as well as trigger landslides and other geohazards (Mateos et al., 2020), while insufficient water leads to droughts, declining water tables, reduced streamflow (Henriksen et al., 2021), and an increased risk of water shortages, over-abstraction, land subsidence (Dinar et al., 2021) and loss of wetlands and biodiversity.

The considerable variations in groundwater recharge and storage across Europe result in differences in groundwater residence times and age distributions (Jakobsen et al., 2019; Broers et al., 2021; Raidla et al., 2019; EGDI, 2023; Fig. 4f), which in turn affect the vulnerability of European aquifers to surface pollution (EGDI, 2023), droughts and floods (Brauns et al., 2020; Koch et al., 2021; Wunsch et al., 2022).

A vast amount of data from Earth observation systems, including in-situ, surface, airborne, and satellite measurements, is required to develop reliable integrated groundwater and surface water models. Fortunately, there have been rapid advancements in the hardware and software for integrated hydrological monitoring and modelling, such as the application of Big Data, IoT data, the semantic web, artificial intelligence, machine learning, and deep learning (Henriksen et al., 2023; Koch et al., 2019,2021; Refsgaard et al., 2022; Wunsch et al., 2022). These developments continuously enhance the availability of data and improve model performance for projecting and assessing the impacts of climate and land use changes, integrating both groundwater and surface water quantity and quality. This enables the simulation of future nutrient loadings to aquatic ecosystems under various climate and land use scenarios, which must be significantly reduced to protect terrestrial and marine ecosystems (Reusch et al., 2018). The EGDI map viewer offers access to digital groundwater quantity and quality data, maps, and publications from EGS that are relevant for evaluating the chemical and quantitative status of groundwater in Europe, supporting the interpretation of groundwater monitoring results from EU member states, water security and the transition to a greener future. Additional information and data on specific groundwater quality and quantity issues can be accessed through EGDI, as depicted in Fig. 4A-F.

5. Geochemical mapping of soils for sustainable societies: From urban to continental scale

Geochemical mapping is an established method for studying the spatial distribution of chemical elements in rock, soil, water, sediment, and plants to document their natural and human-induced variation in various environments (Ladenberger et al., 2015; Reimann et al., 2018). The recent development of analytical methods and visualisation techniques make geochemical mapping a powerful tool for collecting information about the status of the environment, understanding natural processes operating at the continental to local scale (e.g., weathering, tectonic evolution, precipitations rates, etc.) and detecting the impact of superimposed anthropogenic activities. Understanding and documenting the effects of pollution on Earth's surface requires establishing natural background or baseline levels of various elements. It is essential to place the methodology in a temporal context to account for continuous or historical changes. Therefore, Modern geochemical mapping requires advanced quantitative data acquisition methodologies and mathematical, statistical, and spatial methods for processing and presenting analytical results. The resulting geochemical database has an almost unlimited range of applications, such as mineral exploration, environmental monitoring, agriculture, forestry, land use planning, climate change mitigation and adaptation, and medical and forensic sciences. The broad range of applications of soil chemistry data at various scales address many of the UN SDG to various extents and are very relevant for sustainability policies and good practice routines.

A variety of geochemical surveys at continental to regional scale have been carried out in Europe by national members of EGS, e.g., FOREGS Geochemical Atlas of Europe (Salminen et al., 2005), Baltic Soil Survey (Reimann et al., 2003), and GEMAS Geochemical Mapping of Agricultural and Grazing land soil (Reimann et al., 2018). Outside Europe, extensive continental-scale geochemical surveys have been carried out in Australia (Reimann and Caritat, 2017), China (Wang et al., 2015), and North America (Woodruff et al., 2015). The development of a global geochemical baseline database is the primary mission of the International Union of Geological Science's Commission on Global Geochemical Baselines (IUGS CGGB) and the UNESCO International Centre on Global-scale Geochemistry (based in Langfang, China), both established in 2016. Such a harmonised database requires a robust

