Innovation and sustainability in the geosciences

Emily Warrender September 2, 2025

John Marshall, the Director at Skrinkle Reservoir Geology, examines innovation and sustainability in the field of geosciences

Sustainable development can only be achieved with the help of renewable energy and the capture or reduction of greenhouse gases. Many of the materials and opportunities needed to enable this are to be found in the rocks and fluids of the subsurface. To access these, the geosciences, classically associated with the extractive industries, are transforming.

Extraction will continue: a massive increase in mining will be needed, given the need for conventional metals and rare Earth elements in the switch towards electrical energy. Extraction also provides geothermal energy, and a new fuel, hydrogen, has become an exploration target.

Subsurface storage is needed for fuels and energy sources such as hydrogen and compressed air. But also for carbon sequestration, part of the effort to abate the release of CO2 into the atmosphere. And there is a further sequestration need, nuclear waste, as the world brings nuclear power back into play.

The range of extractive and storage solutions are described in Gluyas 2024. They have their own challenges that force the pace of innovation. We will give just a few examples from four key sectors.

Mining.

The energy transition will require vast volumes of mineral production, particularly for electricity grids and electric vehicles. Many critical elements such as lithium, copper and cobalt are currently mined in a limited number of locations, so there is a renewed drive for exploration and development. New technologies are being brought into play: drones equipped with conventional and multispectral cameras are being employed both for identifying new resources and, by flying them underground, for analysing existing mine shafts.

The vast amount of data collected can be visualised using augmented reality, where the data can be overlaid on conventional images, and virtual reality, where the operator can interact directly with the data. Three-dimensional digital models are finding new roles representing modern mine systems and even historical mines by digitising old – even Victorian – mine plans.

Geothermal.

The Earth's natural heat is a vast resource with significant capacity to provide energy. What has been an industry localised to areas with high heat at the surface, such as Iceland, is now becoming more widespread, where in many places, city blocks and campuses can have their own local heat sources. A recent innovation has been the extraction of heat from abandoned and flooded coal and mineral mines. The mine water has been heated by the hot surrounding rocks and can be circulated to the surface by dedicated wells.

The behaviour of hydrothermal water and the surrounding rock – flow rates, temperatures and vibrations – can be monitored by using the relatively new distributed acoustic sensor systems, tolerant of high temperatures. These allow optimisation of the water and heat exchanges taking place. Elsewhere, areas formerly deemed unsuitable for geothermal projects could be accessed by "engineered geothermal systems". Dry, hot rocks are drilled into and then fractured to allow water circulation, generating steam or hot water.

A newly recognised by-product for some geothermal projects is that the hot brines can contain extractable quantities of minerals and gases, such as lithium in Cornwall, UK, where geothermal waters circulate through lithium-bearing granite.

Hydrogen.

Most is at present produced via energy-intensive treatments of hydrocarbons and by electrolysis of seawater. Accordingly, attention has focused on exploration for natural accumulations, and methods used for hydrocarbon exploration are being repurposed. Significant effort has gone into establishing the origins, subsurface movement and accumulation of hydrogen to help identify new reserves for development. Machine learning is being applied to enable rapid screening of potential accumulations. And the hydrogen may not have to be free gas: an approach is being explored where hydrogen source rocks are artificially stimulated to generate free hydrogen, through injection of water to stimulate a process called serpentinisation.

Carbon Sequestration.

The IPCC has recognised that the removal of CO_2 from intensely carbon-generating processes such as cement production and steel making is a necessary part of the energy transition. The CO_2 so captured can then be injected into a subsurface storage site that has the characteristics needed for safe containment of the gas. But it is a low-profit "waste disposal" industry. There is significant pressure on costs.

4D seismic can be used to monitor CO_2 injection behaviour. Successive surveys of the subsurface are compared to identify changes through time: CO_2 plumes have been imaged as they develop, allowing comparison to predictions from digital models. Distributed acoustic sensors are being deployed in boreholes to measure fluid and rock behaviour. These can be left in the hole, thereby saving the cost of bringing in a drilling rig.

The requirement for no surface escape and minimal disturbance has driven improvements in our understanding of the geomechanical behaviour of subsurface stores. Satellite measurements of the Earth's surface can reveal deformation induced by subsurface operations. Acoustic sensors listen to the rocks to identify any vibrations detected. Geologists have learned that they need to start listening before a project begins, to establish a baseline record of natural Earth behaviour for comparison with that during injection.

A novel approach to sequestration has been developed in Iceland where CO_2 is injected into highly reactive igneous rocks to form new minerals. Where rocks of the right type are present, this shows promise.

Enablers.

Our capacity to understand the subsurface is constantly improving, aided by rapid developments in data acquisition and analysis. The information extracted from seismic surveys continues to grow. There are multispectral and chemical sensors and more, using systems from satellites to electron microscopes.

The capacity to assemble and analyse all this is enabled through digitalisation: representing the data in 3D and 4D models, viewing it on conventional screens and in augmented and virtual reality. But to apply this, the key enablers are the geoscientists who understand the context and significance of what they see. Sustainability can be supported so long as there is the will and the supply of well-trained human beings.
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