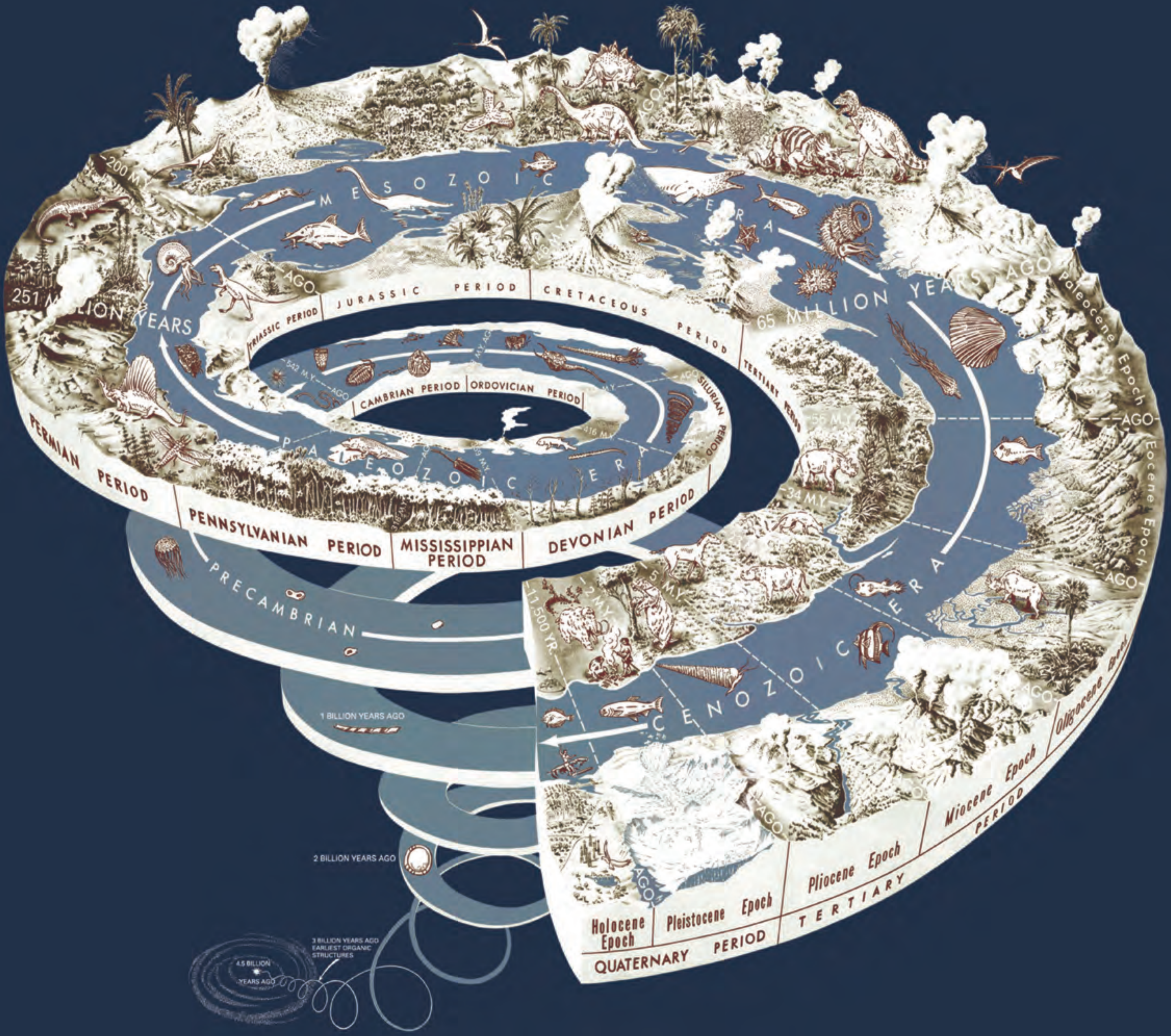

The geologic time spiral – A path to the past: A poster devised by Joseph Graham, William Newman and John Stacy at the U.S. Geological Survey. General Information Product 58, poster, 2008. Credit: U.S. Geological Survey http://pubs.usgs.gov/gip/2008/58/.

