Geology for society in 2058: some down-to-earth perspectives

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Abstract: Social development and rapid growth in the world’s population has followed a remarkable technological development the past hundred years. Revolutions in agriculture and industry, medical innovations and new production technologies, have led to an increased standard of living for a larger part of the Earth’s population. Megatrends for future developments are lining up and predictions for the next 40 years are numerous. Most ideas about our future societies imply new and innovative geo-scientific achievements. Towards 2058, we will have virtually surveyed and mapped every corner of the Earth. We will have detailed 3D images of the urbanized areas, and 4D models to assist to make reliable forecasts in a world of increased pressure on the natural resources and changing ecosystems. By 2058 the Green Stone Age is established, and we will use all elements in the periodic system and more rare minerals to support new materials and technological solutions. The major energy supplies will be CO₂ free. The agriculture will be more efficient, distribution and consumption of food will be more rational, and we will harvest from more marine food chains than today. More than 70% of the people on Earth will live in megacities and urban areas. Our cities will become smarter and greener, cars and public transport will be self-driving and autonomous tools using artificial intelligence to automate functions previously performed by humans. Substantial resources will be used to repair damaged ecosystems, and most important, we will use materials and products that have fewer negative consequences for the environment. The 17 UN goals for sustainable development are guidelines into the future, and geological surveys should serve as key instruments in the transformation into smarter and more sustainable societies. We are already on our way providing critical minerals for low carbon energy solutions, marine knowledge for blue growth, plans for green and smarter cities, and advanced digitalization for public services, as shown by examples in this present paper.

Supplementary material: A high-resolution copy of the Fennoscandian Industrial Minerals Map provided by the geological surveys of Finland, Norway, Sweden and Russian partner organizations is available at: https://doi.org/10.6084/m9.figshare.c.4882428

Geology for society since 1858

When, in 1856, the founder of the Geological Survey of Norway (NGU), Theodor Kjerulf (1825–88), launched the plans for a geological survey to the Norwegian Government his ambition was to build an institution that would be ‘Scientifically necessary, practically useful, and honourable for the country’. Kjerulf, a professor of geology, argued that through the mapping of Norway’s bedrock, mining graduates and geologists would contribute to new information concerning mineral deposits and their extent and potential utility value, so creating a sound basis for exploiting natural resources. In other words, a desire to bring about economic growth and modernization provided the basis for the new institution (Børresen & Wale 2008). Two years later the authorities made their decision, and on 6 February 1858 the NGU was formally established.

Professor Kjerulf was convinced that research carried out by the new institution would strengthen the scientific community in the country and contribute to new, more systematic overviews of the geological resources. For many years, the geological mapping often covered remote and unexplored land areas. Therefore, the literary historian Gerhard Gran claimed that through their work, geologists, like poets and painters, had conquered community after community, so when Norway separated from the union with Sweden in 1905, Norwegians were finally able to say that they owned their country. The geologists at the NGU had thereby participated in both industrial development and the building of a nation (Børresen & Wale 2008; Slagstad & Dahl 2008).

In 1905 the Geological Society of Norway was founded and the Norwegian Journal of Geology was launched. The first paper was written by Dr Hans Reusch, the second director of the NGU, and was given the cryptic title: ‘The Scandinavian divide’ (Reusch 1905). This was a scientifically sound paper on the watershed in the mountains between Norway and Sweden, but we can easily detect the new-born national self-consciousness in between the scientific outlines and arguments. National and regional geological surveys around the world have similar stories to tell. In our societies...
we depend on access to minerals and raw materials, energy and water. Sufficient knowledge of geological resources and geological processes is therefore essential for economic sound and sustainable development. The bedrock, sediment and soil are the foundations of the ground, and our settlements and infrastructures should be built in areas safe from geohazards. To ensure that we do not destroy the natural basis for future generations, it is vital to understand how the development of society impacts on environment and the balance in nature.

Geological maps and geological information provide significant economic benefits to societies (Häggquist & Söderholm 2015). Towards 2058, we will have virtually surveyed and mapped every corner of the Earth. The technologies we need are already here, launched on space satellites, drones, remotely operated underwater vehicles, autonomous underwater vehicles, or brought along by common people crowd-sourcing various kinds of data records from land and sea. Examples of present applications of space satellites and advanced underwater vehicles for mapping of land and seabed are presented in the following sections.

One forward-pointing example of novel, but less costly, mapping methods is the Zanzibar Mapping Initiative (ZMI), a project led by the Revolutionary Government of Zanzibar’s Commission for Lands (COLA). This project is the first in the world to use small drones to update the map of Zanzibar Island. The data is openly available for all purposes related to the island’s conservation and development (Barde & Bonhommeau 2018). Institute de Recherche pour le Développement/L’Institut Français de Recherche pour l’Exploitation de la Mer/GISCAN work on establishing marine data sets to be used for habitat mapping and species observations around Zanzibar and other Indian Ocean Islands. Their specialty is to combine underwater images from various platforms such as kite-surfing and stand-up-paddle boards by using basic camera solutions with positional information from the surface (Barde & Bonhommeau 2018).

In the years ahead, enormous amounts of new data and knowledge from all over the Earth will become available, and in 2058 we will understand more of the extent and limitations of our natural resources. Forty years from now we have fully realized that underground services play an important role in our daily lives. We have advanced significantly in the exploration of the resources and the possibilities that might be there on other planets. We have developed new space infrastructure, with orbiting shipyards and refuelling nodes. In 2058, humans can inhabit space for longer periods, but for the more than 9.8 billion people inhabiting our planet 40 years from now, leaving Tellus is not an option. Instead we must focus on creating the best possible down-to-earth perspectives for our future generations.

**Megatrends and technologies towards 2058**

Resourcing future generations is our common goal and major challenge (Lambert et al. 2013). In 1972 the ‘Club of Rome’ presented a message that global population and economic growth would lead to a lack of resources and ecological breakdown. The prediction has proven wrong; the models used were poorly founded. Estimates of population growth were almost correct, but access to resources has so far not put an end to global economic growth. However, given the uneven distribution of critical natural resources, in particular metals and minerals needed for future technologies, the consequences for both the states that possess such resources and the economies reliant on imports will be considerable. Economic growth will proceed, but paradigm shifts in the use of minerals and materials is a trend eventually leading to intensified global resource competition which may create new global orders.

Population growth influences most global megatrends. The current world population is more than 7.6 billion people. The UN Department of Economic and Social Affairs World Population Prospects: The 2017 Revision’ predicts that the number of people on the Earth is expected to reach 8.6 billion in 2030 and 9.8 billion in 2050. Current generations live longer than ever before, and with roughly 83 million people being added to the world’s population every year, the upward trend in population size is expected to continue, even assuming that fertility levels continue to decline. A stabilization of the human population is projected to occur in the second half of the current century, but in addition to a growing population, higher standards of living will increase the use of natural resources, environmental pollution and land use changes like urbanization. The shifts in global demographic trends will have direct impacts on local environments through time with climate change and increased resource consumption.

The European Environmental Agency (EEA) predicts that economic growth and the use of natural resources, rather than population growth, will be the core driver of future consumption. Following this megatrend, the EEA points out that lifestyles in the rising number of industrialized economies, demand more resources than the planet can produce. Simply explained, a bigger global middle class in 2050 will mean greater spending power (EEA 2011a). To meet the expected trend of intensified global competition for decreasing stocks of resources, we need to find ways of more efficient production and resource use, new technologies and innovation, and increasing international co-operation (EEA 2011b).
In the report on Earth 2050 Global Megatrends by the EEA (2011c) it is pointed out that the resources fuelling national economies also influence the international balance of power, and owning essential resources may further improve emerging economies’ competitiveness and influence. This is particularly evident given the uneven distribution of resources globally. For example, more than half of the world’s stock of lithium, a metal at present essential for hybrid and full electrical cars, is believed to be located in Argentina–Bolivia–Chile. In the report from 2011, EEA predicts that the global use of neodymium, which is an essential material for many high-tech laser technologies, is expected to quadruple over the next 30 years. Since the element is almost only available in quantity in China, growth in related industries will be almost totally dependent on China and its production capacity.

A continuing growth in demand for the resources needed to produce advanced technologies, means we have to turn to minerals and metal deposits hitherto deemed uneconomic. Geological and technological knowledge for expanding and more efficient mining will be increasingly important. In addition, increased mining has several environmental effects, including changing landscapes, polluting water and generating waste. Poorer quality mineral reserves may mean that exploiting such sources is less energy efficient.

Growth in human population and the increasing demand for food, lead to an increasing use of chemicals and hence pollution of terrestrial and marine ecosystems. The potential consequences of global pollution trends include further impacts on human health, with unsafe drinking and bathing water and contaminated food. In Europe, the problem of reactive nitrogen is particularly evident in the Baltic Sea, where the current ecological status is already poor. In many parts of the world huge concentrations of plastic debris cover large swathes of the ocean. According to Earth Day Network’s fact sheet Plastics in the Ocean about 8 million tonnes of plastic are dumped into the ocean every year (Jambek et al. 2015; Earth Day Network 2018). This amount of plastic includes 236 000 tonnes of micro-plastics (van Sebille et al. 2015), of which significant parts goes into the marine food webs and disrupt the marine ecosystems. Jambek et al. (2015) calculated that in 2010, 275 million tonnes of plastic waste were generated from 192 coastal countries, with 4.8–12.7 million tonnes shed into the ocean. Jambek et al. (2015) point out that population size and the quality of waste management systems largely determine which countries contribute the greatest mass of uncaptured plastic entering the ocean. They predict that without management infrastructure improvements, the cumulative quantity of plastic waste available to enter the ocean from land is to increase by an order of magnitude by 2025 (Jambek et al. 2015).

