New approaches to CCS

Bent Kjølhamar[1*], Sverre Planke[2], Helge Bondeson[1], Jan Langhammer[1], Benjamin Bellwald[2] and Malin Waage[3] outline how technology for acquiring and imaging seismic data is being repurposed for carbon capture and storage.

Abstract
While carbon capture and storage (CCS) has been recognized as a major enabler to reduce the amount of CO_2 released into the atmosphere, the industry is still in its infancy. Both new technology and cost-effective approaches will be necessary if CCS is to live up to its potential to reduce global warming in the decades to come. Energy data companies such as TGS can, with help from partners, work on concepts and technologies that will be key for the CCS market, and current products made for the oil and gas market can potentially be repurposed for use in CCS. Technologies are also being developed for the 4D monitoring of stored carbon in the decades to come. Furthermore, the storage of carbon within basalt rocks has been proposed by TGS as an alternative to the sedimentary rocks targeted by most CCS endeavours today.

Introduction
Current global atmospheric carbon dioxide (CO_2) concentrations have reached a level of 415 ppm, and temperatures are likely to exceed 1.5 °C above pre-industrial levels by the middle of this century (IPCC, 2018). The passing of the 1.5 °C threshold may be associated with irreversible, self-accelerating positive feedback in the climate system. To avoid this potential tipping point, global net CO_2 emissions may have to be reduced to zero by 2050 (IPCC, 2018). This target may require up to 20 Gt of CO_2/yr to be captured and stored from 2050 onwards (IPCC, 2018; P4 model), which is a dramatic increase over the current carbon storage capacity of ~35 Mt/yr.

Europe is recognized as one of the global leaders in the development of CCS technologies. In total, six new, larger offshore CCS projects have been announced for the North Sea: Northern Lights and Sleipner projects in the Viking Graben, the Teeside-Humber in the UK, the Acorn in Moray Firth offshore UK, the Greensand in Denmark, the Porthos in the Netherlands and the Hynet proposal in the Irish Sea (Figure 1). Large hubs such as the Northern Lights and Teeside-Humber projects have also been designed to store local and transported CO_2 from heavy industries. In addition, hydrogen production from natural gas via ammonia is a growing industry that needs to dispose of large amounts of CO_2. Some of the new hydrogen players are planning their own CCS developments, such as the Pale Blue Dot in

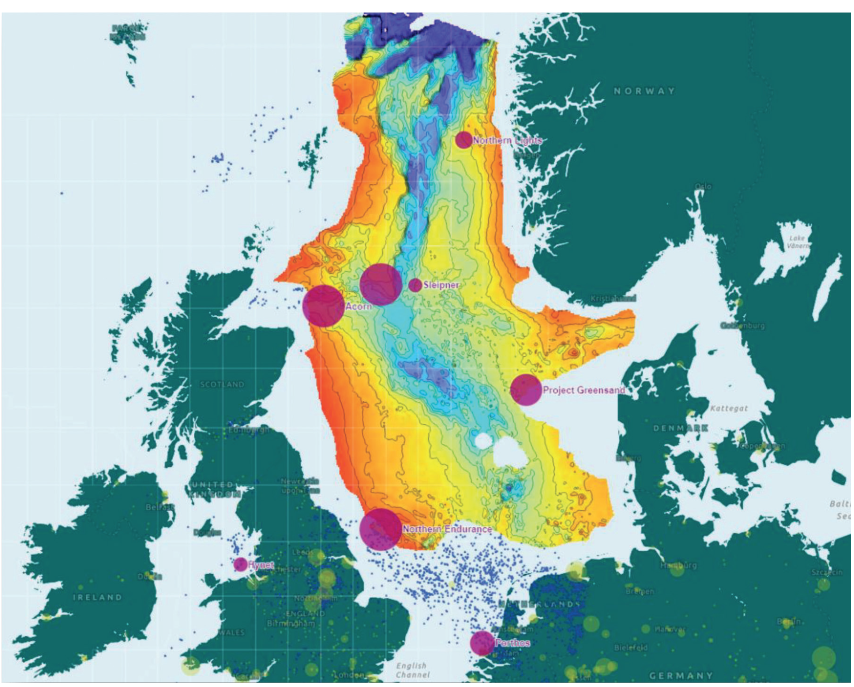

Figure 1 Map of the depth to the Base Cretaceous Unconformity (BCU) showing existing and planned CCS sites in the North Sea (purple circles scaled after planned yearly tonnage of carbon storage) and main emitters (power plants; yellow circles scaled the same way). The map is taken from the TGS 'CCS Pathfinder' web application.

