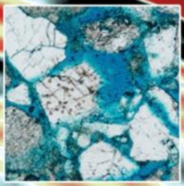
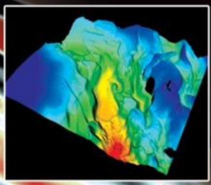
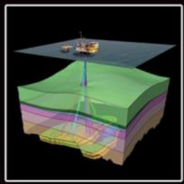

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Date 24th-26th October 2023

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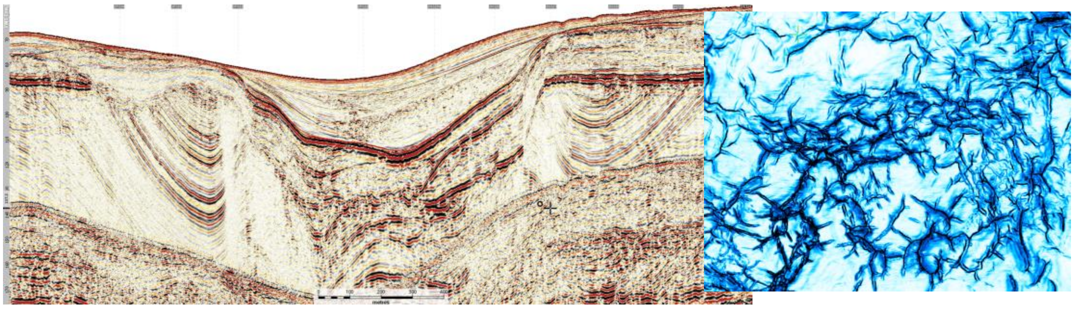

Seismic reflection data allow us to generate unrivalled images of the subsurface, and have become one of the most widely used geophysical surveying techniques for imaging the subsurface, using compressional (P) and, sometimes, shear (S) waves. Whilst hydrocarbon exploration has traditionally driven innovation in subsurface imaging, these methods are now equally vital for the emerging industries of the energy transition.

Advances in data acquisition, processing and interpretation workflows have improved our ability to locate resources, make informed decisions of where to drill complex deep wells, and identify potential hazards and risks. We must now utilise and adapt these methods for uses in offshore wind, carbon capture and storage (CCS), geothermal resources, underground energy storage and nuclear waste storage. These data yield valuable insights into fundamental geological processes from basin evolution, structural and sedimentary geology, fluid–rock interactions and igneous process

This conference will showcase how the latest advances in acquisition, processing, and interpretation of seismic data, both active and passive source, have illuminated fundamental geological phenomena. It will explore how these advances play a vital role in emerging geoenergy solutions as part of the energy transition. It will bring together the geoscientists across industry, academia, and the public sector, to highlight this vital role in characterizing the subsurface and investigating rock and fluid distribution from depths of several metres to several kilometres.

We encourage abstract on, but not limited to, the following topics:

- Acquisition and processing of seismic data
- Interpretation and analysis of seismic data covering:
    - Sedimentary basin evolution,
    - Structural and sedimentary geology
    - Fluid and heat flow,
    - Site characterisation for engineering projects
    - Storage site characterisation
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Seismic Imaging:
Applications in the energy transition and beyond

24 - 25 October 2023

Hybrid Conference – The Geological Society London, and Zoom

Provisional Programme

Day One	
09.00	**Registration**
09.30	**Welcome**
	Session One
09.35	**CO2 storage research and cross-border synergies: Underground CO2 storage potential assessment in the western Norwegian Danish basin"** Simon Blondel, *University of Oslo*
10.00	**Seismic Modelling of CO2 Storage in Geologic Reservoirs using Machine Learning** Adewunmi Abdul, *University of Oxford*
10.25	**Poster Lightning Talks**
10.50	**BREAK**
	Session Two
11.30	**Salt cavern cluster characterisation based on 3D seismic interpretation** Hector Barnett, *Newcastle University*
11.55	**The Crosh Vusta Fault Complex and Solution Mining the Preesall Halite"** Francis Andrew Buckley, *Cuillin Geoscience Ltd*
12.20	**Quantifying the variability in fault density across the UK Bowland Shale, with implications for induced seismicity hazard** Germán Rodríguez, *University of Bristol*
12.45	**LUNCH**
	Session Three
13.30	**Past, present and future of seismic studies in an overlap zone of the Variscan and The Carpathian fold and thrust belts in SE Poland and W Ukraine** Piotr Krzywiec, *Polish Academy of Sciences*
13.55 Virtual	**Repurposing Legacy Seismic Data for Sustainable Marine Renewable Energy Development** M. Clementi, *SLB*
14.20	**TBC**
14.55	**BREAK**
	Session Four
15.30	**Carbon storage seismic reprocessing for the Central North Sea** Arindam Kanrar, SLB
15.55	**PANEL (1) – Where next for interpretation and imaging?**

16.45	**SUMMARY**
17.00	**End of day one**
17.00-18.00	**Drinks Reception**

	Day Two
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09.30	**Welcome**
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10.00	**Seismic Imaging of an Igneous Complex** Simon Gozzard, *CGG GEOLOGY*
10.25	**Marine Gas Hydrates Offshore Mauriatainia** Mark Ireland, Newcastle University
10.50	**BREAK**
	Session Six
11.30	**3D multichannel seismic grid tied to IODP Expedition 313: Tracking sediment transport processes across the U.S.mid -Atlantic continental shel"** Aldiyar Mukhatzhanov, *Rutgers University*
11.55	**3D seismic for IODP site characterization and hazards detection: verified by IODP Exp 400** Mads Huuse, University of Manchester
12.20	**LUNCH**
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13.15	**Fluid and heat Flow along the Balearic margin of the central Algerian basin:Heat redistribution system controlled by the Mediterranean Salt Giant and Plio-Quaternary volcanic structure** Simon Blondel, *University of Oslo*
13.40	**Utilising High Density Passive Seismology for Geothermal Exploration in Built Up Areas"** Charles Dunham, *Newcastle University*
14.05 Virtual	**Monitoring seismic velocity changes in the Critical Zone with a dense array of nodal seismometers** Kevin Davidson, *Birkbeck University of London*
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	Session Eight
15.00	**TBC**
15.25	**PANEL (2) – Where next for onshore imaging?**
16.15	**Closing Remarks**
16.30	**End of day two**

Posters
Subsurface characterization of the Hewett field and its monitorability during CCS Jing Yang, University of Manchester
Seismic geomorphology of Upper Mississippian carbonate in the Solway Basin, East of the Irish Sea Maulana Rizki Aditama, University of Manchester
Deep-water seismic stratigraphic responses to tectonic and climatic changes Xingxing Wang, China University of Geosciences
Importance of igneous intrusions for CCS in the Southern North Sea Vlad Mihalcea, *University of Manchester*
Seismic forward modeling to image sandstone intrusion complexes Saad Almalki, *University of Manchester*

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CONTENTS PAGE

ORAL ABSTRACTS
(In Programme Order)

Session One

CO_2 storage research and cross-border synergies: Underground CO2 storage potential assessment in the western Norwegian-Danish basin

Simon Blondel[1], Sian Evans[1], Torsten Hundebøl Hansen[1], Rikke Bruhn[1,2], Alvar Braathen[1]

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Sitting in between southern Norway and Denmark, in the central North Sea, the Norwegian-Danish Basin (NDB) holds an optimal position for Carbon Capture Storage (CCS) activities in northern Europe (Figure 1). While CCS projects have already been launched in the Danish NDB (i.e., Greensands and Bifrost), the Norwegian NDB remains poorly explored. It is now focusing the attention since the recent opening and licensing of two acreages (Poseidon and Havstjerne) for CCS in 2023.

Previous CCS investigations in the Norwegian NDB mentioned the presence of three main potential aquifers: the Palaeocene Fiskebank formation in the Siri trend, the mid-Jurassic Bryne and Sandnes formations, and the Triassic Gassum and Skagerrak formations. Because there is a limited amount of well data in the Norwegian NDB, the distribution and the petrophysical properties of these aquifers is poorly constrained. Previous studies estimated aquifers volumes using only average thicknesses and highlighted the importance of investigating the seal integrity above salt structures and in major faults. In this study, we aim at refining our knowledge of the NDB for CCS and, to a broader extent, in salt basins in general.

We present our latest results where we adapt petroleum exploration play analysis and yet-to-find concepts to CCS exploration to better assess the storage capacity in the Norwegian NDB. We collected all publically available seismic and well data to build new maps of NDB. We use these maps to re-asses the regional framework and identify the potential storage units. We will use these maps to refine the quantitative estimations of the storage capacity and the integrity of each key CCS play in the NDB.

We study the geometry and the distribution of the aforementioned aquifers and how it is influenced by salt-related tectonics. Most of the salt tectonics activity is occurring before the mid-Jurassic doming. The Triassic formations are highly deformed and several anticlinoform could provide good four-way dip traps for CCS. The mid-Jurassic aquifers are very condensed in the NDB and difficult to image on seismic data. Main depocenters are located in the Egersund basin. The Mid-Jurassic aquifer is thinning towards the south-east of the basin wher it could provide stratigraphic traps linked to salt diapirs. While most salt diapirs are buried beneath the Mesozoic, some diapirs rise much higher, up to the Plio-Quaternary roof. The distribution of these diapirs seem correlated with the main Faults, which would suggest thick-skinned tectonics. This is particularly along the Hummer Fault Zone, which seems to have had a great influenced on the tectono-stratigraphic evolution of the Norwegian NDB.

The integrity of the seal is also investigated. We observe several amplitude anomalies that we interpret as gas accumulations above of salt structures (Figure 2). Well data suggests that the Jurassic source rocks are immature and that this is mainly methane sourced within the Hordaland sealing unit. It is likely that extensional crestal faults provide high permeability paths focusing the upward migration of the methane above diapirs.

