North Sea Transition Authority

TECHNICAL REPORT

Seismic Imaging within the UKCS Energy Transition Environment
Part B: Geophysical technologies

Seismic Measurement Monitoring and Verification (MMV) with particular emphasis on Southern North Sea Carbon Stores and understanding of co-location issues

10 October 2023

1. Executive Summary

1.1 Report Aims

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This report is targeted at two quite different potential audiences:

- Firstly, to provide those without geological knowledge some background into the role of seismic acquisition to aid understanding of offshore carbon stores and how it can impact other co-located marine users.
- Secondly, this report provides an extensive review of the rapidly developing role of geophysical technology to help describe the rock layers below the UK's seabed.

- This research is principally aimed at underpinning the role of seismic data and its ability to identify, define and in the future, monitor, Carbon Storage (CS) sites and complexes. This work now has particular significance following the announcement of the UK governments support to progress four existing licence areas to development and the recent award of an additional 21 carbon storage licences with associated licence work programmes.

For CS to help the UK reach climate change net zero targets and associated carbon budgets, it is estimated that it will be necessary to progress up to 100 projects around the UKCS. This involves completely redeveloping large areas of some of the UK's subsea "geological basins". Given this very large area and the necessary rapid pace, we have only a short time to build upon our existing knowledge, to comprehensively describe both the underground CO_2 storage reservoir and ensure the competency of its surrounding trapping complex. Whilst there are a large suite of geophysical tools available, this report focuses on impulsive, active sourced seismic, generated and reflected back to receivers recorded in the water column. Resulting guidance is focused on the high concentration of CS activity in the SNS issues surrounding future seismic acquisition. Many aspects are also relevant to the other main CS areas (East Irish Sea, Central and Northern North Sea).

The aims are therefore to help inform

1) Wider marine users of the geophysical footprint and help ensure co-located CS developments are carefully planned with consideration to other marine sectors.
2) The development of the appropriate geophysical techniques.

It should be noted many of the seismic imaging techniques covered within this report are also relevant to other parts of the ongoing energy transition. Whilst seismic technology is already deeply embedded in established oil and gas (O&G) reservoir evaluation and asset stewardship. This report attempts to start to cross the divide and considers the relationship of geophysical surveying for the siting of windfarms.

(Refs. 1a , 1b, 1c & 1d)

Two very different potential audiences: Covering fundamentals and deep geophysical dive.

1.2 Report Structure

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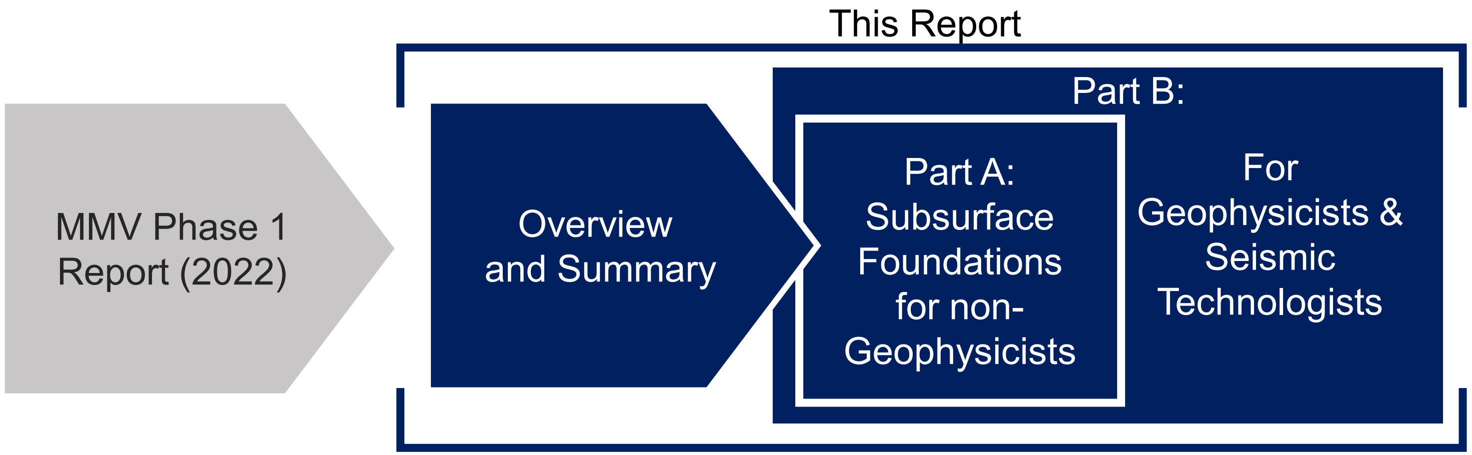
This represents a compilation of NSTA enabled projects, undertaken in collaboration with The Crown Estate led Co-Location Forum. It builds upon a previously published NSTA report "Measurement, Monitoring and Verification of CCS projects, with co-location considerations" (August 2022), and henceforth referred to MMV Phase 1.

This report is complementary to the MMV Phase 1 report issued by the NSTA in 2022. In this report, after an overall report summary (section 1), the report is split into 2 overlapping documents:

- Part A is aimed at providing foundations to non-geophysical audience.
- Part B is created for Geophysicists and Seismic-Technologists.



Part B additionally incorporates technical detail which has been used to support the current assessment of seismic technology in the energy transition environment. Specifically, Part B includes

- The current state of streamer and ocean bottom seismic acquisition and processing (sections 5, 7 & 10),
- Principally for reservoir imaging in the SNS (section 4) but
- Also overviewing site surveys for windfarms (sections 6 & 8).

Part B further includes synopsis of standalone studies into:

- CO_2 detectability using 4D (sections 11 &12) and
- The level of windfarm related disturbance (section 13).

The report concludes a perspective on the direction current technology could develop (Section 14).

CS geophysical report structure: Summary for all. Part A for non-subsurface, Part B for interested geophysicists

Contents and Mapping to study reporting

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This document represents a consolidation of a series of internal NSTA technical projects. This page maps the parts for general interest (A) with those with specialist geophysical understanding (B). This report covers further analysis conducted from 2021 to mid 2023, some of which has been previously presented to co-location forum.

Contents & relationship to parts of report & previous co-location forum projects

1.3 Seismic Technology Executive Summary

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The description of the rock storage (subsurface) for carbon stores, like oil and gas reservoirs, will continue to be heavily influenced by the quality of the initial pre-development seismic reflection image. Both modern data acquisition and extensive processing remains an excellent investment for the entire life of the project, especially as access is becoming an increasing consideration with time. We have one marine area and its underlying geology, imaged by an array of different geophysical "remote sensing" techniques for a range of users and projects.

CS Site characterisation: The majority of the current potential UKCS CS areas is covered with legacy O&G 3D seismic. Once reprocessed to modern minimum standards (broadband & FWI velocity modelling) it is considered suitable phases for pre-development site characterisation during NSTA licence project "appraise" and "assess" phases.

Pre-development CS Baseline seismic: During CS store development the NSTA expects a pre-injection baseline survey will be acquired involving modern long offset (3- 6km), broadband acquisition and enhanced modern processing afforded by the highly efficient streamer seismic acquisition will continue to be the expected mainstay. Seabed (ocean bottom (OB)) seismic is geophysically superior technology but will continue to be burdened by significant cost multipliers compared to streamer. OB seismic is the recommended approach in shallow water (<20m) areas with complex overburden/ reservoir imaging issues and areas increasingly congested with surface obstructions. **The strong recommendation is for modern seismic operations are conducted before windfarm development is undertaken as future intra-windfarm seismic operations will be complex, difficult and costly.**

Injection phase Monitoring seismic: During the active injection phase, 4D (time lapse) seismic is anticipated across certain types of CS complexes. This involves periodically acquiring a new, high repeatability "deep" 3D seismic survey where it is believed CO_2 is injected directly into or has displaced the in-situ brine filled reservoir. Such monitoring will be particularly useful for providing dynamic reservoir data and assurance for those CS stores in early-stage development.

Long term monitoring: It is expected that occasional, as-required, shallow "site survey" seismic acquisition will be required throughout the life and abandonment of projects, particularly for critical risk areas such as around current and legacy wells and geological faults to seabed. Looking even further ahead – full complex "deep" 4D seismic is not only expensive but has an environmental impact. There is a both a need and technology trend to eventually undertake lower impact & cost, highly targeted reservoir monitoring, built upon very accurate model predictions and comprehensive baseline surveys.

Post Closure monitoring: Further consideration is also needed for the appropriate level of post closure/abandonment phase monitoring.

Enabling the energy transition: Sharing marine space is becoming ever more important. Whilst we may strive to expedite by technology solutions (e.g. greater seabed or hybrid seismic), early and open discussion concerning the extent and timing of marine activity will always be the best way to manage the potential of our offshore areas and everybody's expectations. Traditionally long-term planning has been poor, exacerbated by limited awareness of other user's needs and limited data sharing across disparate databases.

Full co-location of CS or O&G closures with windfarms is impossible as some seismic monitoring access can be expected throughout CS site life. Whilst seabed seismic can help to acquire image closer to the edge of a windfarm, it is unlikely any form of seismic equipment will be able to access within the tight confines of current turbine layouts. Partial overlap is only be possible with careful design of future CS monitoring area and windfarm design.

Reprocessed legacy seismic suitable for appraisal. Good pre-development baseline expected.

Acknowledgements

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The NSTA is very grateful to the many individuals & organisations for their willingness to freely provide time, knowledge and data.

Phase 1 2021 MMV Study

2022 Seismic Detection

2022 OBN Study

2023 SNS Seismic Field Trial

2022 Windfarm Noise

2023 Consultations & Reporting

Particular thanks to Graham Lilley (CCS Geops Ltd) and Hemang Shah (Simply Geo) for coordinating the consultation process stages and fielding the authors innumerable clarifications. Special appreciation to those individuals subsequently willing give up their time to help check some of the key details: Colin MacBeth, Maria-Daphne Mangriotis & Phung Nguyen (Heriot Watt Uni/NOC), Dan Davies (TGS), Andrew Wilson (CNOOC), Alex Cooke, Ahmed Sameh, Mike Branston & Krishna Raman (SLB), John Underhill (Aberdeen University), Andrew Long (PGS), Dan Morgan (Scottish Power), Adrian Topham (Crown Estates) and of course, our very patient colleagues in the NSTA.

Very many contributors from Industry & Academia

1.4 Predominant Geophysical technology

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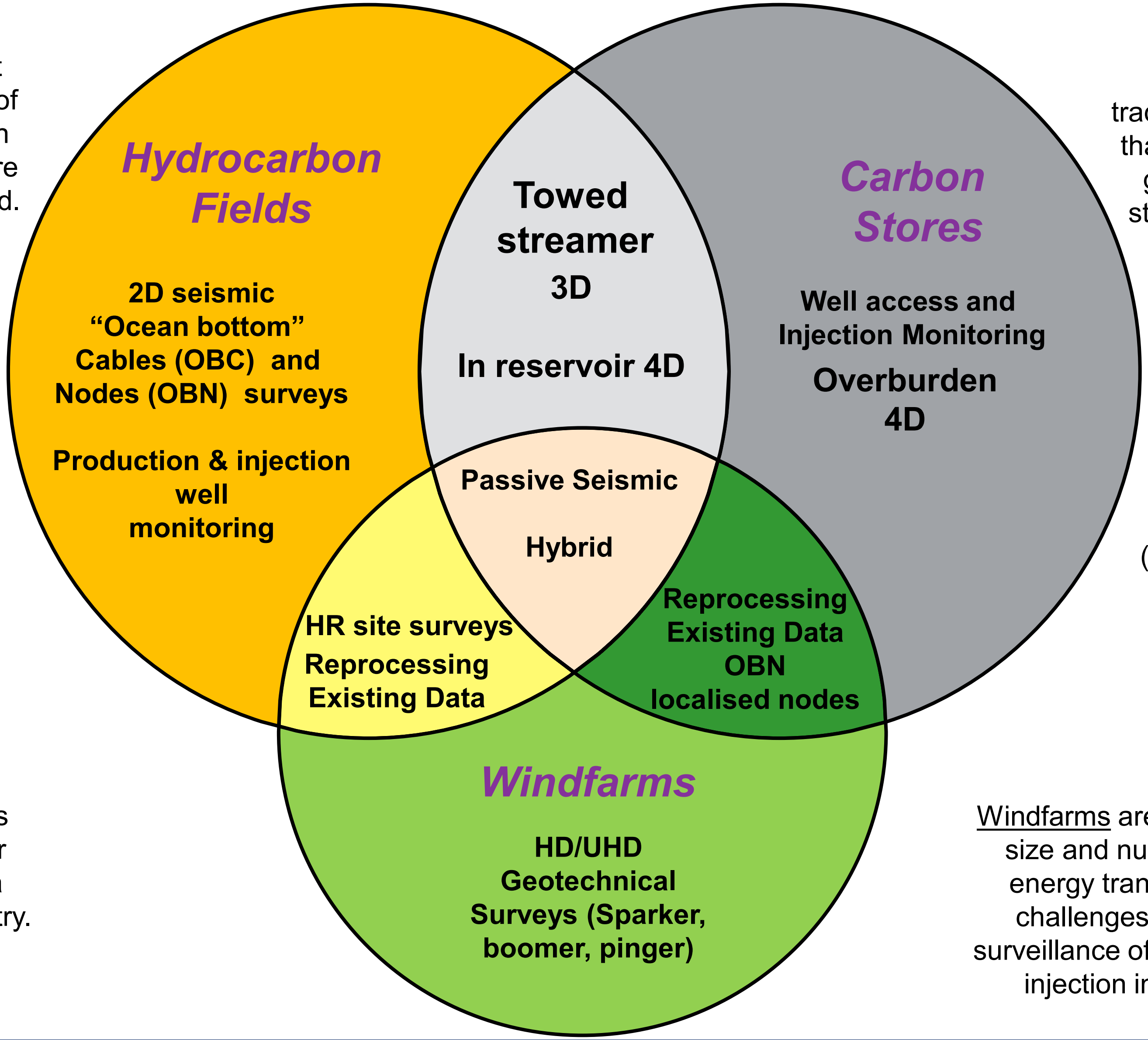
<u>Deep Imaging Geophysics</u>
The O&G industry has helped support and drive the development of an array of highly sophisticated seismic acquisition and processing technologies. These are overwhelmingly seismic reflection based.

<u>One subsurface</u>
Separate organisations (energy company, geophysical acquisition and research institutes) are beginning to utilise new full wave algorithms to understand the overlap.

<u>Shallow Imaging Geophysics</u>
Siting offshore wind turbines, like installing O&G and CS facilities, relies upon very much shallower and higher resolutions, typically undertaken by a separate geophysical acquisition industry.



<u>Carbon Stores</u>
There are many similarities between traditional O&G deep seismic imaging and that being re-employed for CS sites, with greater focus on the overburden rock structure above the injection reservoirs.