(a)

(b)

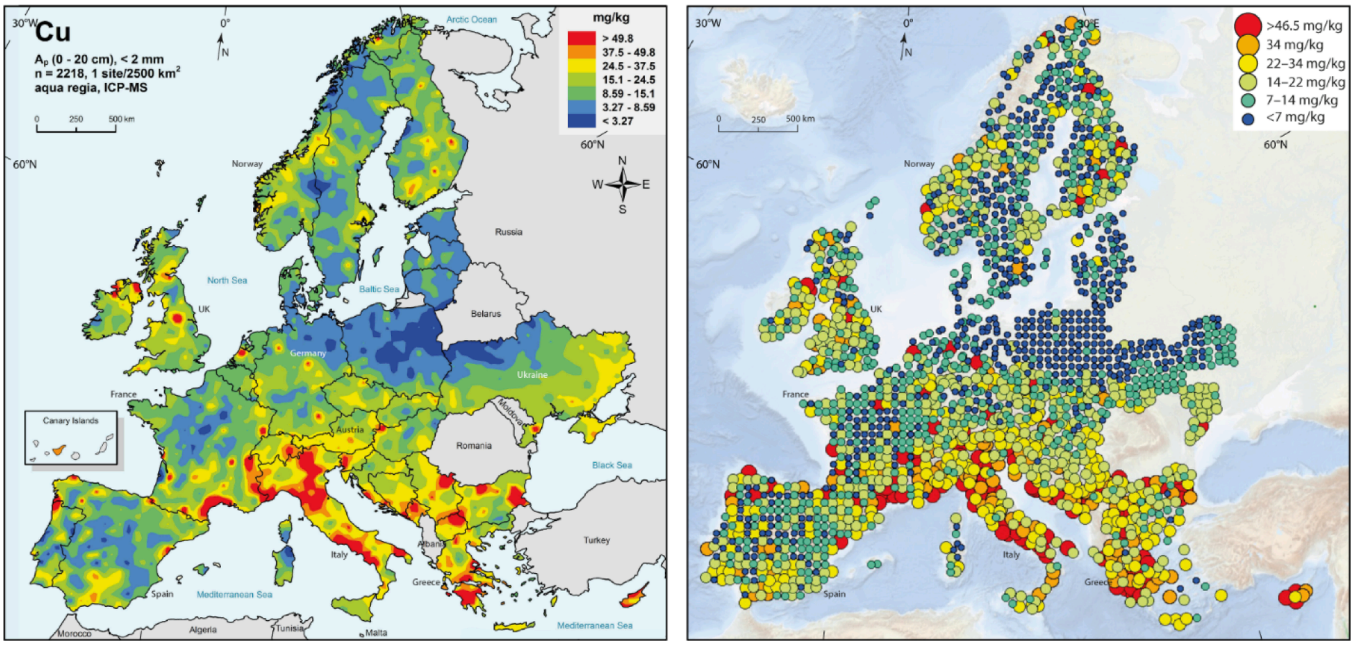

Fig. 5. Copper (Cu) concentrations in agricultural (Ap) soil samples. (a) extrapolated based on the point data shown in (b), modified from Reimann et al., (2014a,b); (b) Point measurements of copper (Cu) concentrations in agricultural (Ap) soil samples, determined by ICP-MS analyses on aqua regia extractions of point samples; (EGDI, 2023j). The Cu data and data for over 50 other elements are available on EGDI. To get the map view shown in Fig. 5b, the user must manually choose the "Cu_Copper_Ap_AquaRegia" WMS layer in the Geochemistry/Grazing and agricultural land (GEMAS) dropdown menu in EGDI (2023j).

methodology (e.g., sampling, analytical protocols, data presentation), enabling qualitative and quantitative comparison of geochemical data at any scale. Additionally, standard procedures for public digital geochemical data are needed to develop global community-driven, machine-readable geochemical databases and best practices (e.g., digital standards) necessary to build a global network of high-quality, trusted geochemical data according to FAIR principles. Continental-scale geochemical mapping projects accomplished during the last decennium provide open geochemical data well suited to be used in the digital world by applying artificial intelligence and machine learning for up- and downscaling the geochemical data for use in Digital Models and ultimately in Digital twins. A broad audience urgently needs databases of harmonised, global geochemical data on various sample types, including policymakers, environmental and natural resource managers, industry, and researchers worldwide in search of solutions to ensure long-term sustainable exploitation of renewable and unrenewable natural resources.