Reimagining applied geoscience for the energy transition

Phil Ringrose offers some framing perspectives on what the energy transition may entail for practising geoscientists working in the Earth-resources industries

WHAT WILL energy-transition geoscience look like? Is there such a thing as sustainable geoscience? And, perhaps more pressing for many, will there be a job for me as a practising geoscientist? These are among the most debated and challenging questions for the current generation of geoscientists, particularly those working in the extractive industries.

I recall when graduating with a degree in geology many years ago, the career advice was essentially to choose between gold, diamonds and oil – these being the main industry sectors that employed geologists at the time. A cliché perhaps – but reflecting the fundamentally exploitative nature of geosciences in the 20th century, with the hunt for energy and the exploitation of minerals and hydrocarbons forming a dominating umbrella for much of Earth science. Actually, I picked a fourth option and took a job as a consultant in environmental Earth sciences, only to discover that 'environmental geoscience' was itself closely connected with 'exploitation geoscience' since we mainly worked on geological aspects of nuclear waste disposal or clean-up of oil spills. Many academic geoscientists 'sitting in their ivory towers' also found it hard to isolate themselves from the exploitation mindset, since several geological disciplines, including igneous and metamorphic petrology or sedimentary basin systems analysis, received research funding motivated by the economic drivers from the mining and petroleum industries.

Now, with two decades of the 21st century behind us, the drive for a more sustainable approach to geoscience, and particularly the Earth-resource industries, is paramount and the urgency of responding to the climate-change challenge is the dominant Earth-science question. The energy transition is upon us – how do we respond?

A revised mindset

In recent years, many university departments have either discontinued or renamed their petroleum geology degree programmes and have reported difficulties in recruiting the next generation of students. Early- and mid-career geoscientists who were in demand a decade ago, especially in petroleum-related fields, are now finding the job market thin, particularly given the current economic slowdown caused by the double whammy of a global pandemic and a global climate crisis. The new Centre for Doctoral Training initiative (see page 34) is a good example of a proactive response to these challenges.

EMERGING TRENDS IN THE AGE OF DECARBONISATION

Some of the emerging trends for geoscience in the age of decarbonisation (based on Stephenson et al. 2019):

1. Energy storage for economies dominated by renewable energy systems, including thermal storage, compressed air storage and hydroelectric dam storage.
2. Carbon capture and storage (CCS), encompassing both CCS for net-zero-emission industries and as a vehicle for enabling negative emissions pathways.
3. Sourcing of raw materials (metals and rare-earth elements) to support the rapidly growing solar and wind power sectors and the associated demand for electrical batteries and power transmission systems.
4. The hydrogen economy, where water electrolysis or methane reforming are used to drive a new 'green-molecule' economy.
5. Nuclear energy, where geological disposal facilities for radioactive waste are successfully deployed to make existing and future nuclear power genuinely sustainable.

(NB: This review did not include other important careers in the field of applied geosciences such as the built environment, geohazards or applied environmental geology and engineering.)

