

Permanent Carbon Sequestration Potential in Offshore Basalt Sequences on the NW European Continental Margins

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A dramatic reduction in global greenhouse gas emissions is necessary to achieve climate change targets. Wide ranging measures are required to reduce emissions with carbon capture and storage forming a vital component. Current carbon sequestration occurs in volumes of Mt/a into dominantly sedimentary reservoir rocks. Pilot tests have demonstrated that basalt reservoirs provide an alternative and permanent carbon capture scenario (e.g. Carbfix project). Here, we use 2D and 3D seismic data combined with well data to identify and map potential permanent and safe carbon storage reservoirs in offshore basalt sequences in the NE Atlantic. Well data support the presence of reservoir properties within extrusive basaltic sequences with porous lava flow tops and volcanoclastic lithologies comprising the most prolific sequestration targets. The basalt sequences are overlaid by several hundred meters of Cenozoic sediments with sealing properties, consisting mainly of marine shales and glaciogenic sediments. We hypothesize that offshore CO₂ sequestration into porous basaltic lava flows may allow permanent CO₂ sequestration of several gigatons per year, however more research and testing is needed to verify this potential.

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1. Introduction

Current atmospheric CO₂ concentrations have reached a level of 410 ppm, and global temperatures are likely to exceed 1.5 °C above the pre-industrial levels by the middle of this century (IPCC, 2018). Passing of the 1.5 °C threshold may be associated with irreversible, self-accelerating positive feedback in the climate system. In order to meet the temperature target, the global net CO₂ emissions may have to be reduced to net zero globally by 2050 (IPCC, 2018). This may require up to 20 Gt CO₂/yr to be captured and stored from 2050 (IPCC, 2018; P4 model), which is a dramatic increase of current carbon storage capacity. Although carbon capture and storage (CCS) may be required to fulfill the 1.5 °C target, the current CCS rates of c. 35 Mt/yr are insignificant compared to the current global CO₂ emissions of 37 Gt/yr in 2019. Therefore, new scientific and technological solutions with large-scale CCS may have to be identified and developed.

Certain basaltic volcanic facies have been proven to be good fluid reservoirs (e.g. Burns et al., 2012). Studies from Iceland show that CO₂ injection into basalt is feasible, and that CO₂ can be rapidly and permanently sequestered within basalt sequences (Oelkers et al., 2008). Voluminous volcanism at 62–54 Ma resulted in widespread basalt-dominated volcanic sequences being deposited along the NW European margins. Basaltic deposits are currently present as thick sequences of subaerial lava flows including seaward dipping reflectors and landward flows, volcaniclastic deposits, subaqueous basalt flows, and sill intrusions both onshore and offshore along the continental margin (Planke et al., 2000; Nelson et al., 2009).

The goal of this study is to identify and map volcanic deposits suitable for permanent and safe carbon storage in offshore basalt sequences in NW Europe (Figure 1). A favorable intra-basalt sequestration sites should be able to permanently store more than 5 Gt of CO₂, which is equivalent to c. 15% of the annual global CO₂ emissions in 2019. Sequestering such large volumes results in a value creation of 150 x 10⁹ EUR, assuming a CO₂ prize of 30 EUR/t. If successful, the approach proposed here could be applicable elsewhere in the world along volcanic rifted margins.