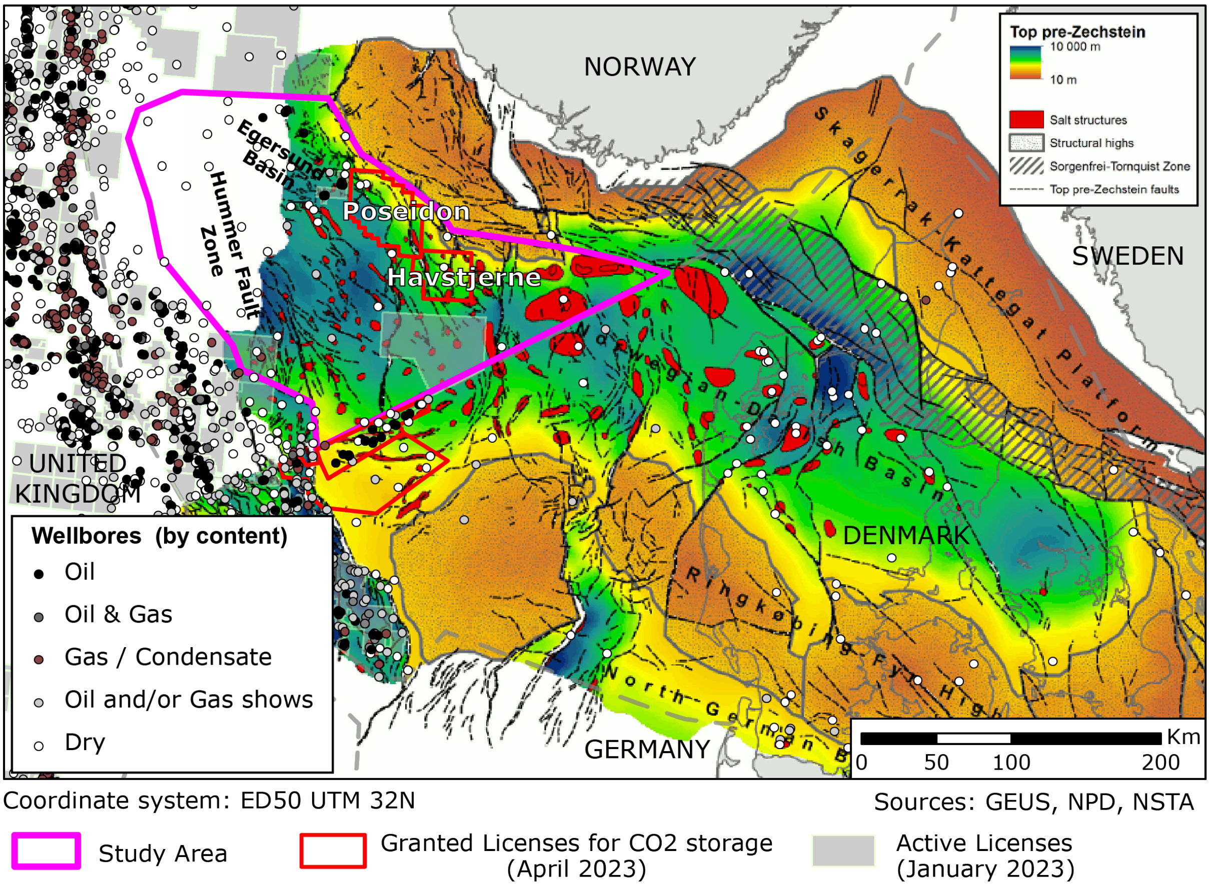

Figure 1 Map of the area of interest and the open acreages in the southern Norwegian North Sea (as of January 2023; Olje og energidepartementet, 2023a, 2023b). Base map shoes the depth to Top Pre Zechstein (modified from Vejbæk and Britze, 1994; GEUS, 2015) and the identified salt structures (mapped by GEUS).

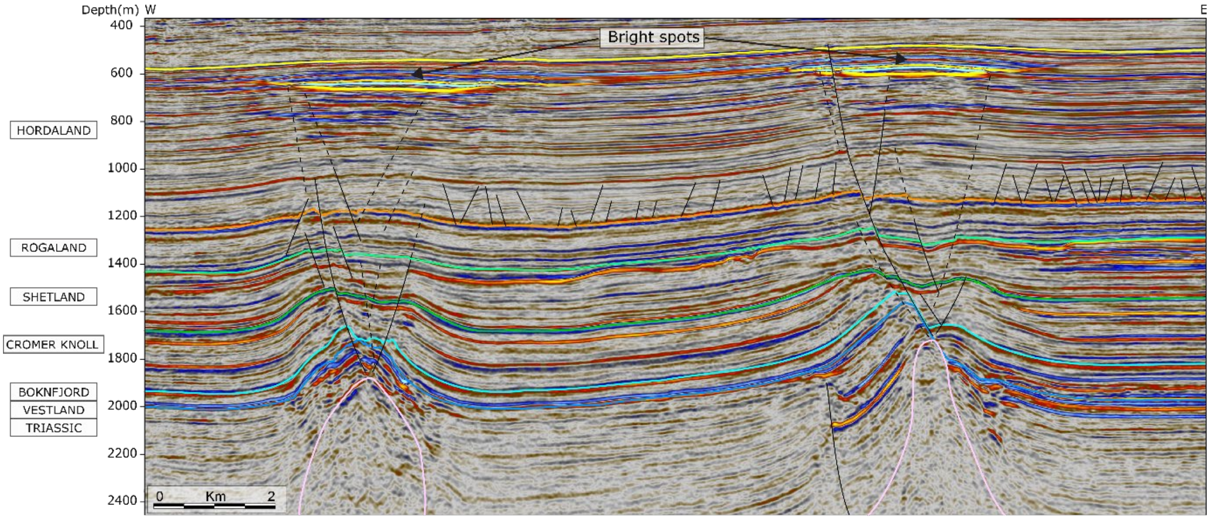

Figure 2 Seismic section showing the bright spots recording fluid accumulations within the Paleogene sediments above salt diapirs. The presence of these bright spots question the permeability of salt-related faults. The position of the seismic section is not displayed.

Seismic Modelling of CO_2 Storage in Geologic Reservoirs using Machine Learning

Adewunmi Abdul, Tarje Nissen-Meyer, Michael Kendall

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Seismic data collected in vast amounts over a long period of time enable detailed characterization of CO_2 migration within reservoir units; such data lend themselves well to machine-learning techniques, both in modelling and analyses. Our research aims to combine the knowledge acquired from numerical modelling of wave propagation with machine learning in order to understand how leakage of sequestered CO_2 into ambient rock formations manifests itself in seismic data.

We outline a methodology that simulates waveforms from a large range of structural scenarios based on the properties of the clastic rocks and fluids from the Utsira formation in the Sleipner field, North Sea. This reservoir has sequestered a large amount of CO_2 which is well imaged using time-lapse seismic reflection data. To start, we create over 100,000 synthetic simulations using the SEISMIC_CPML program which uses the finite difference method to solve the 2D acoustic wave equation. Each simulation serves as a training example for a neural network using a conditional encoder-decoder design. Some of these examples are kept as a validation set during training and other unseen examples are generated and used as a test set to assess the performance of the trained network. The advantage of this approach is that using the machine learning approach to model waveforms is computationally cheaper compared to the traditional approach, such as finite difference waveform modelling. The sensitivity of seismic waveforms to static proxies such as thickness (reservoir, caprock, CO_2), reservoir heterogeneity, fault and fractures, and CO_2 saturation are investigated. Our aim is to assess the potential for seismic detection in a number of leakage scenarios. The knowledge gained from such techniques will enable the conversion of seismic signals into meaningful information for further research directions to optimize CO_2 storage efforts. For example, our approach should be useful in full-waveform seismic inversions, where many realisations of the forward problem are required. In the future we will also use this methodology to consider passive seismic methods for monitoring CO_2 injection in saline aquifers, as they offer a cost-effective, non-invasive, and continuous monitoring solutions.

Session Two

Salt cavern cluster characterisation based on 3D seismic interpretation

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Abstract:

Hydrogen is potentially an important energy vector in pathways to the decarbonization of energy systems, critically in sectors where emissions from fossil fuels are hard to abate. Development of a hydrogen economy will likely require large-scale underground hydrogen storage, including salt caverns that are solution mined in evaporite sequences. To date, storage estimates for offshore areas have been based on regional geological interpretations and do not include detailed interpretations from regionally extensive 3D seismic data despite the internal structural heterogeneity of salt frequently exhibiting enormous variation in structure and complexity. Here we demonstrate how using detailed 3D seismic interpretations is part of evaluating the locations of individual caverns within a larger cluster.

We use detailed regionally extensive interpretations of the Zechstein of the UK sector of the Southern North Sea to characterise the internal structural complexity and use this to constrain predictions of viable cavern locations and storage volumes. We identify and map 6 different structural facies that occur within the Zechstein throughout the basin. Mapping of these facies reveals not just a basin-ward trend of increasing internal structural complexity but also that deformation within the Zechstein is stratified between Zechstein depositional cycle, with areas having heavily deformed Z2 Stassfurt halite and undeformed Z3 Leine halite. These interpretations improve the confidence in characterising the evaporite sequences within the basin ahead of identifying possible cavern storage locations.

We use the detailed seismic interpretations to constrain modelling salt cavern clusters volumes. We adopt a stochastic approach for cavern storage capacity. The workflow incorporates evaluating the uncertainty of key parameters including depth uncertainty, insoluble content, and temperature. The range of values used within the models are constrained using the seismic interpretations and regional well data. Our method demonstrates that the internal heterogeneity within the Zechstein is a key uncertainty in storage capacity estimates for salt cavern clusters.

Through our workflow volumes of individual caverns are calculated and hence the total energy capacity of a theoretical salt cavern cluster. These results indicate that even within a relatively small area of suitable salt (<250km^2) large volumes of Hydrogen (> 500 TWh) can theoretically be stored. Our results show that the two key uncertainties for individual caverns within theoretical cluster sites are: the thickness of the salt, which is in part derived from the residual uncertainty of depth conversion, as thinner salt leads to smaller volumes and vice versa; and insoluble content present within the salt, as 1% increase in insoluble content leads to a 1% decrease in cavern volume.

(See figure below)

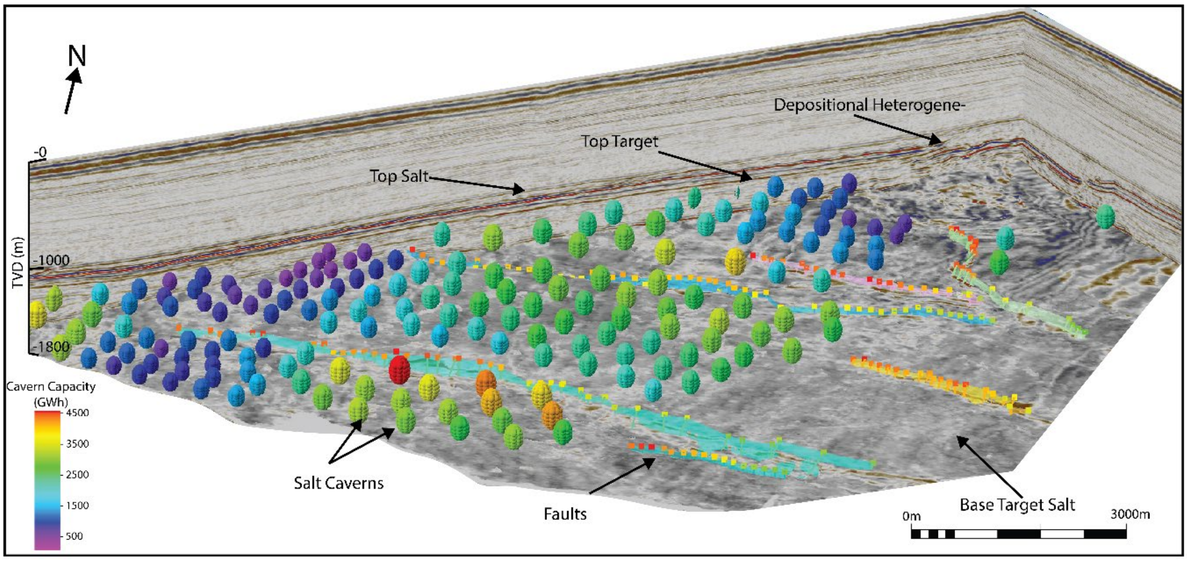

Figure 1. Theoretical placement of salt caverns, coloured with cavern capacities. Cavern location and internal volumetric parameters are constrained by interpretations from both seismic and well data.