Another factor leading to increased consumption is the rapidly increasing global urbanization. Today, more than 50% of the world’s population lives in urban areas. By 2050, about 70% of people are likely to be urban (UNDESA 2018). Demographers estimate that Asia will be home to more than 50% of the global urban population (EEA 2011a). Presently, cities cover just 0.5% of the Earth’s surface, but they consume some 75% of global resources (Schwab & Stettner 2017). The number of megacities, cities with more than 5 million inhabitants, will increase as city borders will expand out of suburbs to include daughter cities. In 2050, half of the world’s population will live in major urban centres and there will likely be at least 40 cities with more than 10 million inhabitants. Today there are 33 such cities. The design and governance of urban areas will have strong impacts on global greenhouse gas emissions and resource demand. Once built, a city can be difficult to alter fundamentally. In many places in the developing world, cities currently risk locking in energy- and resource-intensive models of urban development for decades ahead. The development of smart cities will make it possible for inhabitants to interact intelligently and efficiently with their urban environments, but despite increasing energy efficiency, the energy demands of such megacities will be enormously high (Schwab & Stettner 2017).

Technological breakthroughs will be a much stronger driving force towards 2058 than in previous historic times, and new technologies can help us to improve the mapping, monitoring and management of natural resources and the environment. The time it takes from invention to breakthrough to mass application is getting shorter and shorter. As an example, it took 76 years for the telephone to reach half the population, the smart phone took only about a decade (Schwab & Stettner 2017). This implies that sharing and spreading of new technology will be as important as developing new technologies, and as responsible scientific communities the geological surveys should promote wide adoption of best available technologies for efficient resource use. One example is the rapidly evolving zero CO2 emission technologies that is likely to be a game-changer by revolutionizing the power industry. There is a growing awareness that energy technology innovation will be a key in achieving the political 2°C scenario, and that a comprehensive portfolio of low-carbon technologies, including solutions for de-carbonization, will be needed to achieve the UN climate goals (OECD 2016).

In the report Energy transition outlook 2018: a global and regional forecast to 2050 by DNV GL (2018) it is suggested that the world will need less energy from the 2030s onwards owing to rapid energy efficiency gains; and it is forecasted that primary energy supply will peak in 2032. It is further
forecasted that oil demand will peak in the 2020s and natural gas will take over as the biggest energy source in 2026. However, since existing fields will deplete at a faster rate than the decrease in oil demand, there will be a continuing need for exploration and opening of new oil fields towards year 2040 (DNV GL 2018). Towards 2050 the electricity consumption will more than double to meet 45% of the global energy demand, and solar photovoltaic (PV) and windpower will supply more than two thirds of that electricity (DNV GL 2018). According to the Energy transition outlook 2018 report, the world’s energy system will de-carbonize, and in year 2050 the primary energy mix will split equally between fossil and non-fossil sources. This megatrend, or paradigm shift in energy production and consumption, will require a wide range and high quantities of minerals and materials to meet the rapidly growing need for more wind turbines and solar PVs.

Mapping of the available global geological resources and monitoring of land use and changes in ecosystems will be made more efficient by more than 900 new satellites to be launched within 2020. These will be used for multiple innovative applications such as communication (405 satellites), Earth observations (151), navigation (85), reconnaissance (212) and research and development (75). Among the new satellites to be launched in the next years, twelve or more are expected to be radar satellites, with their ability to drive new applications monitoring volcanic activity, dark polar regions and cloud-covered rainforests (European Patent Office 2016). New technologies and innovative uses of satellite data will become increasingly important for analysing climate change and altering of ecosystems. Along with sampling of data with increasingly higher resolution, computer processing will reveal ever-more complex data. In the future, calculations and monitoring the Earth’s natural resources will be more precise.

There is a complex pattern of predicted megatrends affecting science, technology and innovation towards 2058. However, major changes are already emerging. The geological surveys must address the challenges and opportunities linked to these megatrends, especially taking into account that the technologies change more rapid than ever. Globally there is an increasing awareness and a growing social pressure to act sustainable, and geological surveys should be in the forefront in adopting and implementing the means to achieve the common goals of a more environmentally friendly and sustainable Earth.

**The UN Sustainable Development Goals (SDGs)**

On 25 September 2015, countries adopted a set of goals to end poverty, protect the planet and ensure prosperity for all as part of a new sustainable UN development agenda (United Nations 2015a, b). Each goal has specific targets to be achieved over the next 15 years. Geological surveys provide ‘Geology for Society’ (Smelror et al. 2008; Smelror 2011), and among the 169 UN targets, there are several that involve concrete actions where national geological surveys can and should play an important role (Gill 2017) (Fig. 1). Discussing and solving challenges connected to the UN SDGs require holistic approaches to the complex lineages between the atmosphere, hydrosphere, cryosphere and lithosphere (Lubchenco et al. 2015; Stewart & Gill 2017).

As pointed out by Stewart & Gill (2017) the applied aspects of economic geology (mineral resources, petroleum), hydrogeology (ground water), engineering geology, geohazards and the use of the land surface for agriculture, housing and infrastructure assume even greater importance. The same holds true for the growing use of the seabed for harvesting of marine benthos and the overlying water columns for fish farming. Geologists are also instrumental in providing facts for climatic science, land and environmental management and disaster risk reduction (Stewart & Gill 2017).

Serving ‘Geology for Society’ is clearly the primary task for national and regional geological surveys (Slagstad & Dahl 2008; Smelror 2008, 2011; Smelror et al. 2008), but a key question is should we play an even more active role? Stewart & Gill (2017) argue that our geosciences community needs to broaden its experience, and that we should explicitly integrate ‘sustainability’ into geoscience education, training and continued professional development.

There are numerous examples of how geological surveys are addressing these challenges. In most surveys we are broadening our geosciences perspective by collaborating with biologists, engineers, city planners, geographers, archaeologists, oceanographers and other professionals. One example is the Norwegian seabed mapping programme, MAREANO, which has been developed and carried out in collaboration between the Norwegian Mapping Authority Hydrographic Service (NHS), Institute of Marine Research (IMR) and the NGU (Thorsnes et al. 2008; Buhl-Mortensen et al. 2016). MAREANO provide scientific information on what the Norwegian seabed looks like (high resolution bathymetry, seabed maps and images), its geology, chemistry and the biological communities that inhabit it. The information, including how the seabed environment is affected by anthropogenic processes, is needed for sustainable management of the extensive Norwegian marine territories (around 2.1 million km²). Information and seabed maps with several applications are open access on the web (https://www.mareano.no) and made available on the navigation systems of fishing vessels. By this, the MAREANO
programme meets SDG no. 16, which is to ‘Conserve and sustainably use the oceans, seas and marine resources for sustainable development’.

Another example is the Irish Tellus programme, a national programme to gather geochemical and geophysical data across Ireland, in order to examine the chemical and physical properties of soil, rocks and water. Tellus is carried out by the Geological Survey of Ireland and involves airborne geophysical surveying using a low-flying aircraft and ground-based geochemical surveying of soil, stream water and stream sediment. Tellus has established a product development work stream to produce focused, user-centric data products, the need for which has been identified through stakeholder consultation, independent reviews of Tellus and government policy. Product development is undertaken under five main themes: mineral prospectivity, smart agriculture, environment and health, climate action and education (for more information see: https://www.gsi.ie/en-ie/programmes-and-projects/tellus/Pages/default.aspx).

A second phase, the Tellus Border Project, covering the areas across the border into the six northern counties of Northern Ireland was finished in 2016. The Tellus Projects answers to many societal needs and deliver data and services underpinning several of the UN SDGs’ goals. As concluded by Marie Cowan, Director of the Geological Survey of Northern Ireland, and Koen Verbruggen, Director of the Geological Survey of Ireland:

The Tellus and Tellus Border Projects have exemplified the value of governmental and EU investments in cross-border multi-partner, scientific initiatives where there is a common objective and complementary skills and experience.

(Young 2016)

By 2023, Tellus will have covered all of Ireland (Young 2016).

A matrix visualizing the role of geologist in helping societies to achieve the internationally-agreed UN SDGs have been presented by Gill (2016) and Stewart & Gill (2017). Aspects considered by Gill (2016) are agro-geology, climate change, energy, engineering geology, geohazards, geoheritage and geotourism, hydrogeology and contaminant geology, mineral and rock resources, geo-education, geological capacity building and a miscellaneous category. Gill (2016) concludes that geologists have a role in achieving all 17 of the SDGs. Gill (2016) emphasizes that future engagement must come from the broadest spectrum of the geology community, and effective engagement should draw upon geologists within civil society, the public sector and private sector. In his conclusion, Gill (2016) points out the need to mobilize and motivate the broader geology community to engage in the SDGs and to demonstrate the role of geology within sustainable development to other relevant disciplines, policymakers and development practitioners.

Fig. 1. The UN Sustainable Development Goals to end poverty, protect the planet and ensure prosperity for all as part of a new sustainable UN development agenda (United Nations 2015a, b).
Entering the Green Stone Age

Raw materials have been essential in the development of all human societies through history of mankind, and as stated in the short poem by the Norwegian punk author Gene Dalby: ‘The present time is always Stone Age’. Moving into a greener, more carbon lean, future we become increasingly reliant on access to a growing number of raw materials. Rare minerals for new technologies improving the quality of our lives and the environment are the building bricks in the new Stone Age. Technological paradigm shifts through our history has caused major changes in which minerals have been important to society (Fig. 2). When the standard of living is increased for billions of people the need for mineral resources increases rapidly. The use of most metals measured against national product grows steeply, before it flares out to the level that characterizes industrialized countries.

Consequently, towards 2058 we will see an increased interest in exploration and investments in mineral production all over the world. The use of most metals v. GDP per capita grows almost logarithmically before it flattens at the levels of industrial countries. While the per capita use of copper in developing countries has been around 2.5 kg, the figures in industrial countries has been around 4–5 times as high. The expected significant growth in economy in major developing economies will lead to rapidly growing demands for more minerals, not only metals and building materials, but also rare earth elements (REEs), which are critical elements in the evolving green technology.

The rise in production of renewable energy drives increased demand for mined metals and minerals (Vikström et al. 2013; Elshkaki & Graedel 2014). The solar and the wind power industry grow rapidly and eventually wind, solar and other renewable energies will account for most energy used. Modern solar panels require arsenic, bauxite, boron, cadmium, coal, copper, gallium, indium, iron ore, molybdenum, lead, phosphate, selenium, silica, tellurium and titanium dioxide and wind turbines use bauxite, cobalt, copper, iron ore and molybdenum. A number of REEs are particularly important as they reduce the weight and size needed for magnets in wind turbines. Lithium is needed for modern longer-lived battery systems, and the push for electric transportation and green energy create competition for cheaper and more efficient batteries to store the energy (Grosjean et al. 2012; Vikström et al. 2013).

