The North Sea and West of Shetlands: evolution of prolific hydrocarbon basins

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Introduction

We present an overview of the current state and seismic needs of the North Sea and contrast them with those of West of Shetlands. The first being a highly prolific, near-full maturity hydrocarbon area, while the latter is in a more frontier state. While their maturity appears to reside at two ends of a spectrum, their seismic needs are not so different. The North Sea has been extensively explored for about 60 years (45 since the first field, Forties, went into production), with up to three generations of 3D streamer seismic. Most discoveries have been found using legacy seismic (mostly 2D), but there is a need to find the hidden reservoirs in this area. That necessity calls for targeted reprocessing and even one more generation of seismic data with fewer compromises – options range from multi-azimuth, to hybrid streamer-node

survey, to full blown dense ocean bottom nodes (OBN). The complexity of the West of Shetlands geology (thick basalts, inner flows, hydrothermal vents, gas pockets, sills) has not been fully resolved. Advances in acquisition that are matched to a carefully designed preprocessing sequence are clearing the way to take advantage of recent improvements (some inspired from subsalt experience) in inversion, imaging, and interpretation.

North Sea: from prolific to reaching its full maturity

The authorities opened up the North Sea (map in Figure 1) for hydrocarbon exploration in the 1960s. First oil was discovered during the second half of that decade using what we can call 'paper seismic' – i.e., seismic sections, basic 2D stacks,
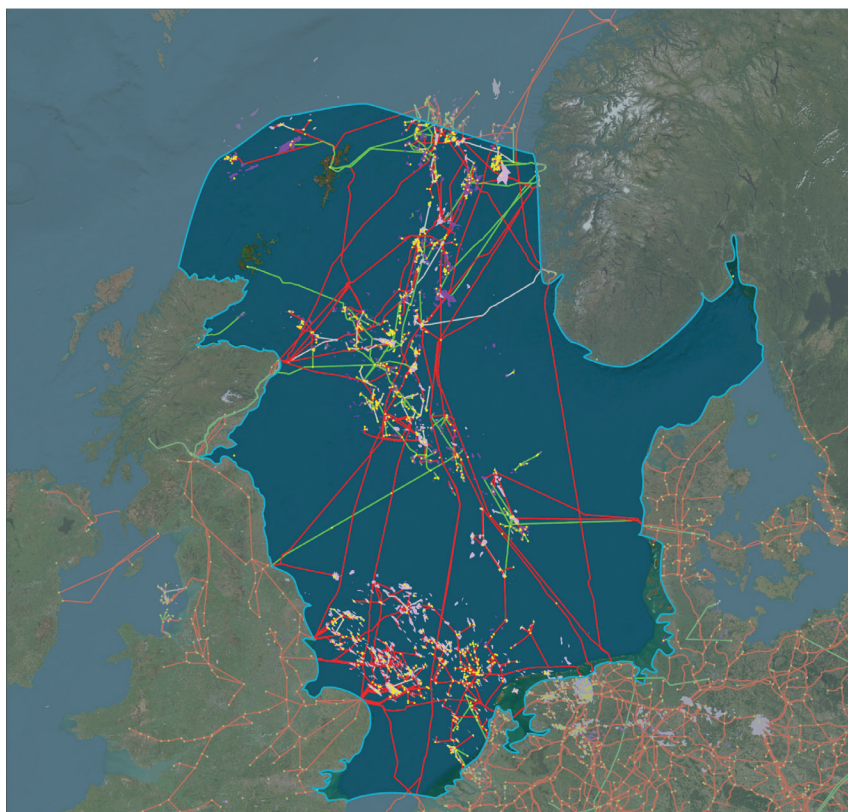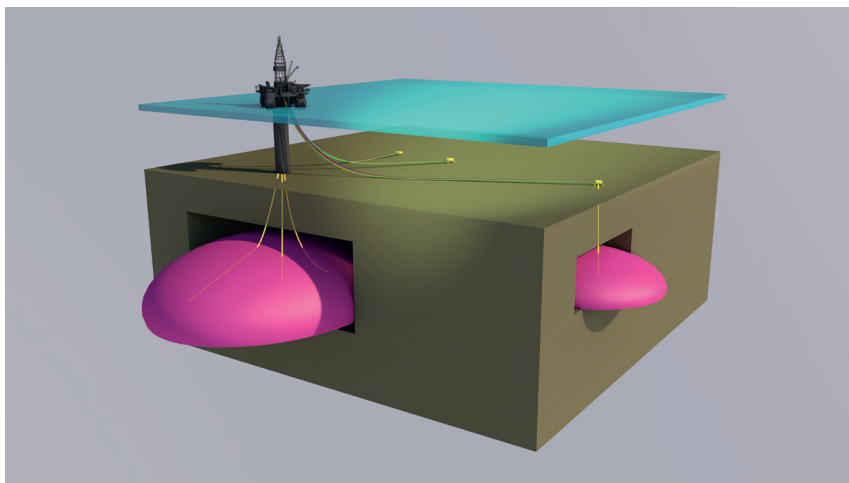