The Crosh Vusta Fault Complex and Solution Mining the Preesall Halite (_Oral_)

Francis Andrew Buckley

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The Crosh Vusta Fault Complex is a fault-bounded, doubly plunging asymmetric anticline in a 2000m thick mudstone and halite sequence belonging to the Mercia Mudstone Group, lying in the East Irish Sea off Barrow in Furness. The structure extends approximately 20km N-S and 5km E-W. Within the top 1000m MSL the sequence includes a predominantly halite interval comprising the Upper and Lower Preesall Halites. These units were the target of a solution-mining project in 2008 - 2010, in which a series of caverns dissolved from the halites would be used as a gas-storage resource, supplying domestic gas at peak-demand and subsequently replenished using cheaper off-peak supplies.

A series of seismic datasets, including 3D exploration seismic, re-processed 3D seismic and high-resolution 2D seismic were used to map structure and stratigraphy across the sequence. The project was initially conceived and planned from a series of exploration 2D seismic data sections, tied back to existing well data, in which the gross morphology of the anticline structure and the Mercia Mudstone sequence was established.

The 2D seismic data were originally shot in the 1980’s and, at the time, were available only on paper records in a standard ‘wiggle-trace’ display, although the data are doubtless now available on the NDR data archive. Overall structure and main faulting events are discernible on the paper records, but vertical and horizontal resolution is poor and confidence in the interpretation necessarily low.

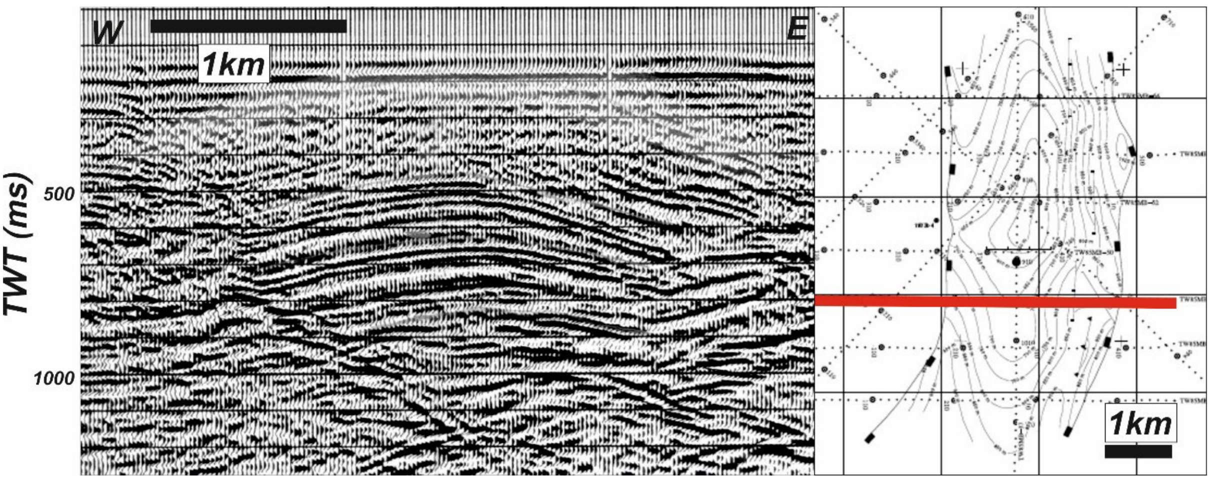

Figure 1: Vintage 2D exploration seismic E-W line across the Crosh Vusta structure

A 1000m-deep exploration borehole was an early requirement to enable Front-End Engineering Design (FEED) studies to proceed, however due-diligent health and safety procedures established for top-hole drilling of hydrocarbon wells required an assessment of drilling hazards using high-resolution site-survey methods. To that end an HR2D seismic dataset was acquired with an E-W line spacing of 100m, but crucially only three N-S cross-lines were acquired. The dataset enabled identification of a series of shallow gas hazards and a crestal fault complex concentrated on the steep NE flank of the Crosh Vusta structure, and also established a seismo-stratigraphic framework for the post-Triassic overburden, including a previously unreported Tertiary igneous intrusion, or possible extrusive lava flow. Location of the exploration borehole was optimised using the HR2D dataset, with the results of the borehole subsequently correlated with the seismic which was then used to construct a 3D model of the Crosh Vusta complex. However, the comparatively steep dips on the structure and the 2D nature of the seismic, including the concomitant lack of 3D migration, caused the introduction of prominent mis-ties between the HR2D E-W lines and the long N-S cross-lines.

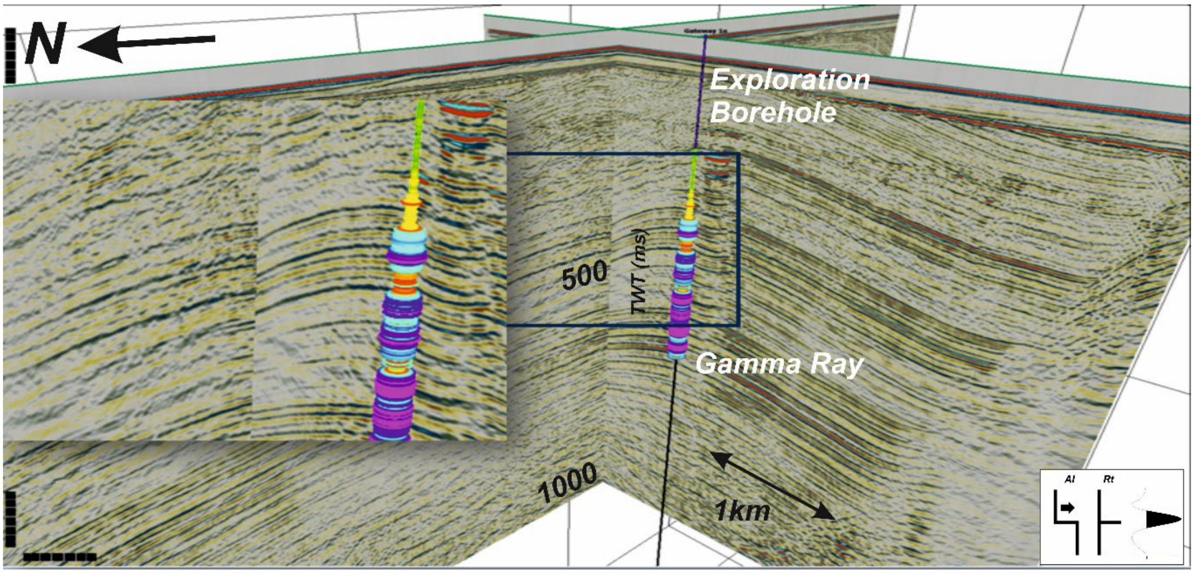

Figure 2: HR2D seismic lines illustrating migration mis-ties caused by steeply dipping reflections; GR curve from exploration borehole wireline indicated

Structural mis-ties and poor cross-track resolution were addressed initially by the use of an exploration 3D seismic dataset, originally acquired as part of the Bains Field development, but these data were subsequently re-processed using a short-offset algorithm which boosted vertical and horizontal resolution, allowing a more detailed model to be constructed. Corelation of high resolution 3D data with Vp, Vs and density log data facilitated an absolute impedance inversion of the seismic, allowing a more detailed characterisation of the structure and the target halite sequences.

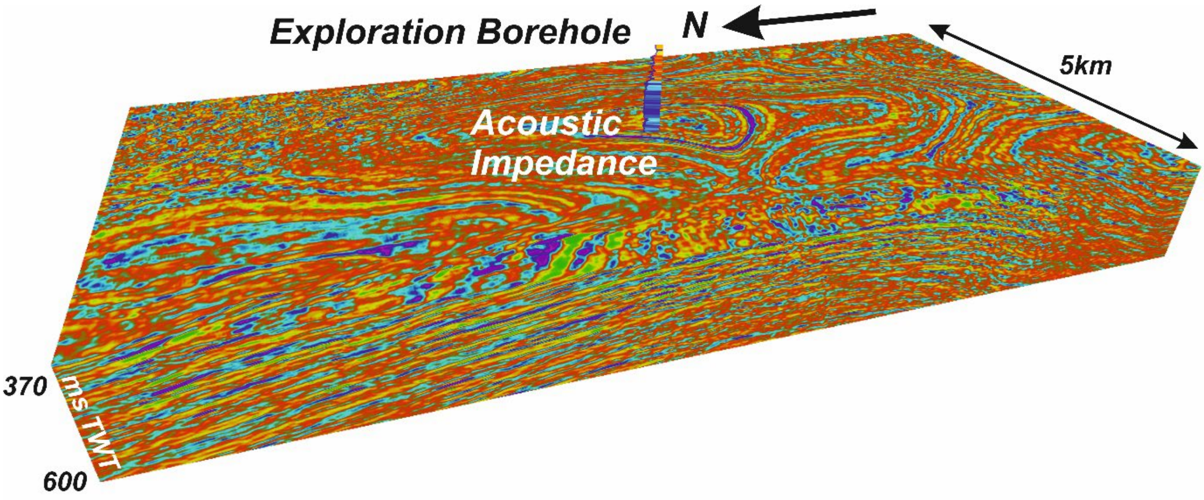

Figure 3: Short-offset reprocessed 3D seismic cube and borehole Acoustic Impedance log curve

Geological characterisation was fed into engineering studies and solution-mining strategies as part of licencing and planning approval workflows, however the project is currently shelved, although there is renewed interest in such projects as part of Hydrogen gas-storage proposals.

The exercise highlights the inherent value to be extracted from archive and legacy datasets, but also the need to acquire new seismic data with the requisite frequency and resolution characteristics to provide answers to complex questions on lithology, structure and petro-physical properties of the sub-surface.

Quantifying the variability in fault density across the UK Bowland Shale, with implications for induced seismicity hazard

Germán Rodríguez and James Verdon. School of Earth Sciences, University of Bristol

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The occurrence of induced seismicity during hydraulic fracturing led to the shut-down of the UK's nascent shale gas industry. Various low carbon energy technologies that involve the injection of fluids into the subsurface, such as Carbon Capture and Storage (CCS), deep geothermal energy, and subsurface hydrogen storage also carry the potential to cause induced seismicity. Hence, there is a need to develop methods to characterize the expect seismic hazard that might be generated by the development and operation of such facilities.