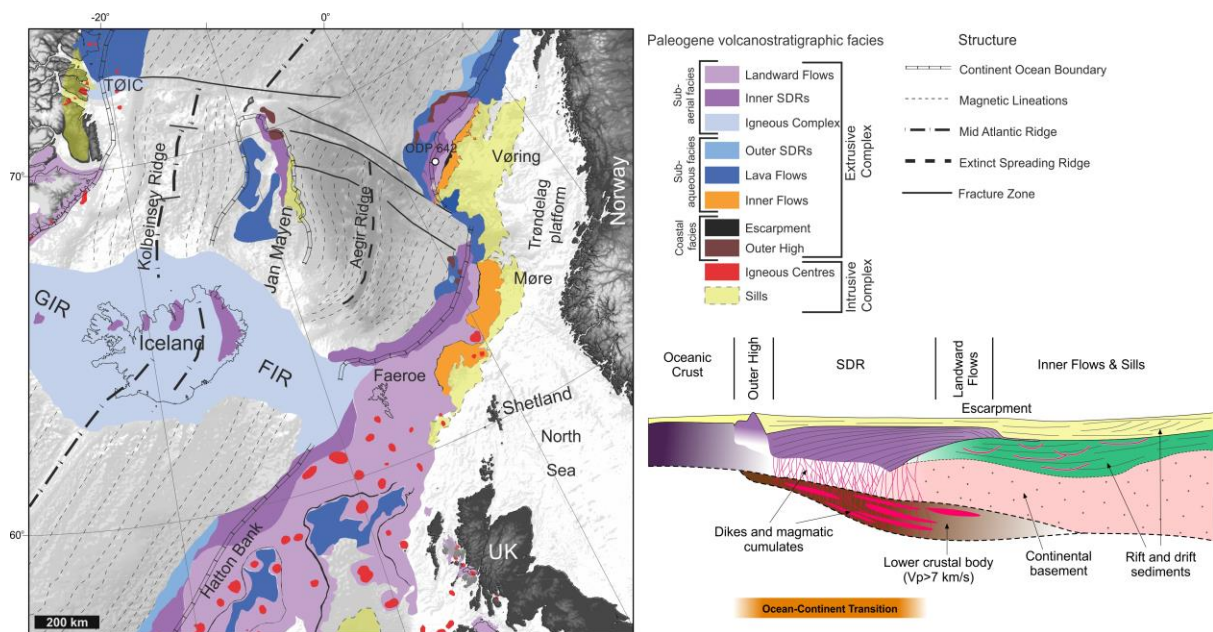


Fig. 1. Distribution of Paleogene breakup-related igneous rocks along the NW European continental margin. a) Volcanic facies map modified from Abdelmalak et al. (2017). b) Schematic crustal profile across the Vøring Margin (crustal thickness ca. 20 km).

2. Data and Methods

A comprehensive 2D and 3D seismic data base have been available for this study, including more than 50,000 km² of high-quality 3D seismic data from the West of Shetland, Møre and Vøring basins (Figure 2). The data have 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. The interpretations have been tied to scientific and industry boreholes across the Norwegian-UK border (Millett et al., 2020).

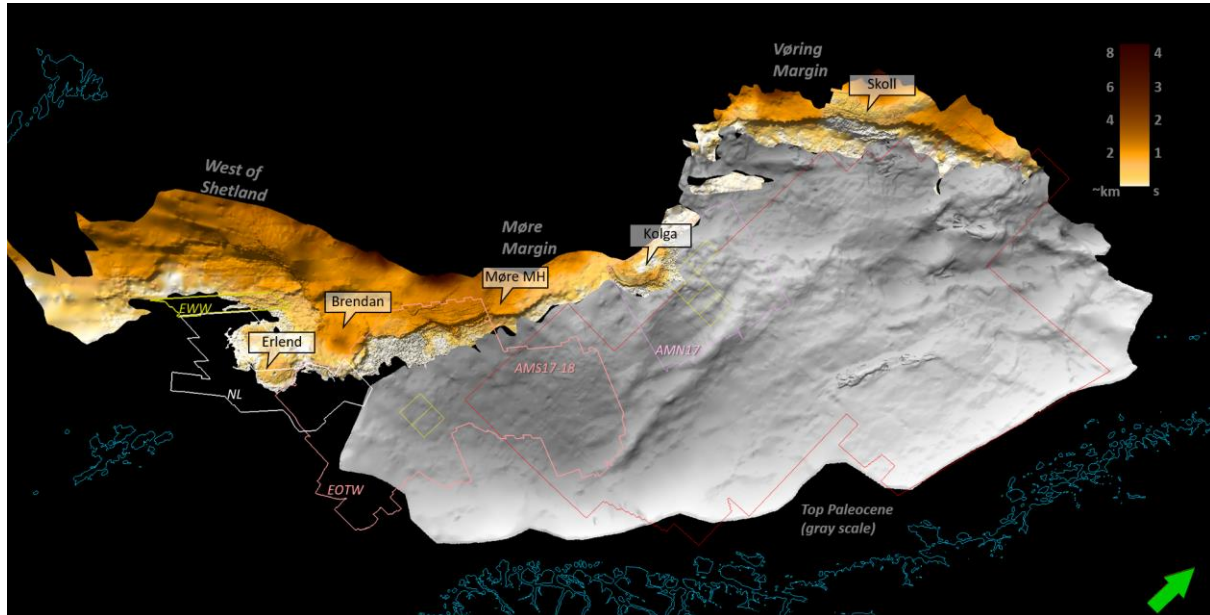


Fig. 2. Regional mapping of basalt distribution and basalt thickness based on seismic reflection data. Structure map of the Top Basalt horizon (overlain by basalt thickness in brown) and the Top Paleocene horizon (in grayscale). The Skoll High, Møre Marginal High, Erlend Volcano, and East Faroe High are the potential test sites for permanent carbon sequestration in the offshore basalts. Seismic 3D data coverage is outlined. Seismic data courtesy of TGS.