Soil is the most common material used in geochemical surveys because of its function in food production and the fulfilment of a wide range of ecosystem services towards healthy interactions between the natural environment and humans, e.g., in the water-energy-food-ecosystem nexus (Fig. 1, de Roo et al., 2021). Continental-scale soil geochemical mapping conducted at a low sampling density delivers reference background levels (Reimann et al., 2018). Conversely, regional mapping with medium to high sampling density offers crucial insights into more localised issues. These include the chemical status of different soil types and groundwater potentially at risk due to human interventions and land use. At the continental scale, prominent features can be observed in the spatial distribution of chemical elements as delivered by two pan-European mapping projects: FOREGS and GEMAS (Reimann et al., 2014a, b). These publicly available harmonised Pan-European datasets allow the assessment of almost 60 chemical elements and describing the factors influencing their distribution. The distribution of potentially toxic elements (PTE) such as Pb, Cd, and Hg largely reflect natural patterns and only in a handful of locations is explained by the vicinity of large cities, power plants, or old mining sites (Négrel et al., 2021; Ottesen et al., 2013). The origin of some PTE in soil may therefore be either predominantly natural or anthropogenic or a combination of both (Albanese et al., 2015). For example, typical anthropogenic copper (Cu) sources in the surficial environment include emissions from metal smelters and mining. In agriculture, Cu compounds are present in fungicides, herbicides, and manure, resulting locally in high Cu contents in agricultural soil in north-western Germany, The Netherlands, and Belgium, and vineyards soils, e.g., in northern Italy and southern France (Albanese et al., 2015; Fig. 5). In the urban environment, Cu used in large amounts in roofing, pipework, plumbing, countless electrical applications, and in cars leads to point Cu anomalies around big cities (for example, Paris is visible as a Cu anomaly, Fig. 5).

High-density geochemical mapping at the local level serves critical purposes such as mineral exploration and environmental monitoring. It can precisely identify regions with mineral deposits and historical mining activities, and pollution-prone areas surrounding urban clusters. Urban geochemistry and land use planning pose challenges, which include determining the background concentrations of potentially hazardous inorganic and organic compounds in different urban compartments. The pollution levels must always be interpreted in relation to the natural background concentrations. Therefore, some countries developed dynamic digital tools for calculating local chemical backgrounds, such as Finland (Jarva et al., 2010) and Sweden (SGU, 2023). With increased sampling density, the spatial resolution improves, and this is efficiently used in urban studies where sampling density can reach a meter scale. Digital interoperative mapping tools have been deployed to monitor and document the urban chemical status in detail. An example of such service is provided by the London Earth project (BGS, 2023), where the spatial distribution of toxic metals can be interpreted in terms of historical town development and socioeconomic problems. Even phenomena such as health deprivation and crime rates can be studied

with the help of urban soil chemistry (Cave et al., 2018). Urban geochemical datasets can therefore be merged with any other database-driven information to assist local authorities, land use planners, and the public with information about the environmental status and health risks in compliance with EU legislation on soil and water.