Lithium is mainly produced from pegmatites (spodumene, amblygonite, eucryptite, lepidolite, petalite, zinnwaldite) and salt-lake brines, with lithium contents of 1–6% and 0.017–0.15%, respectively (Grosjean et al. 2012). Lithium is also extracted from geothermal and oilfield brines. There are large quantities of lithium in the oceans, but since the concentration is only 170 ppb, it would be very costly to extract lithium from seawater salts (Grosjean et al. 2012). Towards 2050 and beyond, the projected lithium demand for various vehicles far exceed the most optimistic present

Fig. 2. Technological paradigm shifting through our history has caused major changes in which minerals have been important to society. Source: https://www.ngu.no/nyheter/rapport-det-gr-nne-skiftet
production prognoses, and if 100 million electric and hybrid vehicles are produced annually using lithium battery technology as projected by IEA (2011), the presently known lithium reserves would be exhausted in just a few years (Vikström et al. 2013).

There is no danger of the planet to running out of lithium, or other REEs. However, without increased exploration and mining, the expansion of renewable energy technologies may be threatened. Today wind and solar energy meet only 1% of the global demand, while hydroelectricity accounts for about 7%. If we want to match the energy generated by fossil fuels and nuclear power stations, we will face a challenging new Stone Age. As an example: We will need 90 times more aluminium and 50 times more iron, copper and silica (quartz) to construct the needed solar energy plants and wind turbines. To meet the increased need for steel, aluminium and copper alone we will have to more than triple the global production of these metals towards 2050 (Vidal et al. 2015). More recent reports indicate that these are conservative estimates.

Scaling up the production of these metals require more basic knowledge of the distribution and the qualities of the resources. We need to map out uncharted frontiers, and we need better geological information on the different prospective currently mined areas in order to develop better models of the potential spatial distribution of the needed mineral resources. As pointed out in a report by the World Bank Group (2017), the actual demand of a number of minerals required for low carbon energy technological solutions will be driven by the range of global climate scenarios; that is the 2° degree (2DS), 4° (4DS) and 6° scenarios (6DS). The World Bank Group report (2017) shows that the technologies needed for the clean energy shift (wind, solar, hydrogen, new electricity systems) in fact are significantly more mineral and material intensive than traditional and current fossil fuel-based energy supply systems. The report further concludes that demand of relevant metals and other minerals rises rapidly between the 4DS and 2DS scenarios. To quote the report:

The most significant example of this being electric storage batteries, where the rise in relevant metals – aluminium, cobalt, iron, lead, lithium, manganese, and nickel – grow in demand from a relatively modest level under 4DS to more than 1000 percent under 2DS.

(World Bank Group 2017)

Most metals and minerals are not in short supply, but the uneven distribution on the globe may create political, economic and environmental challenges. For example, Europe consumes more than 20% of the metals globally mined, but less than 1.5% of the iron and aluminium and 6% of the world’s copper used to come from European mines. Increased recycling of valuable metals is required to meet the growing demands, but still we need to open new mines to cover future needs. This means we first have to identify what mineral resources could be hidden in the remaining poorly surveyed and unmapped regions of the world, including the floors of the seas and oceans. One major challenge is that the costs of mineral resource exploration and extraction will increase as we move into distant frontiers or have to dig deeper into the underground to find the needed resources. When the richer reserves are exhausted, we need to extract the minerals from poorer resources, increasing the extraction and processing costs. Today, between 3 and 5% of total global energy demand is used solely to crush rock for mineral extraction (Daniel & Lewis-Gray 2011). New technologies for more efficient mineral extraction will be developed, including new low-carbon extraction methods like in situ leach mining and microbial bioleaching. Bioleaching is a simple and effective technology for mineral extraction from low-grade ores and mineral concentrates (Bosecker 1997; Schippers et al. 2018). Metal recovery from sulfide minerals can be done by chemolithotrophic bacteria, while non-sulfide ores and minerals can be treated by heterotrophic bacteria and fungi. Bioleaching has for many years been used for recovery of copper, uranium and gold (Bosecker 1997), and is also now used for recoveries of nickel, cobalt and zinc (Natarajan 2018). New mineral extraction processes will allow us to use previously uneconomic ore types and grades. But still, the total demand for energy used for mineral extraction is likely to increase significantly in the years ahead.

Facing this scenario, in 2058 we can expect that the geology the Earth’s areas and most of the oceans is mapped. We have detailed 3D images of the urbanized areas, and 4D models to assist in making reliable forecasts in a world of increased pressure of the natural resources and changing ecosystems. By 2058 the Green Stone Age is established. More minerals and almost the entire periodic system is used to produce the materials we need for everyday life’s new and smart technological solutions and to produce environmentally friendly energy.

We also will have to find ways to better balance the need for specific minerals, with the leftover materials from the production. For example, Elshkaki & Graedel (2014) find that the production of dysprosium (Dy) required for wind power and other green technologies is likely to lead to the production of very large quantities of the coproduced metal thorium. Elshkaki & Graedel (2014) point out that this will require to careful disposal or alternative uses for the thorium in order to minimize ancillary costs and waste of potential useful material associated with electricity production from wind power.
In 2058 the extent of recycling will be higher than the withdrawal of new resources for many metals and minerals. But before we reach this far, we need to increase our mining activities. Without increased exploration and new mining, a shift to greener, more environmentally friendly energy production will be threatened. To meet this, national geological surveys will play an increasing important role. This role not only covers mineral mapping and providing overall estimates of available resources, but also means that surveys should be actively involved in contributing to policy- and strategy-making processes aiming to identify, characterize and safeguard a sustainable resource potential, notably on critical raw materials, through research, development and innovation. Today this mission is addressed in most national surveys, or collaborating assemblies of geological surveys, like EuroGeoSurveys (EGS).

EGS has established a Mineral Resources Expert Group (MREG) with the mission to provide the best available mineral expertise and information based on the knowledge of member geological surveys, for policy, communication, public awareness and education purposes at European level. Currently, EGS MREG focus mainly on strengthening the position of the European minerals industry towards resource sustainability and competitive growth, and the aim is to become the leading partner within a European Raw Materials Knowledge Base and Information Network (or similar form of co-operation) that will be providing innovative tools and expertise to support sustainable minerals supply for Europe. To meet European needs and build a necessary baseline to achieve several of the 17 UN SDGs and the 169 targets, mineral resource information and data sharing and networking by European geological surveys is becoming essential and much needed (see: http://www.eurogeosurveys.org/expertgroups/mineral-resources/).

Groundwater for water supply purposes is often better and cheaper than surface water, and is in many places the most practical, or the only, alternative. However, groundwater is an invisible resource, and requires relatively large investments for mapping and monitoring, so the centralized management of knowledge and data concerning groundwater is of considerable economic value for society (Smelror 2008). Future climatic changes will have a direct impact on distribution and movement of water, and while many regions are facing increased rainfalls and flooding, large regions will suffer reduced availability of surface water, groundwater and hydro-power. Many national geological surveys are responsible for mapping the countries groundwater resources, managing national groundwater databases and carrying out applied research and method development linked to groundwater. In the European countries many geological surveys develop and manage fundamental data for the management of the EU Water Directive, and they are responsible for meeting the needs of public administration for hydrogeological mapping of ground water resources.

In many European countries up to 80% of the drinking water is groundwater. In 2010 more than 1900 ‘mineral water’ brands were officially registered in Europe. The quality and hydro-chemical fingerprints of the groundwater are controlled by many factors, including rainfall chemistry, climate, vegetation and soil zone processes, the interactions between the minerals underground and the water, groundwater residence time and mineralogy of the aquifer (Reimann & Birke 2010). In an innovative study conducted by EuroGeoSurveys, analysis of bottled water was used to provide indicators of the groundwater chemistry at the European scale (Reimann & Birke 2010). The study included 1785 bottled water samples, representing 1247 locations all over Europe. The water was analysed for more than 70 parameters (geochemical elements). The influence of geology in determining element concentrations in bottled water can be recognized for a significant number of elements. One example is the high values of chromium related to the occurrence of ophiolites (Fig. 3), another is the high values of arsenic, fluorine, potassium, rubidium and silicon in bottled water coming from sources related to volcanic rocks. However, the natural variations are very large, usually an order of magnitude of three or four, and for some elements up to seven (Reimann & Birke 2010). The study documented that very few analysed samples (<1%) showed values exceeding maximum admission concentrations for mineral water, as defined by the European Commission (Reimann & Birke 2010).

In many coastal areas, saltwater intrusion with the influx of saline water into freshwater aquifers is a major problem. Such influxes may contaminate drinking water and lead to other problems. Saltwater...
intrusions can be caused by extensive groundwater pumping from freshwater wells in aquifers near the sea. Channels dug for draining, navigation or farming might also cause similar problems. In the future, climatic changes, with sea-level rise and an increase of extreme storm surges and hurricanes, will make larger coastal areas more exposed and vulnerable to saltwater influxes into main groundwater aquifers (Manda & Klein 2019). In particular, small islands are at risk of over-pumping of groundwater, and in many small island developing states (SIDS) careful management of groundwater extraction is necessary. Good knowledge of the geological factors controlling the quantity of water recharging the groundwater system, is a key parameter for all groundwater management strategies. Since the Millennium Development Goals were agreed in 2000, access to an improved drinking water source have increased from 76% of the global population in 1990 to 91% of the global population in 2015, with 73% of this increase being through piped water to premises (United Nations 2015b). However, intensive water use by all sectors in some countries has already outnumbered the amount of available water resources (World Water Forum 2017).