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Acorn. The most cost-effective storage sites will be able to offer the most advantageous prices, both on green energy and waste disposal. These projects are the first signs of a healthy market that is driving technology forward.

Common to all the above projects are subsea storage of CO_2 in saltwater filled reservoirs that require high-quality seismic data for reservoir characterization and leakage monitoring. However, the main challenge does not primarily come from the lack of such data for identifying optimal storage sites – currently available seismic data can be used and reprocessed to sufficient quality. The issues lie in understanding the integrity of the reservoirs for optimized injection, fluid flow, and leakage detection over decades ahead.

Presently, the cost of storing CO_2 is five times the EU market price of CO_2 (ref. budget information from the Northern Lights project). Thus, cost efficiency is a crucial factor for successful CCS projects. Through increased CO_2 taxation, as seen recently in Norway (from ~300 to 800 NOK/ton ($36 to $97)), the value of stored CO_2 in the ground is expected to grow in the coming years. Eventually, the CO_2 price should outweigh the storage cost. Still, to support increasingly positive margins, any associated 4D monitoring programmes to screen ongoing reservoir conditions need to be light and cost-effective.

Low budget 4D monitoring for CCS

Two light seismic technologies are considered particularly appropriate to meet the 4D monitoring work relevant for the CCS market – permanent DAS (Distributed Acoustic Sensing) using optical cables and ultra-high-resolution P-Cable 3D seismic technology.

DAS utilizes standard fibre optic (FO) cables to measure acoustic and elastic waves as an alternative to electrical hydrophones and geophones (Parker et al., 2014). The technology has previously been tested in connection with borehole applications, such as vertical seismic profile (VSP) acquisition (Mateeva et al., 2013). The FO cables can be interrogated by tailor-made topside units containing pulsed lasers and recording devices to output digital traces at certain intervals along the fibre. Any incoming seismic wave – whether active or passive – deforms the fibre in the cable. The measured phase delay of the propagating laser light is proportional to the difference in strain in the fibre caused by any seismic disturbance. The interrogator can sample the laser light at several tens of kilohertz, providing a spatial sampling in the order of magnitude of a few metres. Standard FO cables, telecom cables, and existing FO networks within a field can be used together for this purpose.

In connection with potential new offshore sites for CO_2 storage, a sparsely deployed distributed network of FO cables on the seafloor or in boreholes may provide a cost-efficient monitoring method in either active or passive mode. The data recording of such cables over a specific area can potentially be performed up to 100 km away from the CSS site. This implies that remote, existing infrastructure around offshore platforms, or even shore facilities, can host the necessary instrumentation for interrogation and recording. Using FO DAS technology in this way can have a significant advantage over permanently installed electrical point sensors because it is entirely passive, avoids short circuits, and has a longer lifetime, fewer parts, and no corrosion of sensing elements. We see this technology as a potentially cost-effective alternative to providing reliable 4D data in continuous monitoring and surveillance of CO_2 sequestration.

The P-Cable technology is an acquisition technology for high- and ultra-high resolution 3D seismic data. Many 3D seismic datasets have been acquired over the last decade, but using the P-Cable 3D seismic system in time-lapse studies for monitoring of CO_2 storage is a new and intriguing topic. High-resolution 3D seismic has the potential to detect and monitor CO_2 leakage at carbon capture and storage sites with far higher accuracy at depths of 0-2 km below the seafloor when compared to traditional conventional seismic time-lapse data (e.g., Waage et al., 2018; 2021).

