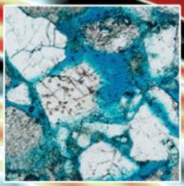
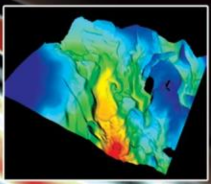
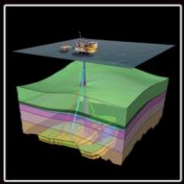

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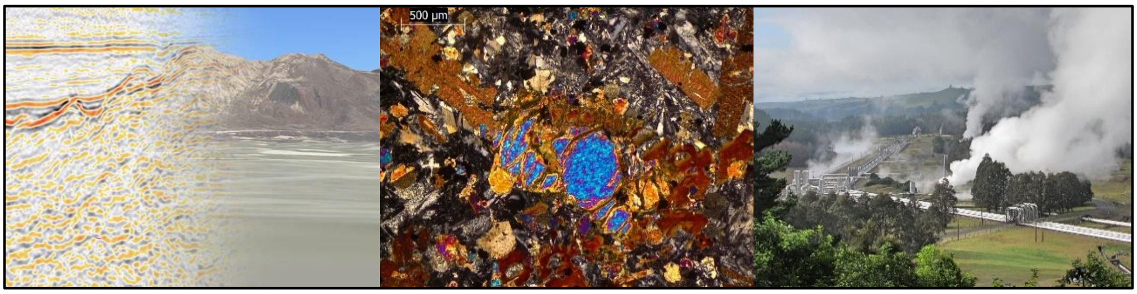
The impacts of volcanism on sedimentary basins and their energy resources

8 - 9 September 2022

The Geological Society, Burlington House, Piccadilly London



A large number of global sedimentary basins are impacted by igneous systemsin the form of extrusives, intrusives and volcaniclastics. Considerable research regarding the impact of these volcanics on hydrocarbon plays has been completed in recent years including the role of intrusions in basinal heat flow and fluid migration, diversion of sediment pathways in volcanic terrains, and influence of igneous material on sealing units and reservoir quality. Sub-basalt stratigraphy also continues to be an enigma in many parts of the world both in terms of seismic imaging and play element definition. There is now an opportunity to disseminate and share learnings globally, which could unlock energy opportunities in in other hydrocarbon basins impacted by volcanism. Increasingly these concepts can also help to develop geothermal plays or delineate carbon capture and hydrogen storage. For example, the knowledge built up by the hydrocarbon industry on reservoir and seal characterisation in volcanically affected basins will have a strong influence on geothermal opportunities and gas storage site definition. The aim of the conference is to encourage global submissions to applied problems across the span of the energy transition. In particular the committee encourage expressions of interest for submissions regarding:

- Margin and basin-wide examples of volcanic systems and their impact on resource plays (hydrocarbons, geothermal, hydrogen, CCUS)
- Global examples of the impact of volcanics on reservoirs and seals from pore to basin-scale
- The influence of volcanics on basinal heat flow and our understanding of geothermal gradients, hydrocarbon charge and impact on geothermal systems.
- Examples of new tools to aid our understanding of volcanic impacted basins (at all scales from seismic imaging to diagenetic analysis).

For further information please contact:
The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
Email: energygroup@geolsoc.org.uk

The impacts of volcanism on sedimentary basins and their energy resources

8-9 September 2022

The Geological Society, Burlington House, Piccadilly London & Virtual

Provisional Programme

	Day One
08.30	**Registration**
08.50	**Welcome.**
	Session One: Basin- and margin-scale processes; learnings and applications to resource plays.
09.00	**KEYNOTE: The impacts of volcanism in sedimentary basins** **Nick Schofield, *University of Aberdeen***
09.40	**Prolonged multi-phased magmatism and its effects on basin evolution from rift to drift – the case of the Austral South Atlantic** Ken McDermott, *Shell*
10.05	**Lava delta formation and implications for sedimentary systems in volcanic basins** Sverre Planke, *VBPR*
10.30	**BREAK**
10.50 Virtual	**KEYNOTE: CO2 mineral storage in basaltic rocks** **Sandra Snæbjörnsdóttir, *Carbfix***
11.30	**Exploration screening workflow in the search for native hydrogen and helium** Carolina Olivares, *CGG*
11.55	**Mapping the Earth's Igneous Record: The complex interaction of tectonics, crustal architecture and basin dynamics** Paul Markwick, *Knowing Earth*
12.20 Virtual	**POSTER INTRO: Petrogenesis and geodynamics of Eocene alkaline intrusions in the pre-salt sedimentary sequence of Santos Basin, Brazil** Viktor Souto Louback, *Federal University of Rio de Janeiro*
12.25	**LUNCH**
13.00	**Poster Session, Lower Library**
	Session Two: Igneous processes and their impact on reservoirs.
13.30	**KEYNOTE: Sediment-hosted geothermal systems: Review and first global mapping** **Monia Procesi, *Istituto Nazionale di Geofisica e Vulcanologia***
14.10	**Lessons learnt from the impact of volcaniclastic rocks on hydrocarbon systems and their application to CO2 storage** Simon Passey, *CASP*
14.35	**Investigating the potential for CO2 storage in the North Atlantic Igneous Province: Reservoir properties and reactivity of the Faroe Islands Basalt Group** Marija Rosenqvist, *The Njord Centre*
15.00	**BREAK**

15.20	**Interaction between volcanic and non-volcanic systems and its implication for prospectivity in the Faroe-Shetland Basin, Northeast Atlantic continental margin** Heri Ziska, *Faroese Geological Survey*
15.45	**Characterizing lava flow reservoir sequences: insights from global examples** John Millett, *VBPR*
16.10	**The impact of Etendeka flood basalts on the diagenesis of the fluvio-aeolian Jurassic Etjo Formation, Namibia** Eric Salomon, *Geozentrum Nordbayern*
16.35	**The role of volcanism in the deposition, diagenesis, and hydrothermal alteration of Aptian Pre-Salt reservoirs from Brazilian offshore basins** Bruno Eustáquio Moreira Lima, *Petrobras*
17.00	**Island Dolomitization in the Cretaceous Calcitic Ocean: A New Insight on the Role of Volcanism in Carbonate Dolomitization** *Mahmoud Samir El-Yamani, Imperial College London*
17.25	**End of day one**
17.35-18.30	**Drinks reception – Lower Library**

Day Two

08.40	**Registration**
08.50	**Welcome**
	Session Three: Heat and basin analysis – the impact on resources.
09.00 Virtual	**KEYNOTE: Role of igneous intrusion in controlling gas migration and contaminant charge in the UKCS** **John Underhill, *University of Aberdeen***
09.40	**Are all basement fault zones the loci of geothermal heat? A paradoxical, but still economically significant, case study from the Southern North Sea** Tiago Alves, *Cardiff University*
10.05	**The first evidence of lower crustal intrusion beneath the Faroe-Shetland Basin** Lucinda Layfield, *University of Aberdeen*
10.30	**BREAK**
10.50	**The Phonolites of the Kerio Valley Basin: Characterising a competing fluvio-lacustrine & alkali-rich volcanic succession within a frontier hydrocarbon exploration realm of the East African Rift** Robbie Cowan, *Tullow Oil*
11.15	**Greenstones as a source of hydrogen in sedimentary basins** Ian Hutchinson, *Kraaivlei Konsulting*
11.40	**Understanding volcanic margin prospectivity; insights from the north and south Atlantic margins** Dougal Jerram, *CEED (University of Oslo)*
12.05	**The Impact of Hydrothermal Vent Complexes on Volcanic Basin Prospectivity** Ben Manton, *VBPR*

12.30	**The thermal impact of igneous intrusives and Cenozoic unroofing in northern West of Shetland: an integrated study based on seismic mapping, new geochemical analyses and basin modelling** Callum Leighton, *BP*
12.55	**LUNCH**
	Session Four: Unlocking resources; data, case studies and operations.
13.35	**KEYNOTE: Tools for understanding how igneous systems affects energy resources and storage potential of sedimentary basins** **Craig Magee, *University of Leeds***
14.15 Virtual	**The impact of igneous rocks on petroleum exploration and drilling operations in the Northern Carnarvon Basin, Western Australia** Michael Curtis, *University of Adelaide*
14.40	**Assessing the Application of Ultradeep Electromagnetic Resistivity Tools to Detect Igneous Formations and Their Associated Hazards Ahead of the Bit** Leanne Smart, *Schlumberger*
15.05 Virtual	**Buried volcanoes as prospective sites for in-situ safe carbon storage** Ricardo Pereira*, Universidade de Lisboa*
15.30	**BREAK**
15.50 Virtual	**Exploratory history of the igneous reservoirs of the Rio Grande Valley (Mendoza), Neuquén Basin (Argentina)** Luis Rebori, *Consultant Geologist*
16.15	**The direct effects of emplacing basaltic lava onto a sand substrate: implications for petroleum reservoirs in sub-basalt and intra-basalt situations.** Clayton Grove.
16.40	**Overthickening on the Norwegian Volcanic Margin: estimating intrusion thicknesses to resolve palaeogeographic uncertainty** Lauren Chedburn, *University of Aberdeen*
17.05	**The influence of sediment thermal maturity and hydrocarbon formation on Hg behaviour in the stratigraphic record** Asri Indraswar, *University of Oxford*
17.30	**Closing remarks**
18.00	**End of conference**

Posters
Magmatically driven hydrocarbon generation and fluid flow in the Namibe Basin of Angola Edoardo Fiordalisi, *University of Manchester*
Exploring links between the North Atlantic Igneous Province and Paleocene–Eocene climate change using sedimentary mercury Joost Frieling, *University of Oxford*
Intrusion emplacement and the interaction with the petroleum system on the North Rona Ridge Alice Hall, *University of Aberdeen*
Emplacement and magma plumbing system of the Mesoproterozoic Derim Derim Dolerites, McArthur Basin, Northern Australia Simon Holford, *University of Adelaide*

Petrogenesis and geodynamics of Eocene alkaline intrusions in the pre-salt sedimentary sequence of Santos Basin, Brazil Viktor Souto Louback, *Federal University of Rio de Janeiro*	
Tempo and distribution of Mesozoic magmatic activity in the Browse Basin, Australian Northwest Shelf Kosuke Tsutsui, *University of Adelaide*	

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CONTENTS PAGE

ORAL ABSTRACTS
(In Programme Order)

Session One: Basin- and margin-scale processes; learnings and applications to resource plays

Keynote – The impacts of volcanism in sedimentary basins

Nick Schofield

University of Aberdeen

e-mail: n.schofield@abdn.ac.uk

The study of seismic and well data from sedimentary basins has arguably led to the largest scientific advancements in the understanding of volcanic systems in the last 20+ years, providing hitherto unknown insights into the storage, transport and eventual eruption of magma.

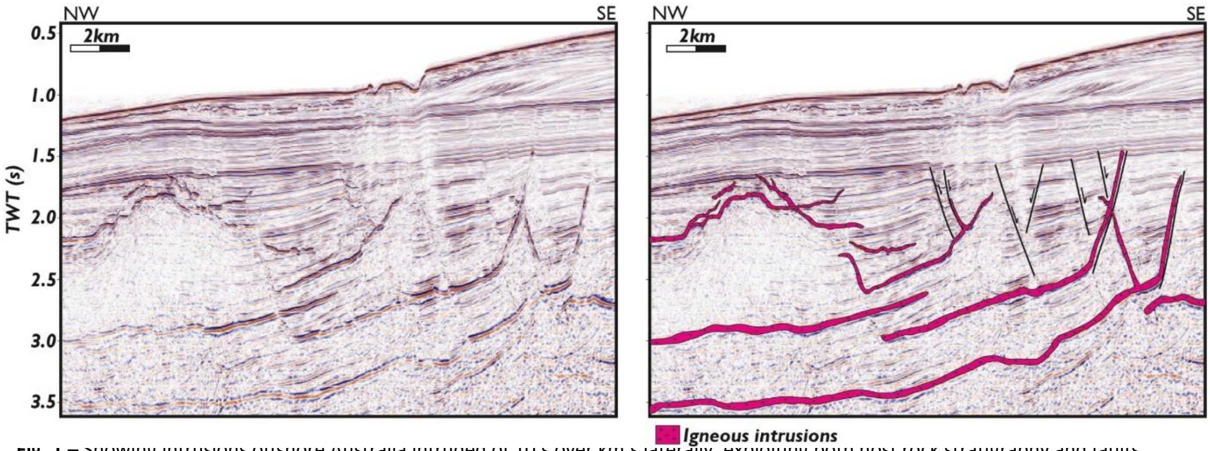

Fig. 1 – Showing intrusions offshore Australia intruded of 10's over km's laterally, exploiting both host rock stratigraphy and faults.

It has been demonstrated that magma can travel over very large lateral (and vertical) distances within sedimentary basins, effectively isolating entire sections of basin stratigraphy (Fig. 1). Imaging of entire magmatic systems is also now possible, from an overlying volcanic edifice to the underlying magma chamber (Fig. 2). Our knowledge of the stratigraphy of large and thick basalt sequences and eruption dynamics have taken large steps forward due to interrogation and integration of subsuface datasets.

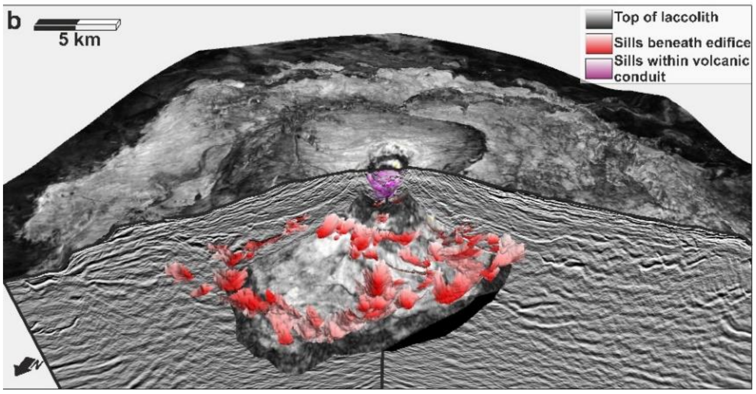

Fig. 2 – Figure showing section through the Paleocene aged Erlend Volcano, NE Atlantic Margin, with underlying magma chamber imaged.

As global hydrocarbon exploration and production increasingly focuses on passive margin basins with evidence for past intrusive and extrusive igneous activity, constraining the distribution, timing and pathways of magmatism in these basins is essential to reduce exploration and production risk.

This talk will explore some of the key milestones in the study of volcanic systems in sedimentary basins, from some of the early wells, which highlighted the need to better understand volcanic systems within sedimentary basins, some of the lessons learned (and often not learned!), and some major successes (and failures). The talk will touch on the discovery of the Rosebank intra-lava oil and gas field, in addition, the role which igneous intrusions play within sedimentary basin evolution will also be examined (Fig. 3). Focus on some of the more counterintuitive effects that intrusive magmatism can have on source rock horizons and generation within sedimentary basins will be explored, as will the knowledge of how intrusions can drastically effect hydrocarbon migration, fluid flow and pressure transfer in the subsurface.

Finally, the talk will look at some of the current unknowns, challenges and the future. Both seismic imaging and drilling continue to be substantially challenged by the presence of igneous rocks within the subsurface. However, exciting opportunities exist, basic igneous rocks represent potential unique opportunities for CO2 sequestration in onshore and offshore areas of the UKCS, including in the highly mature Central North Sea (Fig. 4).

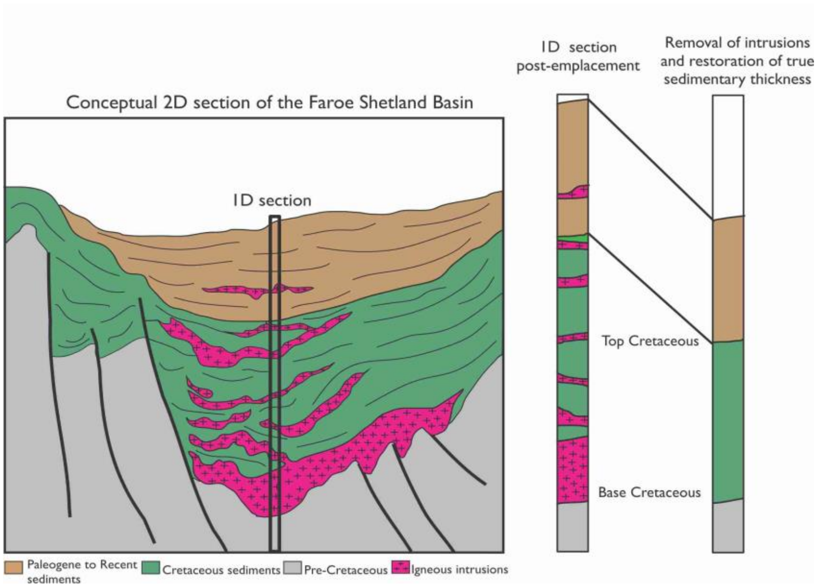

Fig. 3 – Figure showing the concept of 'overthickening' of sedimentary sequences in a sedimentary basin. The intrusion thickness needs to be correctly removed to restore the sedimentary section to true thickness prior to emplacement.

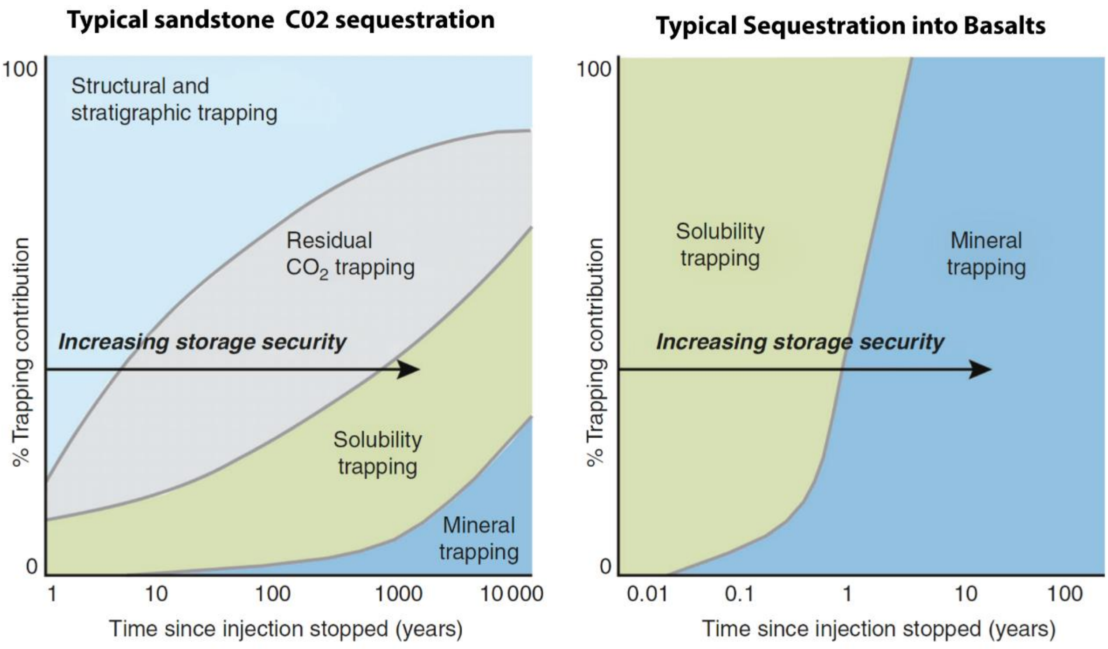

Fig. 4 – Figure illustrating the ability for CO2 to be locked into a solid mineral phase in a matter of months to years when injected into basic igneous rock. This reduces risks associated with seal leakage, that are associated with 'conventional' CO2 sequestration.

Prolonged Multi-phased Magmatism and its Effects on Basin Evolution from Rift to Drift – The Case of the Austral South Atlantic

Ken McDermott, Phil Thompson, Christian Heine, Edith Hafkenscheid, *Shell*

Volcanic or intrusive rocks are omni-present within extensional basins and passive margins systems. Depending on magmatic budget and timing, they can form integral components of basin infill and/or substrate before, during, or after extensional phase of basin formation. Volcanics are often framed in an adversarial role with respect to hydrocarbon exploration and so carry a certain amount of risk that must be accounted for, particularly during basin modelling and fluid phase predictions, reservoir quality, and seal integrity.

But what happens when a basin's foundation is of igneous construction?

Here, we describe and discuss the effect large-scale magmatism can have on basin evolution, palaeobathymetry, and petroleum systems using the southern South Atlantic as a case study.

Much of the South Atlantic is an archetypal magma-rich rift system and we will focus on the region around north and south of the Florianopolis Fracture Zone; the Santos and Pelotas Basins, and the conjugate Walvis and Namibe Basins.

We interpret and systematically reclassify large areas traditionally described as continental crust to be of fully magmatic construction. We show this to be the case through detailed tectonomagmatic mapping utilising Shell's standardised interpretation workflow applied to a comprehensive conjugate seismic database for the South Atlantic.

We identify five distinct phases of magmatism, spanning a period of ~60-70 Myr initiating at c. 145 Ma, that likely represent waxing and waning periods of activity for the Tristan de Cunha Plume. Plate motions during most of the early and middle Cretaceous caused the plume to be localised in the region of the Florianopolis Fracture Zone , captured by the seafloor spreading ridge before being released and localising predominantly on the African side from the uppermost Cretaceous onwards.

The imposition of the paleo-Tristan de Cunha Plume on an extending and diverging lithosphere resulted in a fundamental diachroneity to basin formation and its stratigraphic infill. This diachroneity is further complicated by pulsations in the mantle plume, leading to Rift-Ridge Jumps and abandoned rift centres stranded on one margin or another . This may be of particular importance when considering presence of source rock candidates as well as source to sink studies.

The identification of a prolonged period of extensive magmatism has important implications for palaeobathymetry and ocean circulation, and we highlight its role in the formation of the central South Atlantic Salt Basin and facilitating the preservation of source rocks. The magmatism will also strongly impact regional heat flow (particularly when compared with legacy modelling using a continental basement), and may provide an additional source for CO_2 that has been encountered in the distal parts of these rifted margins.