UN SDG no. 6, to ‘Ensure availability and sustainable management of water and sanitation for all’, is most critical and challenging for the development of all societies. However, recent years’ extreme events with droughts and flooding in many regions have shown that many current land-use concepts are not reasonably adapted to handle these events. Scenarios for future climatic changes, with significant regional changes in the amount and distribution of rainfall, drainage patterns and ground-water storage capacities, provide additional pressure on us. In the 2017 8th World Water Forum announcement, Aloysio Nunes, Minister of Foreign Affairs in Brazil, states that:

SDG6 reflects this understanding by establishing targets for overcoming cross-cutting challenges to ultimately ensure sustainable sanitation and water management and availability for all. To achieve SDG6, we should work on several fronts, such as equal access to drinking water and basic sanitation for all; better water quality and protection and restoration of ecosystems; higher efficiency in water use by all sectors and implementation of an integrated water resource management, among others. In this road, until 2030, international cooperation, capacity building in developing countries, and the support to the participation of local communities and their strengthening will be essential.

(World Water Forum 2017)

Revealing the ocean’s secrets

Understanding the functioning and role of the oceans as part of the Earth’s systems are imperative for our
future societies. The oceans cover more than 70% of the Earth’s surface. As the productive terrestrial parts of our Earth are getting more and more exploited and inhabited, solutions to meet the growing world population’s increasing demand for food, energy, infrastructure and transport have to be found within the ocean space.

Nearly 80% of the ocean space is deeper than 3000 m, while our human activities such as fishing and petroleum production are mostly restricted to the shallow shelves. About 90% of all known living species are marine, and it is estimated that about 98% of all marine species live at and within the sea bottom. This means that the seabed contains the highest biodiversity on the planet. We have limited knowledge about the seabed and deep ocean ecosystems, but we know that they contain many species that are highly specialized, and some that are very long lived. The marine environments are now under varying degrees of pressure due to increased human activities, such as fisheries, hydrocarbon production, deep-sea mining and bio-prospecting. In near-shore areas aquaculture, marine harvesting, society infrastructure and areas for recreation occupy an increasingly larger space. We have much evidence that trawling has damaged sea-floor habitats, and in particular areas with deep-water corals, and we must now take caution not to disrupt the still poorly understood ecosystems of the sea mounts and subsea ridges. The needs to exploit and utilize more and more of the Earth’s marine areas must be met by increased knowledge.

Geological surveys in many countries are actively involved in marine exploration and mapping, and as acoustic methods and technologies have improved over the years, more areas are covered with high resolution bathymetric and seismic surveys. In particular, the increased use of multi-beam swath-bathymetric and 3D seismic-reflection methods, including use of high-resolution P-Cable seismic data, have resulted in high-resolution imaging and penetration of the seabed and allowed us to get much better images of the underwater landscapes, bedrocks and sedimentary cover (Dowdeswell et al. 2016; Jakobsson et al. 2016). For mapping of shallow waters, bathymetric LiDAR system provides high-precision measurements of water depth and benthic environments based on extracts of statistical parameters derived from the bottom backscatter (Collin et al. 2008; Eitel et al. 2016).

We have begun to see the ocean frontiers with increasing clarity (Fig. 4). Significant advances have been made through extensive national marine mapping programmes such as the Canadian Arctic Seabed Mapping Program (Beaudoin et al. 2008; Pickrill et al. 2014), the British MAREMAP programme (MAREMAP 2017), the Irish INFOMAR programme (Dorschel et al. 2010) and the Norwegian MAREANO programme (Thorsnes et al. 2008; Buhl-Mortensen et al. 2016) (Fig. 5). However, on a global scale the geographic coverage with such high-resolution studies is still limited. When the latest International Bathymetric Chart of the Arctic Ocean (IBCAO) was compiled and published in 2012 (Jakobsson et al. 2012), only 11% of the Arctic Ocean had been mapped using modern multi-beam technology (Jakobsson et al. 2016). When the similar compilation was made for the Southern Ocean (IBCSO) in 2013 (Arndt et al. 2013) the coverage was 15%. In 2058 we will have mapped depth and topography, seabed sediment composition, biodiversity, habitats and biotopes, as well as pollution in significantly larger areas of the world’s oceans. We will have gained large amounts of basic and novel knowledge on the marine landscapes (seascapes) and what the seabed consists of. We will have a better understanding of how the biodiversity, the habitats and biotopes are distributed on the seabed, and we will have a better understanding of the relationship between the physical environment, biodiversity and biological resources. We will have more detailed knowledge on ocean current systems and sedimentation patterns, and we have gathered reliable estimates of where, and how much, contaminants are deposited in the oceans bottom sediments.

Today, there are long-term strategies to support sustainable growth in the marine and maritime sectors (aquaculture, marine biotechnology, ocean energy, seabed mining, coastal tourism). Around the world, seas and oceans are drivers for the future economy. In the EU, blue growth is defined as the maritime contribution to achieving the goals of the Europe 2020 strategy for smart, sustainable and inclusive development. As exemplified in Norway, the offshore petroleum industry, shipping, fisheries and aquaculture are main pillars to the Norwegian economy. Together these industries comprise more than 40% of Norway’s total annual value creation and more than 70% of exports. Consequently, Norwegian marine research and science driven technological development have played a major role in the exploration and exploitation of the ocean space and ocean science and technology is a designated strategic area for the government and research institutions. The long-term strategies include plans for new research facilities needed to study an array of marine and maritime topics, including ship design, renewable energy production and fish farming of the future.

Environmental monitoring of the ocean, marine research, marine mining and the offshore oil and gas industry all demand strong technical expertise and advanced engineering solutions. The need for holistic approaches and integrated solutions will bring together experts from cybernetics, control
engineering, oceanography, marine biology, marine archaeology, electrical engineering and telecommunications, and underwater technology to produce new scientific results that would otherwise be difficult to achieve. One example of new and innovative methods developed for more detailed identification, mapping and monitoring of subsea biogeochemical objects, is the underwater hyperspectral imaging (UHI) sensors implemented on underwater robots. The new technology is a spin-off of research undertaken at the Norwegian University of Science and Technology (NTNU), and is now patented by Ecotone, a small private company which is a partner in NTNU AUR-Lab for the verification and prototyping of new underwater robots and integration of new sensor packages. Ecotone’s UHI is designed to identify various marine habitats, ecosystems and objects in the water-column, such as phytoplankton or dissolved organic matter, or on the sea floor, such as sediments, coral reefs or mineral nodules (Johnsen et al. 2016). The mapping and monitoring are done with respect to spatial, temporal, spectral

Fig. 4. Topography and bathymetry map of the Arctic region at 1:5 million scale in a polar stereographic projection based on ETOPO1 Global Relief Model (NOAA National Geophysical Data Center 2011). From: Petrov et al. (2016).
and radiometric area coverage, digital map information and statistics. The full application and robustness of the UHI-method is now to be further tested in various sea-floor terrains and at different scales. The new, rapidly evolving technologies will be used in major national seabed mapping programmes and in more local mapping and monitoring programmes linked to specific industrial needs like infra structure for petroleum installations or marine windmills, for aquaculture, bio-prospecting, or for marine mining. Several geological surveys are involved in seabed mapping and monitoring. Today, the present lack of basic knowledge in terms of modern bathymetric charts puts a brake on the possibilities to develop more substantial and sustainable usage of the marine natural resources. This holds true for European waters, as well as for the rest of the world’s seas. As pointed out by EU Commissioner Damanaki, there already exist large amounts of data among navies, hydrographic agencies, geological surveys, research institutes and coastal protection authorities, who have collected bathymetric information for years. In Europe, parts of these data are now made available through the major EU data infrastructure initiative European Marine Observation and Data Network (EMODnet). EMODnet is co-ordinated by the Geological Survey of Finland (GTK) and delivers seabed maps in scale 1:100 000, covering sediment types, coastal processes, geological risks and natural resources. A study of European Marine Data Infrastructure documents that private companies have collected, shows they hold even more data than public authorities, but these have only been incorporated within the EU initiatives in limited amounts so far. EMODnet has provided the first generation of modern cross-border European marine maps, although fragmented and of variable, mostly low, resolution. The digital terrain model of the European seabed will be delivered at a resolution of about 250 m, which is rather low given the present-day technological capabilities with precisions of centimetres. However, this resolution is four times better than what was previously publicly available on a pan-European scale. Military restrictions on the spatial resolution of marine maps create significant restrictions to their applications. But as experienced in the Norwegian MAREANO programme, and the Astafjorden- and Søre-Sunnmøre projects, significant breakthroughs can be reached even within the existing limitations. In addition to the compilations...
of the bathymetry, the main products of the Astafjorden- and Søre-Sunnmøre projects are a series of special maps designed to meet various specific needs and end users. These maps include sediment types, sites of deposition, seabed slopes, anchoring possibilities and sediment strength and possibilities for digging into the seafloor. Marine benthos and many fish stocks are linked to specific substrates and topographies. The advanced seabed maps have been integrated and tested in navigation systems on trawlers and other fishing vessels, with positive results. The operations have become more targeted and efficient, as less time and less fuel are used to catch fixed quanta of fish. The trawlers can keep clear of areas that might cause damage to the gear, and the operations are also more environmentally sustainable as the fishing vessels can avoid areas with endangered marine biotas.

In 2016, the Nippon Foundation launched an initiative to partner with General Bathymetric Chart of the Oceans (GEBCO) to co-operatively work towards seeing 100% of the world’s ocean mapped by 2030. This initiative led to the Nippon Foundation–GEBCO–Seabed 2030, a global project within the framework of the GEBCO, with the goal producing a high-resolution bathymetric map of the entire world’s ocean by the year 2030. By the Seabed 2030 ambitions, GEBCO, the Nippon Foundation, International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of UN Educational, Scientific and Cultural Organization (UNESCO) are now, step by step, turning a key to lighten up ocean floors. Geological surveys will contribute, with seabed mapping of national territories. Providing open access data and information to a variety of public and private end users is a key to successfully meeting the blue future challenges.

Cleaning up the past and restoring damaged ecosystems

There is an increasing understanding that ecosystems should be viewed as economic assets which produce a flow of beneficial goods and services over time, often referred to as Ecosystem Services (Millennium Ecosystem Assessment 2005). Geology is a fundamental part of all ecosystems (Berger 1998; Baves-trello et al. 2000; Hahn et al. 2014), and geological knowledge is one of the keys to restoring any damaged living ground. This means that basic knowledge of the bedrocks and surficial deposits, and the processes that form and erode rocks, sediments and soils is fundamental for reaching the UN SDG no. 15 to ‘Protect, restore and promote sustainable use of terrestrial ecosystems, sustainable manage- age forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss’. This also holds true for marine ecosystems and is particularly evident for the marine benthic habitats. Water-column food webs build on the availability of nutrients shed into the ecosystems, and the free-water ecosystems are influenced directly by geological factors such as the formation and shape of underwater landscapes and geochemical compositions of the hinterlands and costal zones providing minerals and nutrients to the oceans.