Recent studies of P-Cable 4D seismic data show excellent repeatability (NRMS, 10-40%), indicating strong future monitoring potential (Figure 2; Waage et al., 2021; Waage et al., 2018, Hatchell et al., 2019, Smith and Maddox, 2020; or Waage et al., 2021 and

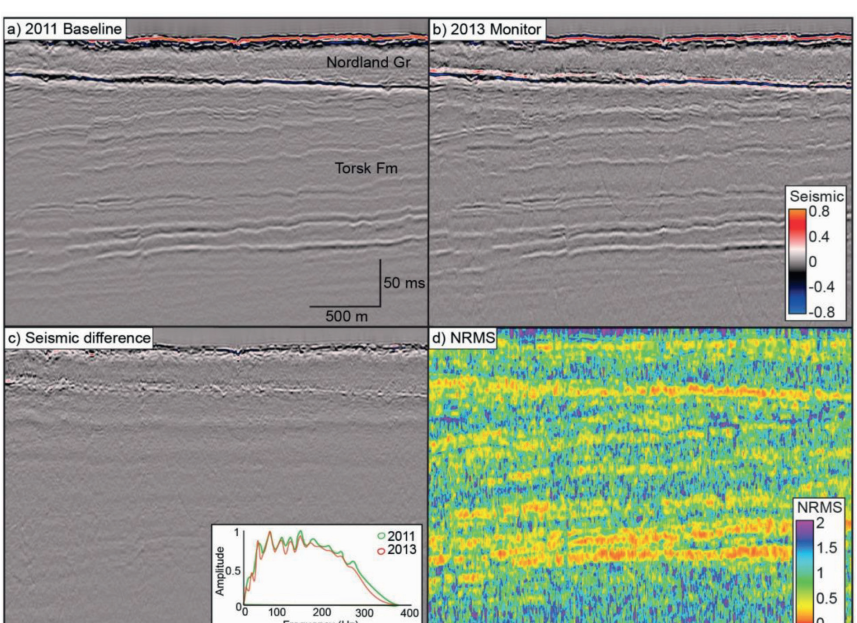

Figure 2 Examples of time-lapse profiles from two 3D P-Cable cubes above the Snøhvit field in the Barents Sea, showing good repeatability. A) Baseline survey from 2011, B) monitor survey from 2013, C) Difference between monitoring and baseline survey data, and D) the normalized RMS (NRMS) section using a 5 ms running interval showing no evidence of fluid seepage across the two-year period (modified from Waage et al., 2021).

