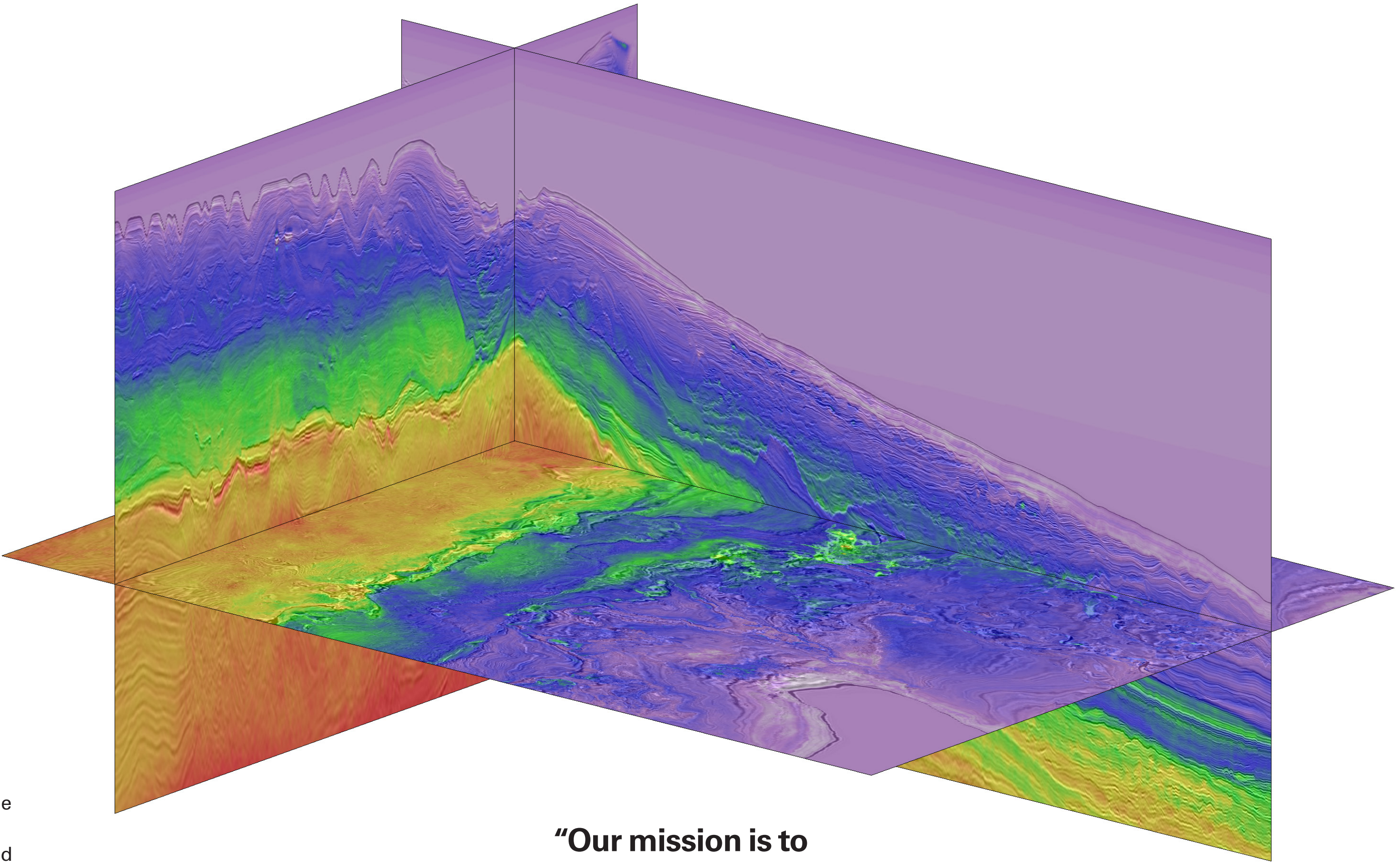
Reverse engineering the Earth

Visualising the hidden structures beneath our feet requires vast seismic datasets, advanced imaging algorithms and deep curiosity, according to geophysicists mapping Earth's interior



A 3D seismic image of Earth's crust off the coast of Côte d'Ivoire down to 4 km below sea level.

When Jules Verne wrote *Journey to the Centre of the Earth* in 1864, he could let his imagination run riot. We knew so little about the interior of the planet then that any flight of fancy was possible.

Since then, understanding Earth's substructures has become a central focus in the search for new sources of energy and is now becoming vital for climate initiatives such as carbon capture and storage. Huge resources are now devoted to understanding what's down there in ever greater detail.