3. Basalt Distribution

We have mapped an areal distribution of the basalt within existing petroleum exploration blocks to be approximately 60,000 km² (20,000 km² in Norway). The Top Basalt reflection is interpreted with a high confidence in the entire region. The base basalt reflection has traditionally been more difficult to identify, however on modern data it can commonly be interpreted with good confidence as a soft reflection. Interval velocities for depth conversion is based on seismic processing velocities and well ties; typical seismic velocities for layered basalt sequences is 4 to 5 km/s. The mapped basalt volume is approximately 90,000 km³ (30,000 km³ in Norway). The seismic facies interpretation shows that the most common facies units are Landward Flows (subaerially emplaced basalt flows), with subordinate Lava Delta (coastal hyaloclastite deposits) and Inner Flows (subaqueous basalt flows).

4. Petrophysical Properties of Basalt Flows

The petrophysical properties of basaltic lava vary significantly from 1 to 60 % in porosity and from 0.0001 mD up to 10's of D in permeability. Lava flow tops with high matrix porosity comprising solidified gas bubbles (vesicles) coupled with brecciation and fracturing from the best reservoir units (porosity commonly 25-45%) whereas dense flow interiors comprise seals (porosity commonly 0-8%) (Figure 3). The susceptibility of fresh basalt to alteration and mineralization often leads to progressive occlusion of reservoir properties with increasing relative depth within volcanic sequences.

The basalt flows of the NE Atlantic include different seismic facies units which are calibrated to well penetrations in numerous locations including industry wells in the Faroe-Shetland Basin and ODP Hole 642E on the Vøring Marginal High. 122 tholeiitic lava flows were penetrated in the c. 770 m Upper Series in Hole 642E, intercalated with thin volcanoclastic dominated sediments (Planke and Eldholm, 1994). A recent re-entry of the 642E borehole conducted an aquifer flow study which resulted in an estimated flow rate of 10-13 m³ (c. 100 mD) for an aquifer thickness of 100 m within the basalt sequence supporting the permeable nature of the sequence (Harris and Higgins, 2008).

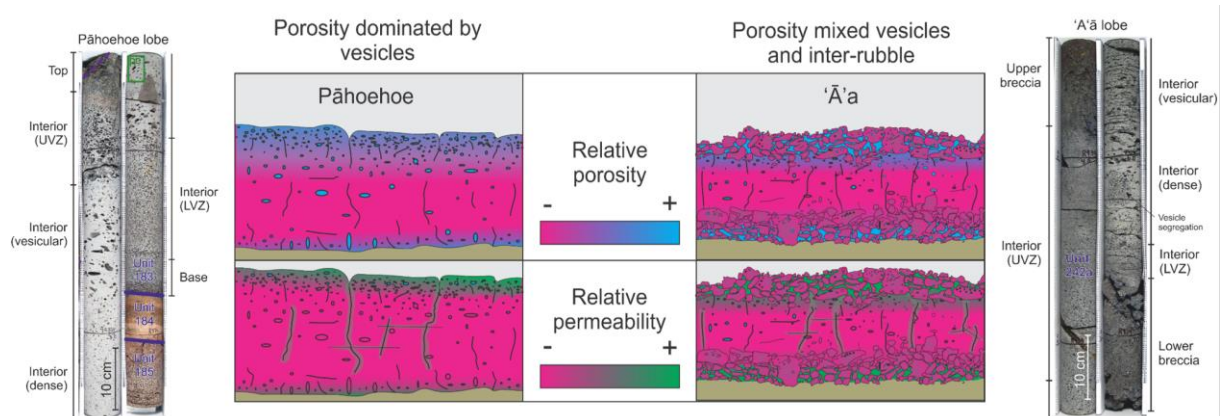


Fig. 3. Variable properties of different primary lava reservoirs. Vesicle abundance, distribution and connectivity form primary controls, along with fracturing where present. Borehole data from Hawaii (Jerram et al., 2019).

5. Offshore CO₂ Sequestration Potential in Basalt Sequences

A schematic model for permanent CO₂ sequestration in basalt on the mid-Norwegian margin is shown in Figure 4. CO₂ is injected into the porous and permeable tops of the basaltic lava flows. These sequences are located at subsurface depths of 1500-3000 m, where CO₂ occurs as a supercritical fluid.