Cleaning up the past and restoring and repairing damaged ecosystems are on the political and public agenda around the world (Palmer et al. 2005; Martínez & Lopez-Barrera 2008; Vitt & Bhatti 2012; Jones et al. 2018). One of the key findings from the Millennium Ecosystem Assessment (2005) was that of a group of 24 ecosystem services, 60% were degraded. In 2058 restoring and designing novel ecosystems for a crowded planet will be a major issue, and the competences and capacities of geological surveys will be needed.

A primer on ecological restoration has been published by the Society for Ecological Restoration (SER 2004). However, geological conditions and geological processes are generally not thoroughly considered in the majority of restorations conducted to date. Determining the reference ecosystem conditions for the area is a key issue when we want to restore a damaged ecosystem. Generally, the ‘natural conditions’ are considered the spectrum of ecosystem conditions, including the composition, structure and function of ecosystems occurring within a defined area over a specified period of time before human disturbance (Goebel et al. 2005). This means that palaeoecological studies and assessments, including recoveries of fossils and traces of DNA left in the soils and sediments, have to be conducted as a basis for the reconstruction targets and plans. The need for assessing geo-indicators in monitoring landscape conditions and changes was addressed two decades ago by Berger (1998), who asked the key question: ‘How can changes in ecosystems be understood without assessing the state of their chemical and physical (landscape) components and without understanding the past trends that have led to current conditions?’

Ecological restoration requires huge amounts of time and resources, as exemplified by the planting of 90 million acres of forest across the northern provinces in China and the restoration of 7.4 million acres of marsh, peatland, floodplain, mangrove and other wetlands in North America over the past two decades (Conniff 2014). Marine ecosystem damage also requires substantial resources to tackle, exemplified by the costs for restoring ecosystem damages after large oil spills. Van Dover et al. (2014) have considered a series of socio-economic, ecological and technological parameters that may contribute to
decisions to undertake restoration in the deep sea and elsewhere. They estimate that the costs for hypothetical restoration scenarios in the deep sea (i.e. at the sea floor deeper than 200 m) may be two to three orders of magnitude greater per hectare than costs for restoration in shallow-water marine systems (Van Dover et al. 2014). Serious large-scale ecological damages like imminent collapse of fish stocks due to overfishing may lead to economic collapse both at local and regional scales. With respect to the latter case, Pitcher & Pauly (1998) argue that rebuilding ecosystems, not sustainability per se, should be a proper goal of fishery management. Pitcher & Pauly (1998) find that sustainability is a deceptive goal because human harvesting of fish leads to a progressive simplification of ecosystems in favour of smaller, high-turnover, lower-trophic-level fish species that are adaptable to withstand disturbance and habitat degradation.

We have become aware that reef-building corals are currently living close to their thermal maxima and that coral bleaching is a major threat in marine tropical ecosystems (Hoegh-Gulberg 1999). Sea temperatures in the tropics have increased by almost 1°C over the past 100 years and are currently increasing at the rate of approximately 1–2°C per century. Corals become stressed if exposed to small slight increases in water temperature (1–2°C) and experience bleaching (i.e. expulsion of photosynthetic symbionts of the corals). Corals tend to die in great numbers immediately following bleaching, which may stretch across thousands of square kilometres of ocean. The United States National Oceanic and Atmospheric Administration (NOAA) reports that in 2005, the USA lost half of its coral reefs in the Caribbean in one year due to a massive bleaching event centred around the northern Antilles near the Virgin Islands and Puerto Rico. Comparison of satellite data from the previous 20 years confirmed that thermal stress from the 2005 event was greater than the previous 20 years combined (NOAA 2019). Current prognoses with an increase in global seawater temperatures, give negative perspectives for the vulnerable tropical coral reef ecosystems (Hughes et al. 2003; Hoegh-Gulberg et al. 2007). As discussed in the following section on climatic changes and geohazards, reducing the risk of climatic changes and undesirable impacts, including ocean acidification and coral bleaching, is about lowering the greenhouse gas emission. On smaller scales there are many positive examples demonstrating that the restoration of ecosystems works. One comes from artificial restoration of degraded reefs, where initial monitoring indicates that both kelp density and fish recruitment as measured by young-of-year juvenile fish density, compare favourably with natural reefs (Seaman 2007). Since much of the recent years and the predicted future human population growth is in vulnerable coastal regions (Martinez et al. 2007) much effort has been put on protecting and securing coastline settlements and infrastructures from the effects of rising sea levels and more frequent storms following climatic changes. Research focusing on the ecological consequences of coastal construction is now extensive, and there are data indicating the potential for modification of artificial, engineering design to influence ecological outcomes (Firth et al. 2016). However, our present ability to achieve specific ecological objectives, such as boosting stocks of commercially important marine species or minimizing the spread of non-indigenous species in marine environments, is still limited (Firth et al. 2016). More detailed knowledge of substrate and species interactions are need. Along with detailed mapping of the distributions and ‘substrate preferences’ of the various marine habitats, we must achieve and apply more knowledge of geological–geochemical properties and geological processes influencing and controlling the marine environments and ecosystems.

Few studies have documented the recovery of ecosystems globally or the rates at which ecosystems recover (Jones et al. 2018). Most studies are on local scales and focus only on parts of the ecosystems or habitats. This is illustrated in the review of Burton & Macdonald (2011) on forest restoration, where one-quarter of research papers dealt with post-mining sites and other locations following other industrial developments (Fig. 6). Burton & Macdonald (2011) found that the vast majority of these forest restoration studies focused mainly on re-establishment of tree species, often with associated consideration of non-tree vegetation. Studies of the reconstruction of soils and the restoration of ecological processes are scarcer (Burton & Macdonald 2011; Macdonald & Quideau 2012). As pointed out by Macdonald & Quideau (2012) the interaction between soils and vegetation is a critical aspect of rebuilding boreal forest ecosystems.

From the geological record it is obvious that bedrock, sediments and soils vary both vertically and horizontally across the landscape, and that geological processes such as formation of soil and water capture and drainage, is the foundation of the various ecosystems and habitats. Macdonald & Quideau (2012) write that: ‘As we rebuild soils following mining disturbance, we need to be careful to recreate a belowground landscape mosaic that is comparable to the undisturbed landscape’. Macdonald & Quideau (2012) further conclude that re-establishing biogeochemical cycling between reconstructed soil and plant communities is one of the most critical factors required to ensure long-term sustainability in reclaimed boreal forest landscape. For us geologists, this is an obvious statement, although for many restoration projects this apparently has not been
sufficiently considered. One reason for not acting ‘ecologically holistic’ might be unrealistic costs, another could be the lack of knowledge of the ‘fundamental ecological services provided by the underground’.

A key issue is therefore to carefully evaluate to which degree the restorations and rebuilding of the natural environments works as planned. Moreno-Mateos et al. (2012) find that over half of the wetland ecosystems existing in North America, Europe, Australia and China in the early twentieth century have been lost because of human activities. In their meta-analysis of 621 wetland sites from throughout the world Moreno-Mateos et al. (2012) document that although ecological restoration to recover critical ecosystem services has been widely attempted, the degree of actual recovery of ecosystem functioning and structure from these efforts remains uncertain. The results presented by Moreno-Mateos et al. (2012) show that even a century after restoration efforts, biological structure (driven mostly by plant assemblages) and biogeochemical functioning

**Fig. 6.** Active coal mining and restored post-mining sites at Bilina Coal Mine (Czech Republic), the largest open-cut lignite mine in Central Europe. Photos: Morten Smelror.
(driven primarily by the storage of carbon in wetland soils), remained on average 26 and 23% lower, respectively, than in reference sites. They conclude that if restoration as currently practised is used to justify further degradation, global loss of wetland ecosystem function and structure will spread.

A meta-analysis of 400 studies worldwide carried out by Jones et al. (2018) document that recovery from large-scale disturbance, such as oil spills, agriculture and logging, suggest ecosystems are progressing towards recovery after disturbances. However, they rarely recover completely (Jones et al. 2018). Jones et al. (2018) also found that recovery rates slowed down with time since the disturbance ended, suggesting that the final stages of recovery are the most challenging to achieve. Another finding was that ecosystems had more complete and faster recovery with decreasing latitudes, that is near the tropics (Jones et al. 2018).

An important observation from the comprehensive meta-analysis of Jones et al. (2018) is that active restoration did not result in faster or more complete recovery than simply ending the disturbances the different ecosystems were facing. This appear to be valid for all types of ecosystems included in the study, from tidal wetlands which show higher percentage recovery per year than grassland and forests, and for all types of damages from oil spills where the percentage of improvements per year was highest to agriculture and logging restorations where the percentages of improvements were their lowest (Jones et al. 2018). However, Jones et al. (2018) found positive recovery rates in all cases. This means that although ecosystems are not recovered completely, parts of the biodiversity and ecosystem functioning are brought back to their respective reference levels after restoration.

The results of Jones et al. (2018) are not unexpected and in line with several previous studies (Tischew et al. 2010; Matzek et al. 2016; Moreno-Mateos et al. 2017). Although humans have experimented with and altered ecosystems for thousands of years, holistic science-based approaches to ecological restorations appear to be restricted. There is a lack of fully integrated approaches to understanding ecosystem resilience, recovery and functioning. Studies on human restoration efforts on ecosystem recovery are dominated by projects that monitor single sites and are carried out over short periods of time (Holl et al. 2003; Jones et al. 2018). Apparently, there is a need to develop better tools to increase the success rate of ecosystem restoration and repair. According to the Society for Ecological Restoration International Science & Policy Working Group (SER), ‘restoration of an ecosystem is achieved if it contains sufficient biotic and abiotic resources to continue its development without further assistance or subsidy’ (SER 2004, p. 3; Seaman 2007).