For scientists and engineers, the challenge is captivating, if not addictive. "We transform raw seismic measurements into 3D images of the Earth," says Gordon Poole, UK Research Manager for Viridien, a multinational geoscience data and technology company, previously known as CGG. Those images sit within a computer, of course, but the secret sauce is in getting the highest possible definition for the Earth image.

Revealing secrets

For more than a century, physicists have been coaxing the planet into revealing its secrets. Early techniques used explosions to send signals underground. "We have various ways to create sound waves at the surface, the resulting wavefront propagates in the Earth, and some of the energy will be reflected," says Poole. From these echoes, geophysicists can infer the properties of rocks the sound waves have travelled through.

For decades, they discarded most of the information in the recorded signal to keep the algorithm complexity manageable. Then in 1984, the physicist Albert Tarantola proposed "full-waveform inversion" (FWI), which extracts orders of magnitude more information from the data by processing every distortion a wave experiences. This includes refractions and multiple reflections, as well as elastic effects and subsurface anisotropy, where the properties of a rock depend on the direction the wave travels.

But it's the "inversion" part of the technique that really makes the difference, says Poole. "We're reverse engineering what must be happening in the Earth."

First, geophysicists build a computer simulation of how underground structures will reflect, refract and distort a signal originating at the surface, using all the wave components they can. Then they compare these digital predictions against the real-world signals they record from their measurements. Now they can tweak the structures in the computer simulation and repeat the process. Once the simulated and real-world signals match, they have a near-perfect simulation of the subsurface structures of interest.

Full-waveform inversion has revolutionised the search for fossil fuel resources but it is also crucial for imaging the rock formations capable of storing the carbon captured from fossil fuel processing and hard-to-abate heavy industry. Carbon capture and storage is seen by the UN and other international organisations as a vital part of global efforts to combat climate change. But the storage system has to be well understood. "After carbon dioxide has been injected, we need to verify that it stays where it's meant to be," Poole says.

Cutting-edge science

This is where another cutting-edge technique comes into its own. Distributed acoustic sensing (DAS) uses underground optical fibre cable to measure tiny external vibrations. "Things that happen outside can distort the cable," says Malcolm Kent, Viridien's Global Head of Carbon Storage. This produces a measurable effect on light passing through it, which in turn reveals what's happening in the ground nearby. "Our mission really is to build a 3D picture of the subsurface away from the fibre cable itself," he says.

> "Our mission is to build a 3D picture of the subsurface"

In effect, DAS turns a standard optical fibre into a massive, continuous string of sensors that measure the ambient seismic wavefield generated by earthquakes, oceans and human activities like transportation. This gives a high-definition readout of the subsurface composition, structure and conditions, and how they are changing over time. Engineers can use existing fibres – subsea internet cables, for instance – but can also run cables where they are most useful, such as within an oil well.

For the storage of carbon dioxide, the potential impact could be very significant. The technique could help to monitor those sites over the long term and check that conditions aren't changing in a way that might allow carbon dioxide to leak. This would strike the right balance between regulatory reporting requirements and the need for a cost-effective approach.

One key to Viridien's success has been its ability to build on breakthroughs in data analysis and data gathering using its immense computing power (see box).

Innovation delivered

High-performance computing has opened the door to a new era in technological innovation. "With increasing computing capability we are able to do what our teams enjoy most, tackling the most challenging data and objectives," says Kent. "We're proud of hiring great people, but equally we want them to have the tools to take on the most advanced projects."

In terms of understanding the Earth, "we're driven by wanting to get closer and closer to the real thing," adds Poole. In a way, it's a new kind of journey to the centre of the Earth. Verne would surely be impressed. ▮

Find out more at: viridiengroup.com

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THE POWER OF PETAFLOPS

Innovations in FWI and DAS are only possible with massive amounts of computing power. It's one reason why Viridien has built its own large-scale, extremely customised, high-performance computing facilities. "Before AI came along, seismic imaging was one of the largest users of industrial high-performance computing," Poole says. "Viridien has 700 petaflops of computational power, highly optimised for seismic imaging.

That already makes them a heavyweight in the world of scientific computing. Recently, Viridien has continued to enhance its focus on efficiency and "green" supercomputing, further reducing its carbon footprint. This allows Viridien to offer results-based computing, where customers pay for the quality of a seismic image or data insight rather than hours on a processor.

Its infrastructure has made the company a key partner for academics. "We are able to lead some projects, but only with limited-size problems," says Romain Brossier of the University of Grenoble. That limit is defined by FWI frequency: academic resources can typically handle up to about 25 Hz, says Brossier. "At Viridien, with its computational power, they can push towards 120Hz," he adds. "When you can utilize five times higher frequency, you get five times more detail."