<u>Carbon Stores</u>
In the long term, carbon stores are expected to move towards targeted monitoring around specific risk areas (e.g. legacy wells & critical faults). This could include minimal 2D, HR only, in well active seismic, in well or seabed passive reservoir monitoring.

<u>Windfarms</u> are expected to increase in size and number with the evolving energy transition. One of the key challenges will be in maintaining surveillance of the subsurface and CO_2 injection in areas of colocation.

Traditionally wide & separate range of geophysical technologies, beginning to see convergence of technologies

1.5 Seismic Technology Development

Seismic technology advancements: Acquisition and processing technologies continue to make rapid advances from the advent of small patch-work 3D surveys 40 years ago. Whilst many of these may appear to be incremental advancements, the complex interplay between acquisition design parameters and highly sophisticated processing algorithms have evolved an industry which is vastly different from its humble 2D origins:

- A dramatic increase in acquisition accuracy, capacity and a large array of different options for in water (i.e. towed streamer) or on seabed (ocean bottom) recording.
- Implementation of GPS navigation from initially vessel based to hydrophones and individual nodes.
- An exponential increase in data storage and computer processing power which enables the implementation of ever more sophisticated processing/imaging algorithms that enhance the strength and reliability of the genuine geological seismic signature from the raw data and supress the various sources of noise.

These have greatly enhanced the resolution and reliability of a pre-development (static) subsurface image as well as being able to detect time lapse (4D) imaging fluid (oil, gas, water, CO_2) movement within the rock pore space.

Deep vs site survey (shallow) seismic: Traditionally, there have been 2 distinctly different geophysical businesses:

1) "Deep reservoir" seismic primarily for O&G but now being re-deployed to image proposed carbon storage sites. This is usually acquired by large, dedicated marine seismic vessels towing both wide and very long recording streamers (cables) a few metres below the sea surface covering very large, 3D areas. By necessity, this requires plenty of space, clear of surface obstructions. In some situations, ocean bottom recording allows acquisition closer to infrastructure or in shallow water and is also preferential for complex geological targets.
2) "Site survey" seismic either for safely locating wells, infrastructure (pipelines, cables, rigs) or increasingly locating wind turbines. This too has a role for CS monitoring. In contrast, it deploys very much reduced equipment, over highly focussed small areas.

This report starts to bridge the knowledge gaps of these traditionally very separate subsurface imaging techniques to help to better inform co-location considerations.

Looking even further ahead – time lapse seismic is an expensive undertaking for simply monitoring and has an environmental impact. There is a strong desire to ultimately move to more passive monitoring. Early research into this topic is included in this report.

Seismic tools and techniques have a track record of rapid development. Increasing overlap between traditionally separate "deep" and "shallow"

1.6 Seismic Technology Toolkit

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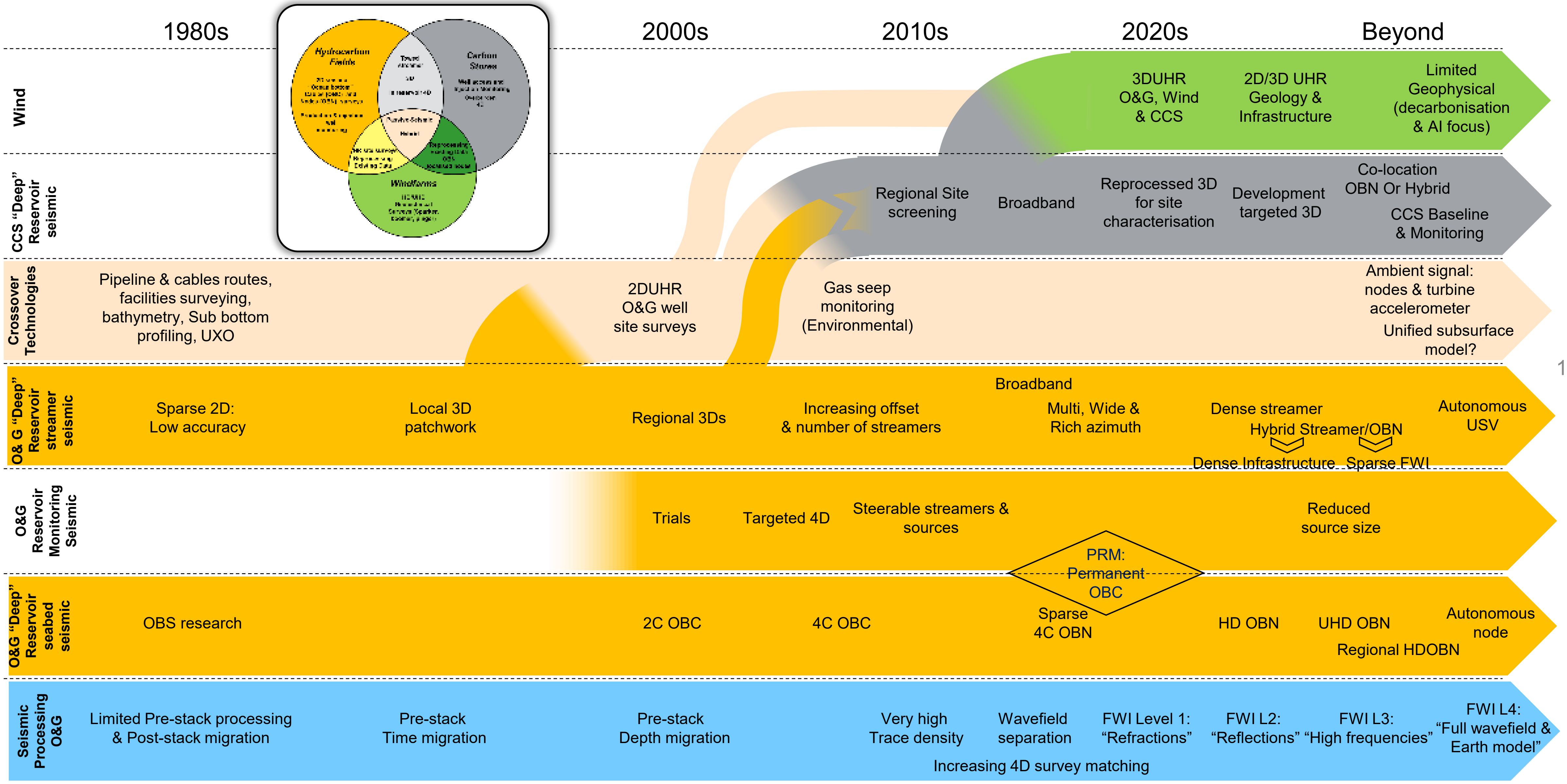

Evolution of seismic technologies: Increasing cross-over and integration

1.7 SNS developments & co-location

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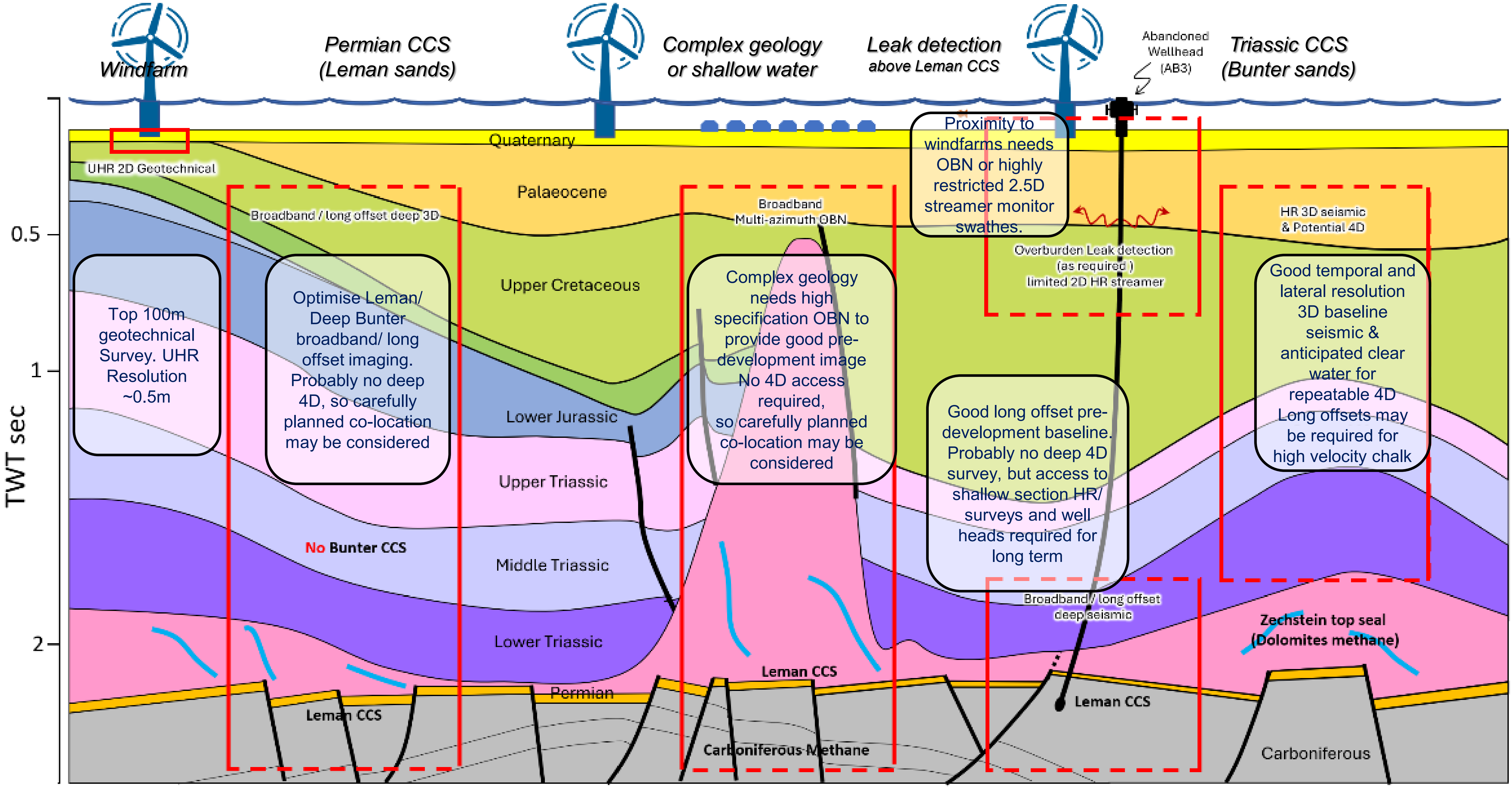

SNS CS targets & seismic type and co-location access considerations

1.8 SNS nodes and site survey target

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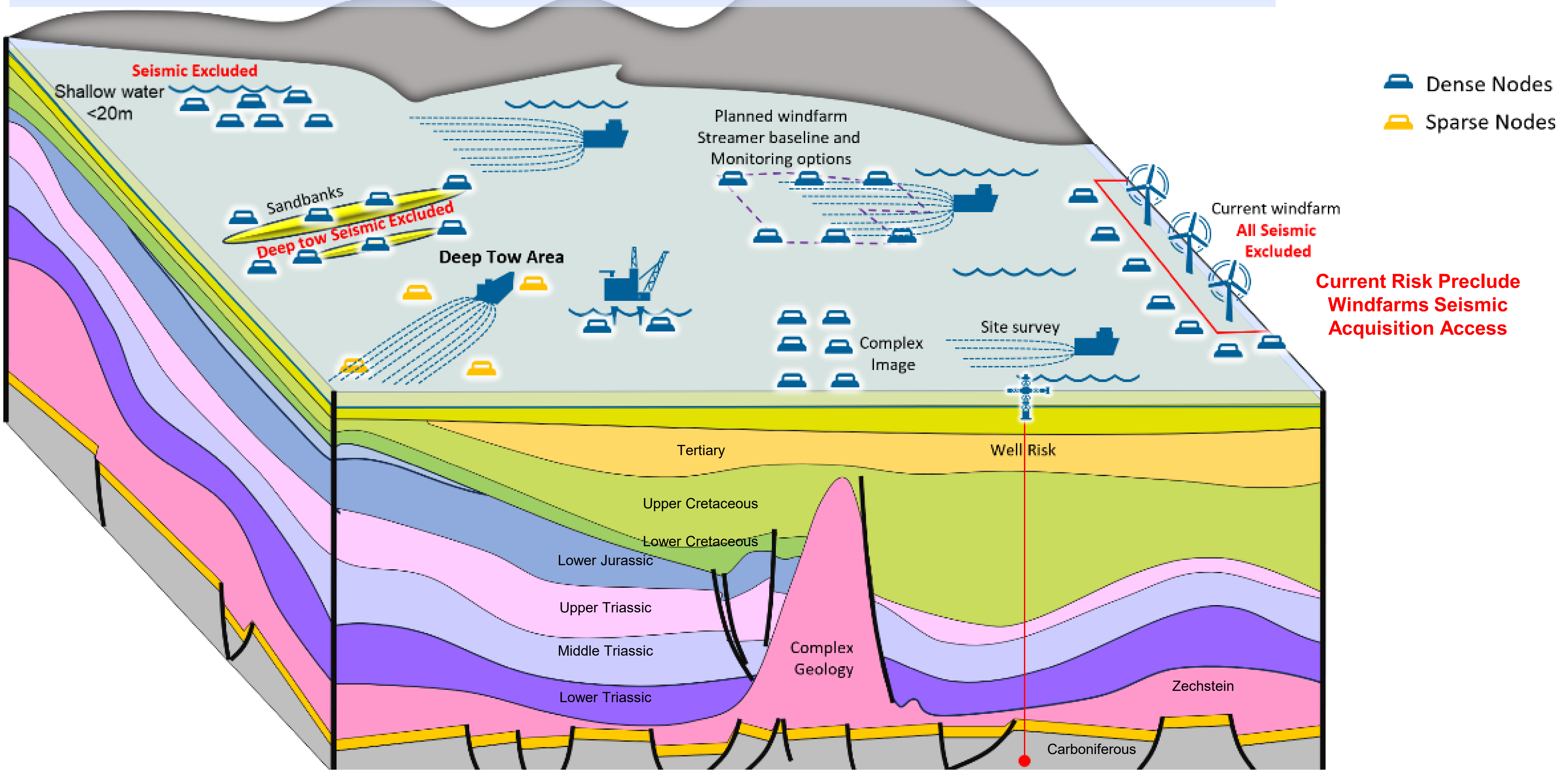
Deep tow seismic is the expected default: Focus on specific node & shallow seismic applications.