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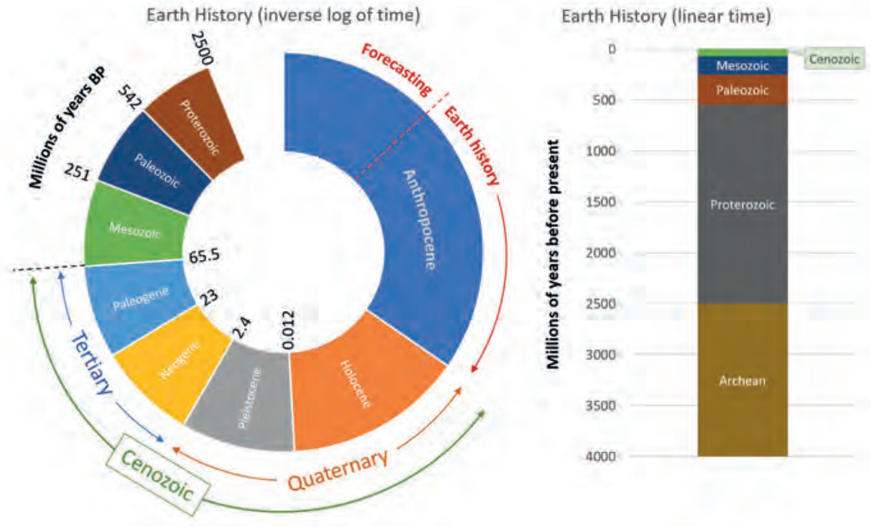

Figure 1: Rescaling the geological timescale to capture the concept of the 'sustainable geoscience timeframe' (left), not forgetting the importance of understanding the linear timescale of Earth history (right).

A recent review of the emerging trends for geoscience in the age of decarbonisation (Stephenson et al. 2019; see box, previous page) provides a snapshot of some of the ways geoscience can contribute to international efforts to keep global warming well below 2°C and points to some of the likely focus areas for many geoscientists in the coming decades. This is a list driven by energy needs, and clearly many geoscientists will work on topics such as climate change, geohazards, and Earth processes.

Climate science and the United Nations Sustainable Development Goals (SDGs) are also important for framing the emerging demands for Earth science in our society and, arguably, geoscientists are uniquely well placed to understand what the SDGs will mean in practice. Our 2030 world will need more access to affordable and reliable energy (not less), significantly expanded renewable energy systems, new investments in infrastructure and a whole suite of upgraded technologies to supply modern, efficient and sustainable energy services for all – in developing countries as well as in mature economies. All of this will require new Earth resources and, most importantly, more intelligent and more sustainable ways of using those resources, including a lot more recycling. The exploitation mindset must be replaced by a sustainability mindset – where (paraphrasing complementary definitions of sustainability from the fields of environmental science, sociology and ecology) sustainable means without significant harm to the environment, including the atmosphere and climate system, and without damaging the long-term ecological balance, for future generations of humans and for other species. Quite a challenge!

Thinking differently is a precursor to behaving differently, and significant changes in behaviour must be a part of the energy transition, which itself is part of the fundamental change to a more sustainable and inclusive society. Three overarching themes emerge:

1. **A focus on younger stratigraphy – with a stratigraphic bias towards the Quaternary and the Anthropocene.**
2. **Different fluids in focus – carbon dioxide, hydrogen and methane being high on the list.**
3. **Environmental intelligence – using space technology, geophysical sensing and geochemical tools to gather information about our planetary living space.**

> **“Thinking differently is a precursor to behaving differently, and significant changes in behaviour must be a part of the energy transition”**

Focus on younger stratigraphy

All geoscientists will have learnt the geological column at some point in their education and then probably spent some time getting to know limited parts of it quite well. The Mesozoic often draws the most attention for petroleum geoscientists, while the Proterozoic and Palaeozoic are likely more important to mining geologists. One significant implication of the sustainability and climate-change challenge is the need to focus on very recent geological history – the Quaternary and Holocene.

The Anthropocene is now widely recognised as Earth's most recent geological time period, marking the current phase of extensive human-influenced effects on Earth system processes. Although not yet officially approved as a formal subdivision of geological time, this period is critical for sustainable Earth science. It sits at the junction between understanding the recent geological past and forecasting possible Earth futures – scenarios that involve modelling the climate system, the hydrosphere, the oceans and the many geological processes involved.