Figure 1 The map highlights the North Sea, and displays the location of the known hydrocarbon reservoirs (oil in purple, gas in lilac, other in grey), the facilities are represented by the yellow dots, and the pipelines are traces in green for oil, red for gas, and grey for other purposes.

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Figure 2 Tiebacks in the North Sea have a maximum distance of 50 km from the main fields that they are to be connected to. This number is not exact, more like a rule-of-thumb based on the expected flow given the average reservoir pressure and geology.

plotted out and interpreted manually. In fact, the majority of the most important discoveries in the area were found this way. By the 1970s, it was clear that this was a prolific hydrocarbon region. In 2020, the reality is very different: the North Sea is reaching its full maturity and, despite modern technology, new economic discoveries have become scarce (see for example the reports published in 2020 by the Norwegian Petroleum Directorate and Oil and Gas Authority). A significant portion of the oil and gas fields in this area will reach the end of their economic lifecycle within a decade. Some of the infrastructure would be best decommissioned as its lifecycle comes to an end – often having already passed through a lifetime extension engineering process, which adds, on average, five more years of use. The rest of the infrastructure begins to become a liability; operating it and maintaining it becomes less cost effective as the production of their associate fields decay and spare capacity increases. There is not much expectation in finding huge new fields in such a mature area, but sustainability of the expensive existing investments depends on marginal discoveries which offer opportunities for clustering and aggregating discovery volumes. Therefore, the game in these prolific basins is to make new discoveries which become economic when tied-back to existing infrastructure (refer to Figure 2).

During the first 15-20 years of exploration in the North Sea, the geophysical tools were more standardized than today. The seismic vessels acquired 2D streamer data, towing a single streamer of about 3 km length and a single source (initially towed by an independent source vessel and later incorporated to the array towed by the streamer vessel). During the first 3-5 years, the source was based on dynamite and then on airgun arrays. By the end of the 1980s, 3D seismic was tested and accepted. In the beginning, 3D seismic acquisition consisted of several passes of a 2D streamer vessel over a polygon (nearby sail-lines). Subsequently, vessels began to be equipped with more streamers and two sources (airgun arrays), with only small variations in acquisition specifications and processing technology. Yes, a few odd ocean bottom seismic (OBS) surveys and high-resolution dense streamer 3Ds existed, but the majority were very similar regarding technology used. In the North Sea, prior to 2003, the cable length remained typically at 3 km, very few 2D surveys had a length of 4.5 km. The frontier tool was 2D, while 3D was

mostly for the mature producing assets had ocean bottom cable (OBC) had specialized and limited use only for production.

From simple paper seismic to modern seismic.

In the late 1980s and the whole of the 1990s there was increased momentum in the development of processing technology based on the wave equation: data driven algorithms emerged, shear-waves were imaged for the first time (P-S imaging), reverse time migration (RTM) and full waveform inversion (FWI) were invented, among other significant developments. However, production processing algorithms did not include these advances and were limited by the compute power at the time. Amplitude versus offset analysis (AVO) is perhaps one exception. AVO started in academia, on paper seismic, the industry adopted it and rejected it with equal fervour in its early days. Successes were heavily, negatively coloured by each failure, making many hands-on geoscientists suspicious of its ability to be a hydrocarbon indicator. However, it finally got accepted near the end of the 1990s. Today we are using and still fine-tuning all those advanced processing technologies whose realization and/or production use was halted by the lack of compute power.