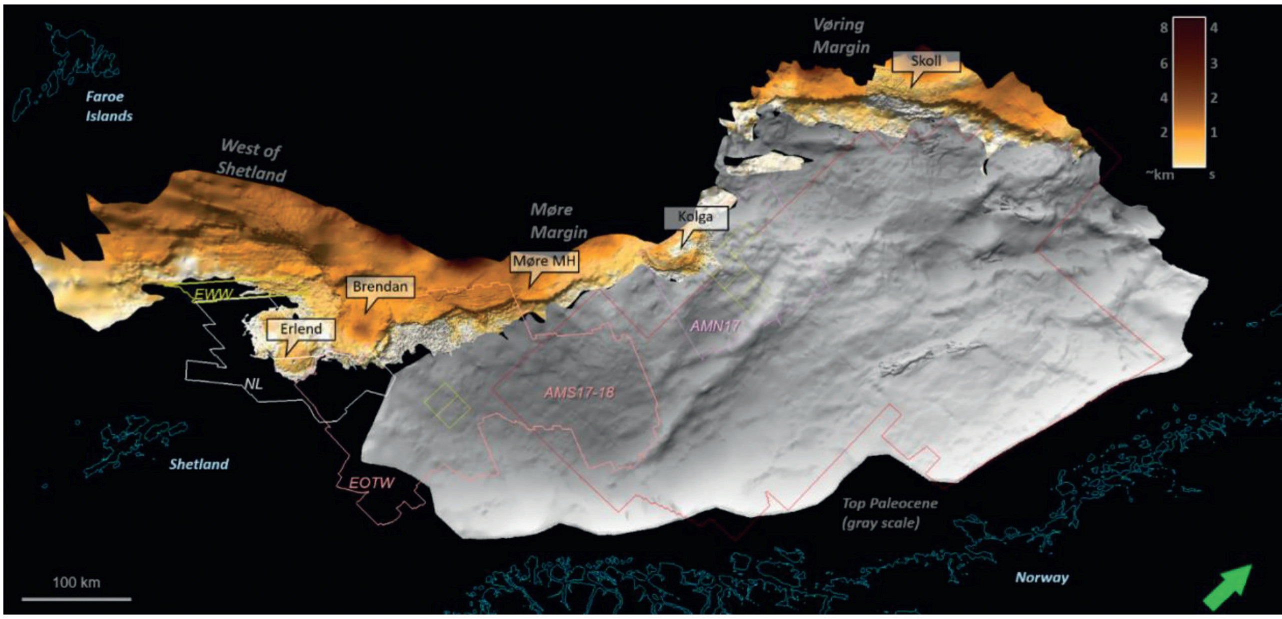

Figure 3 Regional basalt distribution and basalt thickness in the Norwegian Sea mapped using seismic reflection data. This shows a structural map of the Top Basalt horizon and basalt thickness (in yellow-brown) and the Top Paleocene horizon (in greyscale). Structures such as the Skoll High, Møre Marginal High (MH), Erlend Volcano, and East Faroe High are potential test sites for permanent carbon sequestration in offshore basalts. Seismic 3D data coverage (courtesy of TGS) is outlined.

references therein). Their analysis of the detection limits of CO_2 data from a CO_2 storage site suggest the ability to identify minimal amounts of CO_2 (1.3-10.6 tonnes; 3.3-27.4% gas saturation) in the shallow subsurface, about 30-300 times smaller than the amounts that conventional seismic data can detect.

Considering the system's potential to acquire data of high 4D potential (good repeatability and detectability of gases), we conclude that the P-Cable acquisition system can be a valuable monitoring tool in detecting leakage at a small scale and can complement conventional seismic data monitoring of the deeper interval. The P-Cable technology may be an optimal seismic 2D or 3D tool in relation to data density (meter-scale horizontal and vertical resolution; Lebedeva-Ivanova et al., 2018), repeatability, and quality for CCS sites when monitoring the shallow section. The lightweight cross-cable design, using ropes and short streamers, is cost-effective in mobilization and production and could be a technology of choice for yearly repetitions in certain shallow geologic terrains.

Permanent CO_2 storage within basalts

The storage of CO_2 in basalt formations has some particular advantages that could make this an attractive option in the future. When super-critical CO_2 is injected into basalt, it may react with calcium (Ca), magnesium (Mg), and iron (Fe) bearing minerals to form stable carbonate minerals (Oelkers et al., 2008). The two most common reactions are:

$$\underset{\text{FORSTERITE}}{Mg_2SiO_4} + 2CO_2 = \underset{\text{MAGNESITE}}{2MgCO_3} + \underset{\text{QUARTZ}}{SiO_2}$$

and

$$\underset{\text{ANORTHITE}}{CaAl_2Si_2O_8} + CO_2 + 2H_2O = \underset{\text{CALCITE}}{CaCO_3} + \underset{\text{KAOLINITE}}{Al_2Si_2O_5(OH)_4}$$

The expectation is that vast storage volumes for CO_2 in specific macro-porous basalt facies will be discovered worldwide. Flow top reservoirs report up to 45% porosity and flow interior up to 8% (Harris and Higgins, 2008; Jerram et al., 2019). Regional-size porous basalt reservoirs may avoid the expected pressure build-up likely in more constricted conventional sandstone reservoirs. It is anticipated that basalt storage systems could avoid some of the scrutiny required for overburden integrity and injectivity. Recent pilot tests have demonstrated that basalt reservoirs can provide a viable alternative for permanent carbon capture (e.g., Carbfix project onshore Iceland; Oelkers et al., 2008; Snæbjörnsdóttir et al., 2020).

Basalt is an abundant rock type across the world in onshore settings, but offshore it is predominantly found in deep waters. The distribution and facies of extensive basalt deposits have recently been mapped on a comprehensive 2D and 3D seismic database along the northwestern European margins, including more than 50,000 km^2 of high-quality 3D seismic data from the West of Shetland, Møre and Vøring basins (Figure 3). The data has been interpreted using the methods of seismic volcanostratigraphy (Planke et al., 2000), igneous seismic geomorphology (Planke et al., 2017), integrated seismic gravity-magnetic interpretation, and conventional horizon picking. They were then tied to scientific and industry boreholes across the Norwegian-UK border (Millett et al., 2020; Planke et al., 2020).