6. Discussion, perspectives, examples, and future work towards sustainability

The information in some of the displayed maps, primarily in Fig. 4, highlights the variability in geographical coverage due to constraints in time, budget, and resources for compilation and harmonising geodata from national and regional databases. Not all partners could participate in every activity, resulting in "white spots" on some maps where data from certain countries are missing. These gaps are primarily a direct outcome of limited involvement from partner countries, often due to resource constraints. In other cases, relevant data are simply unavailable due to the geological setting (e.g., no exploitable groundwater resources) or because the region has not yet explored the specific resource in question. EuroGeoSurveys' consistent maintenance and update of the EGDI platform will fill the gaps in data representation across all involved regions when data becomes available. This ongoing process is crucial in ensuring the completeness and accuracy of the geographical data presented.

Prioritising the sustainable use of subsurface and natural resources is pivotal for facilitating the green transition and maintaining a healthy balance within socio-economic and planetary boundaries, as depicted in Fig. 6. To attain this goal; we must take immediate action to protect and responsibly utilise natural resources. Sustainable management begins with geoscientific research, mapping of surface and subsurface resources, and spatial planning based on open access to digital data and tools, maps, and models. The digital data and tools, including tailored digital twins, are essential for climate change mitigation and adaptation strategies, such as managing subsurface geoenergy use, locating critical minerals and aggregates for green technologies, implementing near real-time projections by integrated groundwater-surface water models for flood and drought protection, optimising agricultural techniques for carbon sequestration and food production, and predicting geohazard impacts for the implementation of disaster risk reduction measures.

The interplay between the use of natural resources, societal development, and environmental considerations occurs within the resources-society-nature nexus (Fig. 6). Choices made by society regarding the extraction and use of natural resources have interconnected consequences. For instance, the extraction of raw materials for renewable energy technologies is non-renewable, and additionally, it often requires significant water usage, potentially threatening the water supply for households and irrigation. In both cases, recycling may be needed to ensure sustainability. Subsurface use and resource exploitation can also increase the risk of geohazards such as land subsidence, landslides, and seismicity. Therefore, these interconnected relationships must be carefully considered based on geoscientific data when evaluating the environmental and socio-economic risks and benefits of subsurface use.

To understand, control, and predict impacts between the intricate connections in the resources-society-nature nexus (Fig. 6), we must develop digital twins of the Earth and related advanced digital instruments. However, there are challenges to overcome in the implementation and use of digital twins, particularly regarding data availability, uncertainty, distribution, management, and regional and thematic consistency. Collaborative efforts are necessary to provide and transform harmonised data by the FAIR principles of Findability, Accessibility, Interoperability, and Reusability. EGS (EuroGeoSurveys) is leading this effort for geological data in Europe. EGS is diligently constructing the EGDI platform, a state-of-the-art platform that houses harmonised research surface and subsurface data, as demonstrated in the previous sections. The EGDI platform facilitates the exploration and application of surface and subsurface data, enabling advanced digital methods such as machine learning and deep learning to enhance our knowledge and depiction of subsurface features. It integrates increasing digital data from various sources, such as IoT devices, near real-time remote sensing, and in-situ monitoring systems, making them publicly accessible. EGS invites stakeholders to participate in shaping the future developments of the EGDI, with the goal of making it a widely used and