Each case, to properly address the abiotic factors, and to fully integrate the knowledge needed for long-term resistance and sustainability for any ecosystem, fundamental knowledge of geology and geological processes are required.

The spatial distribution of ecosystems and their variations through time can be observed from space. Song et al. (2018) find that, contrary to the prevailing view that forest area has declined globally, tree cover has increased by 2.24 million km² (+7.1% relative to 1982 level) during the period 1982–2016. Large vegetation differences are due to differences in bedrock composition and sediment covers (Fig. 7), and the connections between composition and surface processes in many places are strong enough to produce differences in vegetation that can be seen from space (Hahm et al. 2014). This shows how geological maps are important tools for mapping of ecosystems and for regional restoration planning.

Restoration must involve a good balance between rebuilding past systems and attempting to build resilient systems for the future (Valladares & Gianoli 2007). In addition to land-use changes and habitat fragmentation, future global change scenarios involving temperature rise, significant changes in precipitation and increased frequency of extreme climatic events, must be considered when restoring ecosystems around the world. Technologies and methods for restoration of ecosystems emerged as early as 1800, and over the years these have changed from single objective applications to multi-objective strategies taking into account both ecosystem rehabilitation as well as integrated ecological and socio-economic factors (Zhen et al. 2017). However, many ecosystems are now rapidly being transformed into new, non-historical configurations owing to a variety of local and global changes, calling for major revisions of existing conservation and restoration norm and practices (Hobbs et al. 2009). These challenges cannot be handled properly without basic understanding of the geology and mineralogical compositions of the underground. Being able to model and monitor the controlling geological processes is a key for successful restorations of damaged ecosystems and for building novel ones. In 2058 restoring and designing ecosystems for a crowded planet will be major task for our societies, and the knowledge and contributions from geological surveys will be a major key for successfully addressing these tasks.

### Living with climatic changes and geohazards

Human activity affects and transforms the landscapes, underground and environment around us,
Fig. 7. Variations in vegetation cover are due to differences in bedrock composition as shown in this example from Sørfold, Nordland (photo: Morten Smelror). If you stand in the blue circle shown in the geological map below and look towards north, you will see naked Precambrian basement (Kviturfjellet), marked with light brown on the geological map, and thrust nappe with Caledonian meta-sedimentary rocks covered with green vegetation in front and alongside, marked with green, light blue and brown on the geological map. Photo: Morten Smelror; geological map: NGU.
and the vulnerability of populated areas to natural disaster is partly a consequence of decades of neglect by planning authorities of the dangers of natural hazards. There is also raised awareness of the potential impact of climatic changes on frequency and magnitude of geohazards such as storms, coastal erosion, flooding, avalanches and of debris flows and landslides triggered by heavy rainfall (Bo et al. 2008; Jaedicke et al. 2008; Zhang 2008; Banholzer et al. 2014; Gariano & Gazzetti 2016; Papathoma-Köhle et al. 2016). Other geohazards, such as sinkhole collapse, may also be linked to climatic changes, not immediately caused by heavy rainfall, but by water pumping and drawdown following periods of drought (Yan & Long 2018).

The Intergovernmental Panel on Climate Change (IPCC) 2014, suggest that increase in frequency and magnitude of hazardous processes related to climate change is to be expected at the global scale. Consequently, it is important to identify and map out land and coastal areas that are potentially subject to such geohazards. Further, we need to develop efficient methodologies to incorporate natural disaster reduction into land-use planning and management (Papathoma-Köhle et al. 2016). Geosciences deliver knowledge and understanding of climatic changes and the responding processes on the ground we live on, and geological mapping and process research will provide important contributions when it comes to handling the challenges of our society to adopt to both the current and future climates (Schmidt-Thomé et al. 2010).

Geological surveys work on evaluating the risk of natural disasters such as earthquakes, rock-falls, landslides, avalanches, sinkhole collapse, floods, coastal erosion and tsunamis. Areas where rock fall, landslides and other geohazards are likely to take place must be identified and mapped, and the potential for geohazards in relation to existing and planned settlements and infrastructure assessed. Often there will be a combination of triggering mechanisms and geohazards, such as rock fall into lakes or fjords creating tsunamis (Braathen et al. 2004) or landslides triggered by earthquakes (Zhang et al. 2012). There’s also evidence from several areas that large rock-slope failures increase the probability of further collapses (Hermanns et al. 2006).

In order to assist national and municipal authorities with overviews of where geohazards may occur, geological surveys develop databases that include hazard maps, risk maps, geological data, historic volcanic eruptions, earthquakes, costal erosion, avalanche and slide events, geotechnical data and localization of different types of protection work and monitoring. An example is the new EMODnet Geology shoreline-migration map which was published 9 April 2019, allowing users to visualise pan-European coastal behaviour for 2007–17 at different spatial scales. The map service has a built-in search and zoom functionality by which online users can distinguish areas of landward migration (erosion or submergence), stability, and seaward migration (EMODnet Geology 2019).

The databases produced and served by the geological surveys and their partner organizations are served on the Internet, providing an easy access to digital maps, information on previous hazard areas as well as to hazard assessments (Dehls et al. 2017; Herrera et al. 2017). The landslide databases from 17 geological surveys of Europe comprises 849 543 landslide records, from which 36% are slides, 10% falls, 20% flows, 11% complex slides and 24% remain either unclassified or correspond to another typology (Herrera et al. 2017). The landslide density map covering the 17 countries shows that the variable distribution of landslides covers 0.2 million km² of landslide prone areas.

In many places around the world there are major efforts underway to build networks of observatories to collect vital data on terrestrial and marine active geodynamic processes. These systems collect high-resolution data from land surface, water columns and sea floors (Ruhl et al. 2016). Land and sea-based stations are linked to satellites or cable connections, and factors such as seismic activity, slope failure, pore pressure, water levels, gas hydrate stability and geochemical composition of drainage can be monitored in real or near-real time. The observatory networks provide the means to co-ordinate and integrate large amounts of information across borders and scientific disciplines, as demonstrated by the Global Earth Observation System of Systems (GEOSS) and the Global Monitoring of Environment and Security (GMES). Combined with geological base maps and time series of various physical data, such integrated networks will become more and more important as key tools for early working of potential geohazards in the years ahead of us.

However, monitoring potential geohazards, such as rock avalanches is both costly and challenging. As an example, in Norway rock avalanches can hit settlements and infrastructure directly but may also fall into steep fjords and create devastating tsunamis. Before these areas can be risk evaluated and monitored, they have to be identified and mapped, and geological models of the various sites have to be worked out (Braathen et al. 2004; Ganerød et al. 2008; Oppikofer et al. 2009; Launkes et al. 2010; Hermanns et al. 2012). In Norway, more than 260 potential unstable slopes are identified, and large areas are still unmapped. In practice, today it is not possible to instrument all unstable slopes, and the alternative is periodic monitoring. To fill the need for frequent acquisitions to record variations in movements within a season and to achieve flexible
acquisition geometries to cope with highly variable topography and movement directions, space-based sensors like Sentinel-1 have proved very useful (Lauknes et al. 2010, 2013; Dehls et al. 2017). InSAR time series provide good means to determine potential rockslide movements and therefore provides a direct link between quantitative ground movement data and structures, kinematics and change of slope (Lauknes et al. 2010) (Fig. 8). InSAR time series can also be used to measure rates of subsidence in urban areas and cities, as documented from the cities of Oslo and Trondheim, where the subsidence of a number of buildings are measured in mm/year. In the case of Bjørvika in Oslo, the data from 2009 show total subsidence of up to 1 cm/year (Fig. 8).

Scientists from the NGU, NORUT, PPO.labs and Norwegian Space Center have now started to use data from Radarsat-2 and TerraSAR-X for InSAR operational settings (Dehls et al. 2017). However, scaling up from regional operations, based upon data every 24 days, to a national operation, with data every six days, is still very challenging (Dehls et al. 2017). Up until today, such integrated studies are still not common. Towards 2058, these techniques will be further improved, and new satellites will be made available for both large-scale and single-point rockslide measuring, monitoring and mitigation.

Along the Earth’s lithosphere plate boundaries volcanic eruptions and earthquakes cause serious damage to settlements and infrastructures. Earthquakes occur in response to stress release due to movement of the plates and are particularly abundant near the active plate boundaries. Earthquake warnings of only minutes can make a major difference to the impact of such hazardous events. The daily monitoring of seismic activity is the responsibility of different national agencies (for example, the Meteorological Office on Iceland and NORSAR in Norway), while the geological surveys’ expertise is often more concerned with risk assessment connected to seismic active areas. Evaluation of the risks from geohazards such as earthquakes and volcanic activity is based principally on reconstruction of previous events, their magnitude and rate of recurrence. Through geological mapping and the dating of such events, the record of large destructive earthquakes and volcanic eruptions can be reconstructed. From such data, the geological surveys provide estimates of the risk of forthcoming events, possible magnitude and impact.

The prediction of volcanic eruptions is difficult. Nevertheless, intensive monitoring of eruptions has generated integrated time-series of data, which have resulted in several successful examples of warnings being issued on impending eruptions (Sparks 2003). New technologies and advances in the use of existing methods, such as broad-band seismology, satellite observations of ground deformation and improved field spectrometers for volcanic gas studies, combined with advances in processing and modelling (including statistical methods for quantification of probabilities), will lead to improvements in data analysis and modelling techniques for forecasting of coming volcanic eruptions (Sparks 2003; Blake & Cortés 2018; Kilburn 2018).

In societies where the vulnerability of living on a dynamic Earth is well understood, geohazard risk assessments have priority. When making decisions concerning where to plan developments and how to construct or reinforce them, there always needs to be a viable balance between the risks, on the one hand, and the social and economic gains, on the other. The chances and acceptance for living with such risks will be reduced as increased knowledge on risks and consequences are made public.