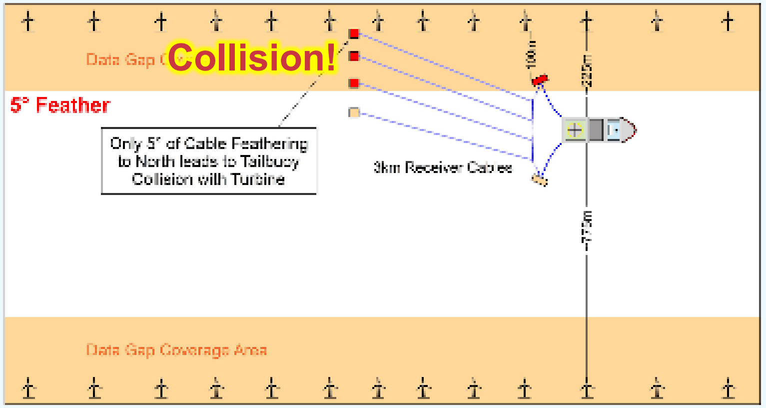
Current Risk Preclude Windfarms Seismic Acquisition Access

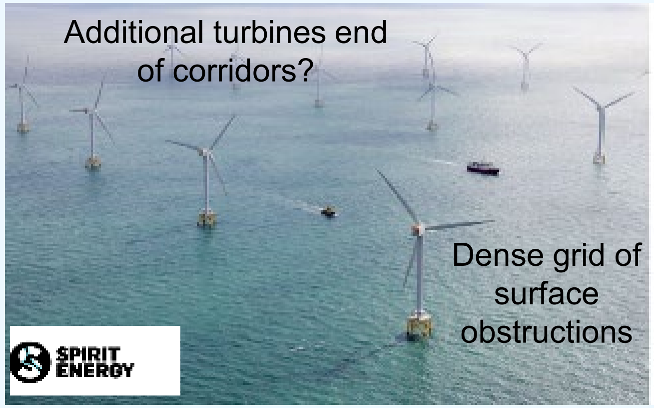
Deep tow streamer seismic expected default: Focus here is on OBN/site survey seismic

1.9 Intra-windfarm Seismic cannot currently co-exist

Streamer Seismic

Unpredictable currents/
Cable feathering
Collision risk
(even for short streamers)





HR (short streamer) seismic vessel within windfarm

Careful pre-planning & operational drills

Risk Loss of propulsion?
No space to drift off
No space to manoeuvre
Standby tug

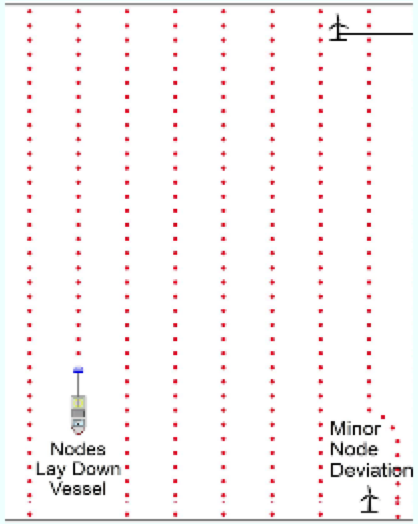
The NSTA is grateful to Chris Ward and Spirit Energy providing the details of this survey

Seabed (node) Seismic In Theory:

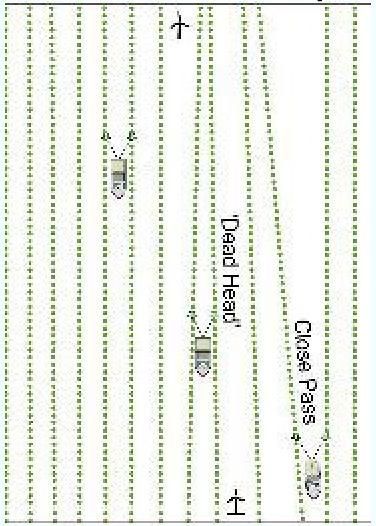
NOAR: Node on a rope

Or very slow ROV deployment & retrieval

Nodes laydown



Source vessel Shoots over the top



Seabed (node) Seismic Practicality:

Turbines shut in during operation?
Loss of revenue

Tall seismic vessels under turbines

Electronics on nodes near high voltage cables
Fibre based nodes?

Fragile nodes

Dropped or unrecovered objects need surveying & removing (Jackup access?)

Collaboration between multiple disparate parties

Seismic crew unfamiliarity

Captain/Party chief & windfarm operator access agreement

Proximity/ exclusion distances

High risk of power Cable entanglement?

See also section 8.6

A lot of effort and significant risk (needs to be fully assessed) for a very sparse dataset

Nodes can be deployed towards edge of a windfarm, but intra windfarm deployment untenable without full (HAZID) risk assessment

1.10 Is Seismic co-surveying possible?

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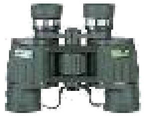
Comparative summary of different seismic technologies and potential for co-surveying



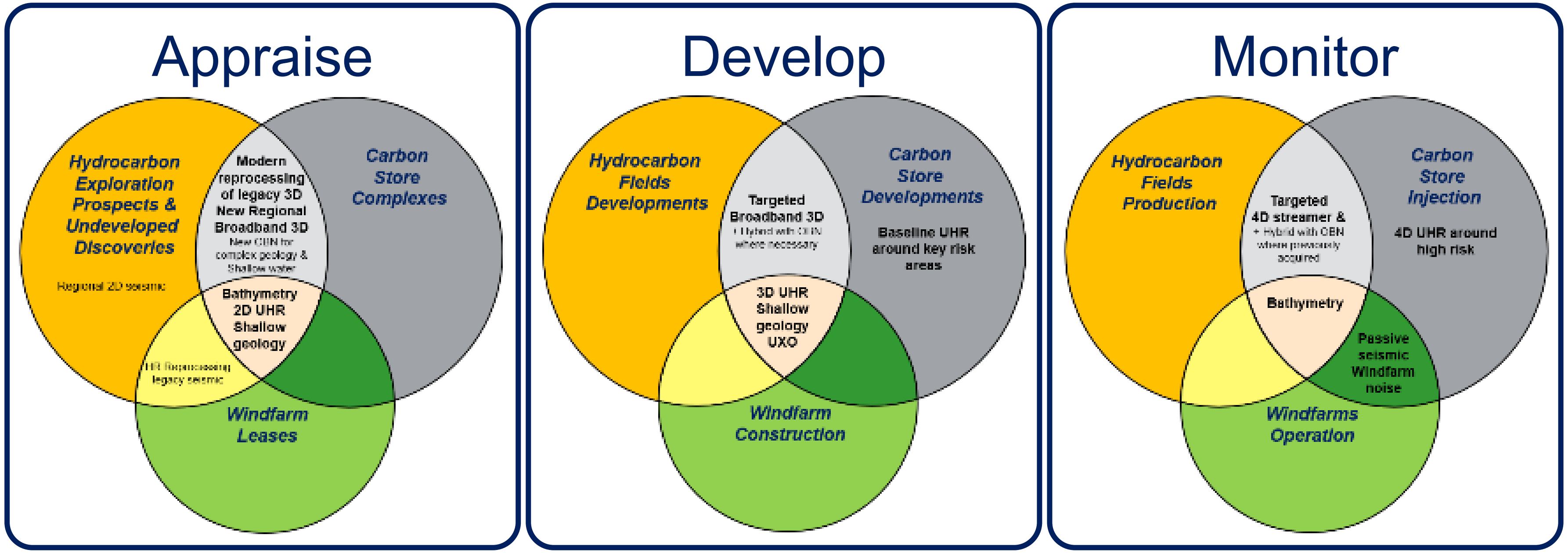
Activity	Target	Current	Trend	Future	Cosurveying?
Windfarm geotechnical Foundations & Route O&G/ CS: geotechnical pipe/ cable route/ Jackup	Seabed-> 100m Resolution: 0.5m Glacial fill, boulders. Scours, Buried objects: Wrecks, mines	Seafloor bathymetry, SSS, SBP, UXO - magnetometer Usually 2D UHR, Increasing interest in micro 3D Cone Penetration test P&S logs	Uncrewed surface vessels (USV) CS Seabed monitoring, Plume identification & sampling	Larger turbines with longer & wider piles: Geotechnical foundation focus rather than seismic 3D UHR (short cable P-cable) (section 5.12) Greater borehole seismic integration	Limited overlap.. Regularly combine equipment - Possible periodic co-inspection?
O&G/ CS site surveys	Shallow methane pockets 0-1000m, Resolution ~5m	Mostly 2D HR Basic well log Lithology, Gamma, Sonic, Resistivity, ROP	Reservoir seismic configured for better resolution	Some P-Cable UHR Uncrewed surface vessels?	Possible overlap
O&G reservoir targeting	1000-4000m Resolution 10-30m	Broadband. Reservoir focussed. Some 4D and/or multi-azimuth (e.g. OBN) Close integration with full well suite inc. density, core, pressures.	Routinely: Broadband & Reprocessing using latest algorithms, Main point of encouragement	Higher proportion of OBN. Lower cost autonomous nodes	No – limited legacy repurposing
CS complex (reservoir + overburden targeting)	300-3000m streamer Resolution 5-30m 600-3000m OBN	Broadband Reservoir targeting with greater emphasis on overburden. Expecting specific 4D	Increasing emphasis on overburden imaging or specific target illumination	Streamer/ OBN hybrid Very low-cost long-term monitoring e.g., passive Integration across range of MMV technologies	Limited overlap

Obstacles: Different industries & clients, very little skills-crossover. No common and open data management.

1.11 Geophysical Co-surveying (O&G, CS & Wind)

Geophysical techniques originally widely deployed in the O&G industry are being further developed for CS applications, albeit with greater emphasis describing the shallow section (reservoir overburden) and monitoring of near surface changes at higher risk locations. Superficially, there appears to be little co-surveying overlap in terms of scale & resolution with the windfarm geophysical activity, although common issues of permitting, access and noise budgets need further consideration.

Main geophysical tool
By project phase



There are signs of some technological convergence, for example:

- Windfarm operators' willingness to screen areas using repurposed legacy seismic, increasingly followed up with limited UHR 3D acquisition, multi-channel processing and the potential to undertake more quantitative assessment of glacial channels & soil strength, particularly increasing turbine size and foundation depth.
- Future potential. Can turbine accelerometers be used to provide subsurface imaging? Is there any benefit for long term node deployment to monitor turbine stability?
- "Deep" seismic for O&G/ CS industry is paying greater attention to imaging effects of the shallow section and operationally now have the capability to provide extensive high resolution shallow 3D. For shallow water 3D acquisitions, a bathymetry survey is increasingly collected.
- Future potential: There are signs of an emergent, revolutionary "single geophysical model" approach (section 14.3) which may provide the capability to incorporate a broad range of geophysical data. Future monitoring co-survey updates which could share more similar parameters to windfarm surveying. For example, we have considered the potential to use windfarms as an ambient seismic signal (section 13). Re-charge autonomous sources and data-drop from nodes at a local substation would make continuous monitoring attractive.

1.12 Geophysical technology direction?

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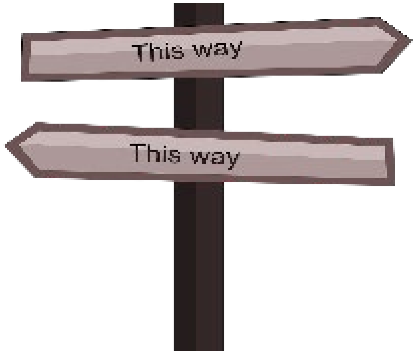
There is a range of seismic acquisition and processing options available, with all options having an associated cost (both financial and effort required for completion).

Much of the current UKCS CS & O&G areas are already covered with legacy 3D and there are many excellent examples of very good and cost effective modern FWI reprocessing of the raw data. Whilst this provides assurance up to CS site characterisation (appraisal) stage, often the restricted acquisition parameters and effects of subsequent O&G production/injection mean that it **could not** be considered as a baseline for monitoring of new field/complex development, let alone 50+ year store management.



The NSTA recommends:

- Good quality pre-development 3D survey with broadband frequencies and long offsets parameters appropriate structural imaging of the CS complex (overburden and down to target depth); this also serves as the seismic baseline for future 4D monitoring.
- High resolution seismic for high-risk features (wells, shallow faults) in the overburden.
- Streamer seismic remains the most cost-effective mainstay, but a targeted hybrid with OBN will be necessary for either a comprehensive velocity field by deploying sparse nodes or localised dense node patches around critical infrastructure.
- The NSTA has no technical preference for proprietary vs multi-company acquisition.

<u>Future Implications</u>

The increasing difficulty of access, operational cost & environmental impact of large-scale geophysical data acquisition implies:

1) If not already available, early acquisition of a modern 3D image. A basin scale re-development strongly suggests that opportunities to work together should be used whenever possible.
2) Greater emphasis on the definition & sophistication of the pre-development geophysical description of the CS complex.
3) Support the development of smaller footprint active or passive technologies within the context of updating the geophysical model.
4) Long term spatial and temporal planning; marine infrastructure designed alongside appropriately scoped geophysical surveys which are phased within co-development timetables.
5) Countries bordering the UKCS are facing the same co-location issues (legacy O&G, offshore wind and early CS activities), so improve cross border planning would enable efficiencies and reduced overall environmental impact of MMV activities.

Part A Subsurface Foundations: Recap

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In this main report Part A is incorporated into Part B. This page provides a reminder of **selected** sections from Part A to help provide background to this research.

Section 2 builds upon the previous NSTA report (“MMV Phase 1” report) to show the storage constraints and volumes of CS targets: the depth range for CO_2 storage, the size and extent of some of the SNS subsurface reservoirs. It highlights those areas around the UKCS where co-location between CCS, Windfarm and O&G activity is currently an issue.

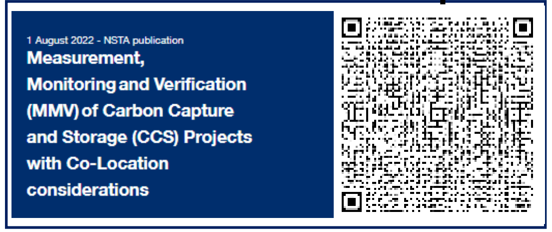
Section 3 offers the foundations for seismic imaging.
Commercial O&G geophysics has been very successfully focussed on enhancing the signal of (P-wave) seismic reflection embedded with a sequential workflow – collect seismic, (re)process & interpret seismic, then build & integrate into geological model, develop subsurface rocks (drill wells – produce or inject fluids) and then repeat.

Introduced are the concepts of vertical scales of O&G or CS subsurface reservoirs vs surface wind turbines, highlighting the different types of seismic resolution available with depth. A brief history of the development and range of seismic options focusses on comparing the very different scales of surface streamer towed for “deep” reservoir vs “shallow” site survey and seabed (aka “Ocean bottom”) seismic and where they could be applied. This section 3 concludes with links to other useful UK databases.