Lava delta formation and implications for sedimentary systems in volcanic basins

Sverre Planke[1,2], Ben Manton[1], Dougal A. Jerram[2,3], John M. Millett[1,4], Benjamin Bellwald[1], Mansour M. Abdelmalak[1,2], Dmitry Zastrozhnov[1], Dwarika Maharjan[1], Jan Inge Faleide[2], Laurent Gernigon[5], Christian Berndt[6], Matthew Pankhurst[7], Peter Betlem[8], Reidun Myklebust[9]

[1]*Volcanic Basin Petroleum Research, Norway;* [2]*CEED, University of Oslo, Norway;* [3]*DougalEARTH, UK;* [4]*University of Aberdeen, UK;* [5]*NGU, Norway;* [6]*GEOMAR, Germany;* [7]*INVOLCAN, Spain;* [8]*UNIS, Norway;* [9]*TGS, Norway;* **planke@vbpr.no*

Lava deltas are formed when sub-aerial basaltic lava flows enter the sea resulting in the formation of escarpment structure and the transformation of lava flows to hyaloclastites. In this presentation, we compare the structure and formation of modern and ancient lava deltas and discuss how they influence the sedimentary system and prospectivity of volcanic basins. Massive breakup-related basaltic sequences and associated intrusions were emplaced along the UK and mid-Norway continental margins in the Paleogene. The magmatism was initiated at about 62 Ma, with a main peak around 56 Ma. This so-called North Atlantic Igneous Province had a major impact on the Paleogene paleogeography and associated sediment provenance, transport, and depositional systems.

Spectacular lava delta sequences are imaged on modern 3D seismic reflection data along the >500 km long Vøring and Møre margins. Here, we have interpreted the top and base basalt reflections and the extent of the lava delta seismic facies unit using the concept of seismic volcanostratigraphy. A shallow stratigraphic borehole, 6403/1-U-1, was cored and logged 40 m into the lava delta on the Kolga High in 2014, whereas IODP Exp. 396 cored seven boreholes into sub-aerial basalt flows or sub-basalt granite in 2021. The seismic mapping documents large lateral variations in the basalt thickness, from a few hundred meters to >2 km. Locally, the basalt is very thin or absent, e.g., on the Kolga, Mímir, Ygg, Skoll, and Grimm highs. Igneous seismic geomorphological interpretation reveals extensive subaerial lava flow fields, as well as volcanogenic debris flows and lava deltas along the paleo-coastline on the different margin segments. The seismic volcanological interpretations are corroborated with studies of field examples of ancient lava delta deposits (e.g., Nuussuaq, West Greenland) and modern lava deltas on volcanic islands such as Hawaii and La Palma (Fig. 1).

Along the eastern side of the Kolga High, a well-defined prograding lava delta and associated kilometer-high escarpment are mapped on the 3D seismic data (Fig. 2). Loading by the kilometer thick hyaloclastite caused soft sediment deformation and rapid burial of underlying sediments. At the crest of the high, the basalts are thinnest and in two places there are windows where no basalt is present. Here, the seismic geomorphology indicates that the basalt was peneplained by wave-base erosion. The seismic interpretation is corroborated by the borehole ties, as hyaloclastites were recovered from the top of the lava delta in 6403/1-U-1 and weathered granite was cored below recent sediments in the basalt windows. In the Møre Basin, early Eocene sediments onlap the Kolga High escarpment (Fig. 2) and post-date the lava delta formation. In these sediments we observe another prograding sequence above and east of the top basalt horizon. The base of this sequence is tied to the base hydrothermal vent reflection mapped further west, having a Paleocene-Eocene transition age (c. 56 Ma). The top of the sequence is tied to the mid-Ypresian Top Tare Formation and is interpreted to have formed close to the paleo-seabed. Lobate features which have high amplitude hard reflections at their tops and soft bases occur close to the Paleocene-Eocene horizon. We interpret these lobes to have formed in deep water. The high amplitude lobate bodies are in places very narrow compared to extrusive lava flows which are also recognized along the margin. We interpret the prograding sequence as well as the lobate features as evidence of deposition of eroded material derived from the Kolga High during the Eocene. Our model indicates that the depositional features observed east of the escarpment could include some granitic component but are likely dominated by volcaniclastic deposits.

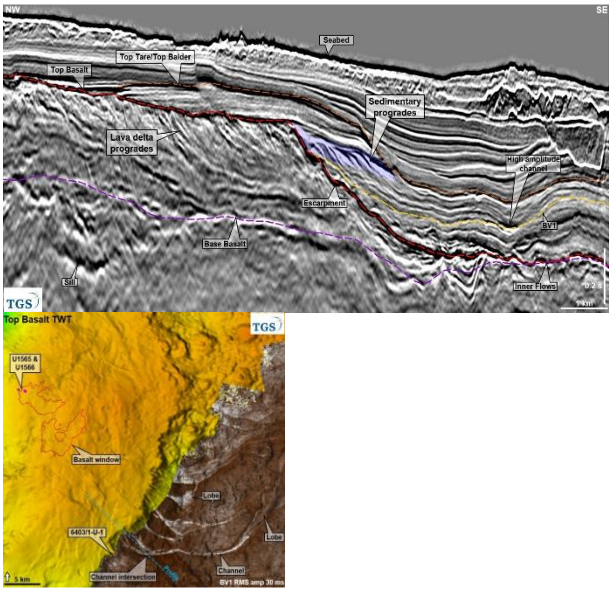

__Fig. 1.__ Lava delta, or Fajana in Spanish, formed during the Cumbre Vieja eruption in December 2021 on La Palma, Canary Islands. Sandy beaches were __Fig. 2.__ Seismic profile across the prograding lava delta on the Kolga High (upper). A smaller sedimentary prograding sequence is imaged to the east of the escarpment, and high amplitude channels (left) are present in the lowermost Eocene sediments. BV1: Base vent.   Data courtesy of TGS.formed during the eruption due to wave erosion.

Keynote – Carbfix: CO2 mineral storage in basaltic rocks

Sandra Ó. Snæbjörnsdóttir[1], Bergur Sigfússon[1], Chiara Marieni[1], Deirdre Clark[2], Thomas Ratois[1], Martin Voigt[1] Sigurdur R. Gislason[3]
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[3]*Institute of Earth Sciences, University of Iceland, Sturlugata 1, 101 Reykjavík, Iceland*

The climate goals will not be met without capturing vast amounts of carbon dioxide (CO_2) from point sources, such as industrial processes and power generation preventing it from entering the atmosphere, and capturing already emitted CO_2 directly from the atmosphere to deliver "negative emissions" as needed by the second half of the century [1]: It is estimated that over 100 Gigatonnes of CO_2 must be captured and safely stored by 2060 to reach the goals of the Paris agreement to limit global warming to 1.5-2°C [2].

Secure geological storage for the captured CO_2 is fundamental: Without safe and permanent storage, CO_2 capture technologies, both capture from concentrated point sources and DAC technologies will only solve one part of the problem. Currently, the most mature carbon storage techniques inject CO_2 into deep saline aquifers or depleted oil and gas reservoirs where the CO_2 may be physically trapped in porous rocks below an impermeable cap rock, preventing it from migrating to the surface. Eventually some of this CO_2 becomes stuck in small pores, limiting its mobility (residual trapping). Over time, the CO_2 dissolves into the formation water a process commonly referred to as solubility trapping of the injected gas. Some of this dissolved CO_2 reacts to form stable carbonate minerals referred to as mineral trapping. As the injected CO_2 progresses from structural to mineral trapping, it becomes more immobile and thus the storage becomes less reliant on a secure caprock. Mineral trapping in such systems may be limited, however, by the low reactivity of silicate minerals in sedimentary rocks and lack of silicate-bound divalent metals, required to make carbonate minerals, and can take thousands of years (Fig. 1a, [3]). The CO_2 stored in well-regulated conventional CCS storage sites in reality has very low risk of leakage [4], but the existence of the risk means public acceptance can be affected.

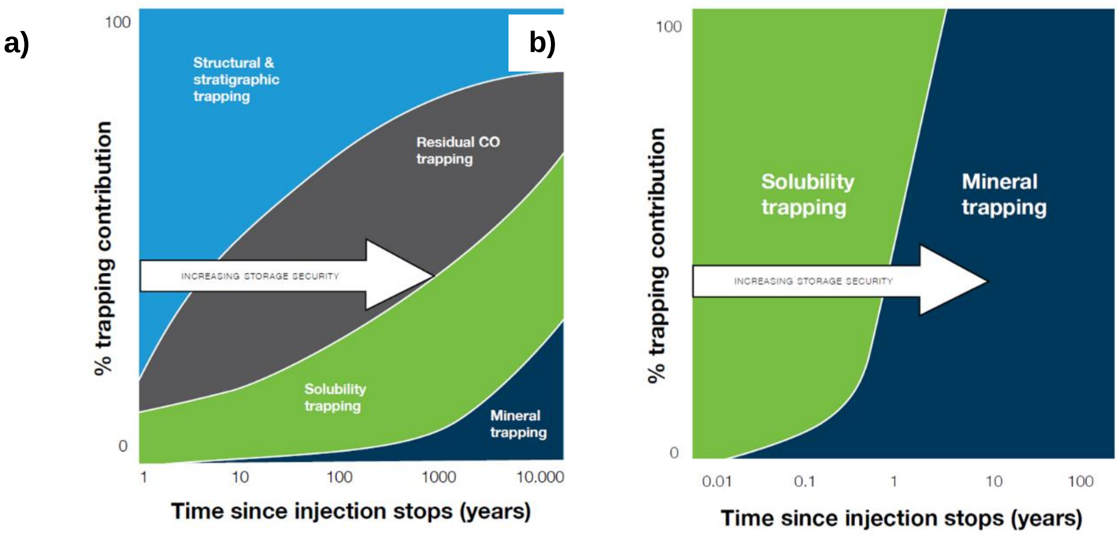

Figure 1 Comparison of CO_2-trapping mechanisms over time when injecting pure supercritical CO_2 into sedimentary basins (part a) and when injecting water- dissolved CO_2 for mineralization (part b), based on data from field injection experiments. Modified from [5].

Despite the urgent need for rapid deployment of widespread carbon storage sites, experience demonstrates that low public acceptance, high upfront investment costs and uncertain future liabilities have hindered the implementation of conventional carbon storage worldwide. Mineral storage of CO_2 has been proposed as a safe and low-cost alternative. The idea of mineral storage of anthropogenic CO_2 was first proposed in the 1990's [6, 7]: Mineral carbonation is a part of the natural carbon cycle, where the carbon moves from one terrestrial reservoir to another. Within the natural cycle, carbon has thousands to millions of years residence time in rocks, which are by far the largest carbon reservoir on Earth. Mineral storage of CO_2 will, however, only be practical if it is possible to accelerate this natural process at large enough scales to address the current global challenge.

Carbfix has demonstrated the rapid mineralisation of CO_2 through injection of dissolved CO_2 into reactive rocks, such as mafic or ultra-mafic rocks, with over 95% of the injected CO_2 mineralised within two years of injection into basaltic reservoirs at ambient temperatures [5, 8]. By dissolving the CO_2 in water prior to or during injection solubility trapping is achieved immediately, adding to the security of the method. Furthermore, the acidic CO_2-charged fluid promotes the release of divalent metals from the subsurface bedrock, which combine with the injected CO_2 and form stable carbonate minerals. Via mineralisation the injected CO_2 is permanently fixed and there is a negligible risk of it returning to the atmosphere. Mineral CO_2 storage offers a vast storage potential and unlocks large regions in the world where CCS has until now not been considered possible. The largest potential lies offshore within the sub-marine basaltic crust, but suitable formations are also widespread onshore, including volcanic formations, mine tailings and unconventional petroleum reservoirs [5]. The addition of CO_2 storage alternatives to the more common injection of CO_2 into sedimentary basins enhances the opportunities for pairing of sinks and sources, reduces transport costs, and increases to the potential CO_2 storage reservoirs worldwide.

Carbfix started out as a research project back in 2006 and was formalized by four founding partners in 2007; Reykjavík Energy, the University of Iceland, CNRS in Toulouse, and the Earth Institute at Columbia University. Following the study of natural analogs for CO_2 mineral storage, extensive laboratory testing and modelling between 2007 and 2012, a series of injection experiments were carried out in the vicinity of the Hellisheidi power plant. After a successful verification of the injection system in late 2011 the pilot injection was commenced in January 2012. Carbfix has since 2014 injected over 80,000 tonnes of CO_2 from the Hellisheidi plant in SW-Iceland into the basaltic reservoir. Carbfix was established as a subsidiary of Reykjavik Energy in 2020. Since then, Carbfix has commissioned two new injection sites, including injection of CO_2 captured directly from the atmosphere in collaboration with the Swiss green-tech company Climeworks. Carbfix is involved with four injection projects to be commissioned in 2022. Emphasis is currently being placed on making this technology more cost effective and exploring its limits in terms of geological properties and injection methods for more widespread deployment of CO_2 mineral storage - with the intention to bring the technology towards climate relevant scale.

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Exploration screening workflow in the search for native hydrogen and helium

Olivares, C., Findlay, J., Kelly, R., Otto, S., Clegg, H., Imrie, A. and Cairns M.

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Native hydrogen and helium have been considered as an alternative energy resource for the decarbonisation of society. However, the generation of hydrogen and helium within the subsurface remains poorly understood and constrained. Hydrogen and helium seeps have been reported worldwide and may indicate large reserves within the subsurface. Hydrogen generation is complex with multiple generation mechanisms. The main source of native hydrogen is ultramafic rocks, which have experienced serpentinization together with water radiolysis. In contrast, helium generation occurs as the result of the radioactive decay of uranium and thorium present within basement rocks.

There are at least two main tectonic settings where serpentinization has operated and represents potential for hydrogen exploration. Serpentinization occurs within ophiolite belts where oceanic crust and underlying mantle have been uplifted and tectonically emplaced within fold belts. Serpentinization also occurs within highly extended basins including rifts (old, reactivated and active), where thick sediments overlie thinned or absent crust, likely above serpentinized mantle. These areas generally lie outside of hydrocarbon provinces. In contrast, different rock types produce varying amounts of helium 4, controlled by the original concentrations of uranium and thorium and the age of the rock. Some of the more significant accumulations of helium are found in large, stable Precambrian-aged crystalline terrains that have remained relatively tectonically stable for long periods of time.

Hydrogen and helium accumulations from basement sources are at risk of dilution if located in close proximity to volcanic centres. Volcanic gases, primarily carbon dioxide, are known to dilute hydrogen and helium concentrations within the subsurface. This risk decreases with increasing distance from volcanic centres and should be considered as part of the hydrogen and helium exploration workflow.

CGG have developed and applied an exploration screening workflow dedicated to identifying worldwide areas with the geological settings and conditions favourable for native hydrogen and helium generation. Importantly, this includes databasing and data analysis where a number of databases have been created to support and focus the search for both gases~~.~~ Furthermore, automation and machine learning methodologies which aid processing of different data types and investigating their application for detecting various accumulations have been implemented. We demonstrate the significant value in combining and integrating data, geological and geochemical generation models and machine learning for high grading those geological features and areas more conducive to accumulating hydrogen and helium.

The use of innovative energy carriers such as hydrogen and helium will play a key role in assisting society with the decarbonisation of high-emission industries, aviation, and other sectors. The workflow which CGG has developed utilising their expertise in data science, fluid systems analysis and exploration screening is a significant step forward in being able to delineate and develop these alternative energy resources in the future.

Mapping the Earth's Igneous Record: The Complex Interaction of Tectonics, Crustal Architecture, and Basin Dynamics.

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Igneous activity can control and/or significantly affect hydrocarbon, mineral, and geothermal exploration and exploitation. These effects will vary depending on the nature and timing of the activity, the structuralization and crustal architecture of the country-rock affected, and the resource being explored for. To understand these effects, we need first to know the igneous record's distribution, timing, and petrology. We are building a global geospatial database of intrusive and extrusive igneous features to address this. Each record in the database includes information on each igneous feature's geometry, age, petrology, and tectonic setting. These igneous databases are part of a larger project, *Reclus*, which is designed to provide the community with a geospatial interpretation of the crustal architecture of the Earth. Here we present examples from the database and outline their application to a suite of resources.

Features in the databases have been defined using remote sensing data (Landsat imagery, radar data, gravity, magnetics) as the primary input, supported by information from secondary sources (other peoples' observations and interpretations), including geological maps and publications. Within the workflow, onshore, outcropping igneous extents are initially captured within a related geospatial database for Bedrock Geology (the Bedrock Geology database forms part of a source-to-sink workflow, including the investigation of placer deposits). Each record is then exported to the Igneous Features Database, where subcrop extents are added where known. When used in palaeogeographic and tectonic restorations, the age information is used to parse those data appropriate for each timeslice. All databases have been designed within ESRI's ArcGIS software and are underpinned by a comprehensive data attribution and management system.

In this talk, we show examples from the igneous databases for two scenarios to show the application and nature of the data at two very different scales: (1) crustal-scale magmatism in which igneous activity defines the basin form and impacts our understanding of magmatic margin evolution; and (2) more localized igneous activity which has more local effects for basin evolution and resources.

Continental margins are frequently differentiated into 'volcanic' and 'non-volcanic' margins, based on the presence or absence of magmatism, most commonly SDRs (Seaward Dripping Reflectors). Most margins are more complex. For example, on the Namibian margin we can differentiate outer and inner SDR packages that are crustal-forming. In our classification, these are shown as either magmatic crust (magmatism, but with no continental crustal component) or mixed-magmatic (magmatism with thin or very thin continental crust). We differentiate crustal-forming magmatism from volcanics filling early formed rifts (basin-fill rather than form), or mantle-related (hot-spot) igneous activity. Each of these has a different impact on accommodation and thermal history. Each also has a different relationship with the pre-existing geological fabric, which in Namibia varies along the margin resulting in three distinct crustal provinces. Recent successful hydrocarbon exploration offshore Namibia (viz., Venus and Graff) proves the economic viability of hydrocarbon systems on magmatic margins.

Understanding why these plays work and predicting future sweet spots for exploration will require the level of understanding and margin variability provided by the databases presented here.

In contrast to the regional example offshore Namibia, the second example is at a local scale. Onshore, detailed, systematic mapping of discrete volcanic bodies and provinces has multiple consequences that can be important for various applications: as expressions of localized thermal hot-spots in geothermal exploration (e.g., Rungwe Volcanic Province, Figure 1); as evidence for denudation and changes in transport pathways (sometimes directly through deflection of older river systems) in source-to-sink analysis (reservoir quality in water and hydrocarbon studies; placer deposits); as the host of epithermal mineralization. We will show examples of each and how these look within the database.

By systematically mapping the distribution of igneous activity, we can better understand large and local-scale relationships that affect resource exploration, from hydrocarbon prospectivity, to critical minerals and geothermal. The examples highlight the importance of understanding resource systems at a range of scales. These databases provide a platform/tool/mechanism to apply a multi-scale and consistent approach.

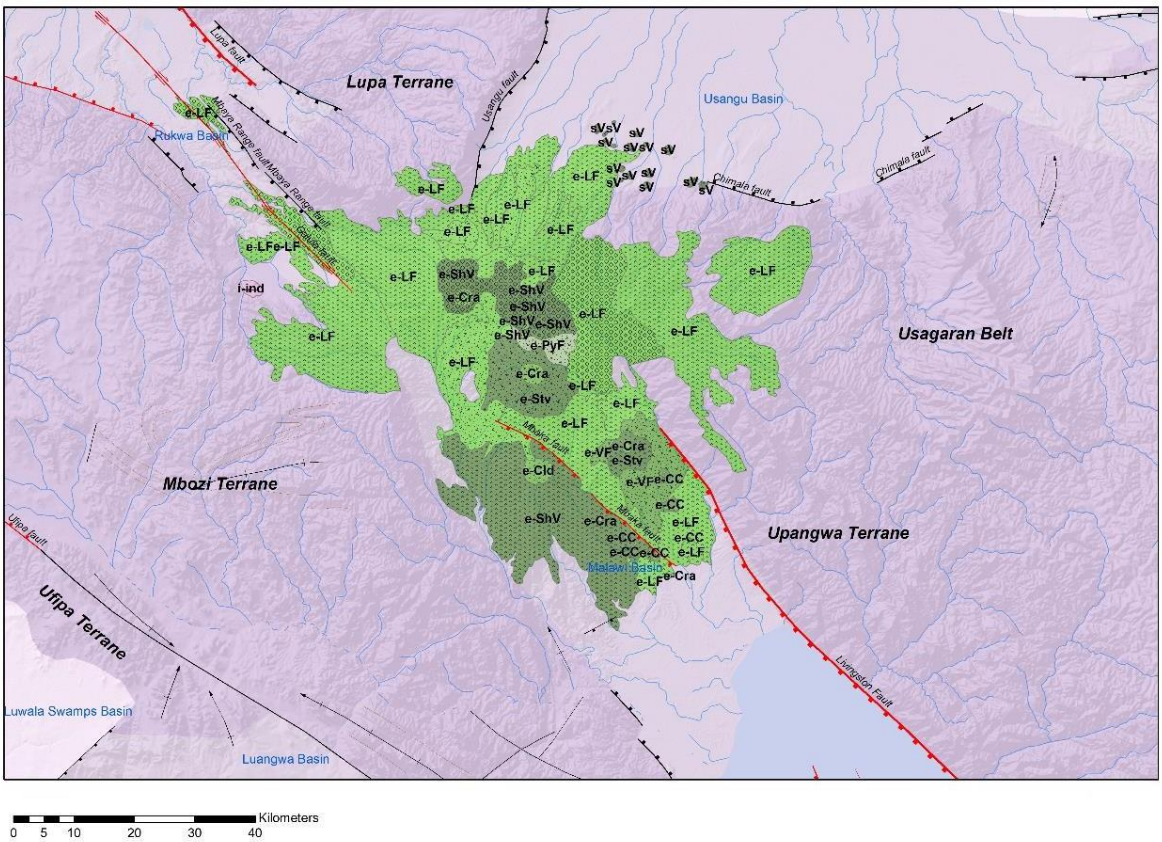

Figure 1. The Rungwe Volcanic Province in SW Tanzania showing the level of detail mapped in the database. The underlying geospatial databases show the crustal architecture of the region, which is here dominated by PanAfrican orogenic crust that was then subsequently rifted during the break-up of Gondwana (Karoo). This part of the Rukwa-Malawi rift system is currently the focus of geothermal research for which understanding the interplay of structure, crustal composition, and igneous activity is critical.

Session Two: Igneous processes and their impact on reservoirs

KEYNOTE: Sediment-hosted geothermal systems: Review and first global mapping

Sediment-hosted geothermal systems: Review and first global mapping

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Sediment-Hosted Geothermal Systems (SHGSs) are hybrid geological systems, where volcanic and sedimentary domains interact, leading to mixtures of inorganic and organic gases. Typically characterized by geothermal (thermometamorphic or mantle-derived) CO_2 and biotic (microbial or thermogenic) CH_4, SHGSs occur in sedimentary basins crossed by magmatic intrusions or involved in volcanic plumbing systems (figure 1). These systems can be of considerable interest for petroleum, geothermal exploration and natural greenhouse-gas emission studies, but systematic studies for their characterization and worldwide distribution are missing.
Here, we provide a review of SHGSs identified so far, and propose methodological criteria for their definition and identification, based on integrated geological and gas-geochemical parameters. We find that SHGSs are typically characterized by: (a) fluids dominated by mantle or decarbonation-methamorphic CO_2 (> 50 vol%); (b) considerable amounts of CH_4 and heavier hydrocarbons (at least 1.5 vol%, generally up to 30–40 vol%), produced by microbial or thermogenic degradation of organic matter hosted in sedimentary rocks; (c) tectonically active sedimentary basins (back-arc, rift zones and foredeep), generally hosting petroleum fields and within ~300 km from recent or ancient volcanic centers. This analysis resulted in a global map including a first set of 33 SHGSs located in North America, Central and Eastern Europe, Far East, Eastern Oceania and Northern New Zealand, and a second set of potential SHGS prone areas, occurring also in South America, North Africa, Middle East and Kamchatka. The potential SHGS areas mapped in this work can represent zones of significant emission of methane to the atmosphere, potential sites with gas-hazard, and new targets for petroleum and geothermal exploration.