We hypothesize that offshore CO_2 sequestration into porous basaltic lava flows might allow permanent CO_2 sequestration of several gigatons per year (Figure 4). However, water depths to some of these waste storage complexes – up to 2000 m – is both a challenge and a benefit. At a water depth of 2000 m and a temperature of 4°C, CO_2 is a liquid and slightly heavier than water. Therefore, any spills at the seafloor should be of minimal consequence as the liquid CO_2 would flow downwards and eventually dissolve into the seawater. Logistically, drilling in deep waters is more costly than, for example, in the shallow North Sea, and transport to offshore sites away from existing infrastructure needs cost-efficient solutions. However, more research and testing may mitigate these challenges.

Seismic processing R&D for intra- and sub-basalt

The Atlantic Margin is recognized as containing a significant amount of the world's remaining hydrocarbon resources. The region contains volcanic features that are very difficult to image sufficiently, even with an advanced acquisition set-up. Numerous attempts have been made, but often without being able to provide the sufficient confidence that oil companies need to derisk their prospects. Recently, large-scale 3D seismic campaigns utilizing three and five sources for better sampling have improved basalt imaging, but significant progress is still needed on the processing side.

For CCS in basalt to be a success, we need to have improved intra-basalt seismic data. The ability to map the volcanic facies in three-dimensions provides a potential for determining optimal basalt reservoirs for carbon storage. The improvements seen so far based on an oil and gas focus can be directly applied for CCS purposes.

In 2017, TGS determined to investigate further what processing techniques could be applied to solve this uncertainty. The first goal was to interpret a horizon beneath thick (1000-2000 m) basalts. The Møre Basin in the Norwegian Sea was the chosen site. A 625 km^2 area was tested with different imaging algorithms, comprising image-guided tomography, Kirchhoff time and depth, directional image stacking (DIS), common offset reverse time migration (RTM), and least-squares RTM. This work achieved a mappable horizon, and further work on improving the result has been encouraged by interested oil companies.

A vision to open up sub-basalt and volcanic areas worldwide to oil and gas exploration by identifying drillable prospects in these areas was devised between TGS, a strategic oil company partner, and the Volcanic Basin Petroleum Research (VBPR) organization. Investigations in transmission losses, mode conversion, post-critical reflections, wave scattering, multiples and peg-legs, attenuation of frequencies, and non-normal moveouts were identified as critical challenges to volcanic imaging, and investigation into these challenges is continuing. The recent focus has been on multiples, sill transmission effects, and velocity building. As a result of the research to image the sub-volcanic, a better understanding of the basalts has emerged.

Due to the large contrasts between the sediments and the volcanic rocks, different multiple types need to be addressed – particularly the interbed multiples that could hide the volcanic structure (Ma, C. 2020). By using, for example, Jakubowicz for the calculation of the interbeds, the multiple model can be better identified (Jakubowicz, 1998). Few wells have been drilled through basalt, so there needs to be an interpretation of different adaptive subtraction testing of which features should be attenuated, as the multiples can have highly variable strength compared to the model.

Where previously the volcanic rock was treated as one unit in velocity model building, it is now possible to identify the different volcanic facies. This has been achieved by velocity model building techniques such as image-guided (IG) tomography and, more recently, dynamic matching full waveform inversion (DM FWI – https://info.tgs.com/dm-fwi) that identify different compartments of velocities corresponding to features within the flow basalts. The example below (Figure 5), from the Vøring Basin in the Norwegian Sea, shows well-defined intra-basalt reflections. These include landward flows and lava delta seismic facies units representing subaerial basalt flows and coastal hyaloclastic, prograding delta sequences, respectively.

Basalt and CCS, hydrogen or ammonia

Over the next decade, a hybrid technological innovation is required to overcome the CO_2 transport cost challenge. In the solution that we propose, natural gas would be used near the carbon storage sites to produce hydrogen and, alternatively, ammonia, and the resulting CO_2 would then be sequestered