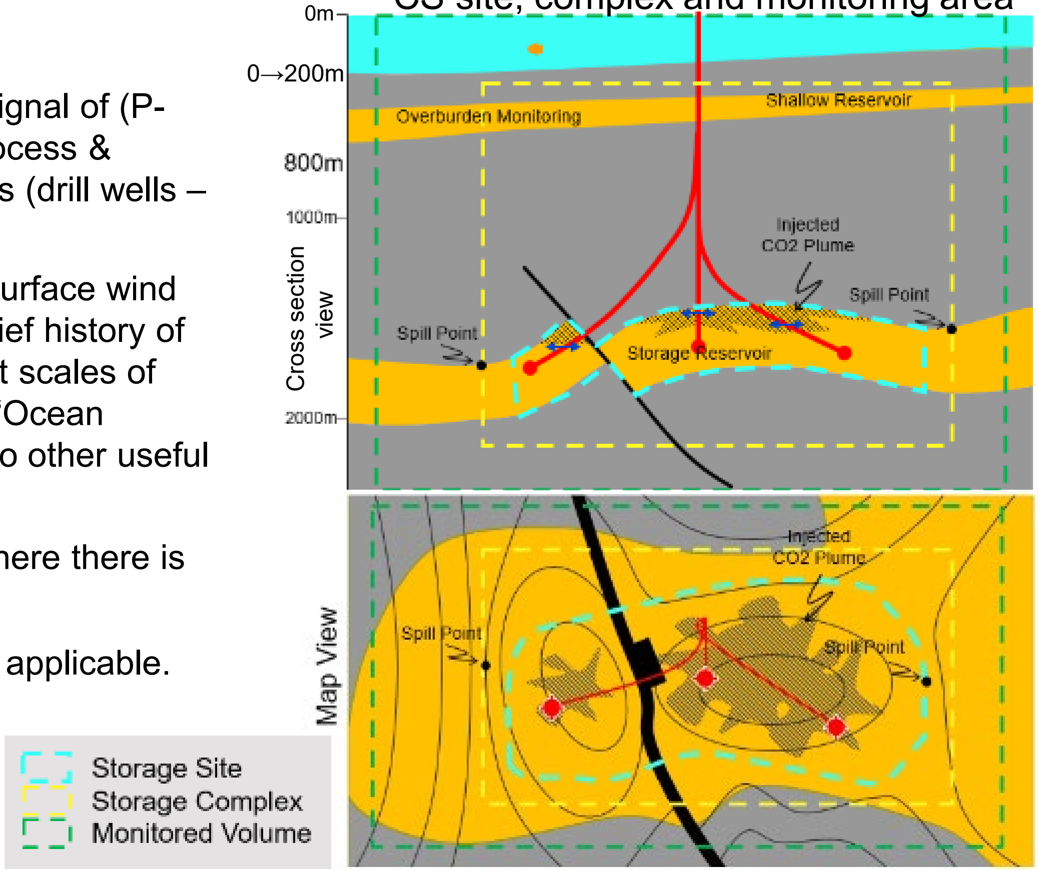
Section 4 summarises the acquisition coverage and history specifically for the SNS, where there is the highest density of CS licences.

Section 12 summaries the areas where 4D (time lapse) 3D seismic is most likely to be applicable.

(Ref. 1a) **“MMV Phase1” Report**



CS site, complex and monitoring area



Part B Seismic Technology Preview

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This more detailed version (Part B) of the report, provides more geophysical technical background and is summarised below:

Acquisition has undergone several discrete step changes to improve productivity, coverage and observational accuracy: principally involving towing more, & longer, streamers in a wider array and deploying more sources. Targeted Broadband or High Resolution seismic is now a standard and the generally expected default for UKCS developments.

- A high-quality pre-injection baseline 3D image supports the entire CCS site description and development and is an imperative.
- 4D (Time-lapsed 3D) seismic monitoring is promising for both aquifer CCS reservoir stores & localised overburden (near surface) monitoring, but unlikely to be of value to monitoring depleted gas or swept oil reservoirs.
- Ocean Bottom seismic is technologically superior to streamer seismic in certain situations, but even with increasing automation & autonomous acquisition, its relative cost multiplier means it is anticipated that it will remain prohibitive for most typical targets.
- This report sets out the range of seismic options available by type and target.

Reprocessing/Imaging existing seismic still remains the most cost-effective technique for improving the 3D image with the advent of many new and computationally expensive and complex techniques. Existing NSTA 5-year guidance remains valid, as data processed during late 2010's, using techniques of that time, are already out-of-date.

The **Southern North Sea** is a particular focus, given the large number of CS licences and increasingly complex acquisition & co-location issues.
All stores are unique, but the existing NSTA stewardship expectations remain valid and specifically for CCS stores, legacy seismic data acquisition *may* be suitable for CCS site characterisation if reprocessed to modern standards. However, there is now the expectation that full carbon storage development requires modern (ca post-2016) seismic targeted for both reservoir and overburden and when applicable, **4D seismic** on suitable aquifer reservoirs. Lower specification near surface monitoring is anticipated for monitoring very low probability situations where flux occurs near existing wellbores.

High resolution **site survey/ geotechnical surveys** for the windfarm industry have very different targets and consequently different vertical (temporal) and spatial resolution. From a co-location perspective, there is limited synergy between these traditionally separate "seismic" industries, although some convergence is occurring.

Careful marine spatial planning for co-location remains a key goal and some suggestions are offered. Marine operations for geophysical data acquisition remains extremely challenging or practically impossible within the relatively tight array of **windfarm infrastructure**. In many CS situations, long offset towed streamer seismic is anticipated to remain the main subsurface workhorse for the foreseeable future, and co-location will remain a critical issue. It will be crucial to have an open dialogue across all parties.

Whilst **acoustic levels from offshore windfarms** are not fully understood, literature indicates they are likely to be low level, in the seismic frequency bandwidth.

2. Recap MMV Phase 1 & CO_2 storage constraints

Section 2 Background

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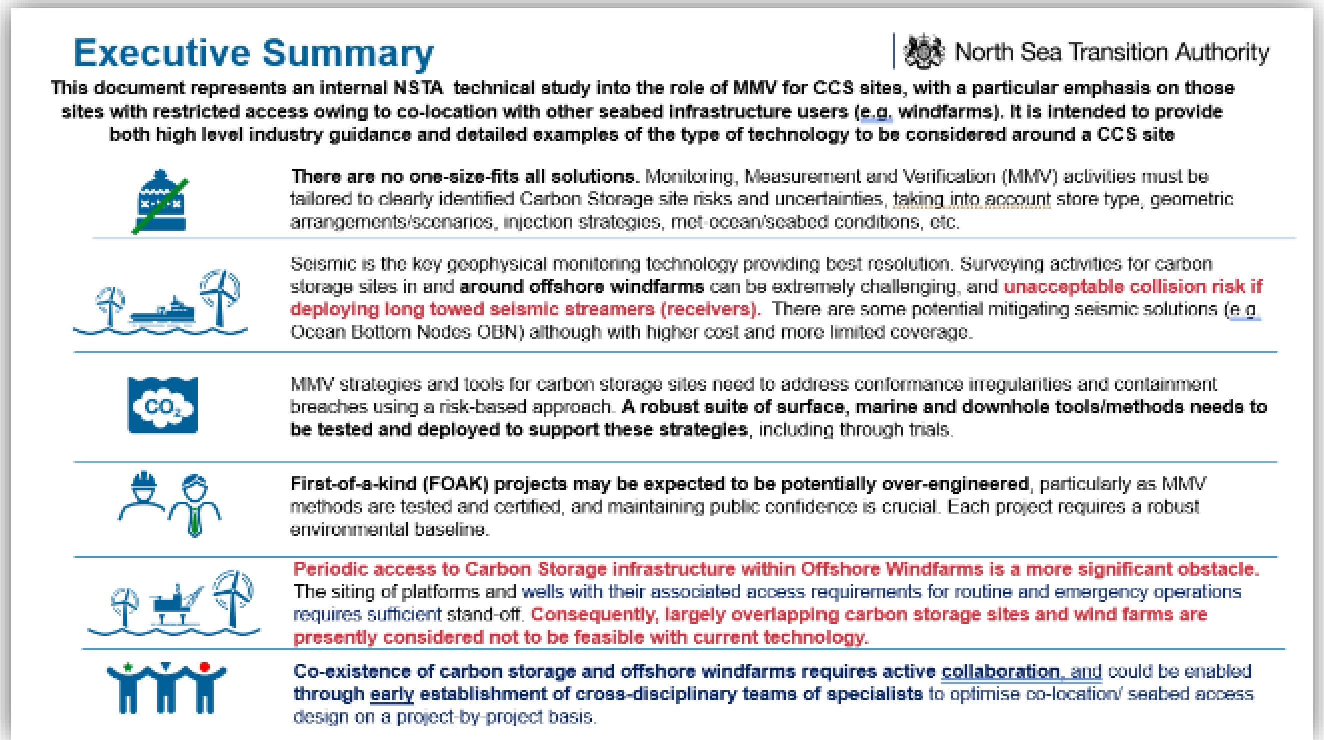
This sections provides a few key slides from the Phase 1 report. Including reviewing the operational considerations for co-location (Section 2.1). ***Ref. 1a***


Executive Summary

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This document represents an internal NSTA technical study into the role of MMV for CCS sites, with a particular emphasis on those sites with restricted access owing to co-location with other seabed infrastructure users (e.g. windfarms). It is intended to provide both high level industry guidance and detailed examples of the type of technology to be considered around a CCS site

There are no one-size-fits all solutions. Monitoring, Measurement and Verification (MMV) activities must be tailored to clearly identified Carbon Storage site risks and uncertainties, taking into account store type, geometric arrangements/scenarios, injection strategies, met-ocean/seabed conditions, etc.

Seismic is the key geophysical monitoring technology providing best resolution. Surveying activities for carbon storage sites in and **around offshore windfarms** can be extremely challenging, and **unacceptable collision risk if deploying long towed seismic streamers (receivers).** There are some potential mitigating seismic solutions (e.g. Ocean Bottom Nodes OBN) although with higher cost and more limited coverage.

MMV strategies and tools for carbon storage sites need to address conformance irregularities and containment breaches using a risk-based approach. **A robust suite of surface, marine and downhole tools/methods needs to be tested and deployed to support these strategies**, including through trials.

First-of-a-kind (FOAK) projects may be expected to be potentially over-engineered, particularly as MMV methods are tested and certified, and maintaining public confidence is crucial. Each project requires a robust environmental baseline.

Periodic access to Carbon Storage infrastructure within Offshore Windfarms is a more significant obstacle. The siting of platforms and wells with their associated access requirements for routine and emergency operations requires sufficient stand-off. **Consequently, largely overlapping carbon storage sites and wind farms are presently considered not to be feasible with current technology.**

Co-existence of carbon storage and offshore windfarms requires active collaboration, and could be enabled through **early establishment of cross-disciplinary teams of specialists** to optimise co-location/ seabed access design on a project-by-project basis.

Phase1 Report

1 August 2022 - NSTA publication

Measurement, Monitoring and Verification (MMV) of Carbon Capture and Storage (CCS) Projects with Co-Location considerations

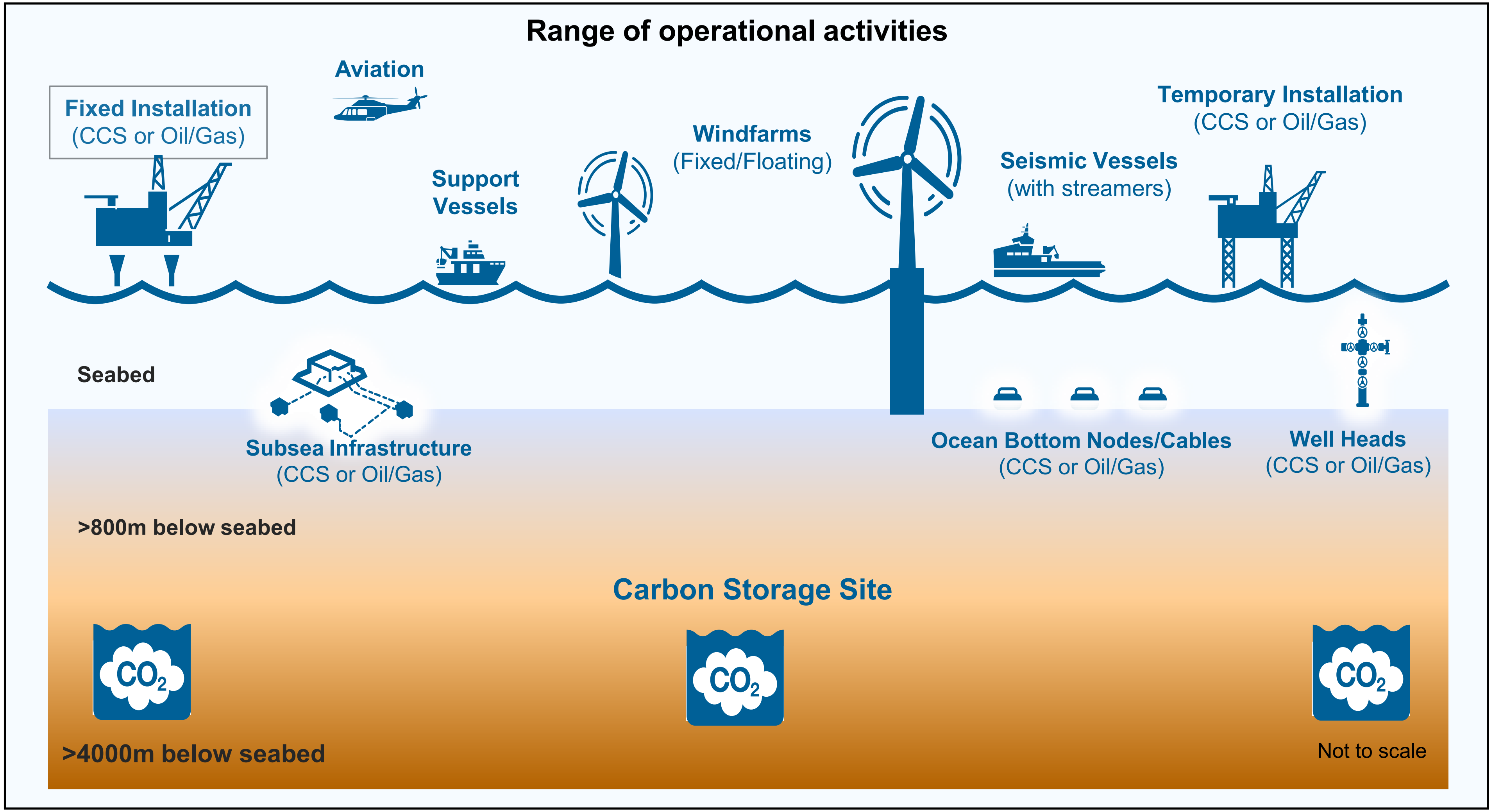
Section (2.2) provides greater context on the depth constraints for subsurface carbon dioxide storage, especially considering the pressure and temperatures for the injection of a super critical CO_2 fluid. Taking these indicators, it builds an example of the volumetric scale (section 2.3) required to achieve sufficient carbon storage and puts this into spatial context of the size of subsurface closures (2.4) required to meet UK carbon storage goals.