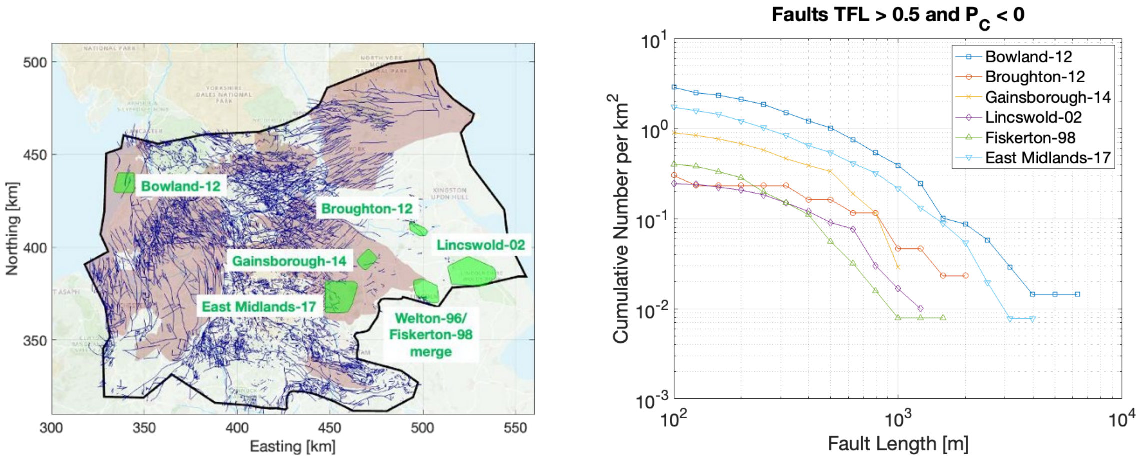
Deterministic characterization of induced seismicity generally use numerical geomechanical models of the subsurface operations that deterministically simulate whether the perturbations will generate slip on an identified fault. However, these methods have struggled to produce accurate *a priori* estimations of induced seismicity hazard. In particular, faults can go undetected in 2D or 3D seismic surveys if they are shorter that the resolution retrievable from a seismic survey, or if they have low (and in some cases even zero) vertical displacement. In such cases, the faults that cause induced seismicity may only be visible via microseismic observations once they are reactivated (e.g., Nantanoi et al., 2022). Clearly, since they cannot be imaged *a priori*, such faults cannot be included in geomechanical simulations, leading to inaccurate characterisations of induced seismicity hazard.

Instead, we develop a method to characterize induced seismicity hazard from reflection seismic observations using probabilistic methods. The seismogenic index, S_I, relates the number of induced earthquakes to the injected volume (Shapiro et al., 2010): $10^{S_I} = bM + N_E/V$. This relationship can be used to generate probabilistic forecasts of the maximum magnitude that will be induced after the injection of a given fluid volume. S_I can also be related to the density of faulting within the volume perturbed by injection: $10^{S_I} = 10^{a}.F/C.S$, where *a* is the background tectonic Gutenberg-Richter *a* value, *F* is the fault density, *C* is the average critical stress change required to activate the faults, and *S* is the storativity of the formation. For a given formation or play, it is reasonable to assume that changes in *a*, *C* and *S* will be relatively minor, in which case variations in S_I will be controlled by changes in fault density across the play.

We demonstrate this approach by application to hydraulic fracturing-induced seismicity in the Bowland Shale. We obtained 3D reflection seismic cubes along an east-west axis across northern England (Figure 1a). To ensure that our estimates of fault density were unbiased, we used an automated fault detection algorithm to map faults within lower Carboniferous strata (Figure 2). We then estimated the slip potential by resolving the formation's stress and pore pressure conditions (with the Bowland shale being significantly over-pressured) onto each fault. The abundance of critically stressed faults varied significantly across the play, with a regional reduction in the intensity of mapped faults from west to east by as much as an order of magnitude (Figure 1b).

We use these observations to inform a probabilistic assessment of seismic hazard. We begin by using the observed HF-IS in the Bowland-12 area to create an empirically-constrained baseline model. We then use the observed differences in fault densities to create an updated S_I distribution that may be more appropriate for the less faulted regions to the east. This updated model shows that induced seismicity of sufficient magnitude to be felt could still be generated by hydraulic fracturing in these regions, however their likelihood of occurrence is reduced by an order of magnitude.

We anticipate that a similar approach could be used to characterise and update the induced seismicity hazard as activities such as CCS and geothermal energy are rolled out across the UK.



(a) (b)

Figure 1: Map of northern England (a) showing mapped faults from the BGS database (blue lines), and the 3D reflection seismic surveys analysed in this study (green polygons). In (b) we show the numbers and lengths of critically stressed faults in the Lower Carboniferous for each survey area.

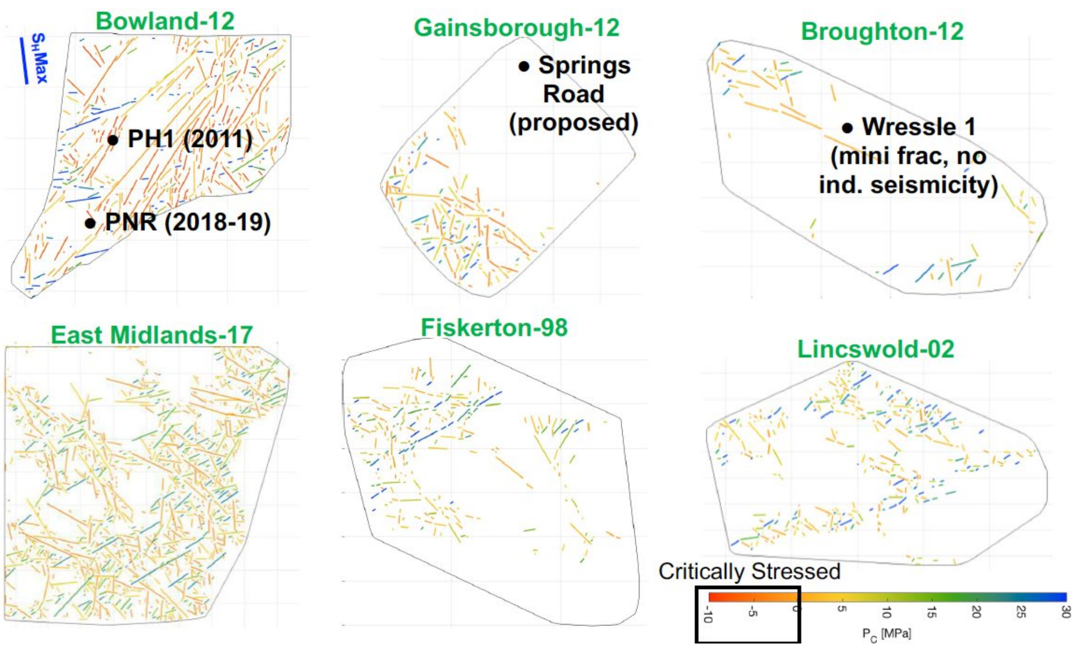


Figure 2. Critical pore pressures (P_C) for all mapped faults in the Lower Carboniferous horizons for each survey area shown in Figure 1. The three shale-gas wells hydraulic fractured to date in the UK are also shown for reference, all of them located inside the Bowland-12 seismic survey. Preese Hall-1

(PH1) in 2011, and Preston New Road (PNR) 1 and 2 in 2018-19. Other wells in different areas were either proposed but not completed, or did not induce any seismic activity.

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Session Three

Past, present and future of seismic studies in an overlap zone of the Variscan and the Carpathian fold-and-thrust belts in SE Poland and W Ukraine

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SE Poland and W Ukraine are located in extremely interesting geological position – this is where SW edge of the East European Craton, formed due to the breakup of Rodinia approximately 560 Ma year ago, and where Variscan and Carpathian fold-and-thrust belts overlap. Additionally, this is where seismic surveying started being used for subsurface studies. It took place just two years after very first seismic data have been acquired in 1921 in Oklahoma, US. First seismic refraction survey in Poland was completed in 1923 in vicinity of Kraków in S Poland. Its goal was to image Miocene evaporites deposited within the Carpathian foreland basin. Then, after this successful pilot study, application of seismic surveying rapidly increased due to intense exploration for oil and gas in the N Carpathians and the Carpathian foreland basin – i.e. the area that in the late 19th and in early 20th centuries belonged to the most prolific hydrocarbon provinces in the world. In 1928 Polish government established state-controlled “Pionier” company with the main goal of exploration for hydrocarbons in new areas and development of new, promising exploration techniques, including geophysical surveying. Within this company Department of Geophysics was soon established and its key employees were sent to Germany, USA and France in order to obtain necessary training and first-hand experience with modern geophysical exploration techniques. Two geophysicists played key role in these early seismic studies. Dr Zygmunt Mitera, who graduated from AGH University of Science & Technology in Kraków, Poland, obtained his PhD in 1933 from Colorado School of Mines. He worked there under the supervision of Prof. Carl August Heiland, one of the pioneers of exploration geophysics, and founder of the Heiland Research Corporation that was producing high-quality seismic field equipment. Dr Mitera was murdered in 1940 by the Soviets during so-called Katyn Massacre. Dr Stanislaw Wyrobek, who also graduated from AGH University of Science & Technology, settled after the WWII in the UK. He obtained his PhD at the University of St. Andrews. His doctoral dissertation was based on results of seismic studies in the Carpathians. After that he was hired by British Petroleum where he kick-started seismic surveying. He and his team located key well that opened up the North Sea basin for offshore exploration. In 1954 Dr Wyrobek moved to British Petroleum headquarters in London where he organized central interpretation office for oversea British Petroleum seismic projects in Italy, France, Germany, Switzerland, Iran, Egypt, Tanganyika, Kenya and Senegal. “Pionier” company conducted its first seismic refraction survey in 1933 in vicinity of Truskawiec (now W Ukraine). First seismic reflection survey was acquired in 1934 in Nahujowice near Boryslaw; this was followed by surveys in Daszawa, Tustanowice and Stryj (now in W Ukraine). Obtained data greatly helped to understand subsurface geology of the Carpathian foreland basin, where gas deposits are hosted by flat-lying Miocene strata, and of the Carpathian fold-and-thrust belt, where traps are related to complex fault-related folds. Obtained results have been published in numerous journals including, between others, first issues of SEG “Geophysics”.

Seismic surveying continued after the war in Poland and in the USSR, and then in independent Ukraine. Results of these studies were used to better understand structure and evolution of the Carpathian foreland fold-and-thrust belt. One of the recent discoveries, based both on reinterpretation of legacy data as well on interpretation of modern data, was the role of tectonic wedging and development of triangle zones. Previous models relied on well-established concept of dominant foreland-verging thrusting. Detailed analysis of seismic data from the area between Krakow and Debica in S Poland proved that in this segment of the Carpathians Miocene evolution of the orogenic front was strongly influenced by tectonic wedging and formation of triangle zones due to the combined effect of a very diversified morphology of the top of the lower plate and of lateral thickness and facies changes of the Upper Badenian evaporites of the Wieliczka formation. Similarly, integration of seismic and geological data from the W Ukraine showed that tectonic wedging occurred also in this segment of the Carpathian front. In this case triangle zone encompasses Eggenburgian-lower Badenian Borislav-Pokuttya unit, known for its rich hydrocarbon accumulation exploited since the late 19th century. This unit is located between Skiba unit, thrust towards the NE, and the Sambir units, with its SW part uplifted along regional backthrust located above the compressional duplex developed within the core of the Borislav-Pokuttya triangle zone. In this segment of the Carpathian fold-and-thrust belt tectonic wedging was triggered by combined effect of large fault scarps developed due to the flexural extension within the top of the lower plate, and due to lateral thickness and facies changes of the Eggenburgian-Ottnangian evaporites of the Vorotyshcha formation.