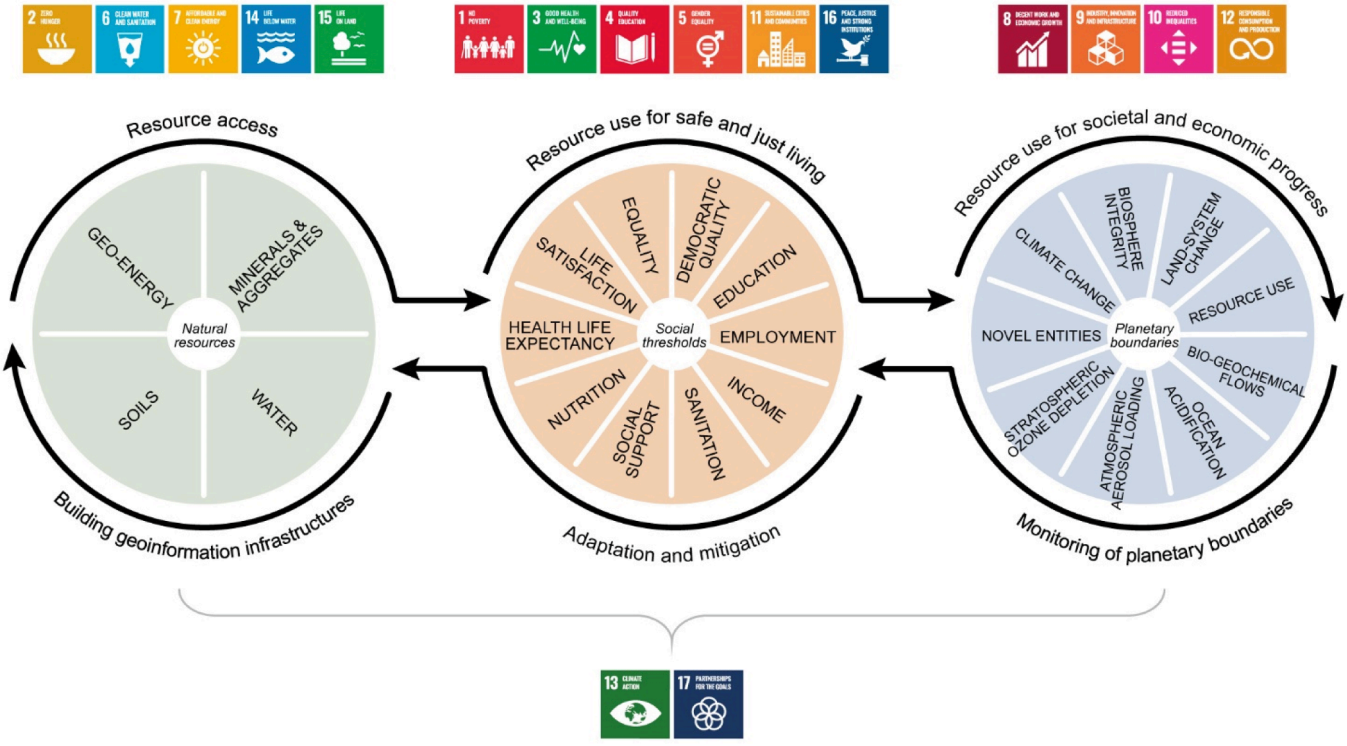

Fig. 6. Relations and interlinkages in the resources-society-nature nexus.

favoured information platform. The platform aims to integrate subsurface and surface geoscience data, supporting the implementation of EU policies and the UN Sustainable Development Goals.

Fig. 6 illustrates interlinkages and feedbacks between the use of natural resources (leftmost circle), social foundations for safe and just operating spaces (central circle, adapted from O'Neill et al., 2018 & Raworth, 2012) and planetary boundaries (rightmost circle, adapted from Steffen et al., 2015).

The top left arrow represents societal development by access to natural resources as a fundamental step for regional safe and just living, while the top right arrow represents the link between resource exploitation, societal development and the status of the planet as represented by the nine planetary boundaries (Rockström et al., 2009; Steffen et al., 2015; Richardson et al., 2023). Six of the nine planetary boundaries including climate change, biosphere integrity, land system change, freshwater change, biogeochemical flows of nitrogen and phosphorus and novel entities (e.g. PFAS) have already been exceeded (Richardson et al., 2023; Cousins et al., 2022) calling for efficient mitigation measures to keep the Earth within a safe operating space and ensure a good life for all (O'Neill et al., 2018; Rockström et al., 2009, 2024).

Continuing from right to left, the bottom arrows represent actions needed to guarantee each circle's sustainable development by monitoring planetary boundaries and implementing necessary adaptation and mitigation measures, which require building efficient geoinformation infrastructures and ensuring FAIR data access, e.g., for digital twin developments. Achieving all UN SDGs is intrinsically connected with development actions (top) or balancing actions (bottom) related to the three circles. Managing the complex interplays requires vital inter- and transdisciplinary research and collaboration in public–private partnerships, which should be strongly encouraged at regional to global levels.