This supports the current co-location map (2.5) showing the distribution of potential carbon storage sites, after the recent 1st carbon storage licence round announcement. (***Ref. 2a***).

2.1 Range of Operational Scenarios

North Sea Transition Authority

Every offshore co-location scenario has different monitoring requirements, critical risks to be managed and different geometric arrangements. These include subsurface constraints (reservoir type, extent and depth, fluids displaced), installation designs (new and existing well stock), marine (incl. fishing) and aviation traffic, met-ocean/seabed conditions etc.



There is no “one-size-fits all” MMV solution

2.2a CO_2 Storage depth range

North Sea Transition Authority

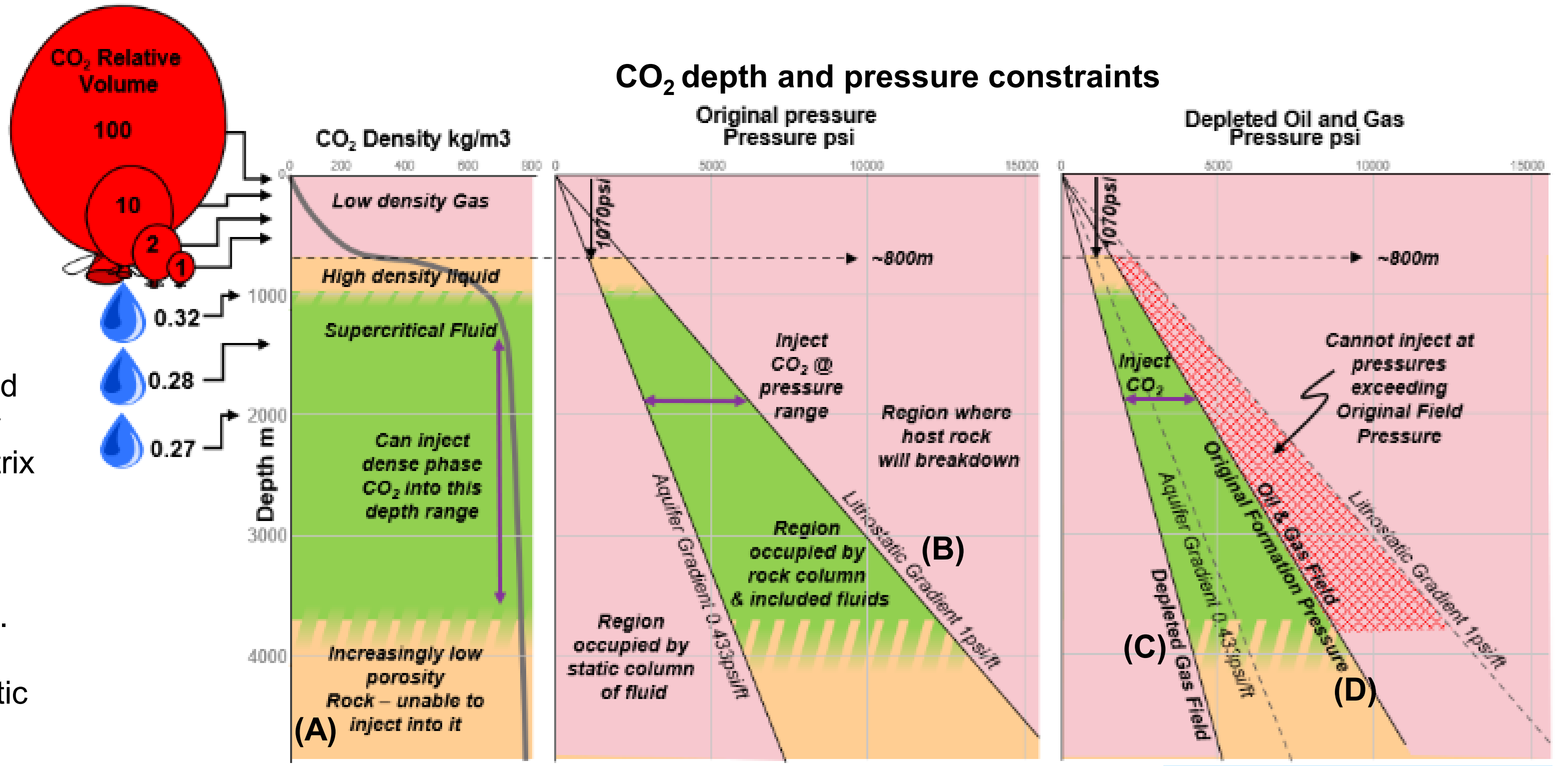
Within the atmosphere, CO_2 is considered to be a gas.
In CS sites CO_2 is generally stored as a "supercritical fluid" which substantially reduces its volume thereby maximising the use of the available subsurface reservoir storage space This has a ceiling at c.800mTVDSS.

Other geological constraints are imposed owing to decreasing porosity, and therefore injectivity, with depth **(A)**.

The physical conditions of pressure & temperature within the subsurface wholly dictate where and how CO_2 can be injected as a supercritical fluid, without compromising the reservoir or seal rocks. This pressure represents the total of the rock matrix and fluid pressures (within the pore space).

As pressure increases with depth:
Aquifer < Injected CO_2 < Breakdown (lithostatic) pressure.

Injection pressures cannot exceed the rock strength (lithostatic gradient) **(B)** as the rock could mechanically break and the carbon store top seal rupture.



(Adapted from Ref. 2b)

22

Hydrocarbon production from legacy gas fields (e.g., SNS) are often leave them heavily depleted to pressures less than aquifer gradient. This is especially true for lower permeability reservoirs or those with poor connection to larger aquifers. In these situations, the CO_2 injection window is shifted to a lower pressure regime **(C)**, with the upper limit always being the original field pressure **(D)**. When reusing a field as a carbon store it is imperative that injected pressures remain less than the original field pressure. A range of CS sites is shown schematically in the phase 1 report (section 3).

2.3 CO_2 Storage dimensions analogue

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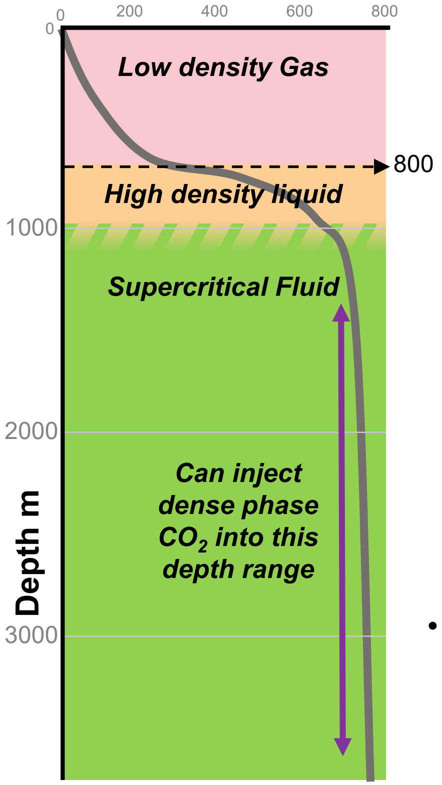
To provide a comparison of scale, consider the capacity contained within the shape of an "open plan" Gherkin (without any walls & floors!).

CO_2 Density kg/m3

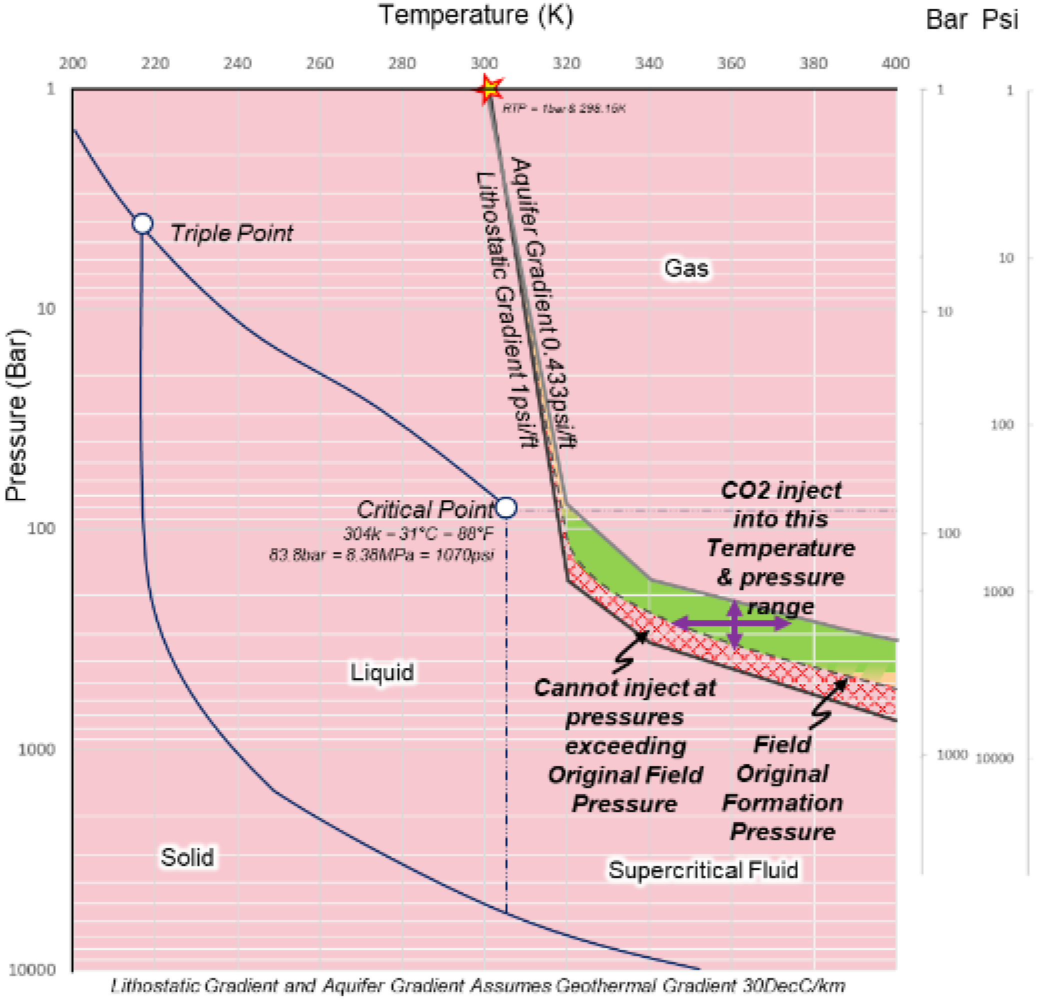


At surface conditions an "open plan" Gherkin has an approximate capacity to contain ~510 tons CO_2.

At 2500m depth

- An "open plan" Gherkin could contain **370 times more CO_2 ~200,000tons** ≈ 0.2Mt
- Typical rock porosity reduces this capacity to 20% of original = **40,000 tons** ≈ 0.04Mt

CO_2 Temperature & pressure constraints



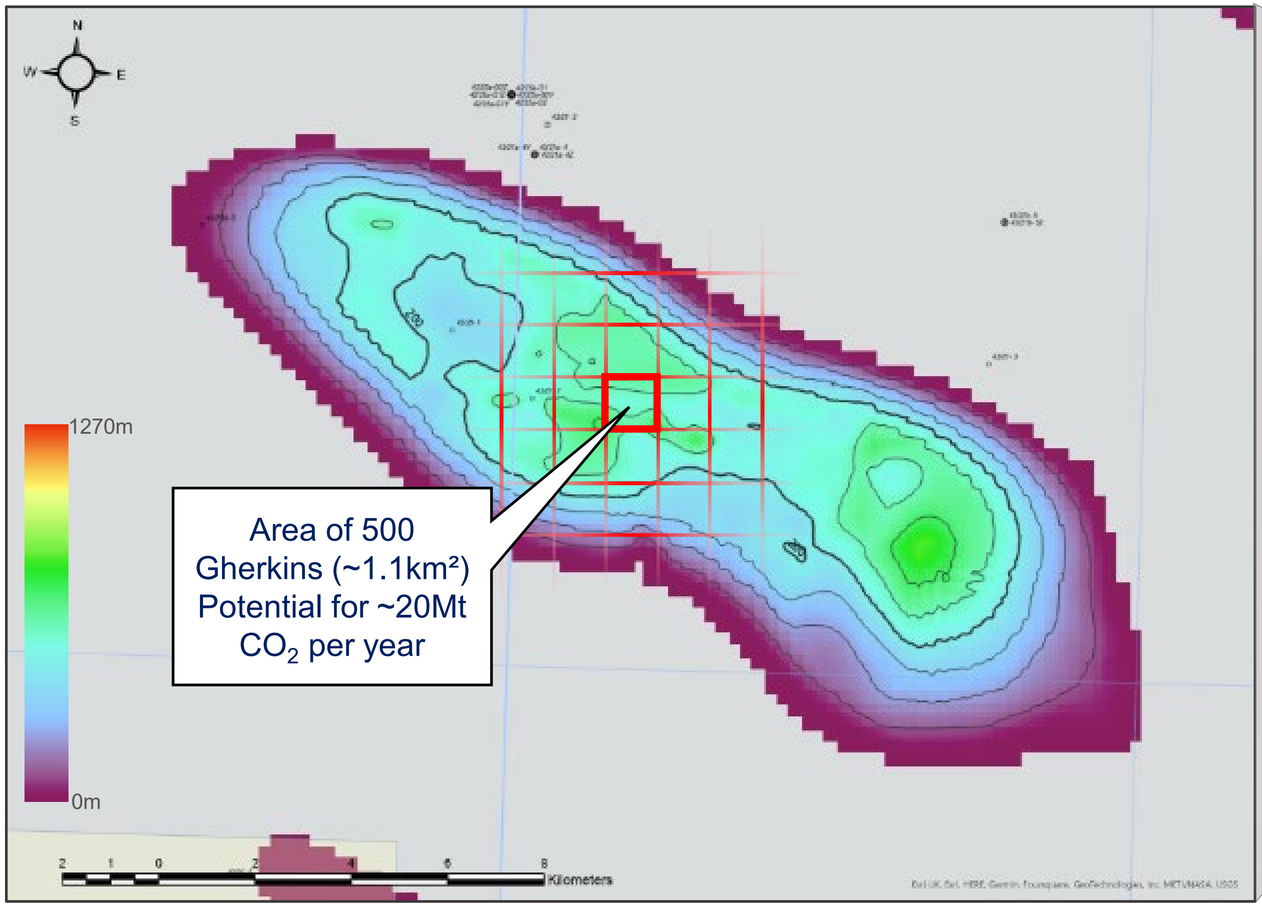
To meet UK 2030 annual CCS target of 20Mt of CO_2 storage, the equivalent of 500 Gherkins need to be filled with CO_2 each year.