A lot of theoretical work and testing of more advanced acquisition technologies such as triple source, source over streamers, spiral shooting, combined use of hydrophones and geophones, multi or full azimuth acquisition techniques was also envisioned, studied, and even described in early literature (refer to, e.g., Barr, 1993). Today 2D acquisition activity is decreasing world-wide. Modern 3D data has long offset recordings as standard (up to 11 km in streamer seismic and up to 20 km in OBS in the North Sea) and is becoming more common for measuring two, three, or even full azimuth seismic. The acquisition specification can be tailored and optimized on a whole host of parameters, ranging from the geologic challenge at hand, cost, efficiency and availability of equipment, to weather conditions and government regulations, among others.

OBN surveying is an example where the costs have restricted large-scale utilization for decades. In the past, surveys only covered areas between 50 and 200 km^2 and OBS was primarily used for production monitoring. In recent years both technological improvements (blended sources) and multi-client business models in the OBS market have lowered the prices and efficiency,

making it attractive for exploration at unseen scales. Utsira OBN (ocean bottom nodes), acquired by TGS and AGS between 2018 and 2019 was the first large-scale acquisition of its kind, covering more than 1500 km² (Figure 3). It was also the first survey in the North Sea long offset FWI was tested.

The frontier region

It has been evident for decades that a prolific basin similar in size to the Northern North Sea exists in the greater West of Shetland Basin. More than half of this oil and gas producing basin, towards the west, is covered by different types of volcanic facies. The oil and gas discoveries to date sit mostly in the non-volcanic dominated eastern side, although recent work suggests that the deeper volcanic intrusions have had a lot to say for migration pathways and traps (if not also about the maturation of the hydrocarbons). The challenge, besides drilling through volcanic rocks, has always been the poor seismic imaging intra- and sub-basalt.

Chevron drilled the Lagavulin well (217/15-1) in 2010, a thick volcanic sub-basalt target. The seismic images had the targets relatively well defined but the drilling of the well encountered several technical problems and no pay. Still in the early 2010s, after almost a decade of exploration and drilling in this frontier, the European energy industry had a goal to uncover the secrets of this complex geology and unlock its hydrocarbon potential. The area was severely underexplored, but data was becoming available at a fast pace. When the Equinor-operated, high impact Brugdan II well in 2012 (6104/21-2 re-entry in 2014) was drilled in Faroese waters, the pre-drilled estimate of

sub-basalt target boundary was optimistically off by more than a kilometre. Besides being geologically challenging, the 2012 drilling programme encountered both technical and weather problems. The sub-basalt structure was almost a guesswork. Other measurements completed post-drilling, such as controlled source electromagnetic (CSEM) data acquired by EMGS, gave a better estimate for the sub-basalt boundary. The re-entry drill reached a depth of 4542 m but was not an exploration success. Thus, the well was plugged and abandoned. The results in the more frontier areas associated with the North Sea were not promising to say the least. By 2015, following years of expensive exploration with no success, oil and gas companies lost interest in the area.

A lot of effort was put into analysing new acquisition and processing technology for sub-basalt imaging in the first decade of this century. The development of the Rosebank intra volcanic oil discovery was delayed a decade or more, and the various operators involved could not image the hydrocarbon reservoirs in seismic data to properly de-risk drilling. A decade later, seismic processing technology has significantly advanced. New hardware solutions have enabled the standard use of key resource-heavy algorithms like SRME, RTM, and FWI. Better and more densely spaced measurements in acquisition are also contributing. Besides legacy 2D data, considerable portions of these areas have been surveyed with modern 3D streamer seismic with offsets ranging from 6 km (the oldest datasets) to 11 km (often to be used in FWI-based model building) offsets and 3 to 5 blended sources, providing high resolution possibilities, low frequencies for inversion, and deep penetration. There is even a 2-component 2D streamer survey in this area and a small patch of OBN data

Earthstar Geographics, Esri UK, Esri, HERE, Garmin, FAO, NOAA, USGS

Figure 3 The highlighted polygon corresponds to the 1584 km² covered by the Utsira OBN survey acquired in 2018-2019. The first large scale OBS survey in the world. The area is ~90 nautical miles west of Stavanger, Norway.

over Rosebank. In analysing recent modern 3D surveys along the Atlantic Margin, we observe significant imaging uplifts in both sub-basalt and intra-basalt. We can now distinguish between thin layers of volcanic and siliciclastic layers and a few sedimentary details are now interpretable beneath the thick and complex basalt sections (Figure 4).