Recently acquired seismic data provided new level of structural imaging not only for the Carpathians but also for the deeper subsurface. High-quality seismic images of the late Carboniferous Variscan compressional structures were provided by globally-unique high-end PolandSPAN® regional seismic survey acquired by ION Geophysical. PolandSPAN® seismic profiles imaged entire Phanerozoic sedimentary cover and crystalline basement of the East European Craton. This data, together with other datasets acquired over last two decades, was used to re-interpret the leading edge of the Variscan fold-and -thrust belt that in effect was moved by approximately 300 km towards the East from its previous position. PolandSPAN® seismic data revealed also complex Mesozoic history of SE Poland and W Ukraine, including several pulsed of hitherto unknown uplifts and regional erosion, possibly related to the large-scale lithospheric buckling.

Future seismic studies should include both high-quality long-offset 3D surveys focused on particular subsurface structures as well as regional seismic transects meant to image entire, often strongly deformed sedimentary cover and crystalline basement. It would be of utmost importance to acquire trans-border seismic reflection data that would allow to integrate datasets from Poland and Ukraine.

Repurposing Legacy Seismic Data for Sustainable Marine Renewable Energy Development

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Summary:

Addressing climate change and achieving sustainable energy solutions requires a significant scale-up in wind energy installations while minimizing their environmental impact. However, constructing wind turbines demands substantial resources, leading to significant costs, particularly for foundations. Optimizing resource use and cost management becomes crucial to ensure environmentally responsible practices.

To promote sustainable wind energy projects, geophysical solutions are being explored. Understanding seabed geology and near-seafloor characteristics aids in identifying optimal turbine locations, considering factors like water depth and sediment composition. Advanced geophysical methods, such as surface wave analysis and joint inversion, provide valuable insights into near-surface velocity models and seabed elastic properties. These parameters are vital for assessing foundation performance and predicting soil behavior under dynamic conditions, ensuring the safety and efficiency of wind energy installations.

Introduction:

The development of marine renewable energy resources requires thorough consideration of the geotechnical and structural properties of the seabed, particularly at depths ranging from 60 to 80 meters underground.

Reflection seismic is a widely used and established technique employed for hydrocarbon exploration and geological research. In engineering applications, it involves using an acoustic source with a high-frequency band (100 Hz to 10 kHz) and a relatively short multi-channel hydrophone streamer towed behind the survey vessel (Ramani et al., 2022). Surface waves, on the other hand, require low-frequency sources and long offsets to generate clear signals, and this requirement is met by legacy oil and gas seismic data acquired in shallow water surveys (Boiero et al., 2013).

By analyzing and jointly inverting the multimodal dispersion curves of Scholte waves and P-guided waves, we can estimate the distribution of shear and compressional wave velocities (VS and VP) in shallow subwater layers.

Method:

The underlying principle of surface-wave methods is rooted in the dependence of propagation depth on wavelengths, leading to geometric dispersion where different frequencies have distinct phase velocities. To determine the local phase velocity of the linear event of interest (Scholte or guided-wave modes), the analysis workflow leverages data redundancy to remove the propagation path's effect from the source to the analysis point (Strobbia et al., 2011). This analysis is typically conducted on 3D acquisition geometries, capturing surface-wave properties at various frequencies.

Subsequently, the dispersion data can be inverted to derive a near-surface velocity model at each location (Figure 1). Boiero et al. (2013) proposed an approach that modifies S- and P-wave velocities to align with estimated dispersive events using secular function solutions. This misfit function allows for the inversion of Scholte and P-guided modes without explicitly associating experimental data points to a specific mode, thus mitigating potential mode misidentification errors in the resulting velocity profiles.

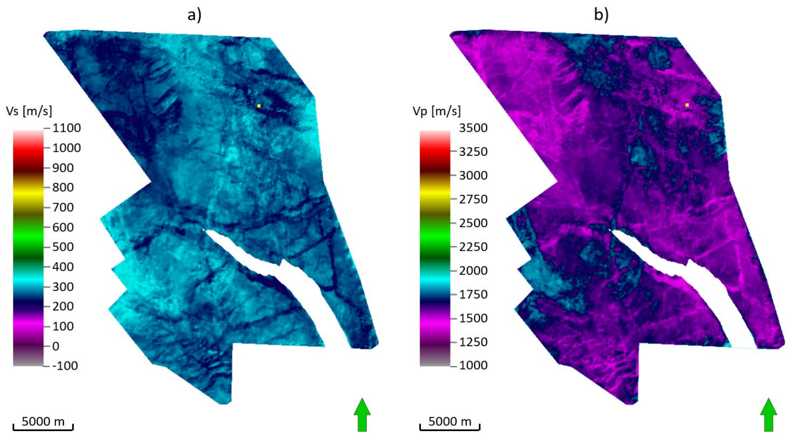

Figure 1 *a) Map of V_S at 10 m below seabed; b) map of V_P at the same depth obtained from a towed streamer survey.*

Figure 1 displays the VP and VS profiles beneath a narrow azimuth survey carried out in the North Sea. By inverting the phase velocities estimated along the source and receiver lines, we can generate a model that highlights the laterally and vertically varying complexities within the region. Traditional approaches would face challenges in resolving these complexities, particularly when dealing with datasets acquired for much deeper targets.

Surface-wave inversion results offer valuable insights into the near seabed, enabling the creation of a robust geological, structural, and lithological model. These results can aid in identifying drilling hazards and can be used to link geotechnical borehole measurements, potentially upscaling results from cone-penetrating tests. If available beforehand, they can also assist in designing the geotechnical survey.

Additionally, (an)elastic parameters derived from surface waves provide access to dynamic properties with significant engineering implications. Small strain Shear modulus (Gmax) is essential for evaluating foundation performance, considering static, dynamic, drained, and undrained conditions, and is sensitive to various geotechnical parameters. Small strain Damping ratio (Dmin) measures energy dissipation in vibrating bodies and, along with Gmax, helps predict ground movement due to vibrations.

Given the importance of dynamic properties, their accurate estimation is crucial for proper foundation design, ensuring resonance avoidance. S-wave attributes are especially critical for foundation design, while VP can be utilized for imaging high-resolution reflection data and combined with VS for petrophysical classification (VP-VS ratio).

Conclusion:

Exploration seismic surveys yield valuable insights into the near seabed by analyzing and inverting Scholte and P-guided waves. Legacy seismic datasets aid in processing surface waves, providing accurate propagation property estimates with high resolution, cost-effectively. (An)elastic seabed parameters inferred from these waves are vital in geotechnical engineering, aiding borehole correlation, survey design, and small strain modulus calculation. Understanding soil stress-strain relationships is crucial for addressing geotechnical challenges. Utilizing surface waves enhances high-resolution velocity model building, supporting safe and sustainable marine renewable energy and offshore infrastructures.

Session Four

Carbon storage seismic reprocessing for the Central North

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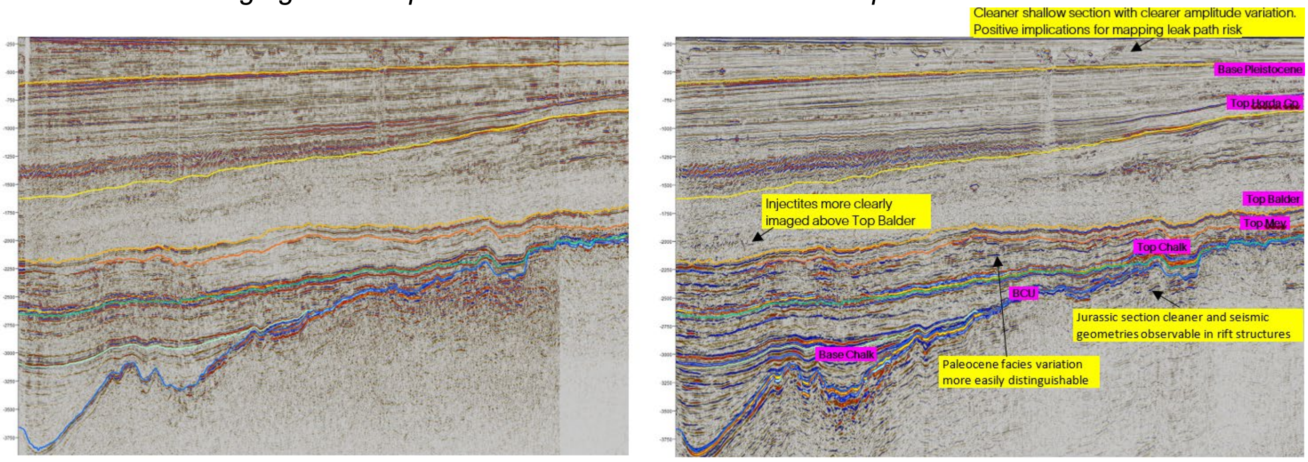
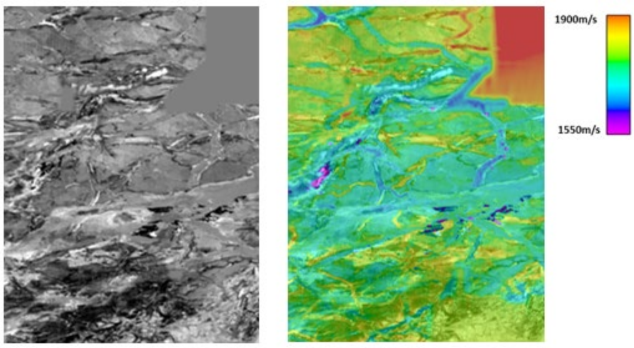
SLB has performed a carbon-storage focused seismic-reprocessing project in the Central North Sea (CNS) aimed at providing a dataset to support the carbon capture and storage (CCS) projects in the area. The available geological datasets, interpretation, well data were used to rapidly assess the key criteria for geological storage locations over a wide area. The established play-based techniques were updated for the key geological criteria required for carbon storage (CS). The study focused on the carbon storage potential of the Paleogene within the CNS – namely the aquifer potential of Mey and Maureen sands.
Play-based techniques have been applied to generate series of common risk segment maps to highlight the high-priority and high-risk CS areas in the CNS. Maps of reservoir thickness, net to gross and depositional facies indicated areas of high, medium, and low risk (Figure 1) to assess the CS reservoir potential of an interval, as described by Barlass et al., 2023. The CS potential maps suggest that the northern sector of the study area towards the Outer Moray Firth consistently mapped as a high potential area for low-risk carbon storage and Palaeocene reservoirs offer significant storage potential. Palaeocene Balmoral and Andrew sands have the broadest low risk carbon storage zones.

Figure 3 – Carbon storage reservoir potential for Andrew member (left) and Captain sandstone member (right). Green represents area of low CS risk, yellow represents area of medium CS risk and red represents area of high CS risk.