Storage at depth significantly increases the capacity to store large quantities of CO_2

2.4a A question of spatial scale

North Sea Transition Authority

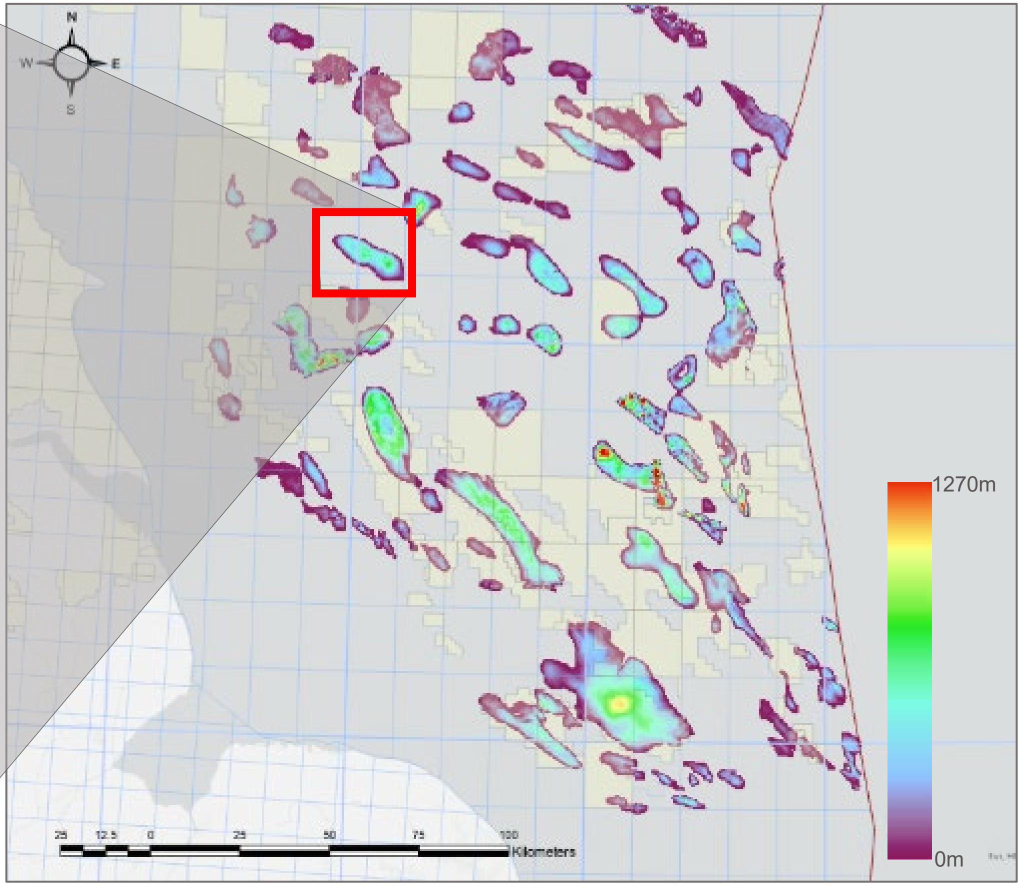
For context, the subsurface footprint of 500 Gherkins is overlain on top of the large potential Endurance carbon storage closure. This can then be compared with the other aquifer closures across the UK sector of the Southern North Sea (SNS).



Endurance structural closure (height) map [CI50m]
More detail on the Endurance project available

(Ref. 2c)

Regional Bunter reservoir closures map

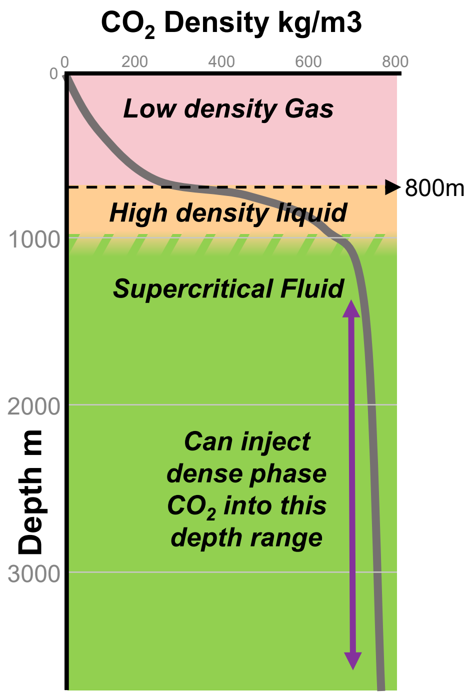


Closure height based upon NSTA regional mapping

Spatial scale of Endurance project and other potential SNS stores

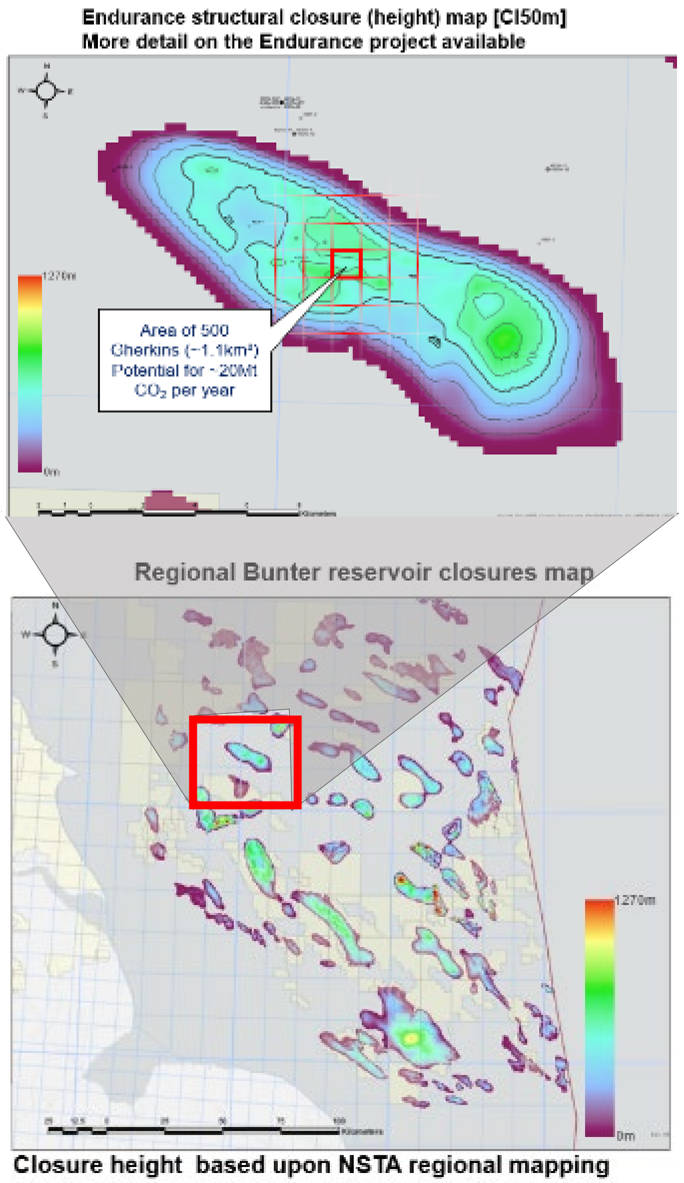
2.4b CO_2 Storage dimensions Summary

To provide a comparative analogy, the **capacity** contained within the shape of an "open plan" Gherkin (without any walls & floors!) is calculated to be 510 tons CO_2.



At surface conditions an "open plan" Gherkin has volume to contain ~510 tons CO2.

At 2500m depth
An "open plan" Gherkin could contain 370 times more CO_2, but the available pore space in the rock to store fluid reduces this to **~40,000 tons**

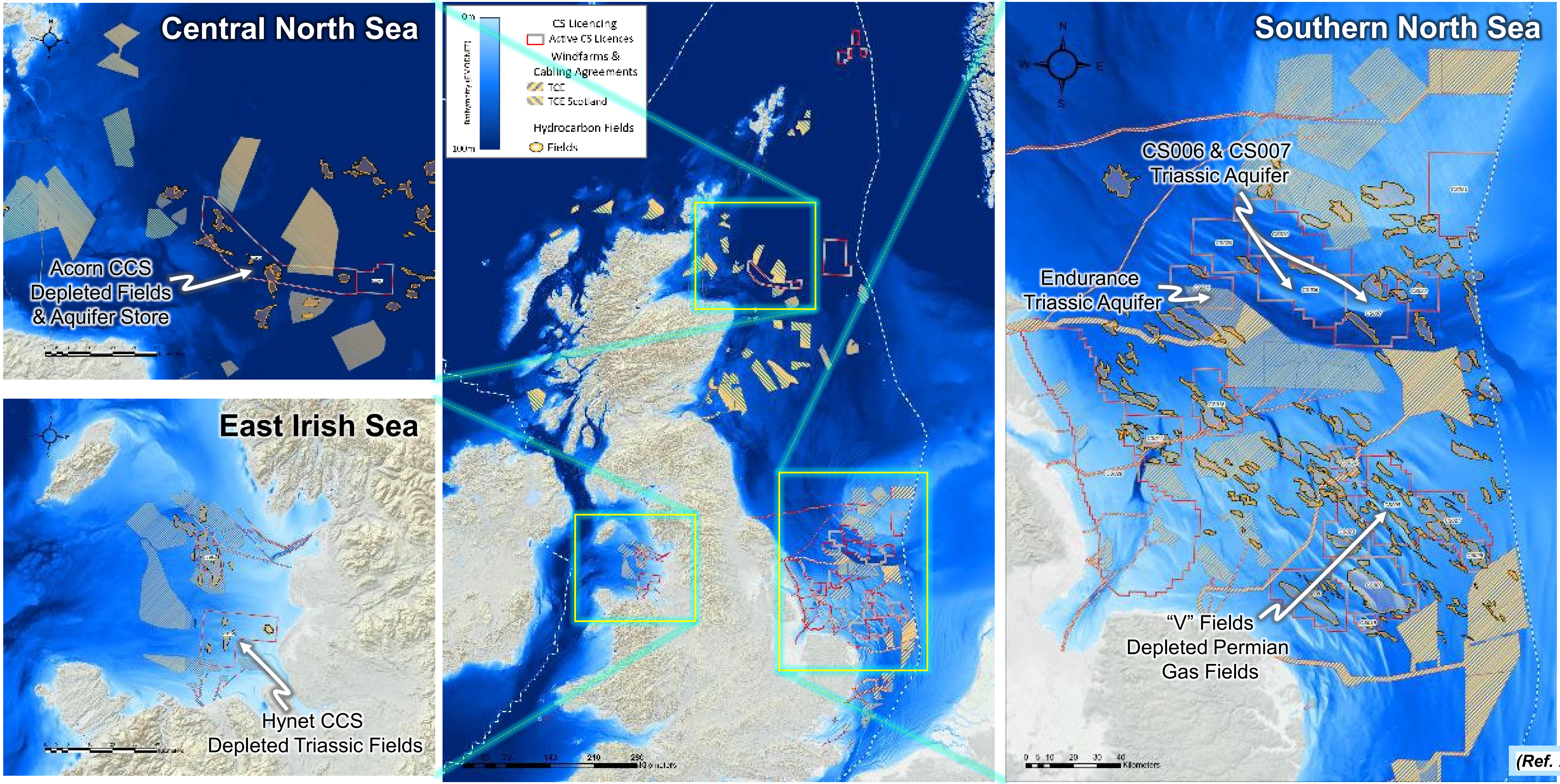


To meet UK 2030 annual CCS target of 20Mt of CO_2 storage, we need to store the equivalent (rock storage capacity) of 500 Gherkins worth of CO_2 each year.

Storing CO_2 at depth enables much larger volumes to be stored: the UK has very many storage areas which could be used

2.5 UK Offshore Current Co-location areas

North Sea Transition Authority



UK marine environment is increasingly being used for a range of energy transition activities; Co-location is an increasing concern especially in SNS

2.6 Phase 1 Report Seismic Monitoring

North Sea Transition Authority

- Very little industry CCS monitoring experience;
  - Large First of a Kind (FOAK) uncertainty.
  - Range of MMV technologies available, but seismic invariably gets highest profile.

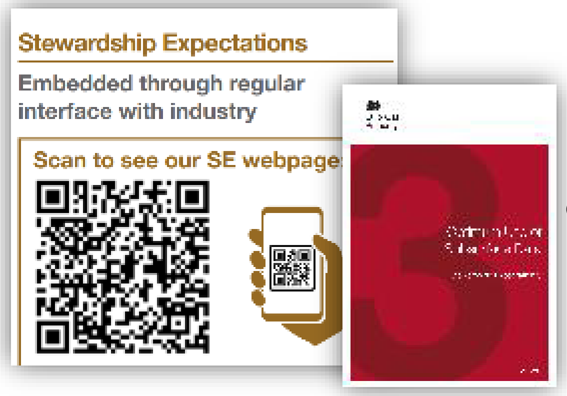
- Ensure operators possess best quality 3D survey for reservoir description & possible 4D baseline;
  - Strong preference for broadband/ modern positioning and most modern processing/imaging.
  - Seismic acquisition footprint is significantly larger than carbon store.
  - Streamer seismic cannot be safely deployed within a constrained windfarm environment.
  - 4D is a very valuable tool for *specific risks/ uncertainties.*

- Careful OBN (Ocean Bottom Node) acquisition can mitigate most seismic monitoring co-location issues:
  - Predicted to remain 2-5 times more expensive than comparable streamer.
  - In complex geology, OBN likely to provide superior imaging at depth. Additional $$m cost cannot be routinely justified.
    - Unless technologies much more cost effective.
  - Streamers remain obvious clear water acquisition technology.
  - Does not remove significant well site access issues.

- Windfarm/CCS/Hydrocarbon/Other User co-location issues are likely to increase
  - Increasing numbers of Carbons stores.
  - Extensive Windfarm leasing.
  - Current CCS & Future Hydrocarbon exploration & development licencing.
  - INTOG (Crown Estate Scotland Innovation and Targeted Oil and Gas: low carbon electricity for O&G installations).

- Long term desire to move away from active 4D seismic monitoring - CO_2 emissions, Cetacean (marine mammals) impact and cost.