Modern surveys in West of Shetlands definitely benefit from the advances that became standard over the last decade, which range from near-field hydrophone measurements for surgical debubble and source signature estimation/compensation, to deep-towed streamers, multiple sources (often wide-towed), and deep-towed single and multisensor streamers. Triple-source has been used since 2017 (Baldock et al, 2018) and penta-source technology since 2020 in this region. Wide-towed multisourcing can achieve an improved spatial sampling and aid in the efficiency of the acquisition. The overlapping records are carefully deblended in preprocessing. Matching modern streamer acquisition with the appropriate technology can enhance the fidelity and resolution of the data. Deep tow streamers not only increase the efficiency of the acquisition work by being less affected by weather downtime (compared to conventional tow of approx. 6 m), but when matched with the appropriate processing technology (3D Deghosting) this also enhances the frequency spectrum of the data at both ends. Low frequencies in particular, have been considered crucial for imaging below complex volcanic structures (Gallagher and Dromgoole, 2008; Spjuth et al., 2012) as there is a large absorption of energy and scattering loses, affecting largely the high end of the frequency spectrum. Because of this, until approximately ten years ago, the focus was on low frequencies (up to 40 Hz), towing sources and streamers deep, and even tuning the bubble produced by the airgun array (Lau et al., 2007). Broadband processing removed the trade-off of the high frequencies in search of the lows.

While 3D Surface Related Multiple Elimination (SRME) has been the key component in demultiple sequences for complex areas and the reduction in compute costs has enabled its cascaded implementation and use to become standard (Cox et al 2018). The latter, combined with the much denser shot coverage from multisourcing, provide more accurate free surface models to be adaptively subtracted from the seismic data. Despite these advances, some classes of multiples, notably interbed multiples, have tended to be ignored in processing flows. They are only indirectly addressed with moveout-based methods that pose a risk to amplitude preservation or can remove non-hyperbolic events with complex ray-paths (around basalt for example). However, it is recognized that interbed multiples create significant difficulties for development-scale interpretation by distorting or masking AVO trends and damaging amplitude consistency along key reflectors. As a result, interbed multiple elimination is increasingly included in standard processing sequences and can improve lateral continuity beneath high contrast reflectors such as sills (Ma et al, 2020).