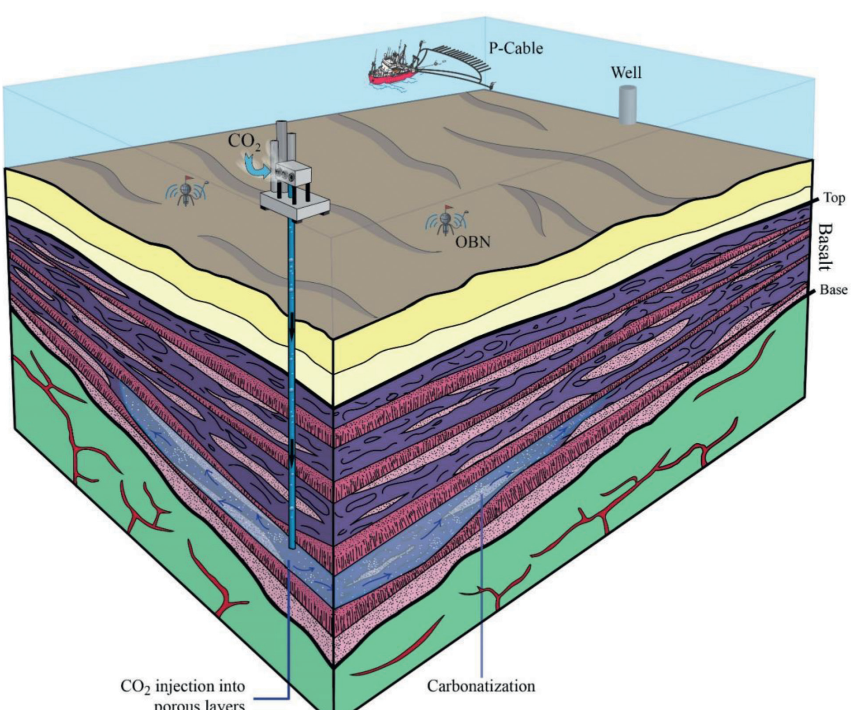

Figure 4 A model for permanent carbon sequestration and monitoring in offshore basalt. The basalt is overlaid by muddy sediments (yellow) and underlaid by intruded shales (red and green). Scientific drilling has recovered more than 100 subaerial basalt flows in the Norwegian Sea. Modified from Planke et al. (2020).

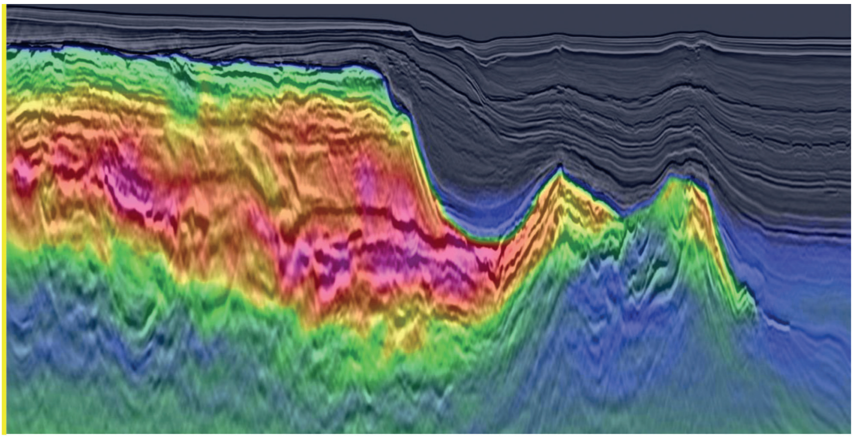

Figure 5 Basalt and sub-basalt depth image with velocity overlay across the Vøring Escarpment in the outer Vøring Basin. The basalt is defined by the velocity overlay in warm colours (light green, yellow and red) within a sedimentary basin (blue). The velocities were derived from FWI and dynamic matching FWI processing. The different warm colours define separate volcanic facies (e.g., subaerial landward flows and coastal lava delta), where yellow is the slowest. The top basalt has an overburden of only a few hundred metres of mudstone.

locally in the sub-surface. Gas tankers can sail with full loads both ways and profit from both the CO_2 storage fee and the sale of hydrogen or ammonia. These gas tankers would be repurposed to run on liquid ammonia – a technology that is currently being tested to power ocean-going ships. For basalt carbon sequestration to be realized, we need to form a larger industry consortium, undertake further scientific work and up-scale field tests, before commercializing industrial-sized facilities. The coming years may provide us with the answers as to which CCS technology will prevail – and by that, we mean the most environmentally friendly and cost-effective long-term solution.

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