Undergoing chemical reaction, the injected CO₂ is permanently sequestered as carbonate minerals in the vesicles, inter-rubble and fracture porosity of the basaltic lava flow tops. The CO₂ may chemically react with Mg-, Ca- and Fe-bearing minerals to build carbonate minerals, which fill up part of the pore spaces. Chemical reactions from other basalt injection sites do not show any clogging related to carbonate formation (Oelkers et al., 2008). Intra-basalt sequences are thus potentially good stratigraphic levels for permanent carbon sequestration.

Overlying marine shale sequences with thicknesses of several 100's meters are potential good seals for vertical fluid migration limiting the risk of leakage from the volcanic reservoir. Repeated tabular flow interiors may further prevent fluid leakage. Low seismic activity and an absence of major faults in the overburden provide additional support for sealing capabilities. Any potential leakage can be monitored by time-laps high-resolution and conventional seismic data. Leakage from the basalt injection sites are furthermore of limited danger for population centers and human activities as it is situated far from the coastline and CO₂ would be in a super-critical state at typical water depths of 1000-1500 m.

6. Conclusion

The Paleogene basalt sequences along the NE Atlantic are potentially favorable sequences for safe and permanent sequestration of very large volumes of CO₂ in the future. Basaltic rocks may have a very good permanent CO₂ storage capacity. Favorable water depths, low seismicity, undeformed strata above injection reservoirs, and unaffected groundwater make the NE Atlantic margin a suitable sequestration location.

The volcanic injection models include extensive multi-layered reservoir-seal pairs. The flow tops of the basaltic lava flows have the potential for carbonate mineralization, whereas the massive tabular flow cores act as barriers to vertical flow. The thin sedimentary overburden characterized by continuous sequences without faulting and breaching acts as a perfect overlying seal preventing surface leakage in the event of leakage from the main volcanic sequence.

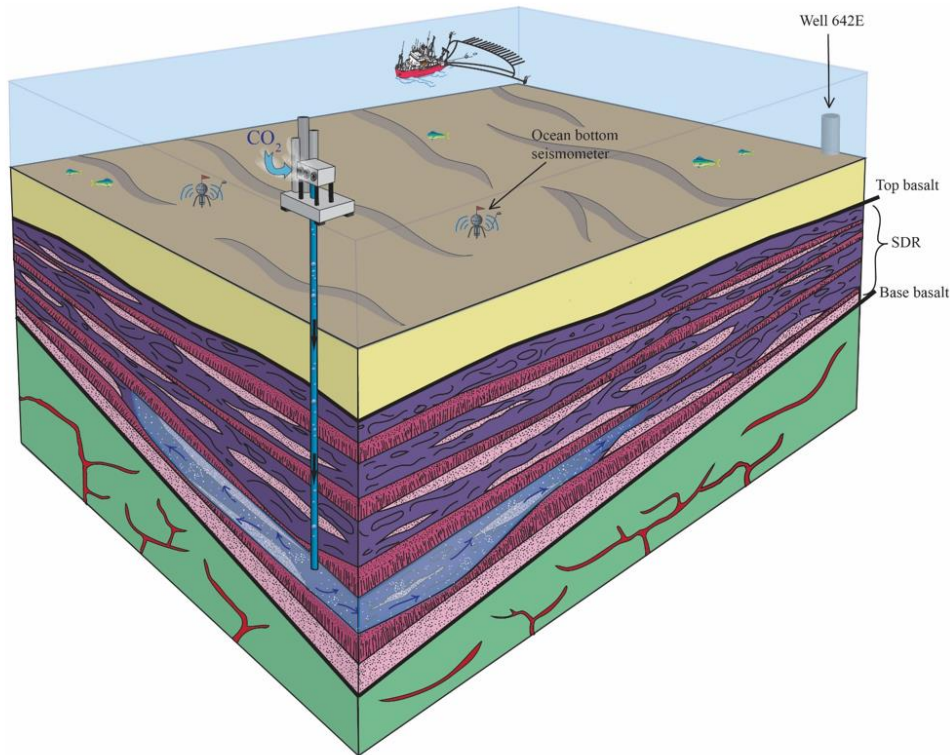


Fig. 4. Model for permanent carbon sequestration in offshore basalt. The basalt is overlaid by muddy sediments (yellow) and underlain by intruded shales (green). SDR: seaward dipping reflectors representing more than 100 subaerial basalt flows in 642E.

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