These advances in preprocessing are clearing the way for improvements in depth imaging in these frontier areas. For example, the use of wave equation-based techniques for velocity model updating and imaging have enabled sub-basalt events to be successfully mapped and geologically meaningful velocities to be estimated (Baldock et al, 2019). Since 2018, TGS has had a focused research programme, SIR (Sub-basalt Imaging and Research), with the specific goal to contribute to refocusing sub-basalt and volcanic areas for O&G exploration globally, by delivering high end velocity model building and imaging that can aid in identifying drillable prospects in these areas. SIR began in 2018 with the application of RTM-based workflows in 625 km^2 of data from the AM18 seismic survey in the Atlantic Margin, and fine tuning the velocity model building that was inspired
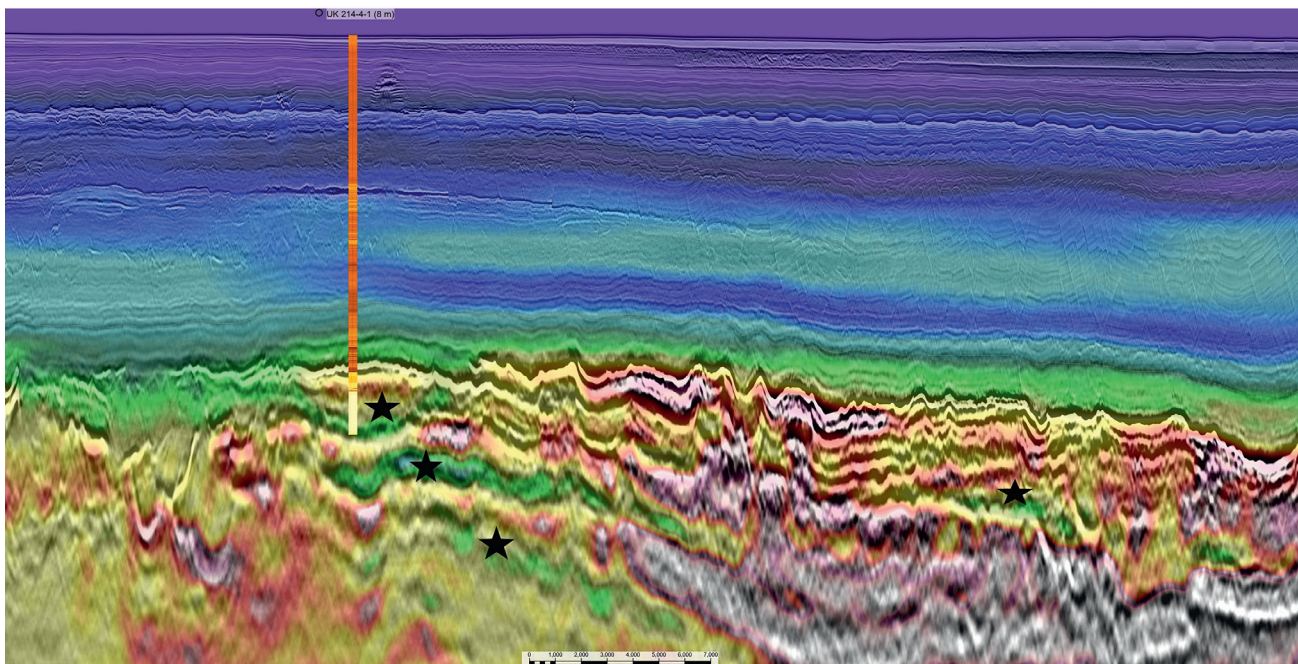
Figure 4 The advanced FWI approach used in the EWW18 3D depth processing gave good model updates in the deeper section. The black stars mark where there are intra basalt velocities equivalent to sedimentary rock. This strengthens the interpretation of potential reservoir rocks sitting in between hard and fast volcanic rocks.
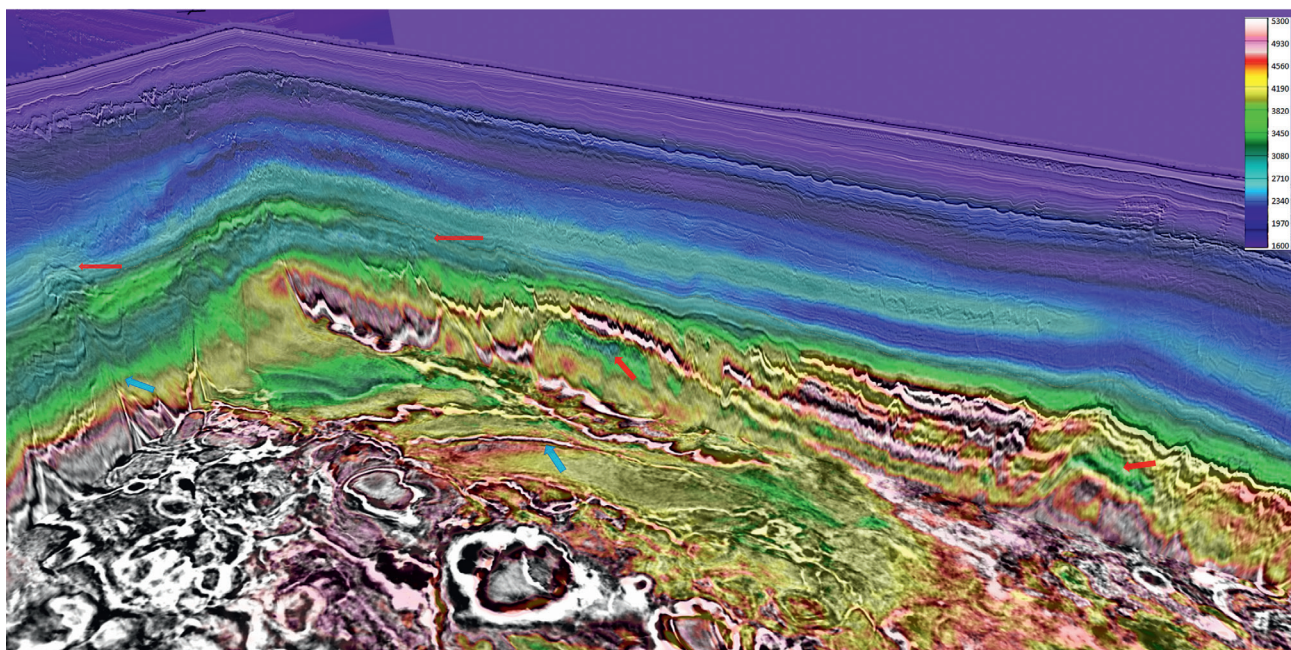
Figure 5 Sill intrusions interacting with lava and sand distribution in EWW18. The final velocity model is overlaid with the seismic. The red arrows from left to right point at:
1) fluid migration, 2) sand remobilization, 3) a sand pocket, and 4) a velocity inversion indicating inter-basalt sediments. The blue arrows from left to right point at:
1) a hydrothermal vent and 2) a sill.