This initial phase of screening has been fundamental to highlight the areas for CS storage and interval leveraging the vast repository of geological data available in the area. The resolution of the public geological datasets limit containment analysis of CS plays. Hence a high-resolution dataset is required to perform the detailed containment assessment. The EastMey area identified both shallow Palaeocene and deeper Jurassic reservoirs as potential storage targets. A reprocessing study was performed with 11 heritage towed-streamer surveys, acquired between 1993 and 2003 to provide this high-resolution dataset. The reprocessing workflow was designed with an extra focus on improved resolution for both shallow and deep targets, signal-to-noise ratio, multiple elimination, amplitude integrity preservation and the production of a single seamlessly merged image cube. Figure 2 (right) shows an example of the 3D Kirchhoff prestack time migration (KPSTM) results with newly reprocessed data which clearly show an uplift in the imaging compared to the existing legacy data from shallow to deep section. Further depth imaging work was carried out with full-waveform inversion (FWI), reflection tomography, and Kirchhoff depth migration (KDM) to reduce the geological uncertainty and provide increased confidence in regional mapping. FWI allowed detailed velocity updates at shallow depths which is highlighted in Figure 3 (right), improving the depth image reliability, and providing direct insights into lithology variations. Containment assessment was performed on the reprocessed dataset focusing on understanding and mapping potential CO2 leakage pathways.

Figure 2 – KPSTM stack image; legacy (left) vs newly reprocessed (right). Note the improved resolution and imaging in the reprocessed data from shallow to deep section.





Conclusions

Regional geological data is an excellent source for rapid CS screening. We effectively identified high-potential CS areas and stratigraphic intervals in addition to identifying key containment risks by utilizing existing geological data. These risks were further evaluated and mitigated by using newly re-processed data designed to address the resolution and imaging challenges associated with the legacy data in the area. Re-processed data helps to develop an understanding of CS containment and capacity in the study area. Seismic reprocessing and associated interpretation have markedly updated and improved the quality of carbon storage play maps over the study area.

Reference

D. Barlass, A. Kanrar, H. Barnett, S. Joyce, K.A. Aleem, J. Bailey, D. Scarpellini, C. D'Aguanno, A. Cooke, C. Field, D. Wheeler, Dedicated carbon storage seismic reprocessing for Central North Sea CCS site selection: 84th EAGE Conference and Exhibition, Extended Abstracts Jun 2023, Volume 2023, p.1 - 5

Acknowledgements

The authors thank SLB for the use of the seismic data and permission to publish this work.

Figure 3 – KDM depth slice capturing shallow Nordland geology (left). FWI velocity depth slice shows different geological packages corresponding to different velocity (right).

Session Five

Seismic Imaging of an Igneous Complex

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Three-dimensional seismic surveys are rarely, if ever, employed to image large igneous systems; rather, they are an exploration tool used in the hydrocarbon industry to understand the stratigraphy and architecture of sedimentary basins where oil and gas may be found. A new seismic reflection survey, offshore Suriname, has been acquired to understand the hydrocarbon prospectivity of both the Mesozoic and Cenozoic sediments. Underlying these Mesozoic and Cenozoic sediments, beneath a major unconformity, lie the Nickerie and Commewijne grabens. These grabens are poorly understood, having been penetrated by only two wells.

This new seismic reflection data indicate that the graben is host to a large igneous complex that has been built through multiple phases of magma intrusion and evacuation. The three-dimensional geometry of these igneous bodies exhibit a diversity of laccolithic, pipe-, sill-, cone sheet, and flow-like forms, that often demonstrate clear structural association. Our observations contribute to understanding of how many of the features seen at large igneous provinces and volcanic rifted continental margins form. The seismic data from the Nickerie and Commewijne grabens showcase the capability to image large igneous systems, which may host minerals critical for the energy transition and aid targeting them.

Marine Gas Hydrates Offshore Mauritania

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Methane hydrates in marine settings are widespread on continental margins and are one of the largest methane reservoirs that naturally interact with ocean system. Dissociation of methane hydrates in shallow waters is a potential mechanism that allows methane to escape to the atmosphere and amplify climatic change or, most likely in deeper marine settings oxidize in seawater and contribute to ocean acidification.

The Mauritanian Continental margin is host to an exceptionally seismically imaged gas hydrate systems in 3D using marine exploration seismic data. 3D seismic data indicate that the succession has high gas saturations, and these are interpreted as having both a thermogenic and biogenic origin. There is evidence of high vertical migration of gas through seismically imaged pipes and evidence of stratigraphic up dip migration which accounts for one of clearest three-dimensionally imaged hydrate systems with a widespread seabed outcrop zone in the world. The base of the marine hydrate is marked by a bottom simulating reflection (BSR) which is the approximate location of the base of the hydrate stability zone (BHSZ) and shallows in a landward direction, eventually intersects the seabed

The data on the margin image the following feature: (1) Landward sections of the BSR reach within <10 m of the seafloor resulting in 'seismically defined' outcrop zones; (2) There are relicts BSRs indicative of earlier positions of the GHSZ during Quaternary glaciations; (3) There are examples of an outcrop zones within canyons, where the GHSZ intersects canyon walls and (5) There is a cluster of giant pock marks which are potentially caused by methane escape due to Holocene warming. There are few, if any, other documented locations that offers this array of features, recording the evidence of the dynamic changes that occur within in a methane hydrate system.

Session Six

3D multichannel seismic grid tied to IODP Expedition 313: Tracking sediment transport processes across the U.S. mid-Atlantic continental shelf.

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The Neogene U.S. mid-Atlantic continental margin is well-suited for the study of sedimentation, sea-level history, and evolution of a passive margin due to its well-documented tectonic history, substantial sediment supply, and reliable chronostratigraphic control. The prograding Miocene stratigraphic succession has been targeted by researchers conducting 2D seismic exploration (Greenlee *et al.*, 1992; Austin *et al.*, 1996; Fulthorpe, Austin and Mountain, 1999) and ocean drilling campaigns ((Miller and Mountain, 1996; Mountain *et al.*, 2010). Integrating drilling with these 2D seismic data has provided a nearly continuous chronostratigraphic framework correlated to Miocene sequence boundaries and ice volume changes inferred from global oxygen isotope ratio ($\delta_{18}O$) records (Miller *et al.*, 1998). But despite advances provided by these seismic and drilling efforts, uncertainties related to the development of sequences, their relationship to sea-level change, and dominant sediment transport mechanisms remain. Specifically, spacing between seismic lines (almost entirely > 5 km) has been too coarse to map incised river systems and confirm or refute that the paleoshelf was subaerially exposed during sea-level lowstands (Posamentier, 2001). Expedition 313 results suggest two sequences (m5.3 and m5.7, 15.6-16.3 Ma and 18.6-18.8 Ma, respectively) contain sediments that reached clinoform rollovers at middle shelf Site M29 (Fig. 1) through fluvial processes (Cosgrove *et al.*, 2018). No elements of sediment transport pathways such as submarine canyons, slope channel-levee complexes, lobes, and mass transport complexes have been identified on the 2D seismic profiles in the Early to Middle Miocene sequences. The lack of evidence of such features leaves open the question of how coarse-grained sands reach clinoform toesets.

To address the issue of spatial seismic imaging and improve understanding Neogene sedimentation, high-density (3.125m x 6.25m CMP bins) 3D seismic data using PCables was acquired in a 550 sq km grid around Expedition 313 boreholes during cruise 1510 of the *R/V Marcus G. Langseth*. Here we present preliminary results of the 3D seismic data interpretation, emphasising the seismic geomorphological analysis of the Miocene clinoforms. Using the industry's advanced interpretation and visualisation tools, such as chromatic geology extraction technology eXchroma$_{SG}$ (Laake and Fiduk, 2013), we show that fluvial incisions into Neogene clinoform topsets are scarce until the onset of global cooling and falling sea level of the Middle Miocene Climate Transition. The only evidence of fluvial incisions we have identified so far is in the coastal plain region of the Middle Miocene m4 sequence (younger than 12.6 Ma). We have mapped within sequence m4 a complex fluvial system comprised of numerous channels and channel belts that cut through thin linear features that we interpret as relict beach ridges.

Our study has yet to detect submarine canyons, slope channels, and submarine lobes at Early to Middle Miocene clinoform foresets and toesets. In their place, we have identified areas of narrow, closely-spaced, relatively short (< 1 km), rill-like features that occur on clinoform foresets (e.g., sequence m5.3, 14.8 – 15.0 Ma; Figure 1) immediately seaward of clinoform rollovers. However, no significant failure scars have been observed at or near the clinoform rollovers. We attribute these to erosion/bypass regions. Interestingly, the North-South orientation of the rill-like features in the m5.3 sequence that should indicate the dominant direction of sediment transport differs 2 from the general NW-SE clinoform progradation direction (Fig. 1). Moreover, the erosion area terminates ~4.5 km updip from

Expedition 313 Site M29 (Fig. 1). Thus, the glauconitic coarse sands in sequence m5.3 interpreted as debrites (Hodgson *et al.*, 2018) are not directly connected to the erosion area. No lobate features at Site M29 were detected.

Our preliminary results of integrating scientific ocean drilling and high-resolution 3D seismic data suggest no significant incisions of alluvial systems into the Miocene New Jersey paleoshelf before 12.6 Ma, even at times of relatively low sea level. The clinoform topsets were most likely submerged, precluding sediment delivery to the clinoform rollovers via incised rivers. Sediment delivered to the shelf by a line source comprising multiple, relatively small rivers was likely remobilised and redistributed by waves and alongshore currents. At the clinoform rollovers, slope instability might have played a key role in sediment delivery to the deeper areas, triggering multiple small-scale unchannelized mass wasting events that were responsible for the accumulation of thick units (~45 m in sequence m5.3) of coarse glauconitic sands at the clinoform toesets.