Figure 1 shows an intentionally provocative re-scaling of geological time using the inverse log of time to illustrate how the understanding of present-day Earth processes is likely to be dominated by the Holocene and Anthropocene timeframe. Certainly, climate change studies use a lot of information from the Cenozoic era and much less from the earlier geological record. Likewise, efforts to predict the availability of groundwater and surface water for human populations will tend to use recent (Holocene) records to calibrate forecasts for the next few decades. This concept is nicely captured in the 'geologic time spiral' (page 24).

The practical outworking of this modified timescale perspective is found in many of the energy transition activities. Building offshore windfarms typically involves foundation engineering of the top 100 m of substrate (typically Holocene and Pleistocene sediments). Acquiring minerals needed for the energy transition, hopefully in a responsible and sustainable manner, will also typically require much more focus on the near-surface environment and hydrogeological processes (even if the minerals themselves come from an ancient rock system). The growing activities in underground storage of CO_2 and H_2 generally focus on storage depths within the 1-3 km interval, with significant work needed on understanding the overburden of the uppermost 1 km.

Such studies on the shallower rock sequence often encounter a 'data gap' or at least a paucity of information for the overburden section. Many petroleum-related drilling and seismic surveys targeted the deep intervals, such that logging datasets and high-quality seismic imaging were lacking in the shallower intervals. Where shallow seismic imaging data are available (such as using broadband seismic acquisition datasets), the shallow sequences reveal much more complexity than previously imagined. For example, in the North Sea basin the top 500 m interval reveals an amazing network of glacial channel deposits from the Pleistocene glaciations (*Fig. 2*). Understanding these shallow glacial deposits has practical implications for the assessment of CO_2 containment systems (Landrø et al. 2019) as well as revealing new insights into the retreat of the British–Irish and Fennoscandian Ice Sheets (Bradwell et al. 2019). Another fascinating development in shallow marine geoscience has been the acceleration in understanding of the submerged Palaeolithic and Mesolithic settlements of the southern North Sea region – especially Dogger Land – provoked by the acquisition of new seismic and well data from offshore wind-farm developments (Bailey et al. 2008; Ward, 2014). I hadn't quite appreciated how much the renewable energy boon would lead to a revolution in marine archaeology.

A different set of fluids

The study of multiphase flow in permeable rock media – an important branch of geoscience and applied physics – has for many decades been dominated by the study of petroleum-water systems. However, the last decade has seen a rapid expansion in the study of CO_2-brine systems and hydrogen-brine systems as important variants of the science of multiphase flow in rock media. We are therefore likely to see several bifurcations of multiphase flow analysis in the energy transition.

Insights from the much-studied oil-gas-water fluid systems are already being applied to CO_2-brine systems and hydrogen-brine systems, but new challenges are also emerging. CO_2 is much more reactive with the aqueous and mineral phases in the host-rock system; CO_2 dissolves in brine (making sparkling water) and can precipitate as carbonate minerals (a form of accelerated cementation). These processes contribute to an important principle in CO_2-storage projects, namely that the stored CO_2 generally becomes more secure as a function of time (Ringrose et al. 2021).