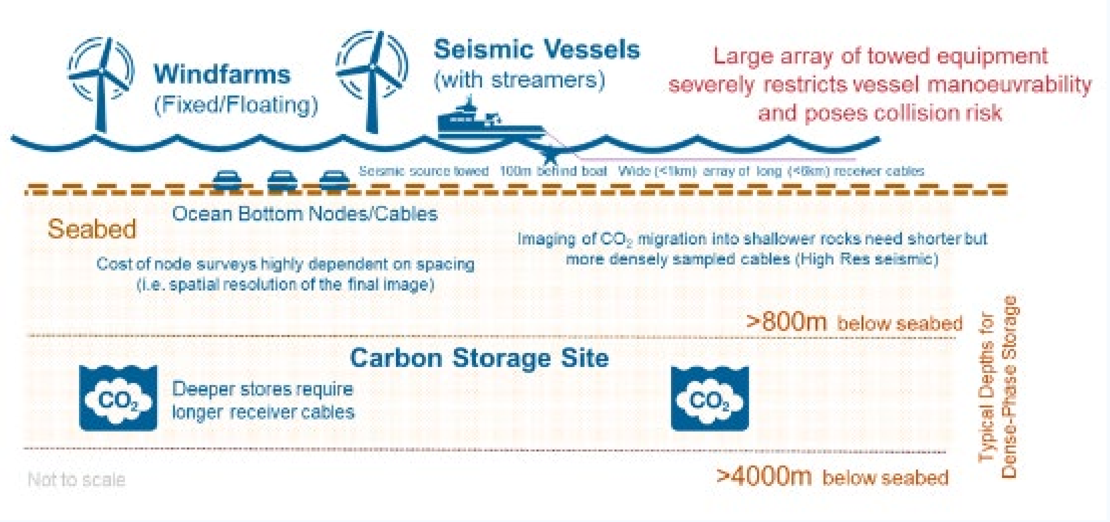
Builds on existing NSTA seismic stewardship expectations



SE3 Expectation (Optimum Use of Subsurface Data)
Consider Acquiring New Data every 10 years
Consider Reprocessing Data within 5 years

(Ref 2e)

Schematic of seismic and co-location issues

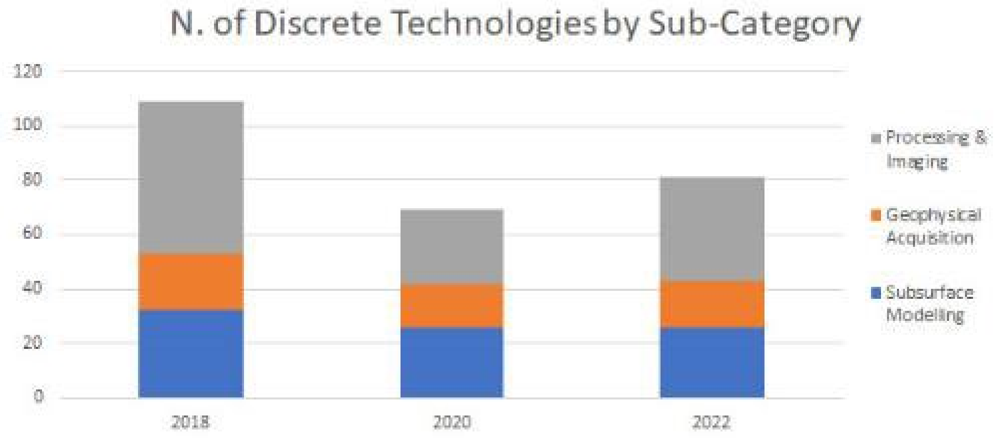


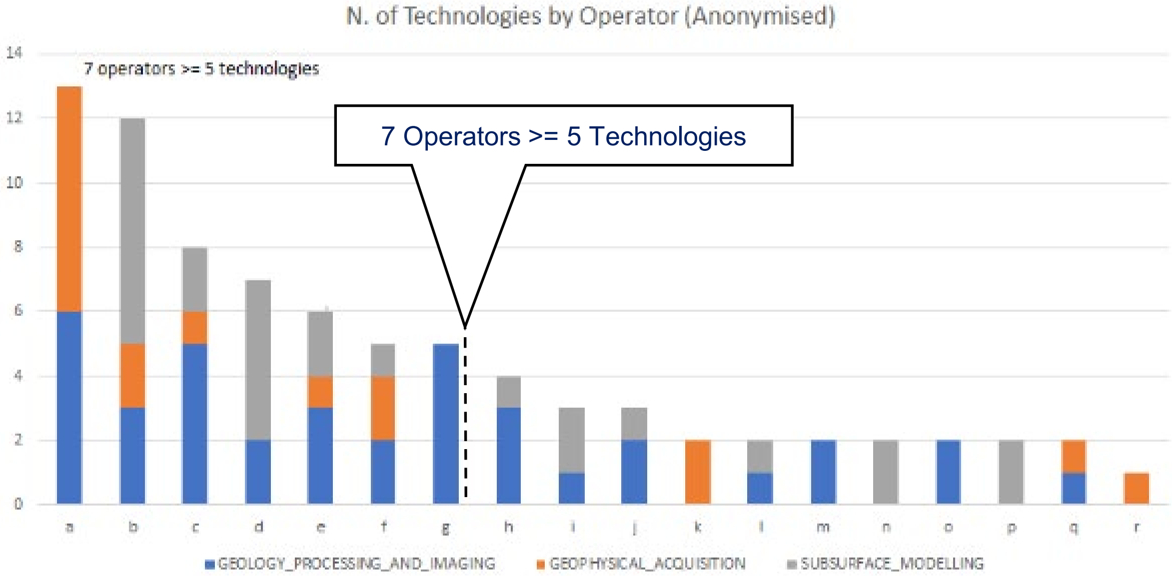
4D will play an important role in monitoring in <u>most</u> first-of-a-kind CS projects

2.7 NSTA Technology Insights 2022

North Sea Transition Authority

The NSTA reviewed 50 technology plans from O&G licensees from 2018 to 2022. Whilst there has been an overall decline in seismic and exploration technology, this highlighted there are specific examples of technology developments which show that innovation is still ongoing. Once familiar with a technology the operator deploys it on multiple assets.





Geophysical acquisition is being channelled to improve illumination of complex or challenging subsurface targets and reducing the cost of acquisition.

- Broadband and wide/ multi azimuth surface
- Ocean bottom seismic: Nodes, high density nodes, nodes on a rope.
- Autonomous deployable/retrievable nodes for reduced cost and footprint. Enabling co-location?
- Vertical seismic profiles, DAS fibre also applied to 4D.
- Passive seismic.
- Ocean output sources (to reduce impact on marine life).

(Refs. 2f & 2g)

Processing and Imaging: by novel modelling and analytical techniques enhancements to OBN methods and emerging technologies to improve reservoir mapping & emerging technologies to improve reservoir mapping
- FWI imaging and dynamic matching FWI.
- Rock Physics.
- Reprocessing, survey merges and seismic uplift.

Subsurface modelling: using AI and machine learning to improve knowledge of reservoir geology and previously hidden volumes, helping to de-risk complex development targets.
- Application of AI/ML to reduce exploration cycle time.
- Fault analysis.
- Optimal well placement.

3. Subsurface Seismic Imaging Foundations

Section 3 Subsurface & Seismic Foundations

The previous section introduced the concept of the spatial scale of the CS targets. This section initially provides some background information regarding the seismic imaging of subsurface targets & seismic acquisition methods which will help to explain the remaining sections.

For many people, the relative scale of surface vs subsurface structures can be difficult to understand. It is demonstrated here from a vertical (height/depth) and geological scale (Section 3.1). This underpins the needs of specific targeted seismic methods for different CS stores (Section 3.2) comparing relative depth of investigation vs resolution. This concept further developed later for site surveying windfarms (Section 6).

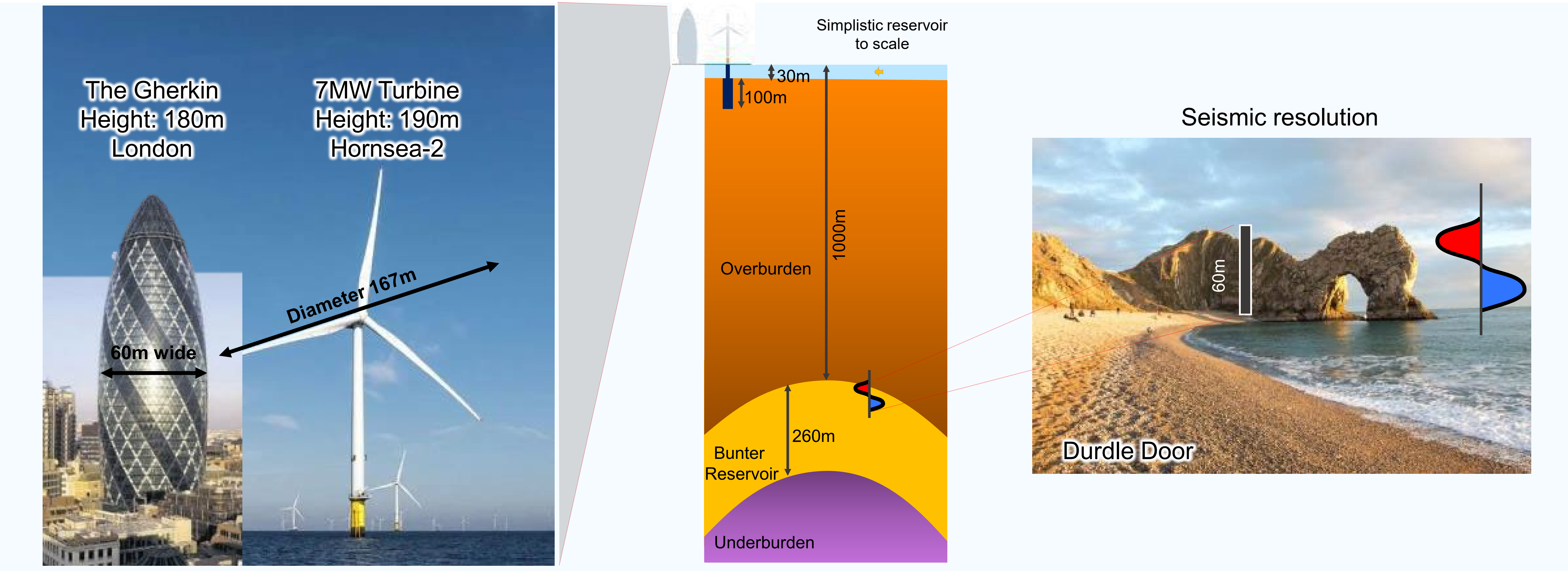
Section 3.3 overviews the streamer seismic survey – its evolution, component parts and introduces the terminology. The spatial extent of reservoir targets and the substantially larger acquisition footprint areas that are needed to image them (section 3.4) is a major component of the cost of surveying and adds to co-location issues.

A series of examples showing the range of imaging possible (Section 3.5) from ultra-high resolution to reservoir high resolution seismic – includes showing the benefit of new acquisition.

This section concludes (section 3.6) with a reminder of various databases from the NSTA, Crown Estates and also includes the UK seismic and well database that is available via the National Data Repository (NDR) which is free to access and download.

3.1a Introduction: Vertical scale

North Sea Transition Authority



Offshore windfarm turbines are increasingly giant structures with future 13-15MW turbines likely to be 300m tall (roughly height of the Eiffel Tower). A key risk to their installation are boulders on the seabed and the nature of the post-glacial sediment impacting stability of foundations and the setting of supporting piles 60m (turbine) to 100m (substation) below seabed that requires a jack-up rig for operations. This is a very shallow target by conventional Oil and Gas (O&G)/Carbon storage (CS) perspective. Whilst **O&G/CS** are also interested in jack-up rig stability more effort is looking at:

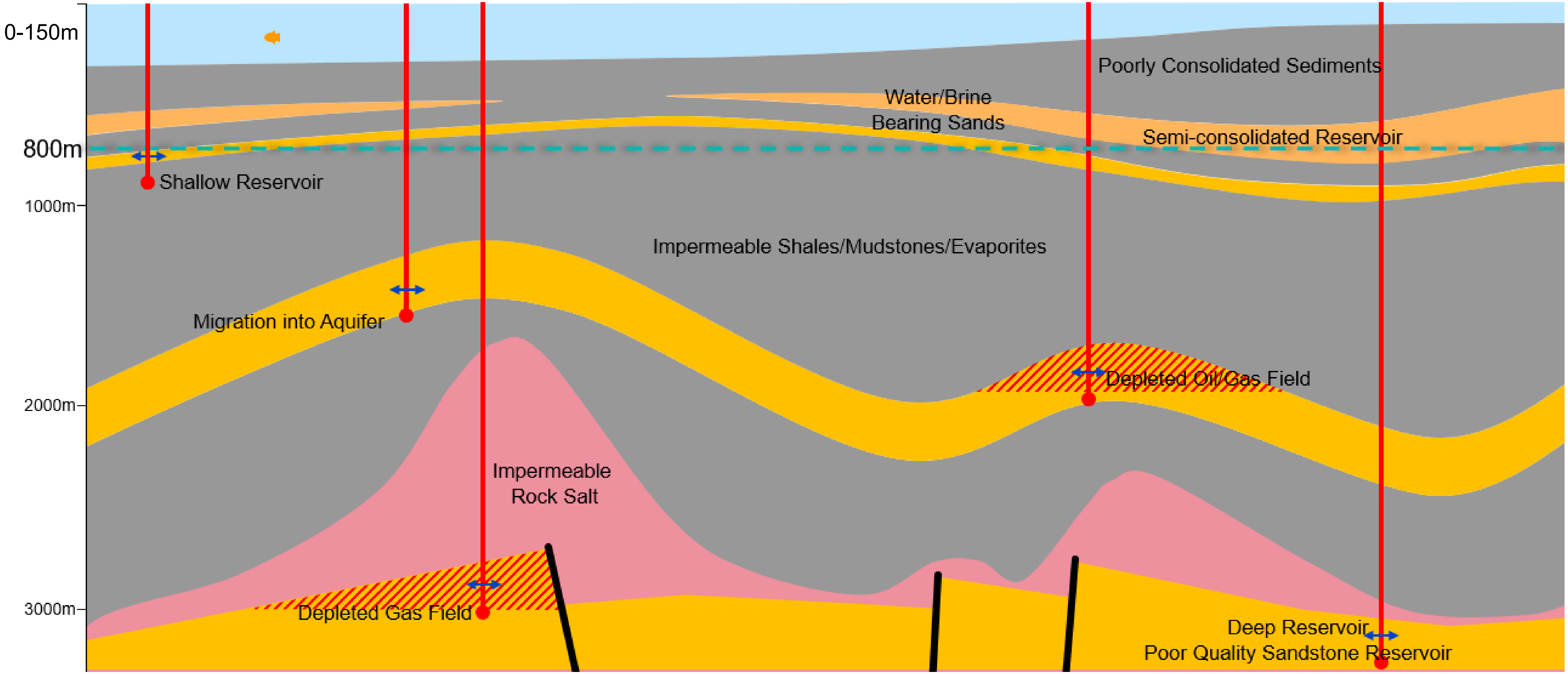
a) The overburden for shallow, naturally occurring (biogenic) gas or indication of carbon leaking from the underlying store.
b) Trying to image the storage reservoir from 800m down to >4000m (for most typical O&G or CS) using seismic data.

It should be noted that the ability of seismic data to resolve fine scale geological details (seismic resolution) decreases with depth beneath surface.