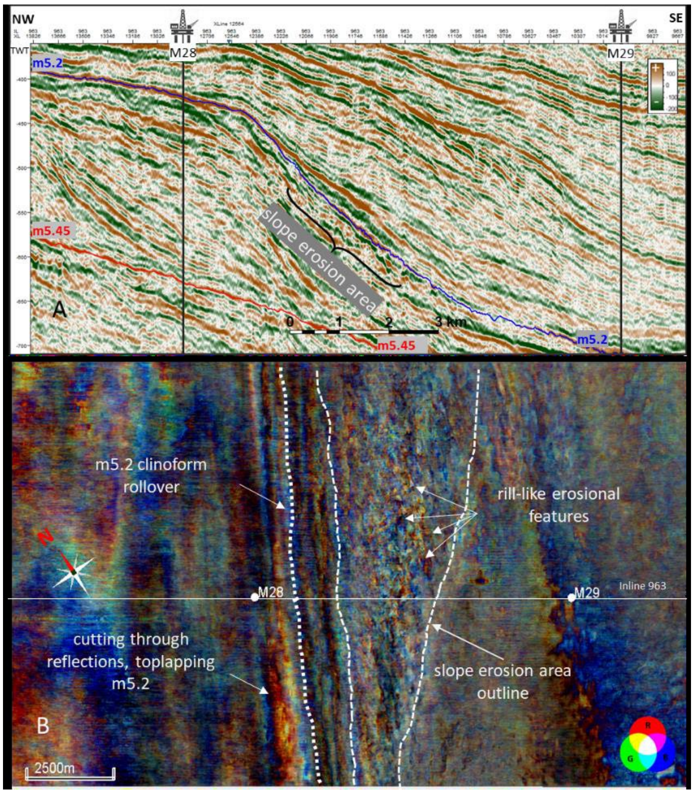

Figure 1 (A) Inline 963 through Expedition 313 Sites 28 and 29, showing sequence boundary m5.2 (blue tracing) that caps irregular reflectors in the foreset slope sediments of the underlying m5.3 sequence (15.7-16.3 Ma), interpreted as a slope erosion area. (B) An RGB blended horizon slice (i.e., map view) using the eXchromaSG colour attribute tuned to reveal heterogeneity in seismic amplitudes 8 ms below the m5.2 surface (i.e., within the m5.3 sequence.) The linear organisation of colours NW (landward) of the m5.2 rollover (dotted white line) results from small changes in the lithofacies of prograding m5.3 sediments. The locally bright colours 2-5 km seaward of the 5.2 rollover, bracketed by the dashed white lines and showing a subtle, roughly N-S orientation, are interpreted as erosional rill-like features formed within the foresets of the m5.3 sequence. These features may indicate the last m5.3 episode(s) of likely multiple mass flows down the slope with no evidence of fluvial transport.

Session Seven

Fluid and heat flow along the Balearic margin of the central Algerian basin: Heat re-distribution system controlled by the Mediterranean Salt Giant and Plio-Quaternary volcanic structures

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Salt Giants are vast and thick accumulations of salt that are of interest for their ability to trap fluids in the subsurface, for their association with certain mineral deposits, and for their high thermal conductivity. The Mediterranean Salt Giant (MSG) is a thick layer of Messinian evaporites (up to 4 km) that is thought to be deposited during an extreme paleo-environmental event known as the Messinian Salinity Crisis (MSC). This study focuses on the Algerian basin, a deep-water under-explored basin in the south-western Mediterranean Sea. Its sediments and its geometry are poorly known and its geodynamic evolution is not well constrained. However, it sits in between the Gibraltar gateway and the rest of the Mediterranean Sea, and could provide key insights on the Messinian Salinity Crisis and strike-slip oblique rifts.

We list the different seismic fluid indicators observed on newly-reprocessed SALTFLU seismic images acquired in 2012 by OGS Explora, to characterize fluid and heat transport systems. We then compare the presence of these fluids with high amplitude heat flow anomalies observed on new heat flow measurements acquired during the WestMedFlux-2 survey (Poort et al., 2020), carried out in 2018 on the R/V L'Atalante in the Algerian Basin and southern Balearic margin.

We observe several seismic amplitude variations that we relate to the presence of fluids. Pockmarks, distorted reflections, pull-down and lateral amplitude variations suggest at least the presence of gas. The presence of these fluids is correlated with negative heat flow anomalies in the Formentera basin, where the mobile salt unit is absent. Next to these high negative anomalies, we also observe high positive heat flow anomalies that we attribute to the presence of recent intrusion that heat up the surrounding sediments by conduction. Several low amplitude anomalies with accompanying push-down and dimming are also observed in the south-central Algerian foredeep. These “gas pockets” may be related to a potential gas emitting source rocks in pre-Messinian sediments. These intrusions could create hydrothermal convection system that redistribute the heat along the margin. In that case, the area of very low surface heat flow in the Formentera basin could record the presence of a recharge zone where fluids infiltrate the permeable basement. The absence of samples and the poor seismic coverage of the basin do not allow to make sound conclusions on the thermal system of the Balearic margin so far.

Utilising High Density Passive Seismology for Geothermal Exploration in Built Up Areas

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Low enthalpy geothermal energy for direct use is a viable option to decarbonise heating[1], particularly in built up urban areas across the UK and the rest of the world. Much of the UK's geothermal potential is in low-enthalpy resources within sedimentary basins[2], the exploration of which benefits from geophysical exploration to characterise the subsurface prior to committing capital expenditure. Seismic imaging will play a vital role in this exploration process, however data acquisition is inherently challenging and costly within built up areas. The recent development of low cost, nimble nodal seismometers has provided a unique opportunity to investigate the application of passive seismic methods using a high-density array in urban environments.

Here we present initial findings from a deployment of 3271 nodal seismometers across a ~5 km^2 area at RAF Leeming in North Yorkshire; data acquisition occurred from July-August 2022. The objective of the project is to investigate the application of passive seismic techniques using a high-density nodal array for characterising the subsurface geology. We aim to build 3-D shear wave velocity models using surface waves recovered from ambient noise, which we will use to develop our geological interpretation alongside a coincident active source reflection survey.

In this contribution we will give an overview of the field acquisition, showing examples of the characteristics of ambient seismic noise recorded by the survey. We will detail our passive seismic processing steps, showing examples of surface waves recovered from the continuous records of ambient seismic noise, as well as our initial 1-D shear wave velocity models. An active 3D seismic survey, acquired at the same time, using a low impact weight drop source will allow us to partially benchmark the passive survey results against conventional methods.

Monitoring seismic velocity changes in the Critical Zone with a dense array of nodal seismometers.

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The Critical Zone (CZ) is the "living skin" of our planet, extending from the bottom of the water table to the top of the tree canopy. Processes occurring in the CZ are subject to a complex and dynamic interplay between soil structure, temperature, pressure, precipitation, and water content. Geophysical methods can be used to image the subsurface portion of the CZ but typically offer a point-in-time snapshot view which does not constrain changes over time. The development of ambient noise seismology allows us to exploit continuous recordings of the seismic wavefield to detect small changes in seismic velocity over time, which may be indicative of changes in the subsurface. In December 2022, in partnership with Stryde, we deployed a "large-N" array consisting of ~1600 seismic nodes at spacings between 5m and 10m for one month at a site in Dumfries, South West Scotland. The site was chosen as it hosts a Critical Zone observatory, recording real-time data on soil moisture and temperature along with other meteorological data. We cross-correlate the noise recordings from this array to retrieve the Green's function and perform coda-wave interferometry to detect velocity changes across the array. We will compare the time series of the seismic velocity changes with measurements of soil moisture, temperature, precipitation, and air pressure to establish relationships and correlations between changes in seismic velocity and environmental factors, and constrain the extent to which external hydrological factors influence seismic velocities. We discuss the benefits of working with the novel technology and the challenges that arise when handling very large datasets.

POSTER ABSTRACTS

Subsurface characterization of the Hewett field and its monitorability during CCS

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Carbon capture and storage (CCS) aims at reducing CO2 emissions from burning of fossil fuels. Monitoring stored CO2 in the subsurface is essential for documenting the safety and stability of CCS. A range of geophysical techniques can be used to monitor the containment of stored CO2 and generate noticeable signals because of CO2 displacement.

This research studies 3 geophysical techniques: seismic, electromagnetic and gravity to evaluate the efficacy of each for a range of storage target formations. The first case study is the Hewett Field located in the SW North Sea with primary targets in the Bunter sandstone and Leman sandstones.

The Hewett Field stratigraphy is constrained by 35 wells and its tectono-stratigraphic setting and closures are defined by a 1994-1995 vintage 3D seismic volume covering the entire structure(Hook, 2020). The field is 30 km long by 5 km wide, with a shallowest closure of the Bunter sandstone at approximately 800 m below sea level and of the Leman sandstone at about 1500 m below sea-level.

The Electromagnetic method is sensitive to resistivity changes in the reservoir. Injection of CO2 would generally decrease the resistivity because of the reaction between dissolved salts and CO2 (Wilson et al., 2012). Seismic velocity is sensitive to changes of lithology, porosity, and fluid saturation. In reservoirs that are porous and of limited rigidity, replacing water with CO2 will have a remarkable effect on the seismic velocity and thus on the reflection seismic amplitude response (Ayres and Theilen, 1999). The gravity method is sensitive to density change in the subsurface. The density of CO2 or combination of CO2 and other fluid can be easily detected or calculated (Gasperikova and Hoversten, 2008). Therefore, a correlation between changes in CO2 saturation and geophysical response are probable, although their detectability depends greatly on reservoir and seal properties, burial depth, fluid saturation changes and pressure. This study should help inform the choice of monitoring techniques for a range of storage targets.

The workflow of geophysical monitoring consists of two parts: first is from reservoir simulation to geophysical modelling, the other is based on geophysical inversion and rock-physics inversion (Dupuy et al., 2021). This research focus on the rock physics modelling and CSEM, seismic and gravity modelling.

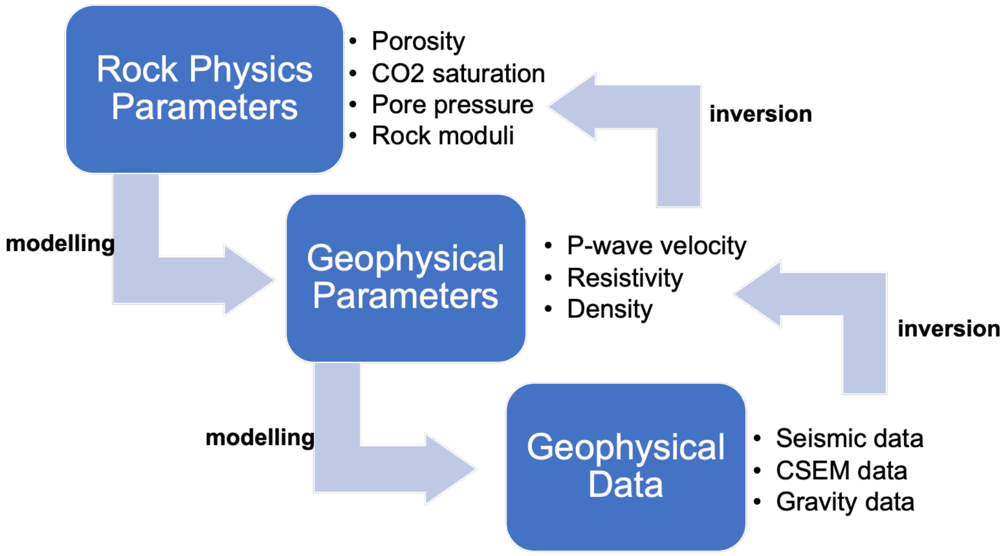

Fig. 1. Workflow for quantitative monitoring

Seismic geomorphology of Upper Mississippian carbonate in the Solway Basin, East of the Irish Sea

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The Solway Basin, situated in the northern domain of the East Irish Sea, lies between the Peel and Lagman Basin. Despite being a target for hydrocarbon and geothermal production in the UK, the reservoir potential of the Upper Mississippian carbonate platforms in the Solway Basin remains unproven. The uncertainty arises from its deeper location and potentially lower seismic image quality. In this study, we utilized 2D seismic lines, a 3D seismic survey, and well data to interpret and reconstruct the morphology of the carbonate deposits within the Basin. The basin's formation can be attributed to sinistral transpression in the pre-Mississippian, characterized by NE-SW lineaments. Our data reveals the distribution of potential carbonate platforms in the upper Mississippian, specifically identified as isolated carbonate platforms located along the flanks of the Solway Basin. These carbonate platforms are patchy and discontinuous, stretching from the shallow water area close to the present-day shoreline to the deeper basin. The back-stepping pattern of these platforms is evident, with sizes ranging from 1 to 3 km, commonly displaying high slope angles (>30°) and occasionally reaching up to 60°, perhaps due to faulting. The incursion of sandstones in the very latest Mississippian, along with changes in relative sea level fluctuations are likely to have played a significant role in shaping the carbonate platform architecture, resulting ultimately in the shrinking and demise of the carbonate platforms. Petrophysical data from geophysical logs in the study area and elsewhere in the Irish Sea Basin indicates <5% porosity, although there is potential for secondary porosity development from fracturing or karstification which could enhance permeability.