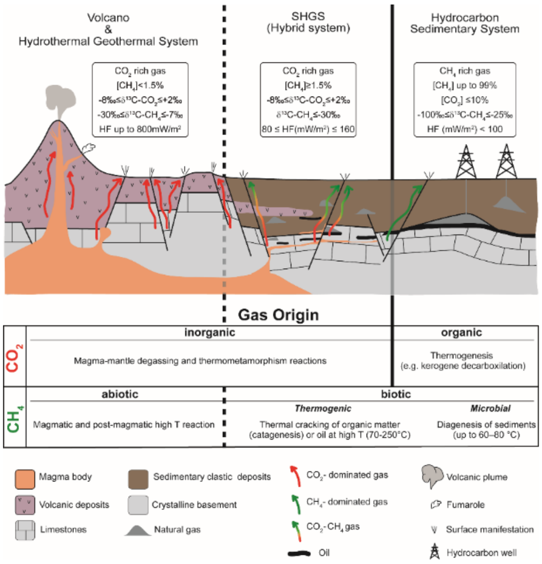

Figure 1: Conceptual geological sketch. The main gas-geochemical features are summarised for the SHGSs (hybrid system) and for the endmembers, volcano-geothermal and hydrocarbon systems. Related CO_2 and CH_4 genetic processes are also specified. The sketch is not to scale (from Procesi et al., 2019 doi.org/10.1016/j.earscirev.2019.03.020)

Lessons learnt from the impact of volcaniclastic rocks on hydrocarbon systems and their application to CO_2 storage

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Volcaniclastic rocks are generally considered to make poor hydrocarbon reservoirs. This is because they contain an abundance of mineralogically and mechanically unstable components that during burial generally lead to a quicker reduction in reservoir quality compared to "clean" siliciclastic rocks. Under favourable conditions however, such as fracturing and/or dissolution of unstable particles, volcaniclastic rocks may act as reservoirs. Indeed, volcaniclastic reservoirs are known, for example, from Japan, Indonesia and Georgia. Alternatively, secondary alteration can retard permeability resulting in volcaniclastic rocks acting as seals in conventional or unconventional plays. It is because of their highly reactive nature and suitable compositions that attention is also turning to the potential of volcaniclastic rocks to store CO_2 through carbonation and thereby, permanently fixing carbon with increased storage security.

Despite the roles volcaniclastic rocks can play within hydrocarbon systems or CO_2 storage, there is still a paucity of quantitative studies characterising them. This is commonly due to their complex secondary mineralisation pathways which can occur during diagenesis and burial. Where data does exist, it is difficult to compare like-for-like due to the application of various, often non-descriptive, naming schemes. As a result, volcaniclastic rocks are generally considered problematic and are often overlooked or avoided during the development of exploration plays. It is, therefore, imperative to quantify the nature, thickness and architecture of volcaniclastic rocks to better understand their role in hydrocarbon prospectivity and CO_2 sequestration in volcanic-bearing sedimentary basins.

Thicknesses and architectures of interlava volcaniclastic sedimentary rocks have been extensively quantified from three well-exposed onshore volcanic analogues, namely East Greenland, the Faroe Islands, and the Blue Nile and Mekele basins, Ethiopia. The latter, for example, consists of well-developed fluvial–lacustrine interlava sequences locally >200 m in thickness. Field mapping combined with multiple analyses (geochronology, geochemistry, biostratigraphy, petrographic point-counting and conventional heavy mineral analysis) of these Ethiopian interlava sequences is shedding light on the sedimentary systems that operated during volcanism and basin subsidence. This research is helping to predict lithofacies distribution and to contextualise diagenetic pathways.

More than 300 interlava (volcaniclastic and siliciclastic) samples have been collected from the three onshore field analogues. The samples cover a range of maximum burial depths (0–5 km) and the volcanic components vary in composition (mafic–felsic, subalkaline–alkaline) and texture (crystalline volcanic fragments to volcanic glass). Sixty-four volcaniclastic samples, with air permeabilities from 0 to 173 mD, exhibit a significant disparity in their helium (mean: 25.3%) and total optical (mean: 1.8%) porosities (Figure 1). The high proportion of porosity <30 µm (minimum optical resolution) is due to the abundance of secondary clays and zeolites. This is supported by subsequent Mercury Injection Capillary Pressure (MICP) and Quantitative X-ray Diffraction (QXRD) analysis. Principal component analysis of these data show that those samples with a greater abundance of zeolites compared to secondary clays (e.g. smectite) have better sealing capacities. Entry pressures for a subset of 33 samples range from 4 to 613 psia that, under surface conditions, could support hydrocarbon column heights of up to 1181 m (3875 ft) and 671 m (2201 ft) for oil and gas, respectively. The corresponding CO_2 columns heights can also be calculated under various subsurface conditions that suggest the volcaniclastic rocks could also act as baffles to CO_2 migration.

The combination of field observations (burial depths, distributions, depositional environments) and analytical techniques (Poro–Perm, MICP, QXRD) is allowing for a holistic assessment of the factors which control mineralisation, and as a consequence, whether the volcaniclastic rocks will act as hydrocarbon reservoirs or seals. Further research will build on these initial results to fully understand the reaction pathways within volcaniclastic rocks and ultimately their interaction with dissolved CO_2 to assess their storage capabilities.

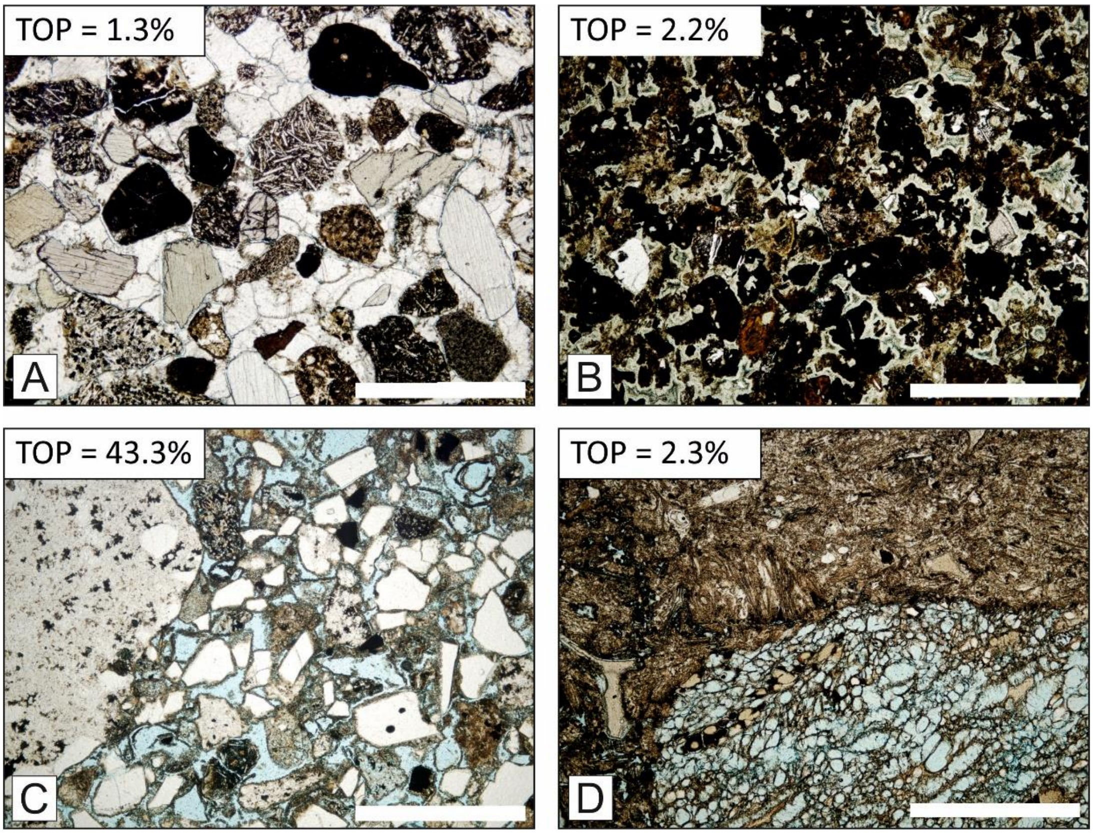

Figure 1. A selection of photomicrographs of volcaniclastic sandstones collected from three onshore analogues (East Greenland, the Faroe Islands and Ethiopia). Volcaniclastic sandstones can show a variety of different compositions, which can lead to a range of Total Optical Porosities (TOP). Pore space is stained blue. (A) and (B) Mafic-derived sandstones, (C) Felsic-derived sandstone, (D) Felsic tuff with pumice clast. Scale bars are 1 mm.

Investigating the potential for CO_2 storage in the North Atlantic Igneous Province: Reservoir properties and reactivity of the Faroe Islands Basalt Group

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Reducing anthropogenic greenhouse gas emissions is one of the biggest challenges of the 21st century and to achieve the current climate change targets, carbon will have to be removed from the atmosphere (IPCC, 2018). Pilot studies in Iceland (CarbFix) and in the US (Wallula) have shown the feasibility of storing the removed CO_2 in basalts by mineral trapping (e.g., Matter *et al.,* 2011; McGrail *et al.,* 2011). CO_2 reacts with the divalent cations released from basalt to create carbonate minerals, immobilizing it for geological timescales (e.g., McGrail *et al.,* 2006). Vast volumes of the Earth's crust consist of basaltic volcanic rocks which hold significant potential for safe, large-scale storage of CO_2 (Goldberg *et al.,* 2008). In this study, we aim to characterize the CO_2-reservoir properties of the basalt sequences on the Faroe Islands, NE Atlantic Ocean (Fig. 1A). These sequences are a part of the North Atlantic Igneous Province (NAIP; Fig. 1A) and comprise an analogue for potential offshore storage units along, e.g., the Norwegian and UK continental shelves.

During fieldwork on the Faroe Islands in June 2020, outcrop studies in the upper stratigraphy of the Faroe Islands Basalt Group (FIBG) were conducted, and virtual outcrop models, photos, and samples were collected. The Glyvursnes-1 and Tjørnunes-2 onshore boreholes were sampled, and the density log, along with grain density estimates from the Glyvursnes-1 borehole was used to calculate two end-member porosity logs through the sequences. The samples were analysed in the lab by optical microscopy, Scanning Electron Microscope (SEM), micro-CT (computer tomography) image analysis, and bulk density measurements to appraise the pore structure of the rocks. In addition, mineralogical and geochemical analyses of five field samples were combined with kinetic experiments to study their ability to release essential divalent cations that may react with CO_2.

The architecture of the lava flow lobes generally consists of an upper and lower crust, either brecciated or vesicular, with a flow low-vesicularity flow core between (Fig. 1B). The vesicles are primarily filled with secondary zeolite and clay minerals; however, some open porosity is also observed. The porosities of the flow crusts were estimated from the micro-CT image analysis and bulk density measurements to range from 3.6% to 36.2%. The highest porosity and connected porosity (Fig. 1C) are found for the unmineralized brecciated flow crusts. Fluid flow simulations through pore network models (Fig. 1C) of selected CT-scanned brecciated flow crusts reveal absolute permeabilities locally reaching up to Darcy-scale. However, the heterogeneity of the samples and secondary mineralization in the pores can quickly reduce the permeability to microdarcy-levels. The studied volcaniclastic interbeds are estimated from the porosity logs to have potentially high porosities (5% to 35%). However, optical microscopy and SEM studies reveal a high clay content, expected to produce low permeability.

The SEM and micro-CT analyses show that the flow cores and mineralized lava flow crusts have a very low current porosity (<4%). However, by combining the volume of the current, open- and mineralized-pore space in the CT scans, the primary porosities of the lava flow crusts were measured to have ranged from c. 10% to 45% accompanied by a primary connected porosity ranging from c. 6% to 42%. The high primary porosity estimates suggest that less altered and buried units in the NAIP could contain good reservoir properties.

Lastly, the kinetic experiments show that the altered flow tops and volcaniclastic sediments were less reactive than the unaltered flow cores. Ca^{2+} was the primary divalent cation released throughout the experiments favouring calcite precipitation in a CO_2 injection scenario. The zeolites have a low cation release rate relative to their surface area. However, the zeolites were still a significant source of Ca^{2+} because their surface area is extremely large. The amounts of released cations from the samples suggest that the FIBG contains rocks that would successfully react with CO_2 in an injection scenario.

In conclusion, unmineralized brecciated flow crusts have the highest reservoir potential in the studied sequences. Volcaniclastic interbeds, flow cores and mineralized basalts will likely work as caprocks or baffles for CO_2 migration. The reactivity of the lavas and volcaniclastic rocks is dependent on prior alteration, however, the rocks are likely to be reactive in contact with CO_2. The presence of reactive, high porosity, high permeability flow crusts in the FIBG prior to alteration gives hope for finding good reservoirs in less altered basalt of the NAIP offshore.

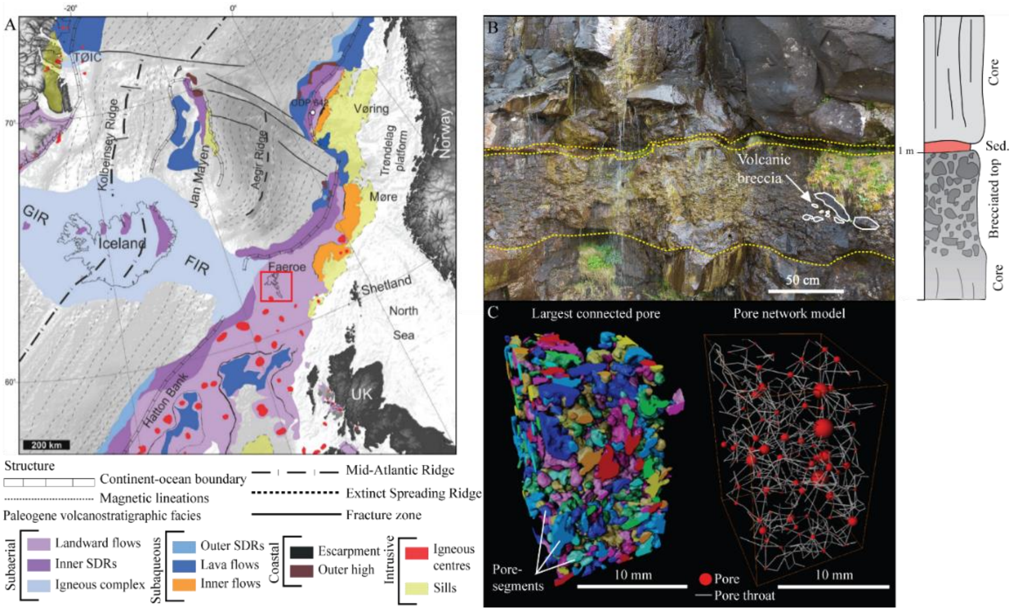

Fig. 1.* A)** *Geological map of the North Atlantic Igneous Province with the location of the Faroe Islands marked (compiled from Planke* et al. *(2020) and Abdelmalak* et al. (2017). ***B) *A brecciated lava flow top in the Enni Formation, Viðoy, Faroe Islands.* ***C)*** *The largest connected pore with accompanying pore network model in a CT scan from a brecciated flow top sample.*

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Interaction between volcanic and non-volcanic systems and its implication for prospectivity in the Faroe-Shetland Basin, Northeast Atlantic continental margin

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*Faroese Geological Survey

Early exploration for hydrocarbons on the Faroese Continental Shelf (FoCS) was driven by the discovery of large volumes of hydrocarbons in Paleocene sands in the Foinaven and Schiehallieon fields on the adjacent UK Continental Shelf (UKCS). The first wells on the FoCS were chasing the same play but did not provide analogous discoveries. The Paleocene sand play was subsequently chased further north-westwards into areas where they are covered by or interbedded with lavas, which negatively impact the ability to map intra- and pre-volcanic units.

We utilize high-quality 2D seismic data, acquired By Western Geophysical in 1994 and 1995 and reprocessed by TGS in 2012 to map the volcanic succession in the greater Judd Sub-basin area in the Faroe Shetland Basin with the purpose of improving our understanding of the structural geometry of the transition from the basaltic succession to the non-basaltic succession. We also re-evaluate the lithology of igneous units from cuttings of two wells (6005/15-1 and 6005/13-1A) and tie the well stratigraphy to the seismic data to calibrate the seismic interpretation.

Geological evolution

The seismic data show that the volcanic succession advanced into the Judd sub-basin area three times during the Palaeogene (mid- to late Vaila, Lamba and Flett times) (Figure 1).

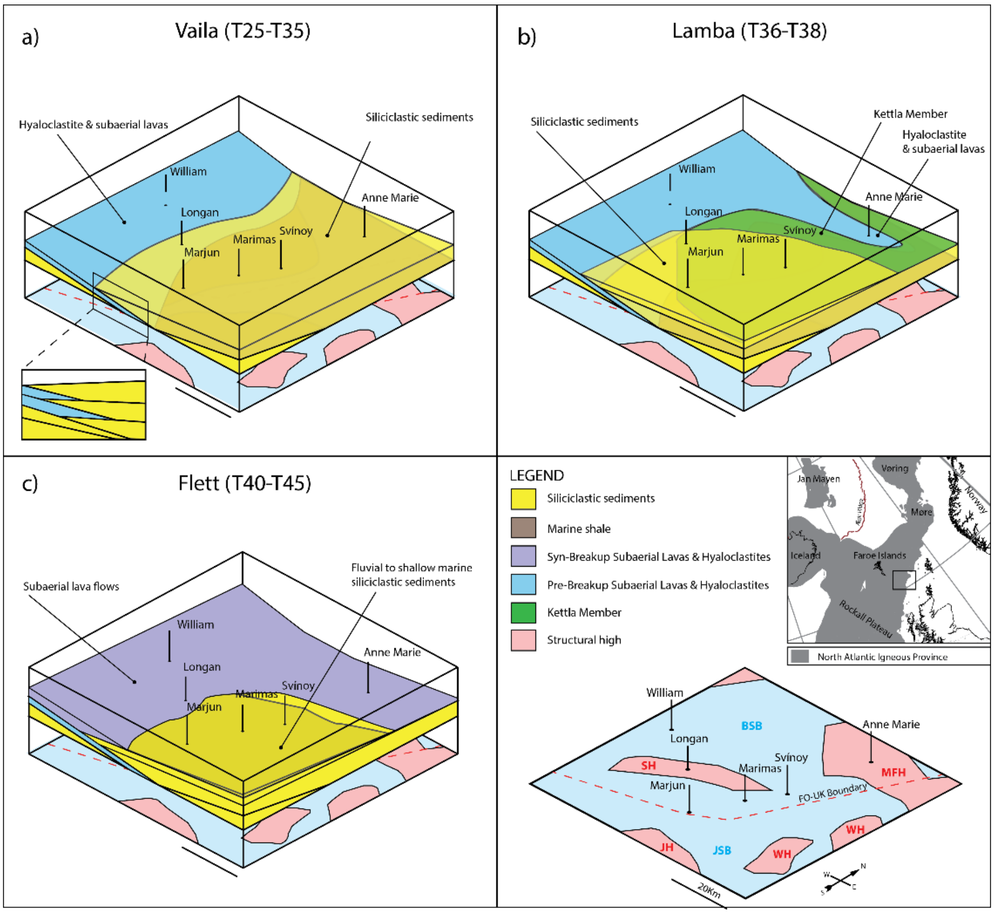

Figure 1: Synthesis of observations from the Judd sub-basin area in the early Paleogene presented as a series of conceptual geological block-diagrams. Stratigraphic T-sequences are used as age intervals. The figure is based on well analysis and seismic interpretations. See inset below for location

The mid- to late Vaila incursion (Figure 1a) advanced three times into a shallow marine environment from the west. Each advance is characterized by lavas infilling the shallow water area with hyaloclastite deposits, which are overlain by subarial basalts, before being buried by shallow marine sediments. A siliciclastic shallow marine sedimentary unit separates the two lowermost basalt sections, while volcaniclastic sediments separate the two uppermost basalt successions.

The Lamba incursion (Figure 1b) into the Judd sub-basin area, extends into the area from the west and north and covers the western, northern and eastern parts of the area. The area towards the northeast (across the Mid Faroe High) is mapped as an elongated nose of mostly volcaniclastic material deposited in a shallowing environment, where the uppermost Lamba age basalt units are emplaced subarially. In the northwestern Judd sub-basin, adjacent to the Mid Faroe High, the volcanic material is deposited as mass flow deposits while the Lamba age volcanic succession is deposited as a hyaloclastite delta towards the northeast of the area where it is drilled by well 6005/13-1A. Siliciclastic sands, drilled by wells in the central part of the basin, reach under the Lamba-volcanic succession. Seismic data quality does not indicate how far under the volcanic succession the siliciclastic succession extends.

A major sea level drop occurred in Flett formation times and resulted in widespread erosion in the Judd sub-basin area creating a dendritic drainage pattern. This was subsequently covered by subarial basalts flowing into the area from the west, north and northeast (Figure 1c). The Flett formation lavas are separated from the older Lamba Formation lavas by dominantly siliciclastic sediments, which can be mapped under the Flett Formation lavas, where they are expected to pinch out, as shown by their absence in wells 6005/13-1 and 6004/8a-1.

Implications for prospectivity

The presence of an active hydrocarbon system in the Area is demonstrated by a thick hydrocarbon column in well 6004/12-1, a thin gas column in well 6004/12-1 and shows in well 6005/15-1. The challenge has been to map potential traps in a basin where the non-volcanic sedimentary section lacks sealing lithologies. The low permeability of basaltic units means these could be the missing part of successful traps in the area. Figure 2 shows potential sealing lithologies.