on salt scenarios to work on basalt. In 2019, a variation of this workflow was applied to 1000 km² of the nearby AM17 survey. The key findings from these first two tests were that the obtained velocity model started to be interpretable, a good correlation with gravity highs was obtained, and faults and strata below the basalts could be interpreted with more confidence. Further work was done as part of the processing on the West of Shetland 'EWW18' survey last year (Hart et al.,2020) that included diving wave FWI, Dynamic Matching FWI (DM FWI) (Mao et al., 2020) and image guided tomography. In 2020, a new phase of SIR has started, in which the 'CVX1101' seismic survey is being reprocessed utilizing the learnings to date, together with 2D synthetically modelled data.

Figure 5 shows the results of model building and imaging on narrow-azimuth streamer data from the EWW18 processing project. The input data was acquired in two different seasons, the oldest only recorded 6 km max inline offsets and had very limited potential for diving wave FWI, the newest data had 8 km and healthier diving wave energy. DM FWI is an implementation of FWI that can utilize refraction and reflection, is less sensitive to cycle skipping and robust in low S/N data. So, while diving wave FWI was used, the addition of DM FWI made a positive impact. The combination, followed by image guided tomography, has successfully delineated velocity inversions associated with sand pockets and inter-basalt sediments with a high degree of resolution.

These frontier areas are essential to the revitalization of exploration in the North Sea, with a long-term perspective. The effect on marketing conditions has been significant with factors such as the maturity of nearby basins, the public and political demand for an energy transition and the unprecedented challenges presented in the this very unusual year 2020 with a global pandemic and huge instability on oil prices after a very long downturn for the oil and gas industry that started in late 2014. Money is tight, the

future seems uncertain, and operators are cautious about taking high risks in exploration. Thus, even if they can be attractive, these areas have not yet seen enough activity.

Instead, the mature areas, as explained in the first section of this paper, are the focus. The current search is for new commercially viable discoveries that can be tied-back to existing or planned infrastructure to ensure the continuation of production. These areas are covered with at least two, often three, generations of streamer seismic data. Modern data and modern processing technologies have been used to create structural maps and greater understanding of the subsurface. There is immense historic and geological knowledge of the basins that claimed their prolific place in the world via 'paper seismic'. Yet the industry is looking for what it has not yet found.

Match the data to the problem at hand

Advances in processing have resulted in superior imaging results from new acquisition and allowed existing narrow-azimuth streamer surveys to be revitalized. However, the key to further unlocking the potential of frontier areas lies not only in processing but also in acquisition. Narrow-azimuth acquisition requires many compromises: in the shooting direction, streamer length, shot and receiver density and so on. While no acquisition design can be free of compromise, experience from frontier, or once-frontier, regions such as the deep-water Gulf of Mexico, show that long offset, full-azimuth datasets are rich with potential for improving the imaging of geologically complex regions.