Reducing the risk of climatic changes and undesirable impacts such as flooding and landslides is also about lowering the greenhouse gas emission. Reductions are achieved by terrestrial and marine carbon sequestration (through carbon storage in plant materials, soil and in marine algae). Geological storage in underground reservoirs is well tested, including as a means for enhanced oil recovery in onshore and offshore formations. CO₂ is captured from different sources (e.g. coal-burning power plants) and is compressed and injected into underground reservoir rocks. In Norway the Sleipner and Snøhvit fields currently store 1.7 million tonnes CO₂ per annum. Worldwide, 20.4 million tonnes per annum are stored through five enhanced hydrocarbon recovery (EHR) schemes that inject anthropogenic CO₂ (source: Global CCS Institute) (Poulsen & van Gessel 2015). The methods are tested, and they work well. Although these projects are successful in implementing carbon capture and storage (CCS), there are also many projects that have failed due to lack of financing, favourable economic conditions, public acceptance and correct timing of all activities involved in the CCS chain (Poulsen & van Gessel 2015).

In Europe, national geological surveys co-operate under EuroGeoSurveys to upgrade their knowledge levels on storage potential by evaluating the latest subsurface exploration and production data from industry activities (i.e. key technical and geological parameters defining suitability, capacity, performance and safety of subsurface storage). Pointing towards 2050, Poulsen & van Gessel (2015) suggest that one option is to prepare portfolios for geological storage by selecting and working along preferred injection sites that can then be easily deployed once capture is being implemented. In this context, the European geological surveys can assist in upgrading knowledge and information to appropriate
InSAR time series provide a good means to determine potential rockslide movements and therefore provides a direct link between quantitative ground movement data and structures, kinematics and change of slope. Upper picture from Osmundneset, east of Hyenfjorden, western Norway, shows an unstable part of mountain which stretches for a length of 1 km. InSAR time series can also be used to measure rates of subsidence in urban areas and cities, as shown by the lower picture of the city of Oslo. Red areas are those with highest vertical movements or subsidence (measured in mm/year). In case of Bjørvika in Oslo the data from 2009 show subsidence of up to 1 cm/year. Illustration: NGU/National InSar Center/John Dehls.
levels for decision support and site planning. However, in the foreseeable future the CO₂ capture and storage are not sufficient to have large impacts on the global carbon emissions. Long-term mitigation of global warming caused by increased atmospheric carbon can only be achieved through less-carbon-intensive energy generation (Hnottavange-Telleen 2008).

**Homo sapiens urbanensis in green and smart cities**

More than two generations ago John T. McGill at the USGS wrote a note on the ‘Growing importance of urban geology’ (McGill 1964), where he among others stated that

A major phase of master planning is the evaluation of the advantages and disadvantages of one use of land as compared to other use, so as to make planning and zoning possible for conservation and maximum beneficial use of land, our most fundamental natural resource. Sooner or later we all pay, directly or indirectly, for unintelligent use of land.

McGill continued ‘The most useful general-purpose maps for urban development are those that emphasize geologic processes and characteristic of geologic materials that are significant to land use and civil engineering’ (McGill 1964). Wise words, but not always followed up, meaning that in practice our present goals of creating smarter cities is very often hampered by yesterdays ‘unintelligent use of land’ (Legget 1980).

UN SDG no. 11 is on ‘Sustainable cities and communities’. In recent years, most geological surveys have advanced in the geoscientific work on urban environments and sustainability. In her introduction to the overview of ‘Urban geology: the foundation for cities’, Helen Reeves, Science Director of Engineering Geology at the British Geological Survey (BGS), writes:

> The geosciences have an important, but often underappreciated part to play in securing sustainable global cities. They can support urban innovation and city performance, reduce our environmental footprint and ensure we are resilient to natural hazards such as flooding and ground instability.

(BGS 2015)

One example of critical use of geological knowledge in an urban area comes from the UNESCO World Heritage Site Bryggen in the city of Bergen, western Norway (Smelror 2011). Since 2002, an intensive monitoring scheme has shown damaging settling rates caused by deterioration of underlying cultural deposits. Lowering of the ground-water level and increased content of oxygen in the cultural layers has caused damage of the wooden historical buildings (De Beer & Matthiesen 2008). The monitoring has focused both on chemistry and quantity of groundwater and soil moisture content in the saturated and unsaturated zone, as well as registration of movement rates for buildings and soil surface. The documented preservation conditions within the cultural deposits as well as oxygen and moisture-content fluctuations in the unsaturated zone have a significant correlation with the different groundwater flow dynamics found throughout the site. By understanding the flow regime in the ground beneath the wooden buildings, means could be taken to stop the damaging development. The investigations demonstrated that groundwater and soil-moisture monitoring, combined with 3D transient modelling are potentially effective routines to improve the understanding of preservation conditions in complex archaeological surroundings and, therefore, protection of archaeological deposits (Smelror 2011).

There are numerous case studies demonstrating the importance of geological information for land-use planning. Geological terrain mapping has been used as an effective tool to identify various geological factors influencing the use of the land and the constructions of infrastructure in the given areas. The output of the geological mapping are various derivative maps, such as construction suitability maps, landform maps, erosion maps, physical constraint maps, terrain classification maps and engineering geology maps (Bin Ramli & Bin Ismail 2013). In addition to compilations of maps, attention is often given to the causes and sources of the geological problems which are known to arise in the different areas.

The geological surveys’ projects on urban geology and smart cities cover many geotechnical aspects and methods. A series of 3D geological models of the urban underground are made available to the planners and city engineers, providing vital information of the sub-surface bedrock and sediments, building materials, soil and bedrock geochemistry, faults and potential unstable layers, ground water and drainage systems, and the potential of shallow and deep geothermal energy (de Mulder & Pereira 2009; Marker 2009; Vázquez-Suñé et al. 2016; Gogu et al. 2017). In addition to their traditional maps of the bedrock and surficial deposits, groundwater and building stones, many geological surveys have developed specific datasets and multipurpose maps/models for the urban undergrounds.

One key challenge is to collect sufficient data to make high-resolution and reliable 3D models of the sub-surface in urban areas covered by infrastructure (Fig. 9). However, prior to constructions in the subsoil or on the surface, geotechnical surveys are often carried out, and in most cities there are large amounts of geotechnical data which can be used in the planning processes. Such historical geotechnical data
are most often useful for getting basic information on the underground geology and its properties, and access to these older surveys and engineering project reports is essential. As an example, the National Database for Basic Underground Surveys (NADAG) in Norway, offer an overview of where and what type of surveys have been carried out, and provide an effective open access data for both data collectors and users, including city authorities and planners, private engineering companies, and the public in general. NADAG was developed by the NGU in co-operation with Norkart AS, Trimble, State Authorities State Road Administration, Rail Nor and NVE (Solberg et al. 2017). Other actors have also provided useful developmental input along the way, and Statsbygg was the first to provide a nationwide dataset.

Holistic approaches, with the sharing of knowledge and information, are keys to success. There are several examples of how interaction and networking between urban decision makers, practitioners and the wider research community can be achieved through various actions. One example is the EU Cost Sub-Urban programme, which was set up to establish a network to co-ordinate, integrate and accelerate the world-leading research into modelling the subsurface taking place in European institutions, and to develop a toolbox to enable subsurface knowledge to be widely disseminated. A main goal was to draw together collective research capabilities in 3D/4D characterization, prediction and visualization of the subsurface, and to deliver this in appropriate forms. Other objectives were to provide training and continuing support and advice to better inform and empower decision makers and other end-users. The idea was also to foster development of policy which reflects the importance of the urban subsurface. As an end result, the Cost Sub-Urban programme could recommend the basis for improved availability, initial use and re-use of subsurface data (Cambell et al. 2017; Gogu et al. 2017; Mielby et al. 2017; NGU 2018).

Better sub-urban planning and optimizing the subsurface use for future cities is moving higher up on the agenda as a rapidly increasing number of Homo sapiens is becoming an urban species. With the need for more urban space, the access to new technologies, and the need to become sustainable and more environmentally friendly, more and more cities now raise their ambitions to become smarter and greener (Casini 2017). A smart city is a city where investments in socio-human capital, urban infrastructure and rational management of natural resources, encourage a sustainable economic development and high quality of life through participatory actions and commitment from community members (Pâceşilă & Colesca 2007; Caragliu et al. 2009).

Fig. 9. Large amounts of data are required to make high-resolution and reliable 3D models of the sub-surface in urban areas covered by infrastructure. This example shows the underground infrastructure to be built at the east side of the central city of Oslo (illustration: BaneNOR, Jernbaneverket). The National Database for Basic Underground Surveys (NADAG) in Norway, offer an overview of where and what type of underground surveys have been carried out, and provide an effective open access data for all users.
Investments in smart cities might appear expensive for developers, but to achieve a sustainable development these are beneficial and necessary means. This also applies to protecting and re-establishing green areas in the urban environments (Fig. 10). Green areas have an important multifunctional role in improving the living environment, and contribute to pollution control (including noise pollution); water conservation; soil erosion control; diminishing bacterial impact on man and animals by purifying the atmosphere; mitigating urban climate (reducing the urban heat island, as well as aridity and pollution). However, the concept of green cities does not only include the re-establishing of urban ecosystems and green corridors which are the visible ‘green elements’ in cities. The development of green cities contains many other components, such as resources and energy saving, and management of waste and pollution.

Demographic trends with increased populations in coastal cities have advocated the need to develop knowledge and tools to meet challenges linked to increased sea-level, increased rainfalls, more frequent storms and hurricanes, and greater risks of flooding. The concept of Blue–Green Infrastructure (BGI) covers an interconnected network of natural and designed landscape components, including water bodies and green and open spaces, which provide multiple functions such as water storage for irrigation and industry use, flood control, wetland areas for wildlife habitat or water purification, and many others (Airoldi et al. 2015; Ghofrani et al. 2017). Multidisciplinary programmes are now developed to face the challenges. One example is the Urban Europe project Green Blue Cities, which seeks to find ways to ‘manage urban storm water in a way that facilitates robust, synergistic and multifunctional green infrastructures that will address today’s and tomorrow’s climate and other changes in dynamic urban areas’ (Urban Europe 2017).