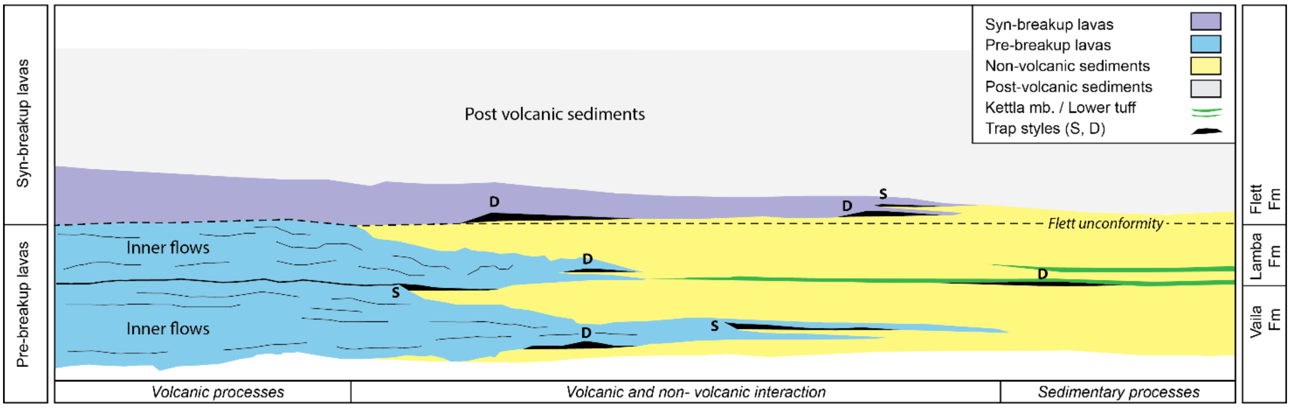

Figure 2: schematic representation of trap types, with an indicative correlation between the volcanic and non-volcanic stratigraphies. S, Stratigraphic traps; d, 4-way dip-closed structures.

Characterizing lava flow reservoir sequences: insights from global examples

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Sub-aerial lava flows form an important and often extensive component of many sedimentary basins worldwide and often represent the dominant lithologies of the emergent parts of volcanic islands such as Iceland and Hawai'i. Lava flow sequences may represent important reservoirs and have been exploited both for onshore and offshore hydrocarbon production, water aquifers, and geothermal energy for many decades, along with more recently for carbon capture and storage (CCS). Despite the important role that lava flow reservoirs already play within some regions, many aspects of these unconventional reservoirs remain poorly understood. Fundamental questions surrounding pore structure, distribution, connectivity, secondary alteration, fracturing, depth dependence, storage and flow capacity can lead to challenging appraisal and development. Within this contribution, we present an appraisal of lava flow reservoirs drawing on extensive recent multi-disciplinary studies including field exposures in Iceland, the North Atlantic and Brazil, fully cored water wells on Hawai'i, commercial hydrocarbon reservoirs in Brazil and India, and scientific drilling results from the North Atlantic including laboratory petrophysical data for porosity and permeability from a range of these different settings.

Primary reservoir properties of lava flows vary depending on a host of differing conditions including magma composition, volatile content, volumetric flow rate and total eruption volume, eruption environment, topography, and distance from source to name a few. This leads to an unsurprisingly wide variation in the initial properties of lava flows. Two end-member lava flow facies are pāhoehoe (lava flows with a smooth continuous crust) and ʻaʻā (lava flows with auto-brecciated upper and lower crusts) which bracket the range of typical possibilities and provide a useful starting point to appraise reservoir properties. A common misconception for lava flows is that vesicles (exsolved gas bubbles 'frozen in' to the magma during cooling) are never or rarely connected. However, laboratory testing and theoretical models support high connectivity of vesicle networks above a percolation threshold often around c. 30% porosity, a value which is reached in most lava flow tops leading to high, potentially multi-Darcy matrix permeabilities. Fractures may also contribute significantly to reservoir porosity and permeability either through initial cooling contraction jointing or primary auto-brecciation at flow margins, as in the case of many ʻaʻā and transitional lava facies. Most lava flows therefore begin solidified life with a complex distribution of isolated matrix pores, connected matrix pores towards the margins, and often complex fracture networks. The distribution of these features is, to a reasonable extent, predictable enabling approximations of primary porosity and permeability for a given flow type, Fig. 1. A key point about these distributions is the proportion of permeable crust, to low or impermeable interior, and that for most lava flows above a few meters thick, both will typically be present. So, lava flows often represent reservoir-seal couplets which, when vertically stacked, impart a significant anisotropy onto any package of lavas that forms a reservoir interval. These core-crust ratios can readily be appraised from sub-surface wireline data when appraising lava flow reservoirs. In conclusion, relatively young lava flows can form excellent reservoirs.

This primary porosity and permeability of lava flows forms the blueprint for everything else that comes after, which is often where complexity can increase dramatically. Even before burial, lava flows can quickly become highly altered due to sub-aerial weathering which can effectively destroy initially good reservoir properties. Basaltic lava flows are highly reactive, a feature that is receiving much interest from the carbon mineralization and CCS perspective. Therefore, fairly rapid burial and effective protection from surface weathering appears to be an important requirement in preserving good primary reservoir properties with burial depth. However, any lava flow that is subsequently buried either by further lava flows or other basin fill will typically reveal evidence for at least some degree of burial diagenesis. The positive for lava flows is that they are intrinsically strong and can withstand pressures associated with burial up to several kilometers with often negligible mechanical influence on vesicular porosity, a feature that separates them fundamentally from most sediments.

However, in addition to ‘normal’ burial, by their very nature, lava flows are deposited in volcanically active regions which often have high geothermal gradients and extensive hydrothermal fluid flow systems which can impart fundamental changes to reservoir properties via alteration and secondary mineralization. How alteration and secondary mineralization progresses with depth has seen significant debate and is most extensively studied within the geothermal industry, but also through field studies of ancient volcanic piles. We present results from fully cored Hawaiian and North Atlantic boreholes to highlight that alteration and mineralization, and their effects on reservoir properties clearly do not evolve simply or linearly with depth, and attribute this to a combination of the initial reservoir properties within lava flow sequences, and the impact of intrusions and associated hydrothermal fluid flow. Clearly no one glove fits all, and in contrast to primary reservoir properties, suitable predictive models for sub-surface lava flows prior to drilling presents a major challenge.

Even after extensive alteration, lava flows can still form effective but typically much tighter reservoirs requiring for example fracture stimulation as in examples from onshore Deccan, India. However, even in these cases, reservoir properties appear to be fundamentally linked to the initial volcanic facies with higher porosity and permeability remaining linked to flow margins rather than flow interiors. Detailed volcanological interpretation and characterization of primary volcanic facies and their initial reservoir properties and distribution therefore appears fundamental to reservoir appraisal regardless of the alteration state of a given reservoir. Post-emplacement faulting and fracturing can also play an important role in igneous reservoir development and should be appraised alongside volcanic facies interpretation. Finally, with the increasing availability of laboratory and wireline data through lava flow reservoirs, the development of fit-for-purpose rock physics models for different lava flow facies is gathering momentum. Initial results are presented which highlight the possibilities and challenges of identifying fluid effects in stiff lava flow facies and highlights the necessity for further study.

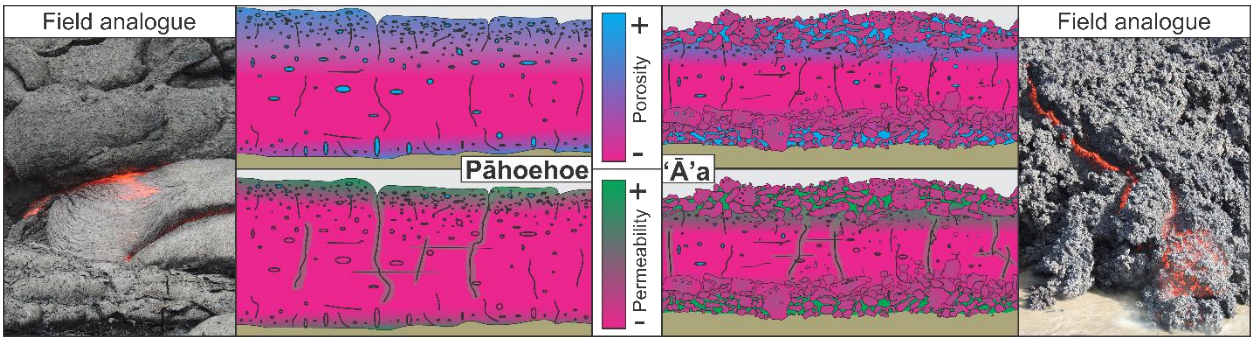

Fig. 1. *Schematic simplified conceptual cross sections through pāhoehoe and ‘a‘ā lava flow facies highlighting key differences in the distribution of primary porosity and permeability.*

The impact of Etendeka flood basalts on the diagenesis of the fluvio-aeolian Jurassic Etjo Formation, Namibia

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The rapid effusion of volcanic rocks of large igneous provinces results in a relatively rapid burial of underlying rocks. In such settings, siliciclastic deposits and potential reservoir rock may on the one hand experience a high degree of mechanical compaction prior to the onset of significant chemical compaction, while on the other hand an increased geothermal gradient or hydrothermal activity may speed up cementation processes.

To assess such impact, we present the results of a study on the diagenesis of the aeolian upper unit of the Jurassic Etjo Formation in Namibia, that was subject to burial related to the emplacement of the voluminous Lower Cretaceous Etendeka flood basalts that reached presumed thicknesses of up to c. 2-5 km, and is today again exposed at the Earth's surface. We have studied the Etjo Formation at three key localities, namely Waterberg, Mt. Etjo, and Gamsberg, that lie >100 km apart from each other. At all locations, the sandstone is texturally mature and quartzose with very low quantities of feldspars and lithic grains. However, petrographic analysis shows that the Etjo Formation has experienced a very different diagenesis at each location with respect to intergranular volume (IGV) and quartz cementation (Fig. 1). Average IGV and quartz cement values are 23.7 % and 6.5 % (Waterberg), 19.7 % and 15.4 % (Mt. Etjo), and 30.7 % and 24.3 % (Gamsberg). Porosity values, based on buoyancy measurements, are on average 21.0 w.t.% (Waterberg), 8.1 w.t.% (Mt. Etjo), and 5.2 w.t.% (Gamsberg). Also permeability, based on air permeameter measurements, varies between the locations with highest values at Waterberg (15 – 2819 mD), intermediate values at Mt. Etjo (14 – 132 mD), and lowest values at Gamsberg (2 – 82 mD).

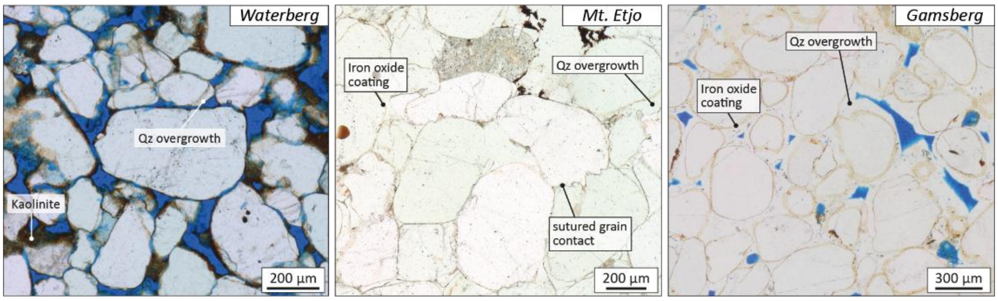

Fig. 2: Thin section photos of the Etjo Fm. at the three study locations highlighting the differences in compaction, cementation, and porosity.

We attribute the differences of IGV and quartz cement to spatial thickness variations of the overlying volcanic rock column. Higher compaction and cementation values at Mt. Etjo compared to Waterberg are likely related to the proximity of Mt. Etjo to the presumed center of Etendeka volcanism. Gamsberg is the only location where a first generation of quartz overgrowth formed prior to Etendeka burial, as evidenced by cathodoluminescence imagery, which likely has stabilized the grain framework to prevent further mechanical compaction during this burial. These interpretations are supported by Touchstone^{TM} numerical modeling for sandstone diagenesis. Permeability appears to be linked to the summed up quantity of quartz cement and eogenetic infiltrated clay.

Our study demonstrates the variability in diagenetic properties that a sandstone formation can attain depending on its location under a massive sheet of flood volcanic rocks.

The role of volcanism in the deposition, diagenesis, and hydrothermal alteration of Aptian Pre-Salt reservoirs from Brazilian offshore basins

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The magmatic events and their related hydrothermal fluids played a fundamental role in the formation, diagenesis, and quality of the Aptian Pre-Salt reservoirs of Campos and Santos basins, offshore eastern Brazil. Hydrothermal vents have been recognized in seismic lines of these basins. On the other hand, the anomalous amount of CO_2 in Pre-Salt reservoirs is ascribed to coeval volcanic events and even possible mantle exhumation, or to the emplacement of intrusive igneous rocks in the subjacent rift succession, rich in carbonate and organic matter. The Brazilian Pre-Salt succession was impacted by igneous activity synchronous to the sedimentation, as well as by intrusions of Santonian-Campanian age. Hydrothermal alterations represent the evidence of a geothermal anomaly, requiring both a mechanism (heat source) and conduits for the flow of fluids through deep fault systems. Such focalization of fluids and their interaction with the host rocks are linked to the origin of carbonate-hosted base metal deposits (e.g., the Pb-Zn Mississippi Valley type deposits) and have also significantly modified the original properties of some Pre-Salt reservoirs. However, the relationship between hydrothermal circulation and igneous rock emplacement based on seismic interpretation are still sparse in Brazilian basins, being even rarer research involving their influence on the carbonate reservoirs quality. In this study, we show that the deposition, diagenetic and hydrothermal alterations of the Pre-Salt reservoirs were closely associated with igneous activity contemporaneous and after the deposition of the Pre-Salt sediments. We found evidence that some minerals such as quartz, chalcedony, barite, saddle dolomite, calcite, fluorite, and APS minerals were precipitated from fluids from a magmatic-hydrothermal system. In addition to that, intrusive magmatism and penecontemporaneous volcanic activity, identified in Pre-Salt cores and in 3D seismic interpretation of the Santos Basin, have influenced the water chemistry and basin evolution. The chemical weathering of basaltic rocks, enhanced in by high pCO_2 generated an alkaline lacustrine system with elevated activity of Mg, Ca, Si and HCO_3, which promoted the precipitation of abundant Mg-silicates, mostly of stevensite and kerolite. Adding the possibility of a $CaCl_2$ hydrothermal marine brine input via seepage, the volcanic rocks could contribute to an uncommon evaporitic basin saturated in calcium carbonate. Besides controlling the water chemistry, the distribution of volcanism influenced the large-scale architecture of the succession. Seismic interpretations suggested that the deposition of this uncommon carbonates was controlled, besides other factors, by the spatial and temporal accumulation pattern of basinal volcanics, which locally conditioned progradational geometries and controlled the shape of the slopes. Nevertheless, the role of extrusive and intrusive magmatism and associated hydrothermalism in the genesis and evolution of the reservoirs and their quality is still poorly understood and matter of considerable geological debate. The importance of recognizing the distribution of these processes and their impact on the Pre-Salt reservoirs must be stressed, since they may represent be either detrimental or beneficial to the porosity, permeability, connectivity, or compartmentalization of the reservoirs, which may considerably impact exploration and field development.

Keywords: Magmatism, Santos Basin, Campos Basin, Hydrothermalism, Vents, CO_2

Island Dolomitization in the Cretaceous Calcitic Ocean: A New Insight on the Role of Volcanism in Carbonate Dolomitization

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Dolomitized atolls are favourable targets to try and solve the “dolomite problem”, as they haven’t been buried significantly and they originate within depositional systems that can be correlated to modern analogues such as the Bahamas. One good example of dolomitized ancient atolls is the Cretaceous Mid-pacific atolls where limestones within up to ~500 m above the volcanic basement are dolomitized (e.g. Resolution guyot; targeted by Ocean Drilling Program Leg 143). Earlier studies on those atolls favoured seawater dolomitization through Kohout model, in part because seawater is a sufficient source for Mg^{2+} ions in modern settings. But a problem is that for dolomitization to occur, the fluids need to have a sufficiently high Mg/Ca ratio. This is more problematic during the Cretaceous than in the modern oceans as Mg/Ca ratio of seawater was ≤ 1. By extension, the proposed seawater dolomitization model for Cretaceous atolls needs to be revisited. To investigate the likely mechanism of dolomitization in Cretaceous atolls, we use core-log-seismic integration and the existing geochemical data collected during Leg 143 (e.g. $^{87}Sr/^{86}Sr$, $^{40}Ar/^{39}Ar$ ages, $\delta^{18}O$, and ICP-AES) from Resolution Guyot, a prime example of Mid-Pacific Cretaceous Atolls.

We observe that the dolomites in close proximity to the volcanic basement show enrichment in iron content with values much higher than seawater dolomites. In addition, we reveal for the first time using seismic reflection profiles, the presence of volcanic sill intrusions in close vicinity to the depths where the succession is dolomitized. As no sills have been drilled in the ODP Site 866 at Resolution Guyot, we attempt to validate the sills interpretation using synthetic seismic modelling based on the thicknesses of the drilled sills in a nearby Cretaceous atoll, Allison Guyot. Our observation on seismic data is that these sills are associated with large (100s to 1000s of meters width) vertical structures cutting through the sedimentary succession, which we interpret as large conduits (i.e. hydrothermal vents) for fluid-flow through the atoll. Moreover, the estimated temperatures of the dolomite from $\delta^{18}O$ are higher than the estimated paleotemperature history of the host rock using the average temperature gradients of Enewetak Atoll as an example Furthermore, the $^{87}Sr/^{86}Sr$ age model for the dolomites and $^{40}Ar/^{39}Ar$ ages of the basement samples are overlapping, which would suggest a temporal coexistence between dolomitization and volcanic activity(ies).

Putting all of these observations together, we propose a hydrothermal dolomitization model for the Cretaceous Mid-Pacific atolls. Sill emplacement and the associated hydrothermal fluids potentially produced a thermal drive for seawater circulation through the atoll. The released volatiles from the emplacement (e.g. H_2O-CO_2-(SO_2)) might have lowered the pH of the circulating fluids causing localized porewater acidification which would lead to releasing magnesium from the alteration of olivine and pyroxene in the basaltic basement. The increase in temperature of the fluid and in Mg/Ca ratio would overcome the kinetic barrier for Cretaceous seawater dolomitization, explain the large-scale presence of dolomite at these locations.

The study provides a unique insight on the impact of volcanic activity on the diagenetic evolution of early Cretaceous shallow-marine carbonates. The possible ages of the extensive dolomitization at Resolution Guyot and volcanic basement are overlapping with the emplacement and the elevated hydrothermal activities of the Ontong-Java and Manihiki Plateaus at 125 Ma and Kerguelen Plateau at 118 Ma, giving a possible global context to our dolomitization model that needs further evaluation. Taking this study as an analogue, the induced dolomitization and venting system would impact the host rock porosity evolution and integrity which are crucial in resource plays assessment.

Session Three: Heat and basin analysis – the impact on resources

KEYNOTE - Role of igneous intrusion in controlling gas migration and contaminant charge in the UKCS

Role of igneous intrusion in controlling gas migration and contaminant charge in the UKCS

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The intrusion of vertical igneous dykes has significant implications for our understanding of gas prospectivity and the occurrence of carbon dioxide (CO2) and nitrogen contaminants in the Silverpit area of the Southern North Sea and northern parts of the East Irish Sea Basins. Whilst many of the prospective gas fields in the Silverpit area contain Carboniferous reservoirs, five closures have proven to contain gas within the stratigraphically younger and structurally higher, Triassic Bunter Sandstone Formation reservoir (Caister B; Hunter; Esmond; Forbes and Gordon). Quite how gas migrated up through a seal consisting of thick (>350 m) coherent Middle–Upper Permian Silverpit Claystone Formation, variable thicknesses of Upper Permian Zechstein Supergroup evaporites, the Brockelschiefer and the Bunter Shale Formation has long been a mystery. It has generally been thought that welding (touchdown) of the Triassic overburden and/or faulting affecting the Variscan (Base Permian) Unconformity might juxtapose the Carboniferous source rocks, breached traps containing Palaeozoic reservoirs and Triassic carrier beds. However, in the absence of total evaporite withdrawal and, hence, any clear welds and complete lack of evidence for erosion of either the Silverpit Claystone Formation or Bunter Shale Formation seals, leads to the conclusion that the vertical migration along the sides of the through-going, syncline-axial, pipe-like fractures resulting from Cenozoic igneous intrusion. Strong support for the hypothesis comes from the close spatial association between gas-field occurrence in salt-cored anticlines and the presence of Palaeogene igneous dykes in the intervening synclinal axes implies that whilst Triassic prospectivity is enhanced in those anticlinal structures that lie adjacent to dyke intrusions, exploration risk is conversely greater where no dykes occur and, hence, where no vertical gas migration pathway can be recognized. Whilst the presence of dykes has introduced gas into the Triassic reservoirs in the SNS their occurrence also introduced natural CO2 in the Triassic Ormskirk Sandstone Formation of the East Irish Sea, something that necessitated a dedicated gas facility at Barrow to handle and remove the contaminant. Although often ignored in studies that seek to identify and map prospective traps, the research demonstrates that an understanding of the density and distribution of igneous intrusions may provide an early indication of gas charge, the presence of contaminants and highlight the occurrence of robust carbon storage sites.

Are all basement fault zones the loci of geothermal heat? A paradoxical, but still economically significant, case study from the Southern North Sea

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Extensional basins are favourable areas to produce geothermal energy, as fault zones crossing their basement rocks in these basins can form large conduits for fluid and heat. This talk will use high-quality 3D seismic data from the Central Offshore Platform (Southern North Sea) to document a 10 km-wide basement fault zone above which fluid anomalies emanate from pre-salt reservoirs (Fig. 1a). The seismic data are complemented by information from 38 boreholes, namely lithological and bottom-hole temperature data. Fluid and heat flow is interpreted to have resulted from a magmatic pulse affecting the northern part of the Netherlands (Bonté et al., 2020).

Fluid blow-out pipes, chimneys and low-amplitude trails occur in a region where NW-striking syn-rift faults intersect the N-striking basement fault zone. In detail, 73% of the mapped fluid-flow anomalies (94 out of 129) occur within the basement fault zone of interest or follow a N-S strike along its shoulders. The documented faults are an imprint of the basement structures formed during the Caledonian Orogeny, being decoupled in terms of their geometry and distribution from the N-S basement fault zone that dominates the 3D seismic volume. An important detail is that fault throw and length do not vary in a systematic way across basement fault zone. Throws vary from 15 to 320 m (Figs. 7a and 7c) while fault length ranges from 325 m to 4725 m with no clear distribution in each of the Sectors investigated (Fig. 1b). Fault geometries are thus similar across three sectors (Sectors A to C) considered in this study, demonstrating no significant strain partition in the study area.