OBN data provides data that is naturally full-azimuth, long offset and high fold. Full-azimuth data improves illumination around complex geobodies at large scales (e.g. basalts and sill intrusions) and small-scales (such as cemented sands), while high fold improves S/N and multiple attenuation. For OBN, preprocessing again is key and while some challenges, such as
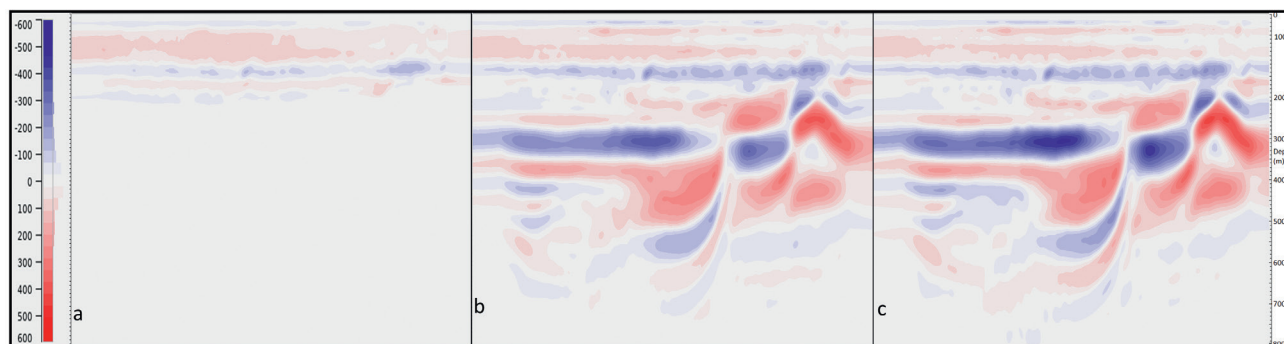
Figure 6 Delta-velocity fields from a 4Hz FWI update; a) with 7 km maximum offset; b) with 12 km maximum offset; c) with 17 km maximum offset. The colour bar shows delta velocity in m/s.

shear wave leakage noise on the geophone, are specific to OBN, the ability to separate the wavefields into upgoing and downgoing creates opportunities for deghosting, demultiple and directional designature through, for example, up-down deconvolution, that are unique to OBN data. These possibilities have been successfully realized at regional scales in the Utsira OBN survey.

OBN acquisition also allows for the recording of much longer offsets than is possible with towed streamers. Offsets of 20 km, 30 km or more, can easily be recorded and provide a solid foundation for detailed velocity model building using FWI. The potential of long-offset FWI has been demonstrated in a test on the Utsira OBN project (Ramirez at al., 2020). Figure 6 shows delta-velocity updates for passes of diving wave FWI with increasing offset, demonstrating the increased reach at depth of the velocity updates with increasing maximum-offsets used. Figure 7 shows the results of diving wave FWI using offsets up to 17 km in the inline direction. Using FWI alone, the localized velocity increases associated with cemented sand features are successfully located.