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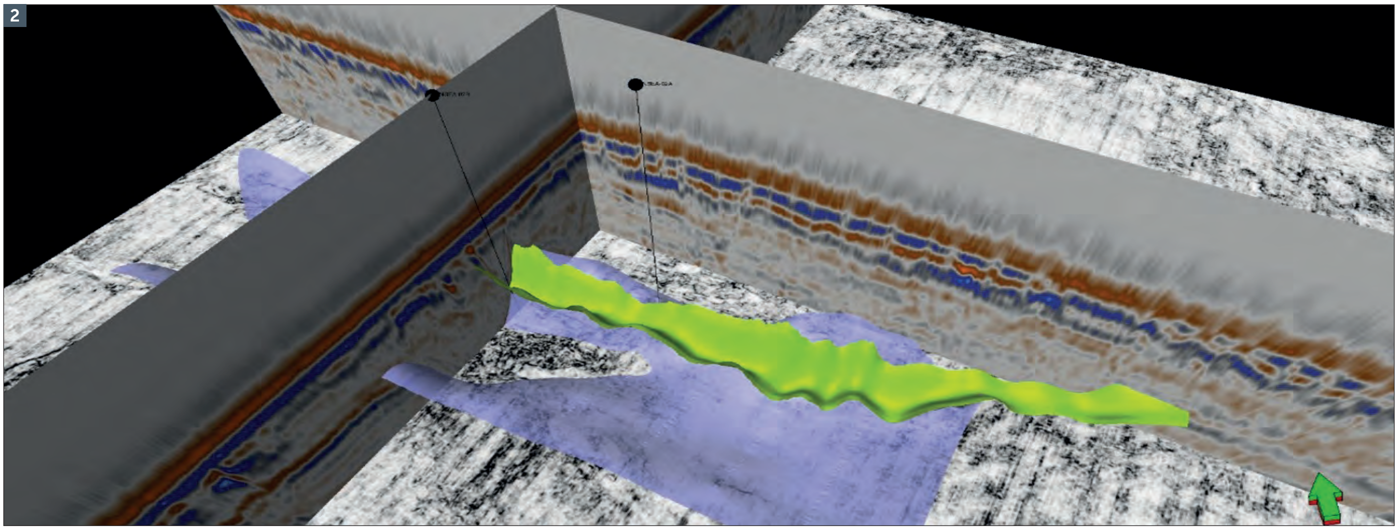

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Figure 2: Imaging Upper Pleistocene glacial channels from shallow seismic data. Green channel object is ~ 500 m wide, ~12 km long and at a depth of ~200 m overlying a broad channel system in blue at ~400 m depth. From work reported by Furre et al. (2015) In: Third Sustainable Earth Sciences Conference and Exhibition 2015(1), 1-5, EAGE. (Image courtesy of Equinor.)

For hydrogen storage, which many argue will be essential in a renewable-energy-dominated world, there is a new set of geochemical reactions to concern us (Heinemann et al. 2021). For example, certain microorganisms frequently present in subsurface formations can be major hydrogen consumers, which can potentially lead to undesirable losses or technical challenges during a hydrogen storage project. However, by understanding the behaviour of 'bugs' over different ranges of temperature, salinity and acidity, these reactions can be controlled and managed. It does mean, however, that the biology of deep microorganisms will be an important theme in future geoscience.

Understanding these new fluid systems will bring novel and exciting challenges for geoscientists working on fluid-rock interactions and flow in permeable rock media. Although too broad to summarise here, perhaps figure 3 will provoke your interest. CO_2 in the subsurface becomes a liquid below a depth of ~800 m, and at those depths it behaves more like the olive-oil/water system than it does like the CO_2-sparkling wine system (*Fig. 3*). There are of course many other factors controlling CO_2 in the subsurface that are not captured by this simple illustration (such as thermal effects on in situ phase behaviour), but it makes a good starting point for discussions at the bar.

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Figure 3: Imagining fluids in the subsurface using two glasses – one with olive oil and water (left) and one with sparkling wine and CO_2 (centre). On the right is a lab experiment showing olive oil (green) trapped as a residual phase in a granular water-saturated porous medium (scale in mm) as an analogue to CO_2 trapping in subsurface rock formations. Modified from Ringrose & Bentley (2021) Reservoir Model Design (2nd Ed.) Springer, Dordrecht. (Photos by Britta Paasch and Philip Ringrose.)