A key piece of information is gathered from bottom-hole temperatures in Sectors A to C. Bottom-hole data record temperatures of ~140ºC at Rotliegend level, confirming the geothermal potential of the study area. However, Sectors A to C do no show much difference in bottom-hole temperatures and corresponding geothermal gradients. Bottom-hole temperatures correlate very well with the PetroMod® thermal modelling, being only 0-15ºC hotter than the models, but also reveal that thermal gradients are now rebalanced across Sectors A to C. This implies that basement fault zones may have rebalanced their temperatures after a main magmatic/heat-flow episode/

We postulate a strong control of the basement fault zone on past fluid and heat flow, as basin models confirm that fluid and heat were mostly produced during the Cretaceous. Bottom-hole temperatures highlight the geothermal potential of the study area. These temperatures nevertheless contrast with the relatively constant gradient of ~ 32ºC/km occurring both in and outside the basement fault zone. Hence, this talk will stress how important is to characterise basement fault zones in detail, as its shows that past fluid and heat flow over such structures does not necessarily correlate with the existence of an enhanced hydrothermal system at present. Nevertheless, as recorded bottom-hole temperatures are within the benchmark values considered across Europe, this work stresses the importance of basement fault zones as key structures to find, and assess, as potential geothermal sites.

The talk will end by concluding that, as seismic resolution and the imaging of magmatic features improves, the reliability of interpreting the presence and timing of formation of fluid migration pathways will also improve. We consider the future use of high-resolution, high-quality seismic data as paramount to understanding the true geometry of magma on continental margins. Many of the so-called ‘ancient’ magmatic systems may still be active at present, comprising areas posed for the exploration of geothermal energy.

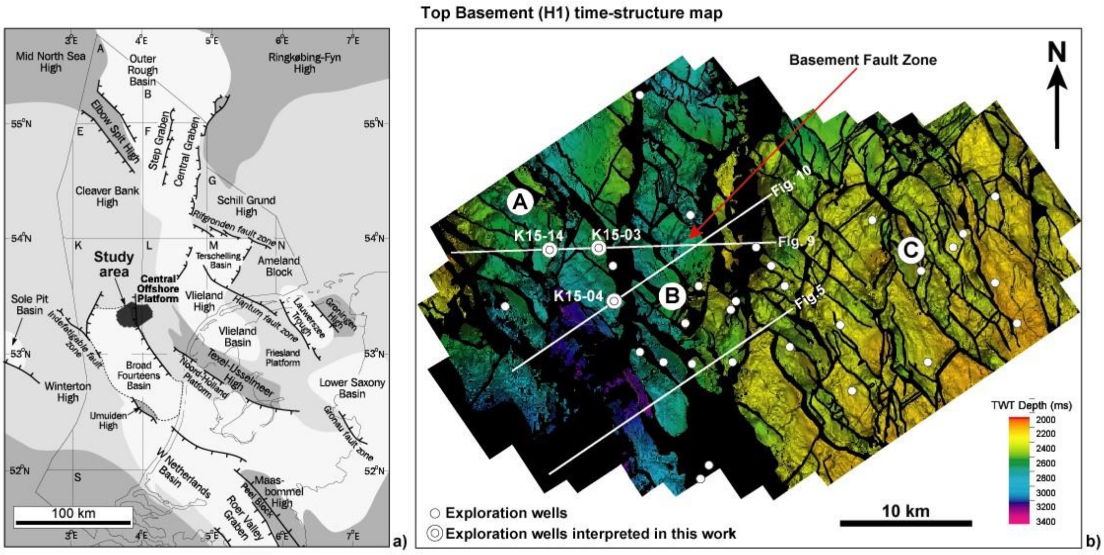

Figure 1 – a) Location of the study area, at the western limit of the Central Offshore Platform, Southern North Sea (modified from Verweij and Simmelink, 2002). b) Structural map of the basement (Horizon H1) highlighting the basement fault zone interpreted in this work. Structural Sectors A to C are shown in the figure, with the latter zone comprising part of the Central Offshore Saddle. The location of industry boreholes and seismic profiles included in this paper is also shown. Figure modified from Alves et al. (2022).

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Lower crustal reflectivity beneath the Corona Ridge, Faroe-Shetland Basin.

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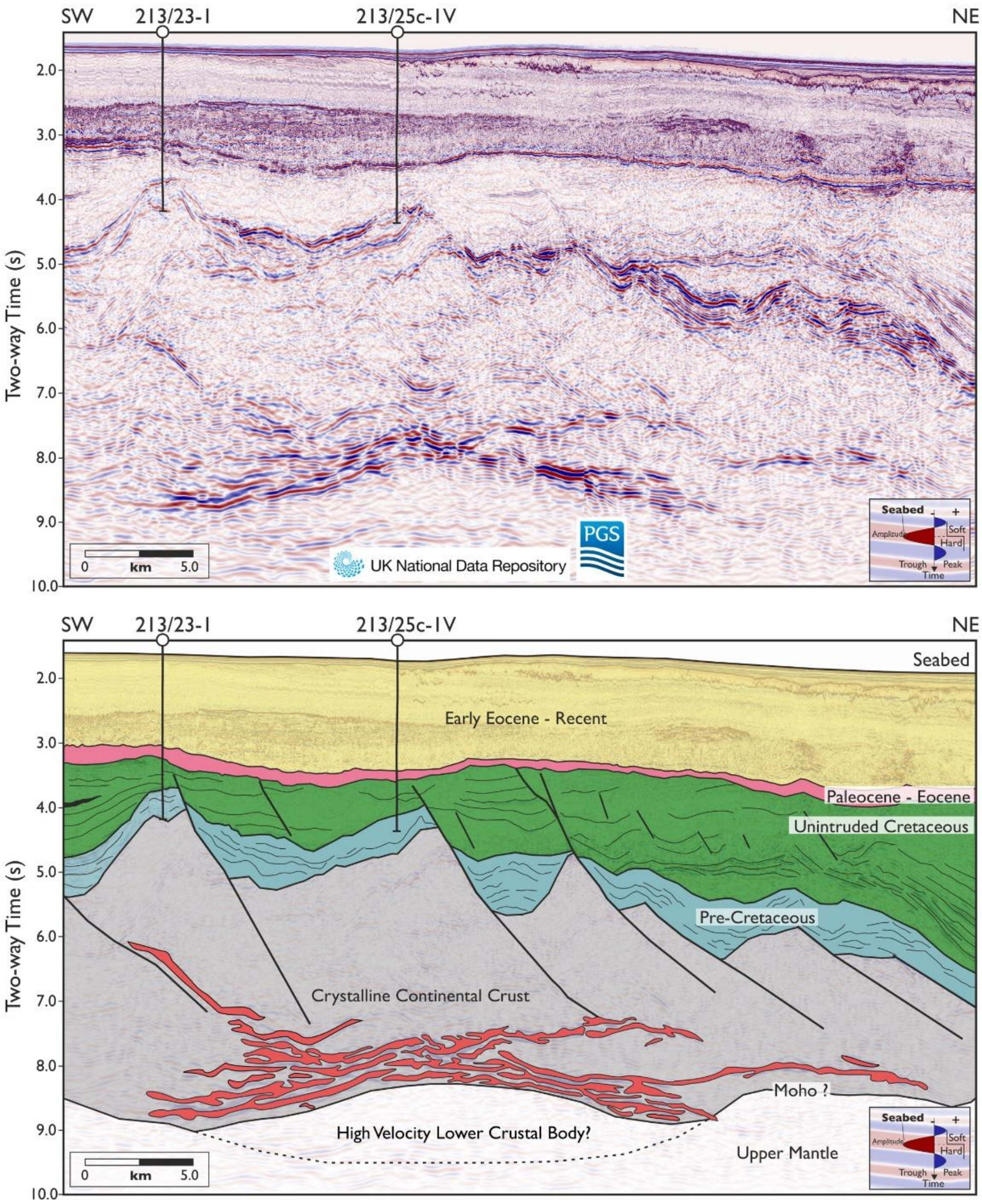
The addition of magma within the lower crust is considered a common process along volcanic margins, including the NE Atlantic, where lower crustal intrusion is well documented and understood to have formed during Paleogene volcanism. Throughout Paleogene volcanism, large volumes of melt generated within the mantle made it through the stretched and thinned crust to be emplaced within sedimentary basins along the NE Atlantic Margin such as the Faroe-Shetland Basin (FSB), forming the North Atlantic Igneous Province (NAIP). A large volume of mantle melt generated during Paleogene volcanism is also thought to have solidified at the Moho and have been emplaced as lower crustal intrusions. The presence of magma at the Moho and within the lower crust (previously described as magmatic underplating) is thought to represent a volumetrically significant portion of the magma plumbing system of large igneous provinces, including the NAIP, although the nature of deep crustal plumbing systems remains enigmatic.

Advances in sub-basalt seismic acquisition and processing have continued to facilitate the imaging of deep crustal structures along the NE Atlantic Margin. However, in contrast to the rest of the NE Atlantic Margin, only inferred evidence of lower crustal intrusion (e.g., permanent uplift and heat-flow) has been published throughout the basin. Nevertheless, the addition of magma within the lower crust and/or proximal to the Moho is understood to have played a significant role regarding Palaeogene uplift and the subsequent deposition of prospective Palaeocene to Eocene sequences within the FSB. The presence of igneous material within the lower crust and/or at the Moho beneath the basin has previously largely been assumed due to the widespread presence of vast flood basalts (The Faroe Islands Basalt Group) and igneous intrusions (The Faroe-Shetland Sill Complex), thought to be sourced from a deep crustal 'magma chamber' located beneath the region during Palaeogene volcanism.

By analysing high-quality 3-D seismic data, we have mapped a series of deep (*c.* 14 to 20 km depth) high-amplitude reflections beneath the central-northern Corona Ridge which are analogous to examples of lower crustal intrusion interpreted along the NE Atlantic Margin. Mapping suggests possible volumes of igneous material may be as much as between 890 km^3 and 1800 km^3, with possible cumulative thicknesses up to 4.28 km beneath the central-northern Corona Ridge, when also accounting for igneous material not imaged within the 3-D seismic data. Gravity modelling of a 2-D seismic line located along the central-northern Corona Ridge also supports the interpretation of lower crustal intrusion. These findings are the first possible seismic evidence of lower crustal intrusion within the FSB, which may have acted as a deep crustal 'magma chamber' during Paleogene volcanism.

With further work, these findings may facilitate further understanding of the extent to which lower crustal intrusion may have impacted basin heat flow and subsequent source rock maturity and petroleum expulsion timing. Our results may also provide more constraint on the amount of permanent Palaeogene uplift caused by lower crustal intrusion and may assist further understanding into the distribution of the subsequent Palaeocene to Eocene input of prospective clastic reservoir sequences within the region.

Figure 1: NE-SW arbitrary seismic line and geoseismic interpretation along the central-northern Corona Ridge through exploration wells 213/23-1 (Eriboll) and 213/25c-1V (North Uist). 3-D seismic data shown was acquired by PGS Exploration and freely available from the Oil & Gas Authority National Data Repository.



The Phonolites of the Kerio Valley Basin: Characterising a competing fluvio-lacustrine & alkali-rich volcanic succession within a frontier hydrocarbon exploration realm of the East African Rift

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In 2015 Tullow Oil drilled Cheptuket-1, the first ever hydrocarbon exploration well within the Kerio Valley Basin (KVB), Kenya. The area, located within the Eastern Branch of the East African Rift, has attracted interest due to the source rock outcrops on its flexural margin (Tugen Hills). The well recorded a complex succession of Miocene to Recent sedimentary rocks and volcanics. The volcanic stratigraphy is dominated by alkali-rich volcanic rocks, including phonolite lavas flows, some of which may represent some of the longest continuous lava flows on Earth. This paper presents the findings of an integrated geological and geophysical investigation where fieldwork in the excellent exposures of the exhumed basin periphery are incorporated with the well, seismic, and FTG data to help form our understanding of the tectonic, magmatic, sedimentary evolution of the basin.

The KVB is bounded by the N- S trending Elgeyo fault, located at the transition between the Tanzanian Craton and the Mozambique Mobile Belt. The presence of NW-SE pre-cursive fabrics may influence the segmental development of the fault and the resultant morphology. Varying fault segment subsidence rates led to depocentre shifts during extension (~16-7 Ma). Contemporaneously, multiple eruptions of low viscosity phonolitic lavas occurred across the region interacting with the prevailing sedimentary systems. Post 7 Ma the extensional axis shifts eastward from the KVB leading to the formation of the Baringo Basin and footwall uplift of the Tugen Hills. Finally, a late-stage local uplift occurs in the north of the basin resulting in a similar structural framework to the South Lokichar Basin. The description of sedimentary logs and sample successions from the exposed Elgeyo footwall, the Tugen Hills and Cheptuket Well, coupled with Ar-Ar ages of interbedded volcanic units, facilitate the interpretation of a palaeogeographies through time. The base of the stratigraphy is represented by predominantly pre-kinematic fluvial depositional environments (~18-20 Ma), which developed into a fluvio-lacustrine setting as the Elgeyo Fault began to subside during a warm, wet climatic period (~16-13 Ma). Highly variable lakes housed a plethora of depositional environments with evidence of alluvial fans, fluvial sandstones, sandy shorefaces, oolitic sands and organic rich, fossil laden muds. Cheptuket-1 is also likely globally one of the thickest commercial penetrations of alkali-rich volcanic rocks, with a diverse suite of wireline and image logs, calibrated with side-wall cores, allowing a high-resolution characterisation of a competing
volcano-sedimentary system.

Greenstones as a source of Hydrogen in Sedimentary Basins

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'Greenstones' are presented as a source of hydrogen by serpentinisation in sedimentary basins. They are formed by igneous (both extrusive and intrusive) and sedimentary rock sequences of Archaean and Proterozoic age as part of granite-greenstone belts, often forming the basement to younger intra-cratonic basins. Significantly the igneous rocks include ultramafic extrusive rocks (e.g. komatiites) and intrusives (e.g. peridotites and dunites), which are olivine-rich and constitute the protolith (source rock) for serpentinisation. Greenstones are usually metamorphosed to greenschist grade and are complexly structured with 'primitive' fold thrust belts whose synclinal keels tend to be dominated by volcanics and their cores by sediments.

A potentially-commercial hydrogen discovery has been made at Bourakebougou in the southern margin of the Taoudeni basin of Mali (Prinzhofer *et al.* 2018). The Taoudeni Basin is an intra-cratonic basin overlying the West African Craton. The most likely source of the hydrogen is currently-active serpentinisation of a greenstone protolith within the 2.2-2.1 Ga Birimian Greenstones of the West African Craton. Where exposed these greenstones are seen to be comprised of metamorphosed peridotites, gabbros and basalts overlain by quartzites, andesites and rhyolites.

Serpentinisation requires an effective supply of water interacting with the olivine protolith at optimum temperatures of 250-310ºC. The importance of the basin setting is that extra-basinal 'source rocks' can achieve the required temperatures by burial under a 'normal' continental basal heat flow regime. The key to generating significant volumes of hydrogen in the subsurface is for meteoric water to access basement along the basin margin ('topographically-driven system') and/or via fault systems within the basin ('fault-driven system'). Major, neo-tectonically-active fault systems are recognised traversing the southern Taoudeni Basin proximal to the hydrogen occurrences.

Hydrogen is expected to migrate and accumulate in basin sediments in the same way as gaseous hydrocarbons. However due to the mobility of hydrogen an important function of the basin setting is that the sediments act as a blanket in slowing down the migration of hydrogen from the source to dissipation in the atmosphere. In this regard 'older' more diagenetically-altered basin sediments (Proterozoic-Lower Palaeozoic), as in the Taoudeni Basin, are likely to be more retentive. Early Jurassic intrusives, common in the southern part of the Taoudeni Basin, have played an important role in sediment diagenesis and probably in forming seals or aquitards to vertically-diffusing hydrogen. However, despite the effectiveness of the seal, retention (preservation) times are expected to be shorter for hydrogen (i.e. on human time-scales). This is important because, unlike for hydrocarbons, the hydrogen source is thereby required to be currently active. This also means that hydrogen resources are potentially replenishable.

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Understanding volcanic margin prospectivity; insights from the north and south Atlantic margins

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Volcanic margins and basins with significant volcanic influence are increasingly being targeted for exploration purposes. Petroleum prospectivity, sites for basalt carbon sequestration (BCS), mineral deposits and geothermal systems present a wide portfolio of interests which are directly influenced by the distribution and nature of volcanics and intrusions. The Volcanic Margin Petroleum Prospectivity (VMAPP) project, which is now in its second phasewas initiated in 2016, aiming to improve understanding of these frontier margins and of the impacts both positive and negative of volcanism in these settings. In the context of hydrocarbon prospectivity, the influence of volcanism, volcanics, and their associated plumbing systems can be seen through all the stages of the total petroleum system (source, maturation, migration, trap,reservoir, seal). This can be mapped out into margin models that help assess the sub, intra, and supra volcanic parts of the system (e.g. Fig. 1), as well as better conceptualizing the volcanic basin framework, to help teams spanning a range of different disciplines from Exploration through to Production..

Fundamental volcanic units such as; lava flows, hyaloclastites and intrusions, are shown to contain key facies and intra-facies variations that can be mapped out in 3D with the aid of exceptional onshore analogues spanning the entire Atlantic margins from examples in Namibia, Brazil, Angola, UK and Ireland, Greenland, and modern Iceland. These key facies and their distributions can be used to help understand reservoir characteristics showing how properties such as velocity, density, porosity and permeability are distributed, and can also then be linked with extensive global core, wireline, cuttings and ultimately seismic data in order to build holistic modern understanding of these systems. A key element behind this assessment is the use of an integrated approach to our understanding. Information from outcrop analogues, modern process and geological models, is integrated into seismic interpretation and constrained further with well data (e.g. Fig. 2). Using each stage to help inform the others, revisiting the interpretations with improved models and understanding, and using additional volcanic margin analogues and examples from an increasing database of VMAPP study areas, the most realistic interpretation of the subsurface is achieved. Currently we have used this approach to assess the volcanic components and their influence within the north and south Atlantic Margins providing detailed Basin Modules, borehole study reports and a number of publications on all aspects of the system from seismic to reservoir and from outcrop to 3D geological models. By building up a volcanic facies model that looks at the types and styles of volcanism from sub-aerial through coastal to submarine in different margin configurations, as well as the styles of intrusions and the processes occurring in their contact aureoles, the true influence of volcanism within basins can be assessed as well as the potential for the volcanics themselves as reservoir targets (e.g. for petroleum and BCS prospectivity).

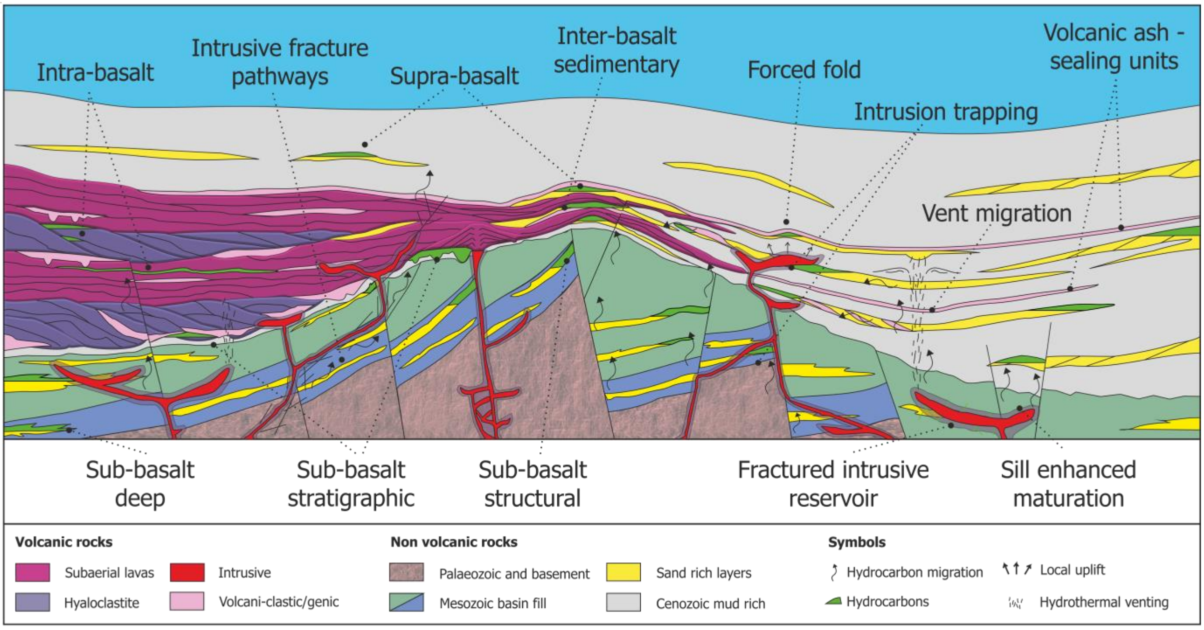

Fig. 1. *Rifted margin model highlighting key volcanic facies, associated facies relationships and structures, and a number of potential plays from sub-volcanic, intra-volcanic to supra-volcanic.*

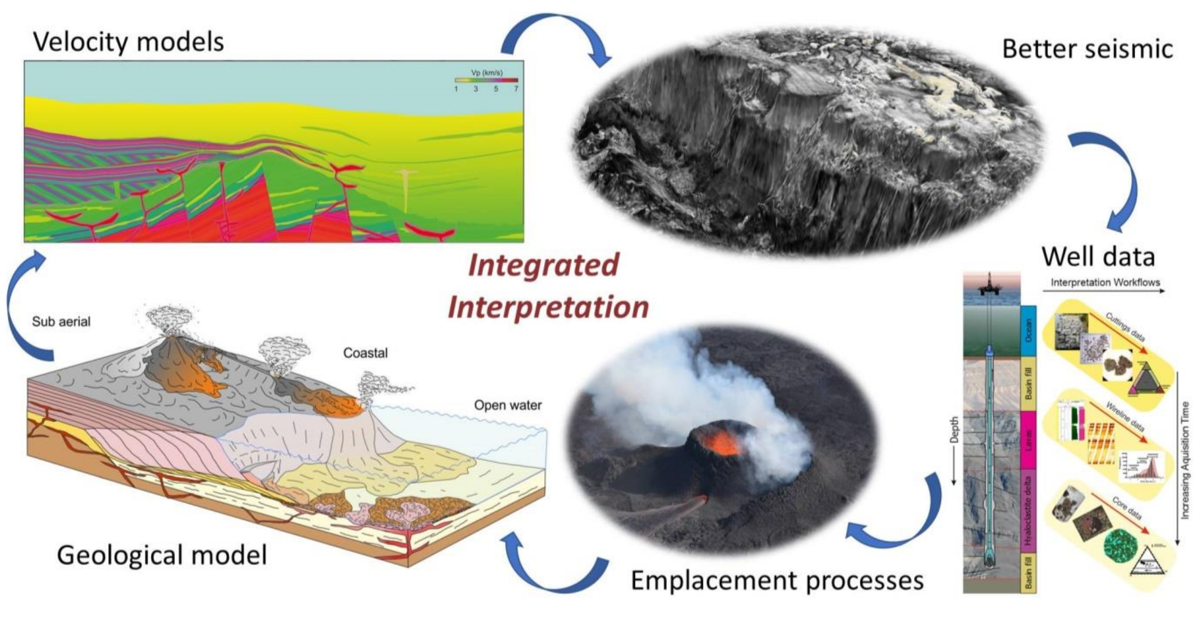

Fig. 2. *Our integrated approach to volcanic margin and basin analysis.*

The Impact of Hydrothermal Vent Complexes on Volcanic Basin Prospectivity

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Hydrothermal vent complexes form as a result of igneous intrusions heating host rocks, generating hydrothermal fluids which are vented at the paleo-seafloor. They also have a long-term effect on fluid migration in volcanic basins. Ancient hydrothermal vent complexes (HTVCs) related to igneous sills are recognized globally both offshore and onshore, nonetheless, they remain somewhat enigmatic structures due to the very small number of intersecting wells.