7. Conclusion

Earth's subsurface holds significant potential as a source of natural resources and solutions to contemporary societal challenges. To effectively utilise the subsurface for mitigating climate change and accessing natural resources like geothermal energy, CO_2 and thermal energy storage, critical minerals, aggregates, groundwater, and soils, a thorough comprehension of 3D and 4D geoscience data is imperative. This entails remote and in-situ observations and projections by models, and digital twins of contemporary and future Earth system changes resulting from natural and anthropogenic forcings.

Given the importance of these resources, the pressures on planetary boundaries, and the vital need for an efficient green transition, accessible and high-quality geoscientific information and knowledge are indispensable. The FAIR data principles can provide a robust framework for managing this information, fostering transdisciplinary research, and promoting sustainable resource management locally and globally. Digital infrastructures like EGDI and organisations such as EuroGeoSurveys play pivotal roles in this context, as they facilitate access to critical geoscience data and knowledge, supporting the attainment of sustainable development goals, the European Green Deal, and other global sustainability initiatives.

However, realising the full potential of Earth's subsurface resources, and eco- and geosystem services necessitates a concerted global effort, cutting-edge technology, and forward-thinking policy. These resources can only be efficiently managed and sustainably utilised if rigorous geoscientific investigation and modelling activities underpin them. Hence, a sustainable future depends on our collective ability to harness and sensibly manage the resources beneath our feet or the sea, highlighting the fundamental importance of understanding, monitoring, and modelling Earth's subsurface and providing open access to surface and subsurface geoscience data to all relevant stakeholders.

We strongly suggest investing in advanced geoscience data collection and access to facilitate the green transition, achieve the United Nations Sustainable Development Goals, and enable efficient and integrated spatial planning of surface and subsurface developments. It is of utmost importance to adopt the FAIR data principles, promote digital infrastructures, encourage global transdisciplinary collaboration, improve geoscientific investigation and modelling, and provide open access to geoscience data. By adhering to these recommendations, we can improve our understanding of the Earth's surface and subsurface processes, ensure sustainable utilization of its resources to benefit society and nature, and efficiently work together towards a sustainable future in regional and global multi-stakeholder partnerships.

CRediT authorship contribution statement

Klaus Hinsby: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Philippe Négrel:** Conceptualization, Writing – original draft, Writing – review & editing. **Daniel de Oliveira:** Writing – review & editing, Writing – original draft, Conceptualization. **Renata Barros:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Guri Venvik:** Writing – review & editing, Writing – original draft, Conceptualization. **Anna Ladenberger:** Writing – review & editing, Writing – original draft, Conceptualization. **Jasper Griffioen:** Writing – review & editing, Writing – original draft, Conceptualization. **Kris Piessens:** Writing – original draft, Conceptualization, Writing – review & editing. **Philippe Calcagno:** Conceptualization, Writing – original draft, Writing – review & editing. **Gregor Götzl:** Conceptualization, Writing – original draft, Writing – review & editing. **Hans Peter Broers:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision. **Laurence Gourcy:** Project administration, Methodology, Conceptualization, Funding acquisition, Investigation. **Sytze van Heteren:** Writing – review & editing, Writing – original draft, Conceptualization. **Julie Hollis:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Eleftheria Poyiadji:** Writing – review & editing, Writing – original draft, Conceptualization. **Dana Čápová:** Writing – review & editing, Writing – original draft, Conceptualization. **Jørgen Tulstrup:** Visualization, Supervision, Project administration, Methodology, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Most data is Findable, Accessible, Interoperable and Reusable through the map viewer of the European Geological Data Infrastructure (EGDI) - https://www.europe-geology.eu/ as described in the paper

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During the preparation of this work the author(s) used ChatGPT and Grammarly to refine and condense the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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