Environmental intelligence and Earth monitoring systems

There is little doubt now that we live in an age of major environmental and climate-related challenges, which many would argue are at crisis levels. This concerns not only our response to human-induced global heating, but also how we address

Figure 4: Distributed acoustic sensing of the shallow subsurface from a submarine telecommunication cable. Left, image processed from conventional seismic (a towed single-channel streamer with a 24-element hydrophone array of 7 m active length). Right, image processed from a seabed telecommunication cable using distributed acoustic sensing (with 4 m gauge length). Both images use the same signal enhancement. Yellow arrows indicate subsurface reflections seen in both acquisitions (the orange, green and blue horizons show the windows used for computing the signal/noise ratios and the spectrum). Images from Taweesintananon et al (2021) Geophysics 86(5), 1-69; https://doi.org/10.1190/geo2020-0834.1, reproduced with permission.

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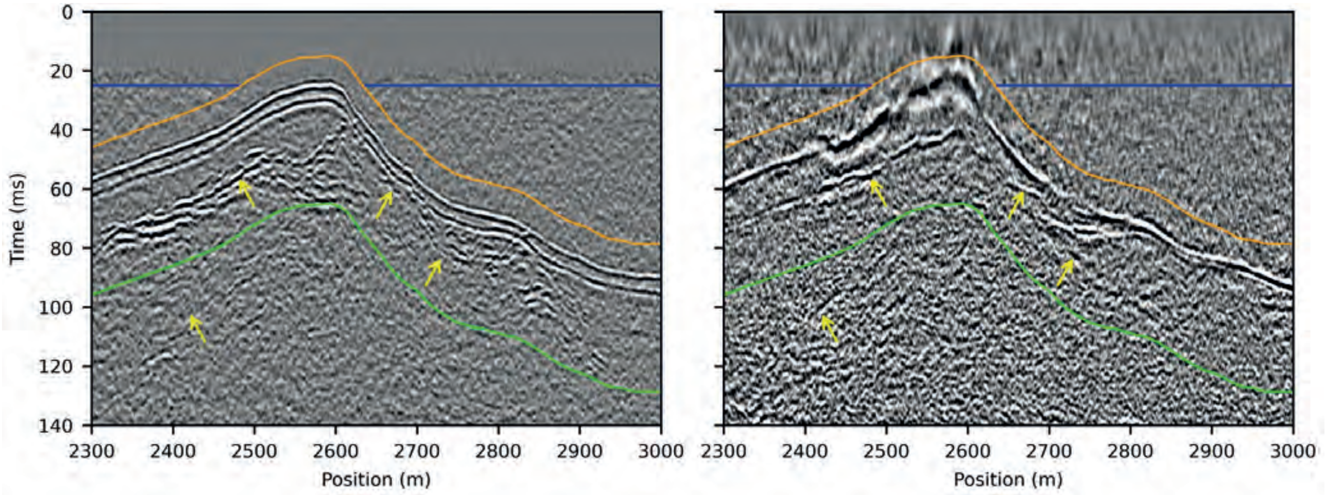

numerous other ecological impacts, such as loss of biodiversity, degradation of soils, loss of forested land and damage to water resources. The energy transition therefore involves both a rapid move to low/zero-emissions energy systems and a drive to use Earth resources without significant harm to the environment.

The sustainability mindset needs to be embedded in everything we do. For geoscientists this means a focus on monitoring and measuring the natural Earth system – the hydrosphere and biosphere, the marine and terrestrial environments, the shallow Earth and deep Earth system. The problem is often that the wider society lacks an appreciation of how important Earth resources are to modern life. Everybody wants 'green' but few really know what 'green' means in practice. As for us geoscientists, we must also admit that there is still much unknown about Earth process, especially longer-term processes. I am reminded of Emily Dickinson's poem *What mystery pervades a well!* where she ponders the mysteries of "water [..] from another world residing in a jar" and writes:

But nature is a stranger yet;
The ones that cite her most
Have never passed her haunted house,
Nor simplified her ghost.

Even as a practising geoscientist, I agree with this sentiment – the natural world is still a stranger and those that cite her most need to do more to understand the 'haunted house'.