In this study we have completed detailed 3D seismic mapping of hydrothermal vent complexes on the mid-Norwegian margin, an area which experienced massive basaltic magmatism c. 56 Ma during the time of continental break-up. We interpreted a conventional and high-resolution processed version of a 3D seismic volume covering 15,520 km^2 (AMN17, courtesy of TGS) situated at the transition between the Møre and Vøring basins. Regionally, a Near Top Paleocene horizon was picked (Fig. 1) and tied to nearby exploration wells, which was followed by geomorphological seismic interpretation. A detailed 3D interpretation on one hydrothermal vent complex, the Bragarfull HTVC, was also completed. The seismic interpretation was used to identify the shallowly buried Modgunn Vent which was drilled by five boreholes during IODP Expedition 396 in 2021 and imaged by high-resolution P-Cable 3D seismic data in 2020.

The Base Vent horizon is a distinct soft reflection which corresponds to the bases of many hydrothermal vents. More than 650 HTVCs have been identified with diameters which range from 100 m to >5 km. Above and beside some HTVCs are seismic amplitude anomalies or mounds, which are interpreted to be caused by hydrocarbons and remobilized sediments respectively. The Bragarfull HTVC has five seismically distinct vent fill facies (Fig. 2). Two of the facies units are separated by an angular unconformity indicating that the depositional events within the vent fill were distinct. Furthermore, along the vent conduit is a seismically incoherent body, interpreted to represent a body formed due to the fluidization of the host rock (Fig. 2). The distinct seismic facies in the vent fill are interpreted to be at least partially erupted mud-rich sediments, due to host rock fluidization. These features, as well as others, indicate that the ancient Bragarfull HTVC is similar to modern eruptive sediment-hosted geothermal systems in NE Java, such as the active Lusi eruption and the neighbouring inactive Porong Structure.

Heating of intruded sediments by hot sill intrusions caused rapid host-rock maturation, released water and generated CH_4 and CO_2. These fluids, which could be in a super-critical phase, close to the intrusions, may propagate through the host-rock and vent at the paleo-seafloor. Fracturing and host rock fluidization affects the basin stratigraphy and may alter reservoirs intersected by HTVCs. Localized fluid-flow features above HTVCs indicate they are preferential pathways for millions of years after the HTVCs were formed.

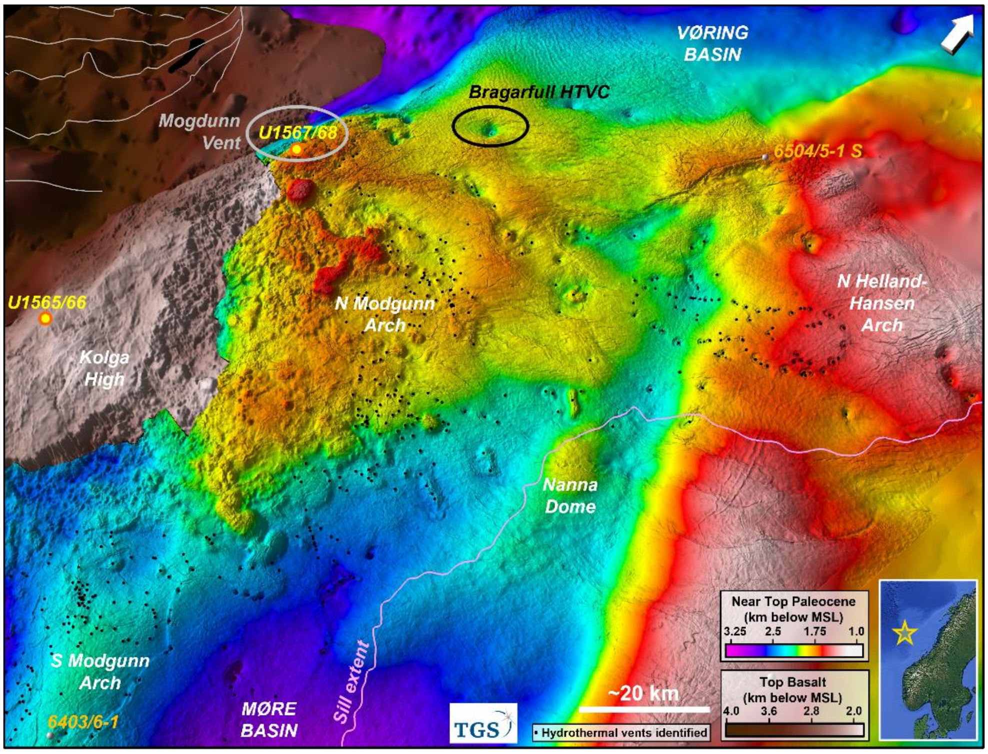

Fig. 1. Distribution of hydrothermal vent complexes in the Modgunn Arch area. IODP Expedition 396 drill sites located. Data courtesy of TGS.

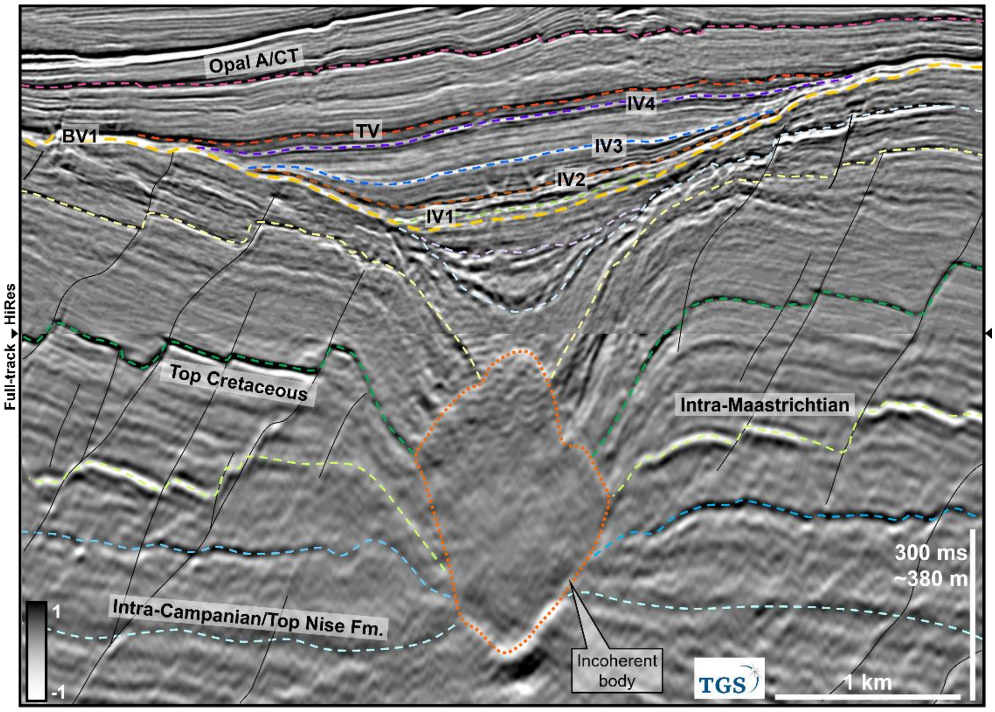

Fig. 2. Horizon interpretation of the Bragarfull hydrothermal vent complex. TV: Top Vent, IV1-4: intra-vent horizons, BV1: Base Vent. Top half of image is high-resolution processed data. Data courtesy of TGS.

The thermal impact of igneous intrusives and Cenozoic unroofing in northern West of Shetland: an integrated study based on seismic mapping, new geochemical analyses, and basin modelling.

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The Faroe-Shetland Basin is a prolific hydrocarbon province, with a complex geological history impacted by both post-rift Cenozoic unroofing and extensive intrusive and extrusive igneous activity (Passey & Hitchen, 2011 and references therein). Despite decades of exploration and research many uncertainties remain regarding how these processes impact the thermal regime and the overall working of the petroleum system. We use heritage and new geochemical data for calibration, and a simple multi-scenario modelling approach to assess the relative impact of unroofing and igneous activity compared with other geological factors on the thermal history of the basin

The Faroe-Shetland region has experienced multiple rift events through the Jurassic, Cretaceous and Paleocene (Fletcher et al., 2013). Within the post-rift stratigraphy the basin has undergone a number of rapid paleo-bathymetric changes and multiple unconformities are observed on 3D seismic (e.g. Smallwood & Gill 2002). These events have been interpreted in terms of transient dynamic support related to mantle convection and the Iceland plume (Shaw Champion et al., 2008; Hartley et al., 2011; Schoonman et al., 2017), which in turn is likely also related to the igneous activity in the area. Igneous activity has been linked to maturation of source rocks, migration of hydrocarbons (Rateau et al., 2013) and pressure transmission from deeper stratigraphy (Schofield et al., 2020). The particular importance of accounting for 'over-thickening' by intrusions in burial history analyses has been demonstrated in the southern Faroe-Shetland Basin (Mark et al., 2018). Learning from these past studies we were able to target new data collection to address specific uncertainties and build these processes into our geological models.

We find that in the deep basin rifting has a dominant control on thermal history and model outputs such as timing of hydrocarbon generation. On the basin margins our newly acquired data demonstrate that the impact of unroofing on post-rift unconformities is less than had been previously thought. New apatite fission-track analyses and vitrinite reflectance data from shallow stratigraphy have been used to calibrate our models. In Quadrant-209, intrusions, and possibly elevated regional heatflow during igneous activity, are likely the main controls on the temperature history and the maximum level of maturity achieved. This result appears to be true even in wells that did not penetrate sills, and achieving an acceptable calibration relies on seismic mapping of intrusive bodies combined with 3D basin modelling. Further south in Quadrant-208, sills on the basin margin become less extensive and their thermal impact more localised. In these areas unroofing may have a slightly greater, but still minor, impact. Based on our new data and model calibration we have created maps showing the magnitude of Cenozoic erosion as well as new maturity and temperature maps, which highlight the importance and variable impact of igneous intrusions across the area. These maps have been used as input to hydrocarbon play analyses and technical risk assessment, which we believe have been significantly impacted by igneous events.

Session Four: Unlocking resources; data, case studies and operations

KEYNOTE - Tools for understanding how igneous systems affects energy resources and storage potential of sedimentary basins

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A large number of global sedimentary basins, and their energy resources and gas storage potential, are impacted by igneous systems in the form of extrusive, intrusive and volcaniclastic rocks. These impacts occur at a variety of scales, from the margin-scale (e.g., modification of heat flow) to the grain-scale (e.g., intrusion-induced cementation). Furthermore, although these impacts are commonly viewed as having a negative effect on energy resource potential, there are numerous examples where they have a positive benefit. Understanding the role igneous activity has in the evolution of sedimentary basins is thus important to the energy transition, and building a more sustainable future.

Seismic reflection data has arguably revolutionised our understanding of igneous activity in sedimentary basins. Yet it is integral to consider that the application of complementary geophysical, petrophysical, modelling, and field-based techniques are critical to interpreting seismic reflection data. Here, I will lean on my own experience and the excellent work of colleagues worldwide to show how reflection seismology reveals igneous systems within basins. We will explore how magma plumbing systems develop, including how they: (1) influence continental breakup, and thus impact the evolution of entire margins; (2) deform surrounding rock to make space, creating structural traps; and (3) induce hydrothermal fluid flow, and its positive and negative impacts. Having established how magma moves through sedimentary basins, we will consider the role volcanic landforms may play in the energy transition. Finally, although this conference is focused on sedimentary basins, we will briefly reflect on the application of these techniques to understanding igneous systems in other setting.

The impact of igneous rocks on petroleum exploration and drilling operations in the Northern Carnarvon Basin, Western Australia.

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The Northern Carnarvon Basin (NCB) is located on Australia's North Western Margin (Figure 1). The Jurassic rifting and Early Cretaceous break-up of the Greater Indian continent from the Australian continent dominates the tectonostratigraphic history of the basin and wider margin. Within the NCB, rifting initiated a series of inboard rift basins (the Exmouth, Barrow and Dampier and Beagle sub-basins) which separate the Exmouth Plateau from the Australian continent.

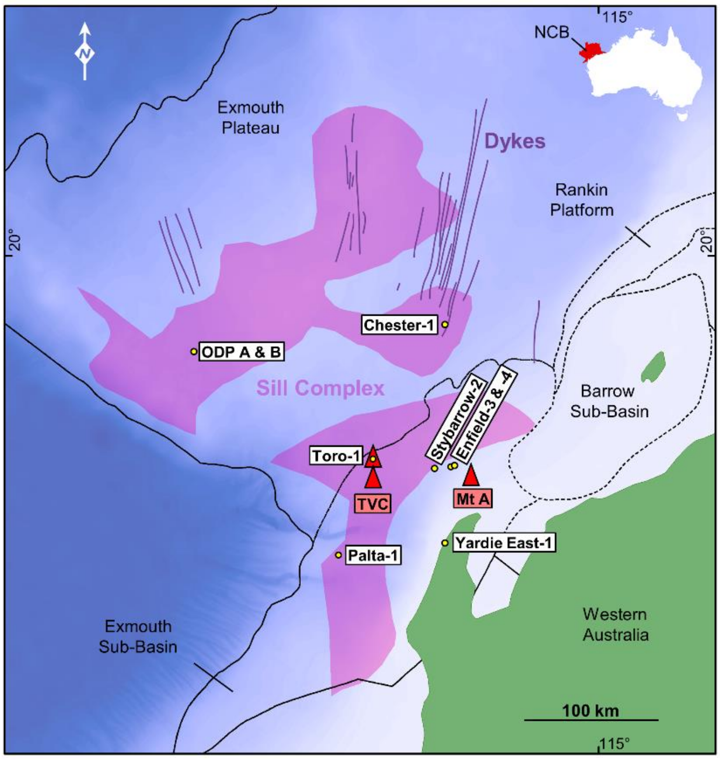

Figure 3: Location map showing petroleum exploration wells and boreholes that penetrate igneous rocks in the western sector of the Northern Carnarvon Basin (NCB). Also shown are the volcanic centres of the Toro Volcanic Complex (TVC) and Mt Aneto (Mt A), the ~50,000 km^2 interconnected sill complex, and the recently interpreted Exmouth Dyke Swarm.

Igneous rocks were emplaced into Exmouth Plateau and Exmouth Sub-Basin during the Late Jurassic and Early Cretaceous prior to breakup (Figure 1). These comprise two volcanic centres (the Toro Volcanic Complex, TVC, and Mt Aneto, Mt A) in the central Exmouth Sub-Basin (Curtis et al., 2021), a ~50,000 km^2 system of interconnected intrusive sill intrusions (Symonds et al., 1998), present within the Exmouth Plateau and Exmouth Sub-Basin, and a recently interpreted dyke swarm present in the Exmouth Plateau (Magee and Jackson, 2020).

Despite this magmatic system spanning ~50,000 km^2 of the inboard NCB, only nine petroleum exploration wells and boreholes (of over 1500 drilled in the NCB) have intersected igneous rocks (Figure 1). These are Toro-1 which intersected the western flank of the Toro Volcanic Complex; Stybarrow-2, Enfield-3, Enfield-4 and ODP 763 A & B which penetrate ashfall deposits, Yardie East-1, Palta-1 which intersect intrusive sills, and Chester-1 which intersects what is most likely a steeply oriented intrusive dyke. In this presentation we review the impact that the igneous rocks have had in each well. We find that, in most cases, either the igneous rocks, their host rocks, or both, have been subject to chemical and thermal alteration.

This alteration has impacted petroleum exploration. For example, contact metamorphism by intrusions in Yardie East-1 over-matured ~1000 m of a source-rock bearing succession. At Palta-1, alteration of a ~100 m thick intrusion meant it was unnoticed during logging; had it not been recognised later, critical information regarding the basin's thermal history would have been missed.

Drilling operations have also been impacted. For example, the alteration of ashfall deposits to smectite, which swells on contact with water, forced a change to oil based muds at Stybarrow-2 and Enfield-3 and -4. And low seismic velocities in volcanic rocks at Toro-1, interpreted as overpressured formation ahead of drilling were in fact caused by altered mafic lavas.

We summarize the technical drilling challenges explorers faced, the impact of the igneous rocks on the target petroleum systems, and what new information the intersected igneous rocks reveal of the basin's magmatic history. We conclude with a review of the alteration processes that have acted on each component of the igneous system and suggest possible migration pathways for heat and hydrothermal fluids within the NCB (Figure 2).

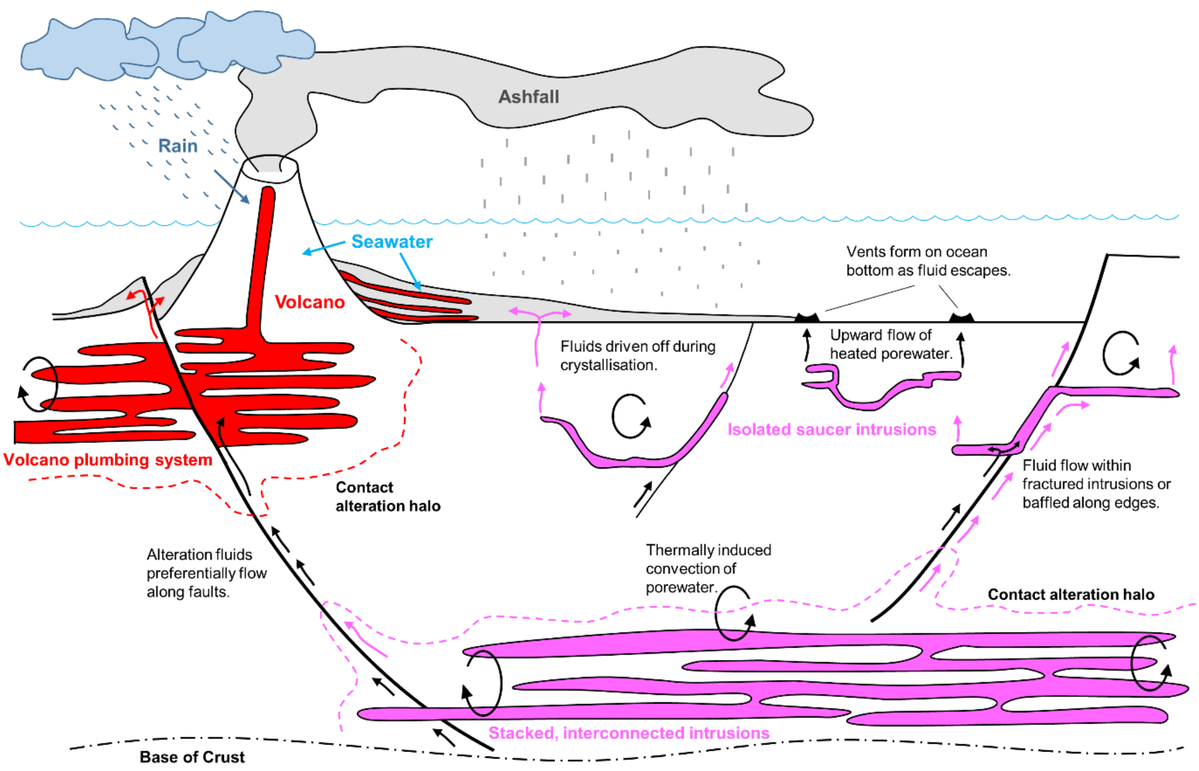

Figure 4: Schematic cartoon showing fluid flow pathways and alteration mechanisms for settings of igneous rocks encountered by wells investigated in this study. Black arrows denote flow of groundwater, pink and red arrows

denote flow of magmatic fluid driven off cooling melt phases, and blue arrows denote flow of rain and seawater. Source: Curtis et al. (in press).

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Assessing The Application of Ultradeep Electromagnetic Resistivity Tools to Detect Igneous Formations and Their Associated Hazards Ahead of the Bit

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The Faroe-Shetland Basin (FSB), located along the NE Atlantic Margin, has been the focus of oil and gas exploration for over half a decade. The region is estimated to hold around 3.5 BBOE of discovered reserves and contingent resources, with the Oil and Gas Authority estimating mean yet-to-find resources of around 6 BBOE within the FSB region. When compared to other areas of the UKCS however, exploration drilling activity here represents less than 7% of the total exploration wells drilled in the UKCS translating to less than 3.5% of the significant discoveries.

Dominated by a complex interplay of structure, sedimentation and volcanic activity, the NE Atlantic Margin presents a challenging environment to plan and drill wells safely and within the planned budget. This is evidenced with the FSB hosting the most expensive wells drilled to date within the UKCS. The limited number of wells drilled in the Faroe-Shetland Basin and their geographical sparsity relative to those of other areas of the UKCS make offset analysis and de-risking a challenge.

The often-unpredictable distribution of igneous rocks throughout the basin presents significant challenges in the planning and drilling of oil and gas wells. It is estimated that around 80% of igneous intrusions within the FSB are estimated to be below seismic resolution, which alongside variation in composition, presents significant issues regarding drilling safely, efficiently and successfully.

Developments in Ultradeep Electromagnetic Resistivity tools have recently progressed from their application in high-angle and horizontal wells to low angle and vertical wells. In doing so it has presented the opportunity to assess their suitability as a de-risking tool in providing the ability to look-ahead of the bit c. 100 ft. TVD, and to assess the potential for use within basins impacted by volcanism, such as the FSB. The 214/28-1 well, drilled in 1984 was confirmed to drill through multiple igneous intrusions. As such, the log data from this well was used as input into the modelling workflow to confirm the validity of the tool to detect these igneous formations ahead of the bit.

This volume of investigation is a step-change in drilling wells in this area by affording the ability to see drilling hazards & geological events ahead of the bit enabling key-decisions to be made proactively and safely.