Deep-water seismic stratigraphic responses to tectonic and climatic changes

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Deep-water sedimentary evolution and the associated processes could be archived by stratigraphic architectures and sedimentary features (e.g. grain sizes, geochemical proxies and sedimentary structures), which are sensitive to tectonic and climatic changes. Although seismic data has a lower vertical resolution compared to the sedimentary records of boreholes, they have advantages to show the continuous lateral variation in stratigraphic architectures and sedimentary features. Utilized the high-resolution 2-D multichannel seismic profiles and Ocean Drilling Program data, this study investigated the late Miocene-Quaternary deep-water seismic stratigraphy, sedimentary evolution, and responses to regional tectonic and climatic variation at the northeastern margin of the South China Sea. The results show that the late Miocene-Quaternary stratigraphy consists of three units (i.e. SU 1, SU 2 and SU 3) with different architectures. Accordingly, the late Miocene-Quaternary could be divided into three stages, with the period of 10.5-6.5 Ma, 6.5-0.9 Ma, and 0.9 Ma-present. SU-1 is featured with sheeted drifts, while SU-2 and SU-3 are dominated by mounded, lenticular drifts in association with moats. These architectures indicate that bottom currents intensified from stage 1 to stage 2, which was related to the sill uplifting at the Luzon Strait under the influence of tectonic collision between the Luzon arc and Eurasia since ca. 6.5 Ma. SU-2 and SU-3 are separated by a basinwide high-amplitude seismic reflection, across which the average sedimentation rate increased from ~28 m/m.y. in SU-2 to ~144 m/m.y. in SU-3. The high sedimentation supply since ~0.9 Ma could be linked to the mid-Pleistocene climate transition, which resulted in abundant rainfall that promoted the Taiwan orogen to contribute more sediment supply to the South China Sea. This study indicates that deep-water seismic stratigraphic features could be linked to tectonic and climatic changes, which is significant for understanding the coupling relationship between tectonic, paleoclimate, paleoceanography and deep-water sedimentary processes in the marginal seas. Our results also implies that seismic stratigraphy could be a powerful tool to reveal the tectonic and climate changes with earth evolution.

Importance of igneous intrusions for CCS in the Southern North Sea

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The Southern North Sea (SNS) basin has been a major gas-producing basin since the 1960s, owing to the fortuitous overlap of a Carboniferous gas-prone source rock, an early Permian reservoir and a late Permian evaporite seal (i.e., the Zechstein Supergroup). Salt tectonics in the basin led to the formation of significant structural closures in the overlying Triassic sandstones, which are largely water-bearing and underlie mudstone and evaporite sealing intervals. The SNS is close to major onshore industrial sources of CO_2, and the presence of depleted gas fields and a regional aquifer makes it an ideal site for the storage of this greenhouse gas on a national and local scale. However, borehole, magnetic and seismic reflection data shows that NW-trending Paleogene igneous dykes, originating from the Mull igneous centre, offshore NW Scotland extend >400 km offshore into the SNS. For example, reflection seismic data reveal a complex series of aligned depressions (i.e., craters) forming long (>200 km), linear chains and troughs at top Chalk level (e.g., Brown et al., 1994; Wall et al., 2010). These features overlie interpreted dykes and are thought to have resulted from the explosive interactions between magma and a shallow chalk/ooze deposit (Wall et al., 2010). The dykes are inferred to intrude Paleozoic-Mesozoic strata, cross-cutting sub- and supra-salt reservoirs and their top seals, possibly compromising their retention capacity. Therefore, the selection of potential sub- and supra-salt carbon storage sites may need to account for dyke presence. The seismic expression of dykes, the development of igneous-related structures (i.e., small sills and craters) affecting the intruded rocks, and the interactions between salt and magma are relatively poorly understood. By using 2D and 3D reflection seismic and borehole data, we take a fresh look at these, and hopefully contribute to the overall understanding of CCS integrity in the SNS.

Figure 1 shows a cross-section through the three, c.120-200 km-long, segmented chains of craters associated with the SNS dykes. The individual craters range from c.100 to 200 ms TWT (c. 120 to 240 m) depth and c. 0.1 to 2 km width. The craters are underlain by downward-deflected reflections and zones of seismic disturbance, which we interpret as a velocity push-down and dykes, respectively (Figure 1). Distinguishing between artefacts and dykes is difficult, and only possible in the areas within the chains where craters are poorly developed or absent. In these areas, the presence of thin (c. 50-300 m), sub-vertical seismic disturbances are more likely to represent dykes (see Magee and Jackson, 2020) than artefacts. Intrusion-induced faulting and additional discrete craters revealed by a variance extraction along the top Chalk structure map may correspond to additional dykes not yet documented. Time-thickness maps of overlying Tertiary sedimentary packages, including the crater infill, constrain the timing of crater development to the early Paleogene. Deformation patterns add further evidence for subsidiary processes involved in crater development (i.e., chalk removal through dissolution). Similarly, groups of narrow, linear faulted blocks within craters may reflect submarine landslides that contributed to crater widening. Within the Zechstein Supergroup, high-amplitude, sub-horizontal seismic reflections flanking the inferred locations of dykes were identified. These reflections could correspond to dyke-fed sills (e.g., Underhill, 2009; Wall et al., 2010; Schofield et al., 2014).

Our work help us better determine: (1) the criteria required to attribute sub-vertical seismic discontinuities/disturbances to dyke presence; (2) how to better constrain the geometrical properties of dykes (e.g., dyke thickness) based on their seismic expression; (3) how dyke emplacement affects host rocks by deciphering the processes involved in the formation of intrusion-related structures (e.g., craters and intrusion-induced faults); and (4) how host rocks control magma emplacement mechanics (i.e., vertical vs. lateral emplacement). Our findings may also lead to a more robust risk assessment of CCS in the SNS. Dykes may act as barriers for CO_2 flow and thus compartmentalise target aquifers, although, conversely, fractured dykes and intrusion-related damage zones may allow CO_2 leakage. The mapping of dykes and

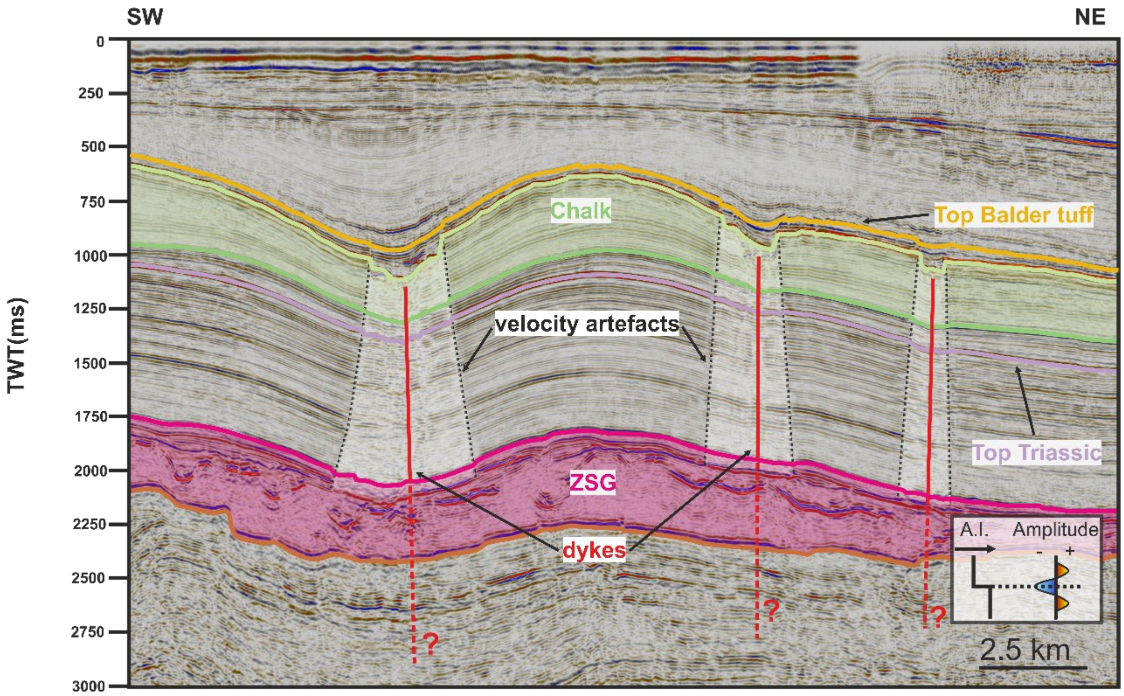

Figure 1: Seismic section showing the craters affecting the Chalk and the inferred locations of the dykes. The seismic imaging underlying the craters is affected by velocity artefacts. The full sub-salt extent of the dykes is unknown.

estimating the extent of intrusion damage zones based on dyke dimensions and our understanding of magma-host rock interactions should provide key constraints for selecting potential CCS sites in the SNS.

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Seismic forward modeling to image sandstone intrusion complexes

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Sandstone intrusion complexes is an important type of reservoir for petroleum production and evaluation of sealing integrity and may be a future target for Carbon-dioxide capture and storage (CCS) in the North Sea Basin offshore NW Europe. Seismic imaging of such structures is challenging but has now improved to the extent that they are being targeted explicitly in exploration. However, few studies of imaging limitations and specificities exist in the public domain. This research explores resolution and imaging limitations related to sandstone intrusion complexes using full wave field seismic modelling approaches to quantify the reflection response of models with various geometries and varying acquisition orientations. Understanding the influence of dip angles and acquisition geometries on imaging of sandstone intrusions informs the interpretation of intrusion complexes in legacy data and the choice of acquisition and processing parameters for new seismic surveys for petroleum exploration and/or CCS baseline surveys. This study found that wing-like structures with dip angles between 10 and 30 degrees were detectable in seismic sections, while those with dip angles between 50 and 90 degrees were undetectable. The study also found that dikes above the reservoir affect the reflection characteristics of the reservoir surface and lead to an increase in chaotic patterns in the top reservoir reflection. The noise produced by the dikes became stronger with increasing thickness and for greater dip angles than 30 degree and less than 70 degrees. In conclusion, this research has quantified the imaging limitations associated with wing-like of sandstone intrusions and their associated crestal dyke complexes using full-wave field seismic forward modeling.

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