While OBN acquisition arguably provides seismic data with the least compromise, other acquisition methods can also be utilized to help extend the lifecycle of the North Sea existing infrastructure by helping to find and derisk new prospects. The current geophysical efforts in the most mature areas within the North Sea and the frontier Atlantic margin have some similarities. Within the mature areas, we are in a very data rich environment where well density and many generations of 3D data reprocessing exists. Still there are new plays discovered intentionally like Dugong and Echino South, but also not intended like Evra and Iving, where stacked Early Jurassic and Late Triassic reservoirs had pay. These fortunate discoveries, the history of the area, and, hopefully, this manuscript show that there is plenty of room for better imaging and improved geologic understanding. There are plenty of challenges to be overcome even in an ultra-mature basin. Residual free surface multiples, damaging our interpretations, often prevail despite our best processing efforts, interbed multiples are pervasive and often ignored in processing. Our asset team members have been asking for help in identifying and removing them for
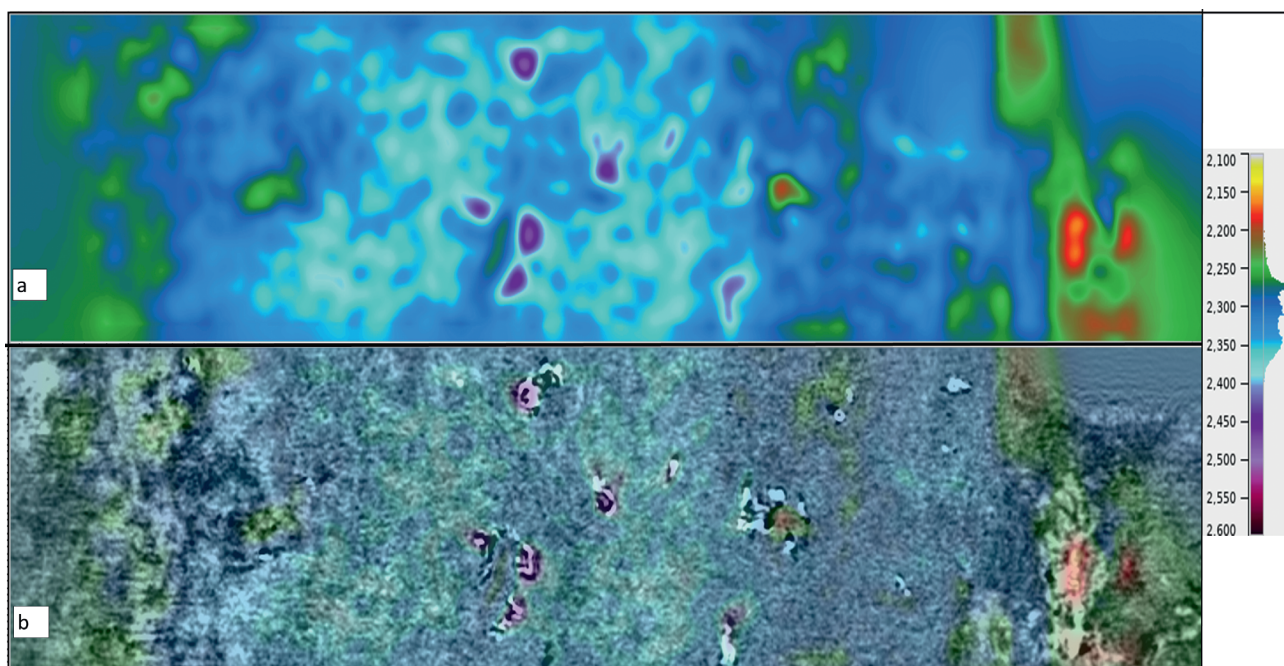
Figure 7 Depth slices through cemented sands at 1410 m; a) velocity model after three passes of diving wave FWI up to 8 Hz and 17 km maximum offset; b) the velocity model overlain on the seismic (Kirchhoff PSDM).

at least a decade (if not more), they are especially troubling when interfering with weak intra-reservoir reflectors, damaging not only interpretation but inversions and well-planning for mature fields. Thus, demultiple remains challenging and the new focus is not limited to identification and attenuation of free surface multiples, but also on the implementation of internal multiple identification and attenuation. This renewed focus on demultiple will provide better data for model building and more imaging successes. Looking for 'golden needles' in a haystack of existing knowledge has proven valuable the recent years. In the frontier regions, there is hope for 'elephants' concealed by volcanic rocks, where improving the sub-basalt processing on better sampled data is the key to unveil the riches.

Conclusions

The industry cannot expect huge discoveries in frontier areas or profitable marginal tie-back discoveries if we do not take any risks and don't put in the necessary work. There needs to be a real commitment to exploring these areas and dealing with the challenges they present by matching them to the appropriate technology.

The North Sea oil and gas industry is in a very different position now, after approximately 50 years of claiming its place as a prolific hydrocarbon area. The focus has begun to shift from exploration to energy transition as operators and governments target carbon reduction and green energy promotion. However, the huge amounts of investments, and the continuous need for hydrocarbons still fuel the need to find the subtle traps – those reservoirs yet to be found and which can be tied-back to existing infrastructure. The maturity of the North Sea contrasts with the underexplored frontier, volcanic region. The future is hard to predict but surely in both regions, mature 'needles' and frontier 'elephants', there is a need for advanced marine seismic methods with fewer compromises. The future is not only about deployment of sophisticated survey designs, it is also about matching such designs and the geological complexity with the appropriate processing sequence, working together across geo-disciplines, and learning from the past.

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