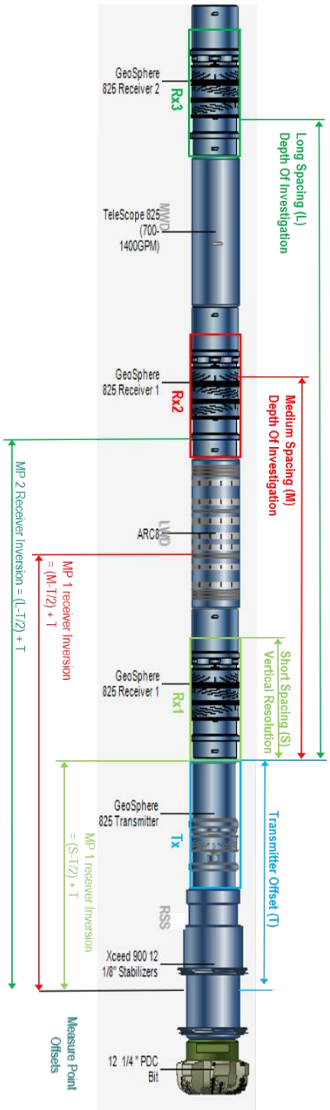

Figure 5: BHA configuration used in Modeling

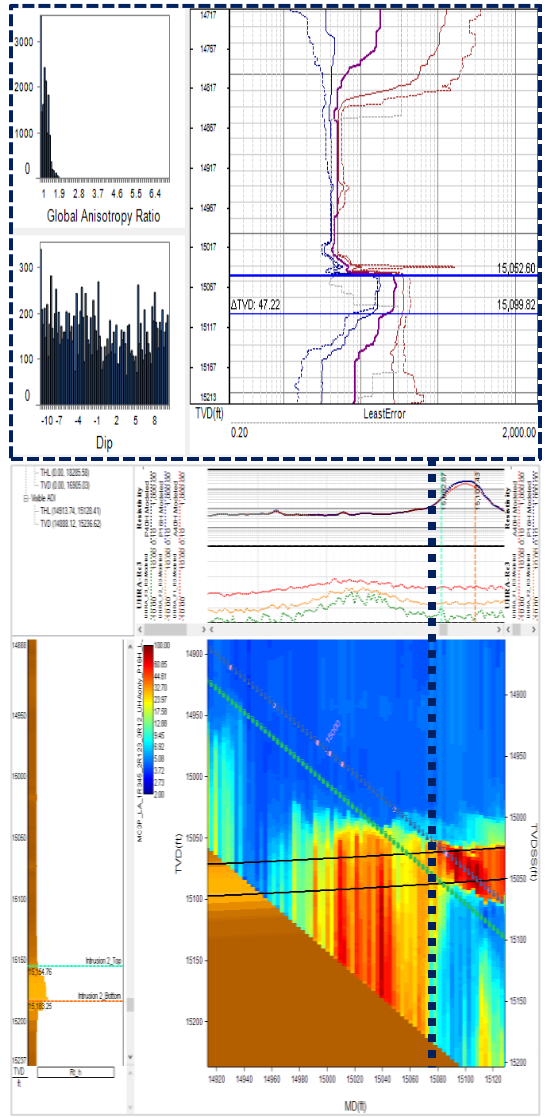

Figure 6: Modeled response of Igneous Intrusion Ahead of the Bit

Buried volcanoes as prospective sites for in-situ safe carbon storage

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Greenhouse gas emissions from anthropogenic sources, specifically CO_2, are undoubtful contributions to climate change. Achieving a sustainable net-zero CO_2 balance between industrial sources and natural sinks requires active and innovative approaches to mitigate this problem. Induced carbon capture and sequestration is perceived as a prospective technology to tackle impacts on climate and populations. Research and technological advances carried out in last decade have addressed the feasibility of capturing CO_2 in mafic and ultra-mafic rocks through *in-situ* mineral carbonation, a natural interaction of fluid and minerals towards the formation of new stable carbonate materials (Snæbjörnsdóttir et al., 2020). This process has been described to occur naturally in several locations worldwide, namely in peridotites and serpentinites from the Samail Ophiolite of Oman (Kelemen et al., 2019). Industrial applications of this concept have been successfully implemented, with the most significant example happening in the CarbFix project (Iceland), with mineral trapping described to occur on basaltic lava flows within a period of 2 years (Snæbjörnsdóttir et al., 2017). Recent studies have contemplated permanent carbon storage in the oceanic crust or alternatively in ancient and buried volcanoes on continental margins (e.g., Holford et al., 2021).

Herein, we report the feasibility of a Late Cretaceous volcanic edifice on central West Iberian Margin, the Fontanelas volcano, located offshore Portugal, as a site for in-situ mineral carbonation. This feature can be considered as a study case for the application of this technique on similar volcanic edifices on continental margins. Based on 2D and 3D high-resolution seismic reflection surveys, the Fontanelas volcano is revealed to comprise a 2800 m high edifice, extending throughout an area of about 500 km^2, and an estimated rock volume of 327 km^3 (Pereira et al., 2022). The Fontanelas composite volcano includes highly vesicular olivine-rich alkaline basalts assigned to pillow lavas (and hyaloclastite) at its crest, infilled with naturally formed carbonate minerals. Furthermore, the observed internal layering of the edifice, combined with favourable petrophysical properties, suggests that this is a suitable candidate for in-situ mineral carbonation.

Based on the overall nature and architecture of the volcanic edifice, we modelled the volume of CO_2 that could be safely injected and stored, and therefore provide a benchmark applicable for similar edifices on other passive margins. Grounded on deterministic estimations, our analysis indicates that on a base case, the volcanic edifice has the potential to capture nearly 1.2 Gt CO_2 into new stable mineral phases. Considering that during the 2015-2018 period, the Portuguese energy sector emitted an average volume of about 48 Mt CO2 eq per year, our estimates suggest that the volcanic reservoir is likely to permanently and safely store an equivalent of 24 years of the country’s industrial emissions.

Comparing with other oceanic magmatic sequences worldwide, buried volcanic edifices on continental margins emerge as remarkable locations and favourable candidates for expanded in-situ mineral carbonation. Buried volcanoes, although smaller in their individual storage volume when compared with seafloor basalts and serpentinites at the oceanic crust, can be easily characterised through geophysical surveys, drilling and investigated with dedicated rock sampling campaigns to fully unveil a volcano's internal architecture, rock chemistry and mineral assemblages. Moreover, the analysis of mineral and petrophysical properties of individual magmatic flows can provide critical information on the effectiveness of the injection process. This would allow a comprehensive understanding of specific mineral reactions between silicates and fluid, and what new mineral carbonate phases would form. This concept can be escalated to similar extinct volcanoes buried on continental margins worldwide, namely on the continental margins of the North Atlantic, the South China Sea or South Australia.

Our analysis additionally provides insights on the overall concept of in-situ mineral carbonation on buried volcanoes to reveal the geological controls that can lead this technique towards a future pilot phase that can effectively and safely be applied on an economic scale. Ultimately, results suggest that ancient, buried volcanoes on passive continental margins can be considered for safe carbon storage and contribute to mitigate the impacts of anthropogenic carbon emissions.

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Exploratory history of the igneous reservoirs of the Rio Grande Valley (Mendoza), Neuquén Basin (Argentina).

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Although there are records of hydrocarbons on the surface from the times of the Spaniards settling in the southern region of Mendoza, and exploratory studies for the presence of oil seeps west of the town of San Rafael towards the end of the 19th century, with an even production from the first part of the 20th century, it was not until the 80s where the field and well studies by the Argentinian government company YPF began. The possible productivity of igneous rocks is recognized by finding them in outcrops and wells of the region forming sills and dikes in different formational units of the Neuquén Basin. In addition, it was also observed the interaction with the most important source rocks of the basin and related it to hydrocarbons manifestations on surface.

The survey of stratigraphic profiles and the drilling of exploratory wells allowed to analyze the interactions of these dikes and sills with the productivity of this oil region. The Mudlogging Control as well as the evaluations with DSTs were decisive to define these unconventional reservoirs for the time.

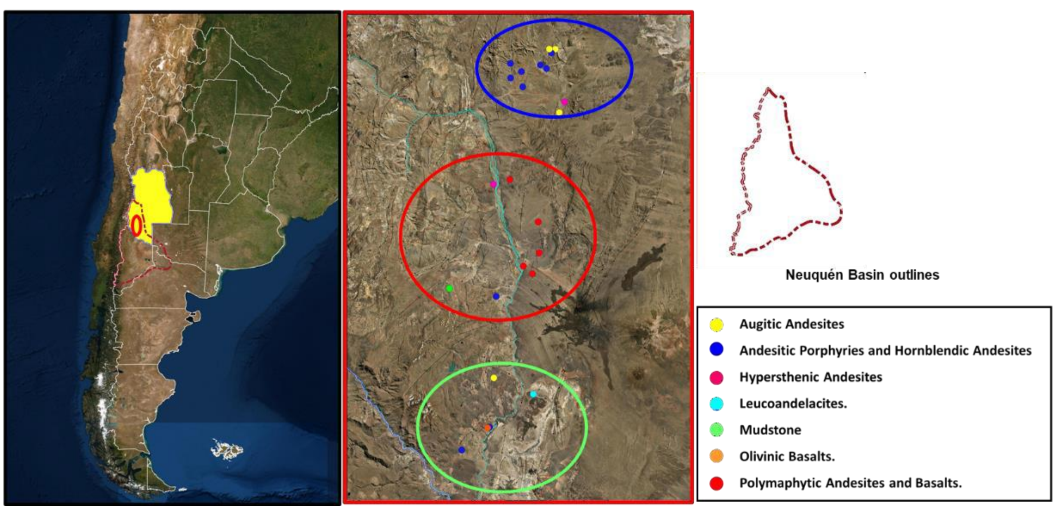

Figure 1

From petrographic reports on samples from outcrops and cores, six lithological types could be distinguished in the igneous units for this region, which in turn define three zones along the area that covers from the north of the Rio Grande Valley to the south of the province of Mendoza. Figure 1. Recent works confirm the belonging of this volcanism to two predominant cycles from the late Oligocene to the Miocene ("Molle") and middle to upper Miocene ("Huincán").

Although in igneous reservoirs it is difficult to forecast final accumulated (EUR), sills that intercepted the generating rocks of the Vaca Muerta and Agrio formations have had "explosive" and accumulated "surprising" productions. A well with sills in the Vaca Muerta Fm stands out for having had initial production greater than 1,887 bbl/d oil and accumulating 979,952 bbl/d oil in three years, representing 80% of the total accumulated by the well. Figure 2. In the Agrio Fm one of the wells in the Rio Grande Valley began production with almost 1,258 bbl/d oil and accumulated 446,577 bbl/d oil until January 1984, 80% of the total accumulated by this well. Figure 3.

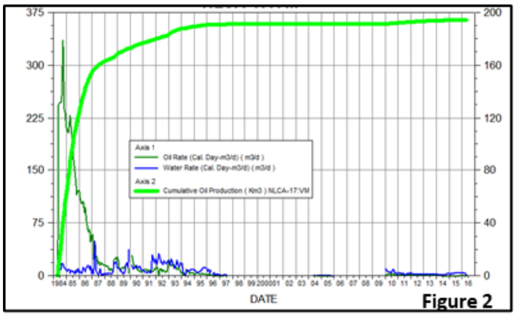

Figure 2

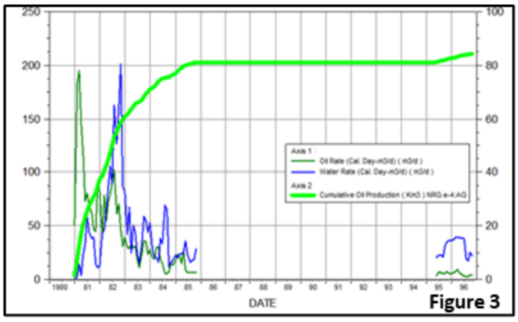

Figure 3

Thin sections of the latter well confirm cooling fractures with microliths of the same mineral phases developed at the edges. Figure 4a - crossed nicols. And opaque minerals and hollows filled with bitumen. Figure 4b - parallel nicols.

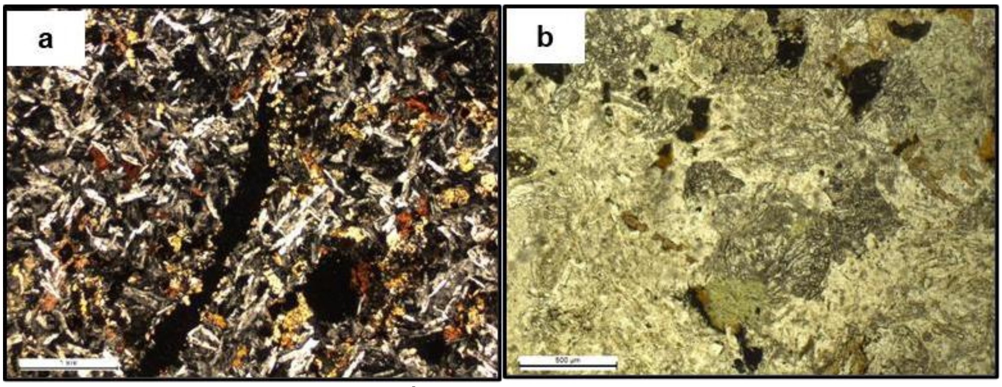

Figure 4

The Neuquén Basin in the southern part of the province of Mendoza has been one of the first regions in the world where studies were initiated to understand the impact of volcanism in a sedimentary basin in a region of a fold and thrust belt. Production results were greater than expected although establishing the number of wells for the complete development of the accumulation was rather difficult to forecast.

The direct effects of emplacing basaltic lava onto a sand substrate: implications for petroleum reservoirs in sub-basalt and intra-basalt situations

Clayton Grove and Dougal Jerram

The rifting of the Atlantic, is associated with the creation of numerous sedimentary basins of economic importance due to the exploitation of their petroleum systems. These basins exist on both sides of the modern Atlantic Ocean and stretch from South Africa to Norway on the eastern margin and from Argentina to Canada on the western margin. Igneous activity is frequently associated with the Atlantic Rift, often concentrated at locations where a mantle hotspot is inferred to have existed. The igneous rocks encountered are usually associated with the sedimentary rocks, are often voluminous, and affect all aspects of the petroleum system. Igneous rocks affect source rock maturity, hydrocarbon migration, trap formation, sealing, reservoir deposition and reservoir quality. Here we address the direct effects of emplacing hot basaltic lava onto sand substrate as one aspect of reservoir quality. Other aspects of reservoir quality influenced by igneous rocks include the diagenetic effects caused by the emplacement of igneous intrusions and hydrothermal fluids associated (e.g. Grove 2014; Grove et al., 2016) and the diagenetic effects of mixing volcaniclastic sediments with potential reservoir siliciclastic sediments (Clark, 2014) and indeed the potential of the igneous rocks themselves as potential reservoirs (e.g. Wang & Chen 2015; Millett et al 2021). We term the diagenesis (and pyrometamorphism, Grapes 2010) related to the hot igneous rocks as direct effects and the later diagenesis during burial that is influenced by the regional igneous activity as indirect effects (e.g. mild hydrothermal activity caused by elevated pore water temperature and mineral reactions related to pore water chemistry changes). Here we examine the direct effects only.

We use case studies from paralic sediments interbedded with recent lava flows in Iceland, Miocene fluvial sediments interbedded with basaltic lava flows from the Columbia River Basalts, USA (CRB), Miocene fluvial and laucustrine sediments interbedded with the Snake River Basalts, USA (SRB) and Lower Cretaceous aeolian sediments interbedded with basaltic lava flows from the Etendeka LIP, Namibia. Both volcaniclastic and siliciclastic sediments have been studied. The examples we present have sharp sediment lava contacts where no measurable sediment/lava mixing has occurred.

The case studies all show that there is increased sediment compaction immediately below lava flows and associated mineral diagenesis related to the enhanced breakdown of unstable minerals in the short-lived sub-lava hydrothermal regime and in some cases the precipitation of new mineral phases. The most measurable direct effect that reduces reservoir quality is increased compaction near to the base of lava flows. The overall magnitude of porosity loss is related to the thickness of the overlying lava flow, with background porosity being regained by 4 m below the thickest lava studied. A zero porosity contact zone (ZPCZ) (~ 0% porosity), due to mineral precipitation, was only encountered in the Cretaceous Namibian examples, where it was always < 10 cm in thickness, with a broader low porosity effected zone away from this.

The results suggest that lava has a measurable direct effect to reduce porosity of subjacent sediments, which is related to the thickness of the lava flow. We quantify this and provide a method to predict the effect. The prediction for Rosebank is that the ZPCZ expected is to be minimal (below well log resolution), if present at all and the distance below the lava to background porosity of 19 % and 21 % to be between 1.8 m and 3.8 m for lava flows of 5 m and 10.5 m in thickness. Similar predictions could be applied to other exploration prospects in the extensive intra-basalt play provided that the expected lava flow thickness is known. We show that the magnitude of porosity reduction, under exploration circumstances is sufficiently low to be already bracketed by standard porosity uncertainties and does not pose a reservoir quality risk, except for very thin predicted sandstone beds. It is important to note that the effects of sill intrusions are more dramatic away from host sediment contacts, such that the correct interpretation of lava flows vs sills would have markedly different implications for the prediction of reservoir quality.

Overthickening on the Norwegian Volcanic Margin: estimating intrusion thicknesses to resolve palaeogeographic uncertainty

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Magmatic sills are commonly imaged as bright geo-bodies on seismic data owing to their high acoustic impedance. The characteristic aspect ratios of these features in the subsurface combined with the typical resolution achievable at depth in most seismic datasets mean that these are commonly imaged as tuned reflector packages making thickness estimation challenging (Eide et al. 2017). A further challenge in establishing the total thickness of intrusions within a sedimentary section is the occurrence of even thinner unresolved intrusions below the resolution of the seismic data (Mark et al. 2019). This difficulty in resolving thinner intrusions can lead to a gross underestimation of their occurrence in prospective sedimentary basins, something that has an impact for our understanding of petroleum systems.

Consideration of this total thickness of intruded igneous material in a temporal context is critical as the intrusion of igneous material (for Norwegian margin in the Paleocene-Eocene (64-53 Ma)) post-dates the deposition of the Cretaceous sedimentary sequences within which the intrusions lie today. Accurate prediction of the thickness of seismically imaged sills that lie below the tuning thickness ($\lambda/4$) but above the limit of detectability of the seismic data (typically between $\lambda/30$ and $\lambda/8$) remains elusive. This study presents a workflow to account for the thickness of tuned igneous intrusions within a basin through modification and application of the seismic net pay method of Connolly (2005, 2007). When applied in combination with the existing 1:1.4 relationship for imaged to not imaged intrusions defined by Mark et al. (2019) the methods provide a means to determine the thickness of imaged, partially imaged (tuned) and un-imaged intrusive material within a sedimentary package.

Application of this method has allowed the relative thickness of intrusive material to be derived across a representative 2D seismic line in the Vøring Basin (Figure 1) and incorporated within a 2D basin model. Results show that cumulative sill thicknesses range from 30 m to 460 m increasing potentially up to 1100 m if associated unresolved intrusions are accounted for using the 1:1.4 ratio (Figure 1).This assessment has allowed the first back-stripped restoration of a pre-rift basin geometry that “de-sills” the section to account for the impacts of “overthickening” (Mark et al. 2019). It is noted that the sequence thickness, subsidence history and consequent basin architecture are significantly different to reverse-models without intrusions removed.

This example demonstrates that the location of potential depocenters, such as those of the Upper Cretaceous fan systems forming the main reservoirs in the Vøring Basin, could be quite different to those predicted in restorations that do not account for the effect of intrusion thickness. Developing this means of modelling the distribution of intrusions has important implications in the ability build accurate charge and reservoir models utilised in the exploration and development of hydrocarbon resources and the wider study of volcanic basins.

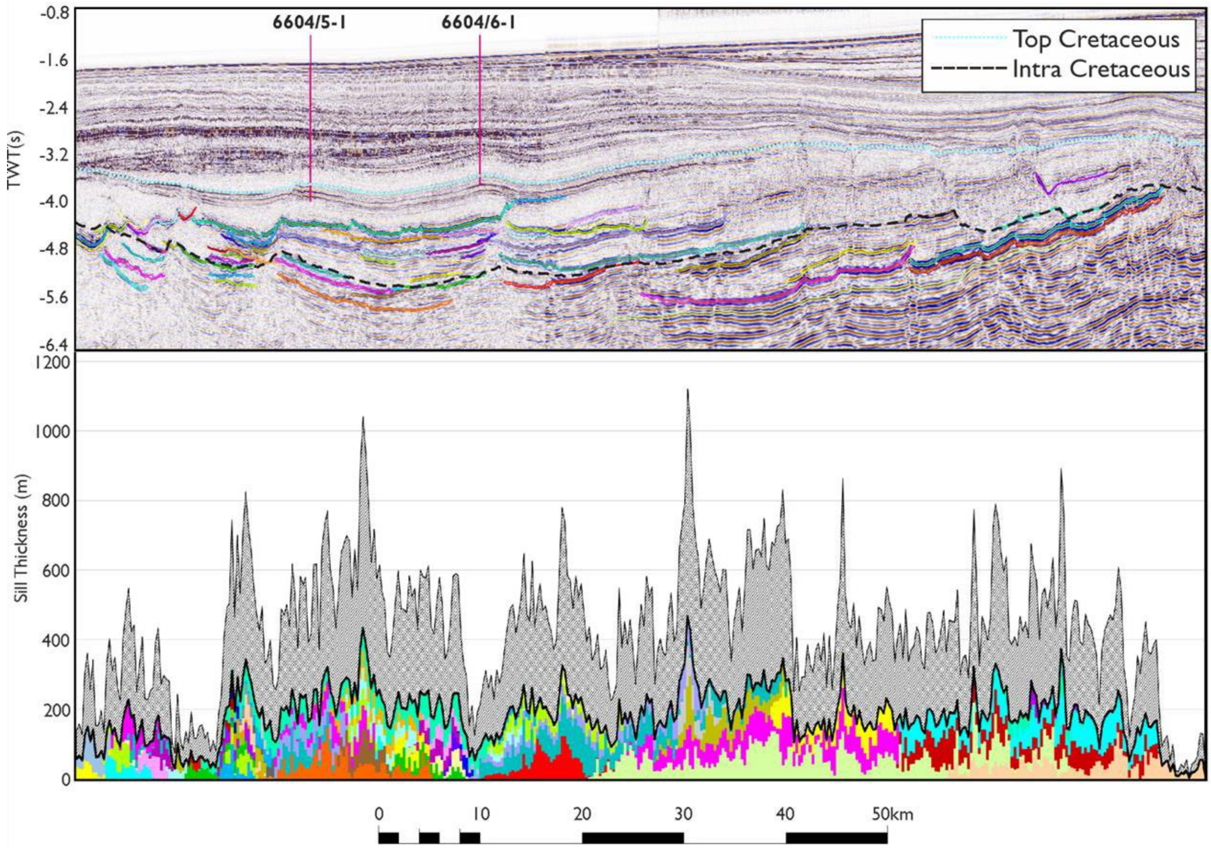

Figure 1 – The Balderbrå heroline with the cumulative thickness of the tuned sills in the coloured region and the 1:1.4 ratio of Mark et al. (2019) applied to this cumulative thickness to calculate a potential thickness of associated unresolved intrusions in the grey shaded area of the graph.