This is where the ongoing revolution in remote sensing has a major role to play. Monitoring Earth's surface by satellite and probing Earth's interior using geophysical and geochemical sensing tools will be vital in the coming decades. A number of exciting and fast-moving innovations (see box, left) mean that geoscientists now have an unprecedented set of tools and methods to monitor Earth, and with the 'sustainability mindset' that we need to develop, we will have access to plenty of data to better understand the natural world.

So how should we re-imagine geoscience in the resource-utilisation professions? We are not here just to find resources and exploit them, we are available to help our society use Earth resources in a sustainable way. Every resource, including water, metals, minerals, hydrocarbons, porous storage units, and geothermal resources, needs a 'Handle with Care' label attached, and advanced, intelligent Earth-systems analysis must be integral to what we offer society. I find that exciting – I hope you do too.

EXAMPLES OF RECENT ADVANCES IN EARTH MONITORING SYSTEMS

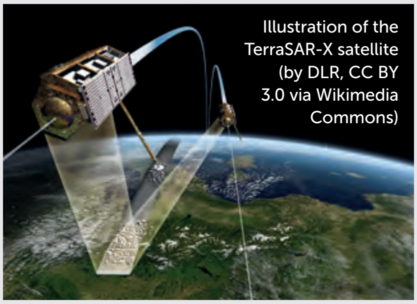
Illustration of the TerraSAR-X satellite (by DLR, CC BY 3.0 via Wikimedia Commons)

- From space, we can now detect emissions of CO_2 and CH_4 with increasingly higher levels of accuracy and precision. For example, publicly available data is provided by the SCIAMACHY instrument on Envisat, AIRS on the Aqua satellite, the GOSAT and GOSAT-2 satellites, the OCO-2 satellite and the OCO-3 instrument mounted on the International Space Station. These satellites are important both for monitoring human-made emissions of greenhouse gases and for understanding natural emissions (from the oceans, terrestrial plants and volcanoes).
- Also from space, we can now measure mm-scale ground deformation on an almost daily basis. Interferometric synthetic aperture radar (InSAR) has in the last decade gone from a niche activity to a routine geodetic monitoring system. The satellites currently in operation include COSMO-Skymed and TerraSAR-X (in the X-Band) and Sentinel-1 and Radarsat-2 (in the C-band). Several nations now have complete InSAR coverage available for the public, allowing you to check subsidence or uplift around human-made structures and cities (Bischoff et al. 2020) or in relation to natural hazards such as landslides (Carla et al. 2019). The method can also be used to monitor pressure changes associated with CO_2 storage (Vasco et al. 2010).
- On Earth's surface, most geoscientists are used to the value of seismic imaging to see what 'lies beneath our feet', but perhaps less aware of how the quality of those images has improved over the years. For example, broadband marine seismic acquisition can increase the usable frequencies from a few Hz up to 200 Hz (compared to conventional acquisition system typically between 8–80 Hz) leading to much better imaging of shallower and deeper features in the same survey. Furthermore, time-lapse seismic methods allow fluid movements and pressure changes in the subsurface to be detected with increasing levels of accuracy (Landrø 2001) and have been shown to be very suitable for monitoring CO_2-storage sites (Chadwick et al 2010).
- At and below Earth's surface, fibre-optic sensing is opening up a whole new box of possibilities for monitoring. Fibre-optic cables are cheap and can be used for multiple purposes. For example, a standard telecommunication cable can be used to image the subsurface (*Fig. 4*; Taweesintananon et al. 2021) and to detect earthquakes (Lindsey et al 2017). Dedicated fibre-optic layouts, using surface and downhole fibre-optic cables can be used to monitor CO_2 storage sites (Harris et al 2017) or landslide hazards, and in some cases traffic noise can be used as the seismic source (Dou et al 2017).

Acknowledgements
I thank Martin Landrø (NTNU) and Kit Taweesintananon (NTNU) for advice and insights on fibre-optic sensing and Anne-Kari Furre (Equinor) for advice and insights on seismic interpretation.
A list of further reading is available at geoscientist.online

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