As pointed out by McManus et al. (2018) the effects of climate change and an expanding human population are driving the need for the expansion of coastal and marine infrastructure (CMI), and thereby introducing hard substrate into the marine environment on a previously unseen scale. To help develop Blue Green infrastructure, geological surveys can and should contribute with knowledge on the local bedrock geology, its mineralogical and chemical compositions, and by this provide information on the potential for replacement of cement for waste aggregates in concrete coastal and marine

**Fig. 10.** Green areas have an important multifunctional role in improving the living environment, and contribute to pollution control (including noise pollution); water conservation; soil erosion control; diminishing bacterial impact on man and animals by purifying the atmosphere; mitigating urban climate (reducing the urban heat island, as well as aridity and pollution). Photo: Monica Løvdahl.
infrastructures. As discussed by McManus et al. (2018) this may in fact contribute to ecological enhancement of the coastal cities’ nearby marine environments.

Urban development and expansion require large amounts of energy. An efficient way to meet the rapidly raising demands for heating is to use geothermal energy from shallow sources (Smelror 2012). Geothermal energy is extracted from within the Earth via water, occurring either in liquid or steam state. By using geothermal heat-pumps, geothermal energy can be obtained from low temperature sources and used to heat workplaces, hospitals, schools and our homes. More than 80 countries around the world today use geothermal energy for heating. Since ground-source heat for household warming is commonly extracted from shallow boreholes between 100 m and 200 m deep, the key factors controlling the effect and economy of installations for extracting geothermal energy at shallow depths are mainly linked to the overburden, hydro-geological activity underground, and the capability of the rocks to act as reservoirs and water carriers. We therefore need information on the spatial distribution, the porosity and the permeability of the geothermal reservoirs to evaluate the geothermal potential of a certain area.

Geothermal energy for heating is not widely used in Europe (Fig. 11), but the potential is substantial. In the Paris region, a limestone reservoir with an area of 15 000 km² provides temperatures ranging between 56 and 85°C and has been exploited to heat the equivalent of 150 000 homes for more than 25 years. From a geothermal heating plant, water at less than 100°C is sufficient, and 60–70% of the energy used in Europe is for low temperature applications. Studies carried out by GeoForschungsZentrum Potsdam (GFZ) have shown that large areas of the North German basins, the foothills of the

![Fig.11. Drilling for deep geothermal energy in southern Germany. Photos: Morten Smelror.](image-url)
Alps and the Rhine Graben are suitable for extracting heat from the ground. A geothermal heating plant established in Neustadt Glewe in Meckelburg has been using water at a temperature of 98°C from a depth of 2300 m since 1995. GFZ has estimated that, looking at the geological and the geotechnical requirements, it would be possible for 17,000 plants to generate heat from the North German basin alone (Smelror 2012). However, one limitation is that geothermal energy must be used close to where it is generated, as it is not economically viable to transport such energy over long distances.

Expanding urban areas rely on access to enormous amounts of building materials. An important task for geological surveys is to keep records of potential mineral reserves and resources of particular interest both on national, regional and local levels (Fig. 12). These records should be designed to meet national Planning and Building Act criteria and be validated to meet societal demands in 50–100 years from now, or even longer perspectives. This example from Norway shows how much of the landmark mountain Gaustadtoppen will be required to provide the city of Oslo with natural construction materials towards year 2040 (c. 339 million tonnes of crushed rocks). Source: https://www.ngu.no/nyheter/rapport-det-gr-nne-skiftet

![Fig. 12. An important task for geological surveys is to keep records of potential mineral reserves and resources of particularly interest both on national, regional and local levels. These records should be designed to meet national Planning and Building Act criteria and be validated to meet societal demands in 50–100 years from now, or even longer perspectives. This example from Norway shows how much of the landmark mountain Gaustadtoppen will be required to provide the city of Oslo with natural construction materials towards year 2040 (c. 339 million tonnes of crushed rocks). Source: https://www.ngu.no/nyheter/rapport-det-gr-nne-skiftet](https://www.ngu.no/nyheter/rapport-det-gr-nne-skiftet)

Increased uses of natural stone have other advantages compared to concrete and asphalts, such as resistance to freezing and high-pressures. Building smarter and greener cities for the future require an effective and optimized use of subsurface knowledge and data. This is best achieved by holistic approaches, involving the complete network of local authorities, planners, regulators, environmental scientists, engineering companies, together with service providers for water, energy and transport, and representatives from the civil societies. In 2058, we have demonstrated that we can minimize the environmental impact of urban expansion and future development, and major cities have in fact become significantly both smarter and greener.

**Bigger, better data: the never-ending story**

The needs of the large group of users of geodata are infinite, and the increasing use of such data no longer follows traditional institutional barriers. Geological surveys have for many decades advocated that systematic and co-ordinated use of geodata is an important prerequisite for the sustainable management and use of land and natural resources (Smelror 2008). Today users of geodata expect high-quality customized products in which information from a number of disciplines is integrated and adapted in a clear
manner. The use of internationally accepted standards enables the integration of internal and external services across organizations and technological platforms. One example is the One-Geology project where the geological surveys have demonstrated that they can work and share data according to common standards in an interoperable way to create a common product, like on the dynamic digital (on-line) geologic map of Europe (http://www.onegeology-europe.org). Other examples are the cross-border Circum-Arctic geological and geophysical maps provide by geological surveys and co-operating institutions involved in the Arctic and High North Territories (Harrison et al. 2008; Gaina et al. 2011; Petrov & Smelror 2015) and the Fennoscandian Industrial Minerals Map provided by the geological surveys of Finland, Norway, Sweden and Russian partner organizations (see Supplementary Material).

Services such as information on potential geohazards are also shared across organizations and land borders, as demonstrated by the European PanGeo project (Demicheli et al. 2013). PanGeo was a 3-year collaborative project of the European Commission that started in February 2011 with the aim to provide free online geohazard information for 52 of the largest towns in Europe. Geohazards in these towns could potentially affect up to 13% of the EU population (Demicheli et al. 2013). PanGeo provides free access to ground instability geohazard information for national and local authorities, civil protection agencies, geological institutions, insurers and businesses, and the general public, providing environmental and land reporting services. PanGeo describes the spatial location and extent of geohazards for all the towns mapped. Each polygon within the ground stability layer is linked to a full interpretation made by that country’s national geological survey. PanGeo data are created by combining satellite measurements of ground and building movement, and geological information held by national geological surveys. The European Commission’s Urban Atlas land use data also provides insights into what types of urban land use are affected by geohazards described in the ground stability layer (Demicheli et al. 2013).

Towards 2058, geological surveys will continue to be active within almost all fields in which society has needs for geo-scientific knowledge and geological information. During the period of their existence, the surveys have generated a substantial amount of information on the Earth’s crust, its natural resources, its geological (physical and chemical) processes, and on the geological history of lands and oceans. This massive information and knowledge database asset will become even more valuable when the pressure on space and resources on a more crowded Earth continues to increase. A continuous improvement of the qualities of earth science observations and geodata, and the opportunities of machine learning, will help us find solutions to key problems facing future generations. Today, a series of data analytic tools, such as cluster analysis algorithms, are successfully used for rapid and integrated analyses of complex geoscientific databases and are considered usable various exploration tasks. In the future, new advanced methods will be developed to better mimic and assist human analyses of complex geodatabases.

The collective mission of geological surveys are to make this geological information and data easily accessible to end users in industry, government agencies, government institutes, public administrations, technical offices, academia and research institutes, as well as for private individuals (Smelror et al. 2008). The development, operation and maintenance of national databases and maps of geological properties and processes therefore represent key tasks.

In general, data distribution policy varies between the countries; consequently, in some of the surveys supply of selected information or materials is chargeable by law. Others, like the Geological Survey of Norway, have made the information available on an open access basis. The internet is developed as the main distribution channel as it gives easy access to key information for all users. The format is developed to fit mobile devices such mobile phones and tablets. The open access databases are updated continuously. Over the history of the geological surveys, and at present, securing the growing volumes of geological and environmental information has consistently proved to be efficient and economically advantageous for society. According to the Chinese philosopher and reformer Confucius (BC 551–479), ‘the essence of knowledge is to have it and to apply it’. We believe it is also essential to share it!

Conclusions

In 2058, we can expect that we have mapped the geology of the Earth’s areas and most of the oceans. We will have detailed 3D images of the urbanized areas, and 4D models to make reliable forecasts in a world of increased pressure on the natural resources and changing ecosystems. The Green Stone Age is established, and more minerals are needed to produce the materials for everyday life’s new and smart technological solutions and to provide, store and distribute environmentally friendly energy. In 2058, the extent of recycling will be higher than the withdrawal of new resources for many metals and minerals. Until then we need to increase our mining activities, since increased exploration and new mining is needed for a shift to greener, more environmentally friendly energy.
efficient way to meet the rapidly raising demands for heating is to use geothermal energy from shallow sources, as well as deeper sources. To meet the UN SDGs, national geological surveys will play an increasingly important role, not only in mineral mapping and providing overall estimates of available resources, but also in being actively involved in contributing to policy- and strategy-making processes aiming to identify, characterize and safeguard a sustainable resource potential, notably on critical raw materials and energy, through research, development and innovation.

Ecosystems are economic assets which produce a flow of beneficial goods and services over time (i.e. ecosystem services). In restoring damaged ecosystems, and designing new, non-historical configurations on a variety of local and global changes, geological knowledge is needed. In 2058, restoring and designing ecosystems for a crowded planet will be a major task for our societies, and the knowledge and contributions from geological surveys will be a major key for us to successfully address these missions.

In 2058, the vulnerability of living on a dynamic Earth is well understood, and geohazard risk mapping and assessments have priority. When making decisions concerning where to plan developments and how to construct or reinforce them, there always needs to be a viable balance between the risks of geohazards on the one hand, and the social and economic gains, on the other. However, the acceptance for living with such risks is to be reduced as increased knowledge on risks and consequences are made public.

In 2018, more than 70% of all humans will live in urban areas. To build smarter and greener cities for the future we need an effective and optimized use of subsurface knowledge and data. This is best achieved by holistic approaches, involving the complete network of local authorities, planners, regulators, engineering companies, together with service providers for water, energy and transport. The needs of the large group of users of geodata are infinite, and the increasing collection and use of such data no longer follows traditional institutional barriers. The collective mission of the geological surveys is to make this geological information and data easily accessible to end users in industry, government agencies, government institutes, public administrations, technical offices, academia and research institutes, as well as for private individuals.

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Correction notice The copyright has been updated to Open Access.

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