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The influence of sediment thermal maturity and hydrocarbon formation on Hg behaviour in the stratigraphic record

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Mercury (Hg) is considered both a pollutant and a safety hazard during production of hydrocarbon fields due to its corrosive effect on pipelines and hydrocarbon processing facilities, as well as its high toxicity. Naturally emitted via volcanic exhalations and other processes, Hg is globally dispersed in the atmosphere, and finally sequestered in sediments with organic matter (OM). Consequently, Hg in sediments is increasingly used as a proxy for deep-time volcanic activity, though its behaviour in OM-rich sediments as they undergo thermal maturation is not well understood.

We here present a dedicated evaluation of the effects of thermal maturation on sedimentary Hg contents and, thereby, the impact of thermal maturity on the use of Hg/TOC proxy for LIP volcanism. Our study focuses on three cores (kerogen Type I/II) with different levels of thermal maturity from lowermost Toarcian sediments (Posidonienschiefer above T-OAE) from the Lower Saxony Basin in Germany. We measured and analysed Hg contents, bulk organic geochemistry, and total sulfur in these three cores. The comparison of Hg data between the three cores indicates that Hg concentrations in the mature/overmature sediments have increased > 2-fold compared to Hg in the immature deposits. The loss of mass by hydrocarbon expulsion might have played a role in the relative increase of Hg, but its redistribution in the sedimentary sequence caused by the mobility and volatility of the element under relatively high temperatures may also have contributed to Hg enrichment in distinct stratigraphic levels of the mature cores. Generally, elevated Hg concentrations together with organic carbon loss by thermal maturation within and slightly beyond the oil-gas window temperatures will inflate Hg/TOC in mature sediments, suggesting that thermal effects have to be considered when using TOC-normalized Hg as a proxy for far-field volcanic activity.

POSTER ABSTRACTS

Magmatically driven hydrocarbon generation and fluid flow in the Namibe Basin of Angola

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Magmatic intrusions can affect all petroleum system elements in a sedimentary basin, highlighting a need to constrain processes of interaction between magmatic activity and petroleum system evolution. This will lead to a better understanding of when magmatic activity creates exploration risks or opportunities, and can unlock new hydrocarbon plays and resources. The Namibe Basin of Angola formed in the Cretaceous as part of the South Atlantic rift. It was affected by multiple syn-rift and post-rift magmatic events, which had a significant impact on the petroleum system evolution. In particular, the basin contains significant onshore bitumen occurrences at several localities along the basin strike, evidence of a possibly working petroleum system within this magmatically influenced basin. The origin of the bitumen in the Namibe Basin was therefore investigated in order to assess the impact of the magmatic activity on source rock maturation and hydrocarbon generation, re-mobilisation and preservation, highlighting exploration risks and opportunities within a magmatically influenced sedimentary basin.

The Namibe Basin onshore stratigraphy is characterised by a Pre-Salt succession of Hauterivian volcanics, overlain by spring/lacustrine carbonates and fluvial to marginal marine siliciclastics. Aptian evaporites are overlain by Albian to Maastrichtian Post-Salt marine carbonate and terrestrial-marine siliciclastic units. The basin was also affected by Coniacian-Santonian magmatic activity. Onshore Pre-Salt units with good source rock properties are rare, and they are thermally immature in the studied areas. However, in the immediate Post-Salt, units with very high TOC (7-14%) and excellent source rock properties (HI>600 mgHC/gTOC) have reached thermal maturation. These Post-Salt source units are close to major Coniacian-Santonian volcanic centres. Bitumen is observed within both Pre- and Post-Salt stratigraphic sections at multiple locations along the basin strike. In the Pre-Salt, this bitumen is associated with calcite and quartz cements in fractures and carbonate vuggy/fenestral porosity, showing bright yellow-orange fluorescence under UV light. In contrast closer to Coniacian-Santonian volcanic centres, non-fluorescent pyrobitumen and gaseous inclusions are observed. Bitumen-bearing calcite veins in the Pre-Salt section were geochronologically constrained within the period of Late Cretaceous magmatic activity. Furthermore, calcite stable isotopic signatures are compatible with contributions from magmatically derived fluids. In the immediate Post-Salt, bitumen is in situ, occurring as stratabound laminae within matrix and in local jigsaw-like fracture networks. Bimodal, high-wax *n*-alkane distributions observed in the pyrograms suggest a lacustrine origin for the Pre-Salt bitumen, while Post-Salt bitumen is characterised by less waxy, marine-like *n*-alkane distributions. Significant levels of β-Carotane and Gammacerane confirm a lacustrine source rock depositional environment for the Pre-Salt bitumen, also characterised by hypersaline and reducing conditions. Finally, maturity-dependent biomarkers indicate that Pre- and Post-Salt hydrocarbons were generated at early to middle thermal maturity stages, with Pre-Salt bitumen showing higher maturity.

These observations suggest different hypotheses for the Pre- and Post-Salt bitumens. Since no effective Pre-Salt lacustrine source rock is observed onshore, the Pre-Salt bitumen must have been generated by a mature lacustrine source rock offshore, where a 3-5 km thick Pre-Salt succession is imaged by seismic data. Given the hypersaline and reducing character indicated by biomarker data, this source rock could be a Bucomazi Fm. equivalent, a well-known prolific regional Pre-Salt source unit in Angola. The source rock generating the Pre-Salt hydrocarbons might have reached maturation mostly through conventional burial processes, although magmatic activity might have, nevertheless, contributed to source rock maturation by enhancing the regional geothermal gradient. Hydrocarbons migrated or re-migrated via permeable pathways and possibly in association with magmatically driven fluids, reaching the present-day onshore. Closer to volcanic centres, those hydrocarbons were cracked into pyrobitumen and gaseous products. In contrast, the Post-Salt bitumen likely derived from the forced maturation of Post-Salt marine source rocks onshore, as confirmed by its more in-situ setting (auto sourced system).

Combined, this study shows how magmatic activity and regionally enhanced thermal gradient can accelerate source rock maturation, representing an exploration opportunity when source rock immaturity would otherwise be a risk. However, magmatically driven fluid flow represents a risk to be taken into account when assessing migration/re-migration pathways, although traps on the magmatically influenced migration or re-migration pathways may be characterised by a relatively low risk for petroleum charge. Finally, oil near magmatic intrusions may undergo cracking processes and subsequent dissipation, which can be nevertheless regarded as an opportunity if exploring for lighter hydrocarbon products.

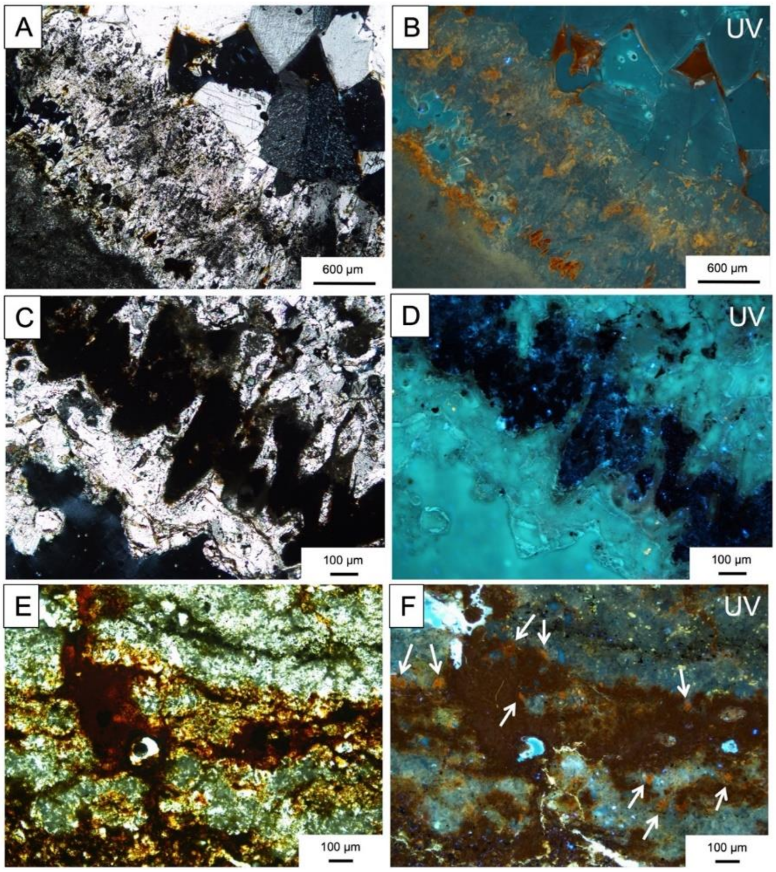

Figure 1. Examples of bitumen occurrences in the onshore Namibe Basin. A, B (UV light): Fluorescent bitumen within calcite veins, mostly generated via conventional burial processes, although the hydrocarbons were then likely remobilised via magmatically driven fluid flow. C, D (UV light): Non-fluorescent pyrobitumen within carbonate veins, likely generated via burial processes and remobilised

during magmatic activity (similarly to the bitumen shown in images A and B), but observed near major volcanic centres. Blue inclusions may represent trapped methane resulting from oil cracking processes. E, F (UV light): In-situ bitumen, observed near major volcanic centres and generated via source rock forced maturation processes. Orange fluorescing kerogen remnants (indicated by the arrows) are observed surrounding the bitumen.

Exploring links between the North Atlantic Igneous Province and Paleocene–Eocene climate change using sedimentary mercury

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The North Atlantic Igneous Province (NAIP), a large igneous province (LIP), was emplaced between ~62 and 50 million years ago (Ma), with a voluminous burst of volcanic activity centred around 56-54 Ma. Global paleoclimate reconstructions from this Paleocene and Early Eocene interval indicate progressively warmer conditions, with several superimposed warming events or 'hyperthermals', such as the Paleocene–Eocene Thermal Maximum (PETM; 56 Ma). These hyperthermals represent transient massive perturbations to the carbon cycle, marked by substantial global warming, ocean acidification and negative stable carbon isotope excursions. International Ocean Discovery Program Expedition 396 to the Mid-Norwegian continental margin recovered a suite of Paleocene–Eocene sedimentary and igneous materials. This notably includes a unique and extremely expanded succession comprising of up to ~80m of PETM (ash-rich) sediments and volcanic ash layers infilling a hydrothermal vent crater. The craters on the Mid-Norwegian margin and similar structures associated with other LIPs were previously identified as surface expressions of a potent carbon release mechanism: the venting of thermogenic carbon generated in the thermal aureoles around volcanic dikes and sills intruded into the underlying sedimentary basins.

In recent years, much progress has been made towards understanding the role of deep earth processes and particularly LIP volcanism on paleoclimate through the application and refinement of proxies as sedimentary mercury (Hg) content. Large scale and especially LIP volcanism are considered important Hg emitters that may result in increased sedimentary Hg content. Here, we present a first set of bulk sedimentary Hg content data from the sedimentary strata within the hydrothermal crater, spanning the PETM. Combining our new data with biostratigraphic, stable carbon isotope, and lithological constraints, we aim to shed light on the timing of hydrothermal crater formation, duration of hydrothermal activity within the crater after formation, and the timing and characteristics of emplacement of NAIP flood basalts during the PETM.

Intrusion emplacement and the interaction with the petroleum system on the North Rona Ridge

Rona Ridge

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The Faroe-Shetland Basin (FSB), located on the NE Atlantic Margin between the Faroe Islands and Shetland, has been the focus of hydrocarbon exploration for 50 years but has faced multiple challenges, largely due to the igneous activity associated with the basin. The extensive Palaeogene Faroe-Shetland Sill Complex (FSSC) covers much of the basin, intruding into the Mesozoic and Cenozoic sedimentary fill, which is of great interest in terms of hydrocarbon prospectivity.

The Rona Ridge, host to the giant Clair Field, one of the success stories of the basin, is a basin-bounding basement high situated in the north-east of the FSB. North of the Clair Field, as well as several small gas fields (e.g. Edradour, Glenlivet), there are numerous undeveloped gas discoveries on and around the high (e.g. Freya, Glendronach, Victory), proving the existence of a working petroleum system. This also makes the area an attractive opportunity for further exploration activity, which is crucial in a time where lower carbon, domestic production will be vital in reaching the 2050 net zero goal.

Although there is evidence of a working petroleum system, it is clear that the role intrusion emplacement has is not well understood. Towards the north of the Rona Ridge, exploration success begins to dwindle, and evidence of igneous activity increases. However, there is potential for another large hydrocarbon discovery in the area within multiple stratigraphic levels, e.g. Devonian Clair Group, Lower Cretaceous Victory Formation. Improved 3D seismic data over the north Rona Ridge area offers enhanced imaging of faults, as well as beneath the intrusions, allowing enhanced mapping of the ridge structure, as well as identification of magma flow directions. This can be used to consider the potential role the intrusions may have played in petroleum migration in the area.

A previously identified prospect named Audacious (Fig. 1), located in Quad 208 on the north Rona Ridge, was first recognised as part of the UK 23rd Licensing Round and re-evaluated during the 27th round between 2013 and 2015 by DONG Energy. Audacious is interpreted to contain Lower Cretaceous shallow marine sandstones, analogous to the nearby Victory Field, located 45 km to the southwest within the West Shetland Basin. The prospect lies within the area of intensive igneous activity along the northern Rona Ridge. The licence identifying the Audacious prospect was relinquished in 2015 due to non-commercial recoverable volumes on a standalone basis, making an argument for exploration of other smaller accumulations in the area with the potential of a tie-back option. Within this area, a series of sub-basins, with a complex fault pattern, host large intrusion bodies which appear to have been fed from several magma sources. Mapping these magma sources can aid prediction of their thermal impact on the petroleum system.

Igneous intrusions in sedimentary basins are often seen as a hindrance to exploration, creating potential impacts on maturation and causing drilling challenges, however recent work suggests that intrusions may play a key role in the migration of hydrocarbons. The aim of this presentation is to discuss potential play types along the north Rona Ridge, the impact the intrusions have on the petroleum system, and the main challenges which may be encountered during exploration and development.

Emplacement and magma plumbing system of the Mesoproterozoic Derim Derim Dolerites, McArthur Basin, Northern Australia

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Over the past decade the increasing application of high-resolution seismic reflection data has revolutionised our understanding of the emplacement of sub-volcanic mafic sill complexes in sedimentary basins, highlighting the critical roles of interconnected sheet intrusions in facilitating lateral crustal magma transport, of host rock mechanical properties in dictating emplacement processes, and providing the important insights into how igneous intrusions affect basin resource potential. However, most recent studies of mafic sub-volcanic magmatic plumbing systems in sedimentary basins have been biased towards the Mesozoic-Cenozoic geological record in offshore settings, where intrusive systems are predominantly characterised by geophysical datasets. The extensive Mesoproterozoic Derim Derim Dolerites which intrude the greater McArthur Basin in the North Australian Basin provide a unique opportunity to study the emplacement and magma plumbing system of a mafic intrusive system due to its abundant intersection by numerous petroleum and mineral drillholes. To date, studies of the Derim Derim Dolerite have largely focused on geochronological and geochemical aspects, but understanding its emplacement is particularly salient given its interactions with prospective unconventional shale gas reservoirs in the Velkerri Formation, which represent potentially the world's oldest petroleum system. Here we integrate lithological, petrophysical, geophysical and remote sensing data to provide new insights into the emplacement and magma plumbing system of the Derim Derim Dolerite.

The Derim Derim Dolerite is a fine- to coarse-grained dolerite that is mainly expressed by a suite of sill intrusions within the Mesoproterozoic Roper Group within the McArthur Basin of northern Australia. Recent geochronological data suggest these dolerites form part of a broader ~1330-1295 Ma mafic Large Igneous Province that extends into the North China Craton. There are widespread exposures of sills in the northern McArthur Basin, with dykes less common and mainly interpreted from aeromagnetic data. They have been penetrated by at least 20 boreholes, with thicknesses ranging from <1 m to >170 m, though our analysis suggests that many thin (<5 m) intrusions may have gone unrecognised due to extensive alteration. Analysis of intrusion thicknesses indicates a positively-skewed distribution, with a large number of thin intrusions, and progressively fewer thick intrusions, consistent with data from mafic intrusive complexes from the Karoo, Gunnedah and Faroe-Shetland basins. The combined thickness of intrusions identified by this study is >1.3 km, with almost 60% of intrusions emplaced in or at the base of the shale-dominated, organic rich Velkerri Formation. Many intrusions have been fully cored, enabling their contacts with sedimentary host rocks to be studied; these are generally sharp, but occasionally peperitic, indicating a range of brittle and non-brittle emplacement processes. The impacts of these intrusions on petroleum systems are mainly characterised by localised heating and alteration of organic-rich host rocks, though oil bleeds and shows associated with fractured dolerites have been observed. Whilst the seismic expression of the intrusions is typified by continuous, layer-parallel reflections, photogrammetric analysis of exposed intrusions often reveals evidence for complex, multi-lobate morphologies.

Petrogenesis and geodynamics of Eocene alkaline intrusions in the pre-salt sedimentary sequence of Santos Basin, Brazil

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Santos Basin is the most prolific oil-producing province in Brazil where thick layers of Late Aptian evaporites seal the voluminous Pre-Salt carbonate reservoirs. The identification and discrimination of igneous rocks and processes are challenging for modeling Brazilian pre-salt reservoirs since volcanism may input thermal and fluid gradients that affect the source and reservoir rocks as much as sealing and trapping in petroleum systems. Lamprophyres and phonolite intrusions were sampled in the Pre-Salt sequence of well 1-BRSA-905-RJS in northern Santos Basin nearby the Cabo Frio Structural High in SE Brazil. These alkaline rocks indicate the existence of a strongly silica-undersaturated trend. However, fractional crystallization modeling as well as Sr-Nd-Pb-Hf isotope data shows that the alkaline lamprophyres are not suitable parental compositions to the evolved felsic phonolitic magmas. The Sr-Nd-Pb-Hf isotope compositions of the lamprophyric magmas represent mixing of EM1 and Trindade plume mantle components. The EM1 is possibly related with the melt- and/or fluid-induced metasomatic processes on the subcontinental lithospheric mantle (SCLM) that occurred beneath the South American Platform during the Neo-Proterozoic-Cambrian subduction processes associated with the final stages of the Gondwana amalgamation, as recorded by the TDM ages (601-499 Ma) of the studied intrusions in Santos. $^{40}Ar/^{39}Ar$ analysis presented integrated age of 41.06±0.02Ma and 38.62±0.02Ma for phonolite and lamprophyre samples, respectively. A “plateau” age assignment for the true crystallization age of the sample could not be obtained due to the discordance in the ages of individual steps. This discordance was attributed to loss of radiogenic ^{40}Ar that can happen in nature due to reheating events or metasomatism. An interaction between the Trindade plume head and SCLM is proposed for the geodynamics of Santos Basin at 40 Ma. The presence of an anomalously hot mantle represented by the deflected Trindade plume head beneath Santos at the Eocene is supported by the petrological and geochronological data. Therefore, it may be relevant to consider high geothemal flow regimes in basin evolution models proposed for Santos during the Eocene.

Keywords: Pre-Salt intrusions, Santos basin, lamprophyre, phonolite, Sr-Nd-Pb-Hf isotopes, Ar-Ar dating

Tempo and distribution of Mesozoic magmatic activity in the Browse Basin, Australian Northwest Shelf

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The Browse Basin is one of the major hydrocarbon provinces in the Australian Northwest Shelf where significant gas and condensate discoveries have been made in the Jurassic and the Lower Cretaceous reservoirs in recent decades. This rift-margin basin is characterised by its tectonic-magmatic activity throughout the Mesozoic, with thick sequences of extrusive intrusive, and volcanoclastic rocks having been identified from both well and seismic data, and which are recognized as one of the major challenges for E&P activities in the region. For example, the Warrabkook-1 and the Buffon-1 wells targeted the Middle-Early Jurassic sequences of a seaward dipping clinoform and a mound structure, respectively, which both turned out to be over 400m of poor-reservoir-quality volcanoclastics (Rollet et al., 2018; Symonds et al., 1998). From a hydrocarbon production perspective, dykes have been suspected to inhibit fluid flow in the Jurassic reservoir (i.e. reservoir compartmentalization) of the Ichthys Field; given that these intrusive rocks are below seismic resolution, they contribute to significant uncertainty during field development planning (Yamamoto et al., 2020).

Despite their recognised influence on the petroleum system, to date there has been no regional synthesis of Mesozoic magmatic evolution of the Browse Basin. This has led to a poor understanding of the dynamics of the magmatic plumbing system in this rift basin, which is likely to impact both reservoir distribution and quality. To tackle this problem, this study aimed to investigate the basin-wide record of Mesozoic igneous activity using over 100 exploration/appraisal wells and regional 2D and 3D seismic data in order to analyse the basin architecture, the distribution of intrusives and extrusive rocks, the petrological characteristics of igneous and sedimentary rocks, and their correlation to seismic facies and geomorphologies. A succession of Mesozoic paleo-environmental maps of the Browse Basin was also interpreted, which illustrate transitions of igneous rock distribution and types through geological time.

Our analyses indicate that although igneous activity has sporadically continued within the basin throughout the Mesozoic, the most aggressive period of magmatism occurred during Bajocian to the Callovian time; a large part of the outboard-southwestern basin was covered by 400-500m thickness of lava deltas in a marginal to shallow marine setting (e.g. Warrabkook-1), whereas gigantic submarine volcanoes formed under marine environment in the northwestern basin (e.g. Buffon-1, Grace-1, Kontiki-1). In the central basin, where the Ichthys Field is located, the igneous rocks occur as mixture of altered igneous rocks, volcanic ash, and likely re-deposited fluvio-deltaic sediments. Subsequent episodic magmatism during the Berriasian resulted in a series of submarine volcanoes and submarine lava flows being erupted in a deep-marine environment, which are mainly concentrated in the northern part of the basin (e.g. Ichthys North-1) indicating a focused magmatic plumbing system during the Lower Cretaceous.

Our study provides a basin-wide framework of Mesozoic magmatism in the Browse Basin within a tectono-stratigraphic context, and yields new insights into the tempo, distribution and nature of magmatic activity that will be beneficial for future exploration activities, field development planning, and assessments of the feasibility of CCS in the Browse Basin.

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