Comparative vertical scale of SNS turbines, Endurance reservoir and seismic resolution

3.1b Range of UKCS Carbon Storage sites

North Sea Transition Authority



(Ref. 1a)

Typical range of different aquifer and depleted oil/gas carbon stores in the UKCS

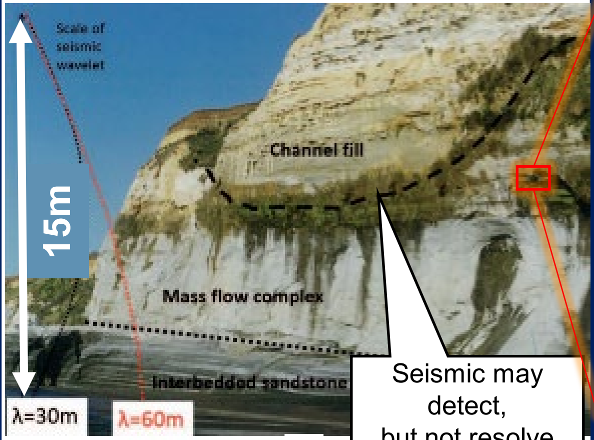
3.1c Seismic resolution and detection

North Sea Transition Authority

A seismic source emits a controlled pulse of sound into the subsurface. This expanding wavefront interacts and reflects back from rock layers. The different rock layers have differing acoustic properties (based on the rock density and speed-of-sound velocity parameters).

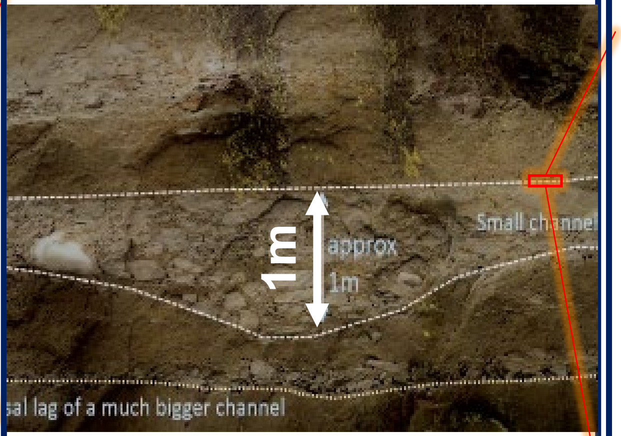
Seismically Detectable

(Ref. 3a)



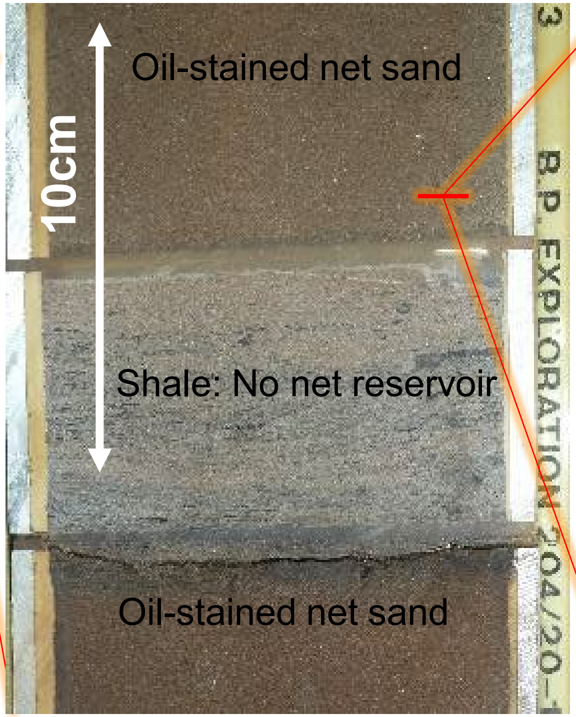
Seismic resolution relies on the frequency of the input impulse frequency at the target. Generally, at typical CS reservoir depths the wavelength is 60m. Seismic resolution is defined as ¼ wavelength, in this case ~15m. This implies that the base channel fill cannot be seismically resolved.
However, seismic attributes can *detect* changes down to 1/30 wavelength.

Seismically Not Detectable



This is a small channel; the dimensions are typical in Quaternary drainage systems in the SNS. This channel may be detected with UHR/UUHR shallow geotechnical surveys, but at CS reservoir depths this channel is far below seismic detection limits. Channels similar to this could negatively, or positively affect CS injectivity.

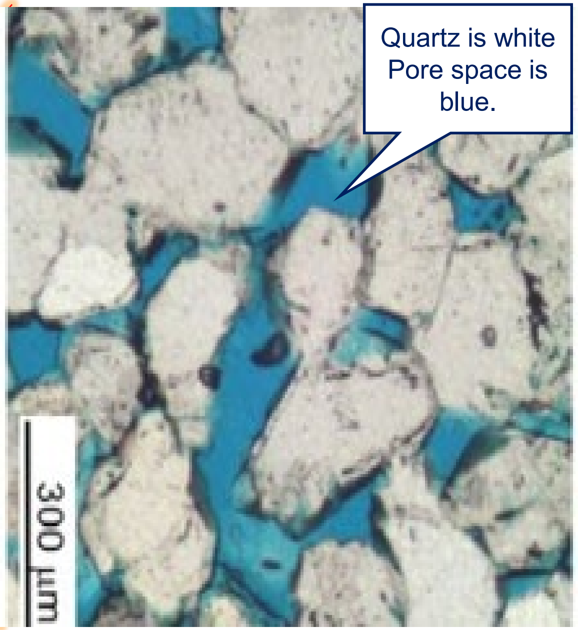
Core Scale



Core recovered from wells allows an understanding of cm scale variations in geology. These variations may directly affect the volumetrics and injectivity associated with a CS.

Pore Scale

(Ref. 3b)



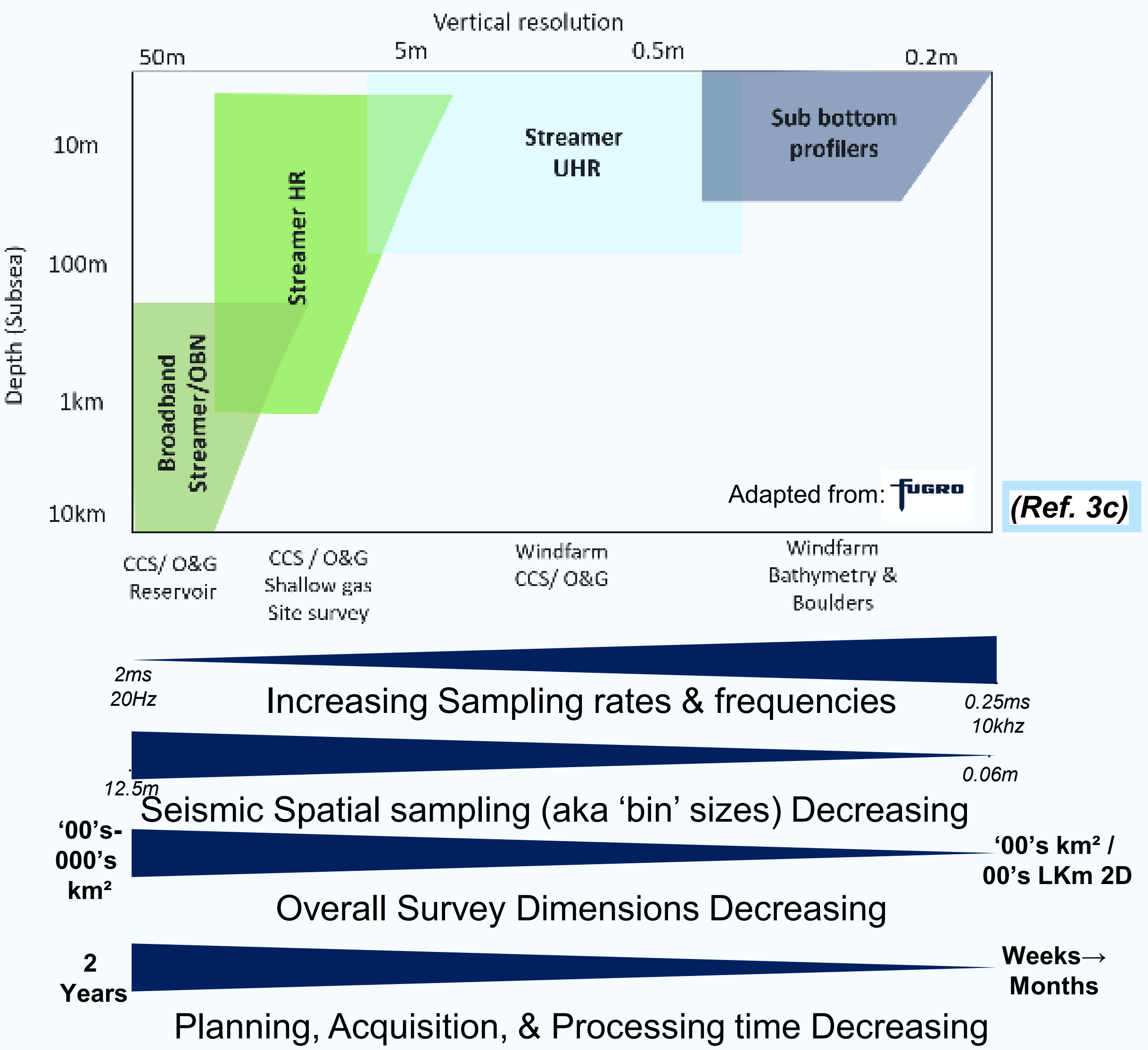
Good quality sandstone - Reservoir

Thin-section analysis shows the mineralogy of the rock (recovered from core-plugs, SWCs or cuttings). This allows an understanding of the porosity, permeability and chemical reactivity of the rock.

Most geological details in reservoirs are much smaller than seismic imaging can capture

3.2 Depth of Investigation & Seismic Resolution

North Sea Transition Authority



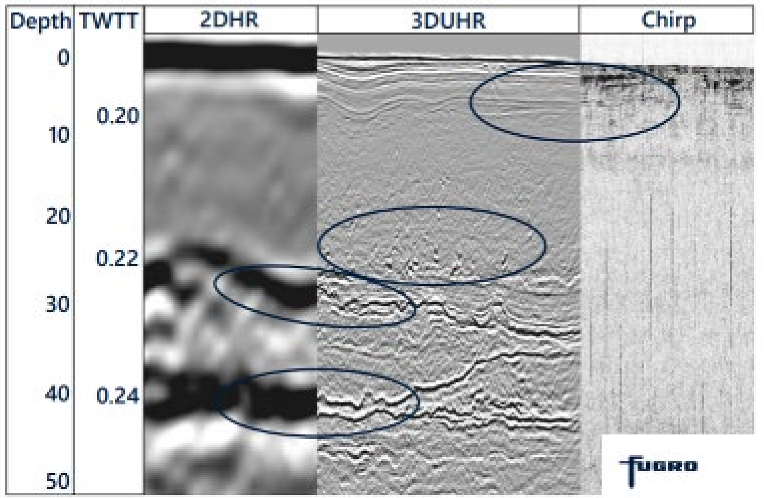
(Ref. 3c)

A seismic source emits a controlled pulse of sound into the subsurface. This expanding wavefront interacts with the rock layers. The different rock layers have differing acoustic properties (based on density and velocity parameters).

- Seismic survey design is optimised against survey objectives:
  - Depth of objective
  - Required resolution
  - Area of investigation

- Increasing individual components generally leads to increasing cost associated with planning, acquisition and processing times.

Comparing HR, UHR and UUHR seismic



Comparative seismic techniques: resolution and depth of penetration

3.3a Seismic: A history

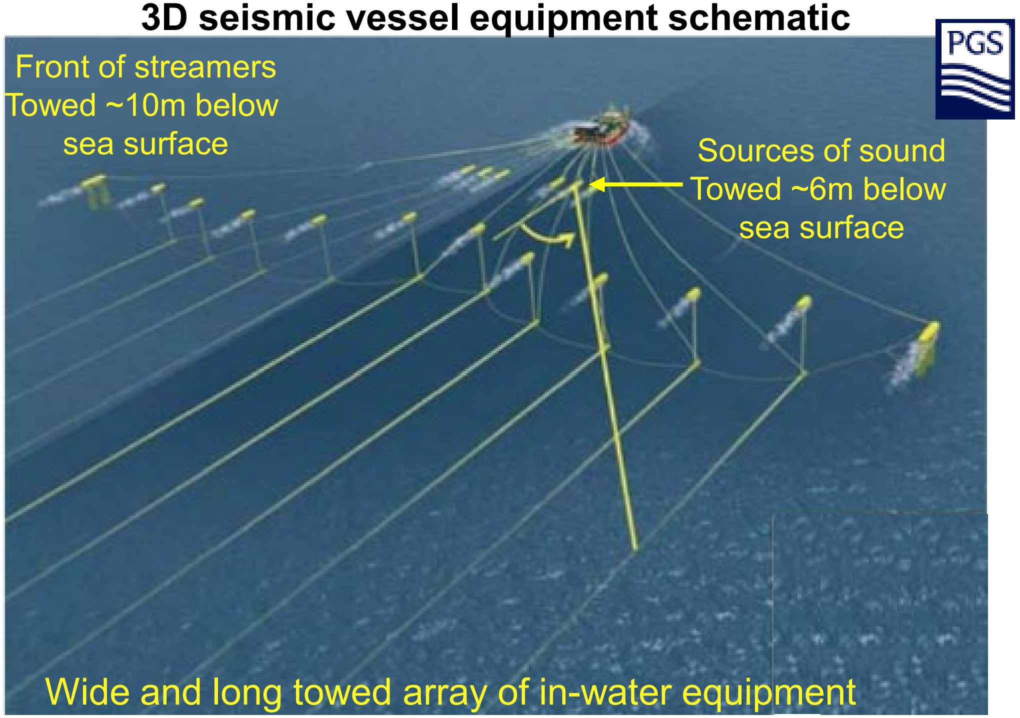
North Sea Transition Authority

Modern seismic acquisition, processing and imaging is scarcely recognisable from its origins, although the fundamentals of 1) acquisition involving towing seismic source(s) and receiver cable(s)/streamer(s) at <5 knots from the aft of a diesel-powered vessel on a designated track, and 2) processing the raw data to maximise accuracy & fidelity of the final interpreter's image. The technology has grown significantly in density, detail and accuracy.

Acquisition

- 2D data – 1970/1980's; single recording streamer.
- 3D data – 1980's to Present; Large multiple (~16) streamers and optimise depth in water for signal and noise. Navigation improves with GPS data advancements. Multi–azimuth, Wide Azimuth & multiple smaller seismic sources.
- 4C data – 2000's to Present; includes Shear Component acquisition through geophones coupled to seabed. (OBC, OBN) or via multi-component streamers.
- 4D data – 3D+Time; Repeatability to image changes in subsurface. Usually, streamer but can also be seabed seismic at extra cost & complexity
- Modern HR/ UHR 2D or 3D seismic using increasingly dense spatial and temporal sampling, usually with smaller sources and shorter cables for O&G High Resolution Site Surveys / Shallow Gas Hazard surveys.

3D seismic vessel equipment schematic



Processing:

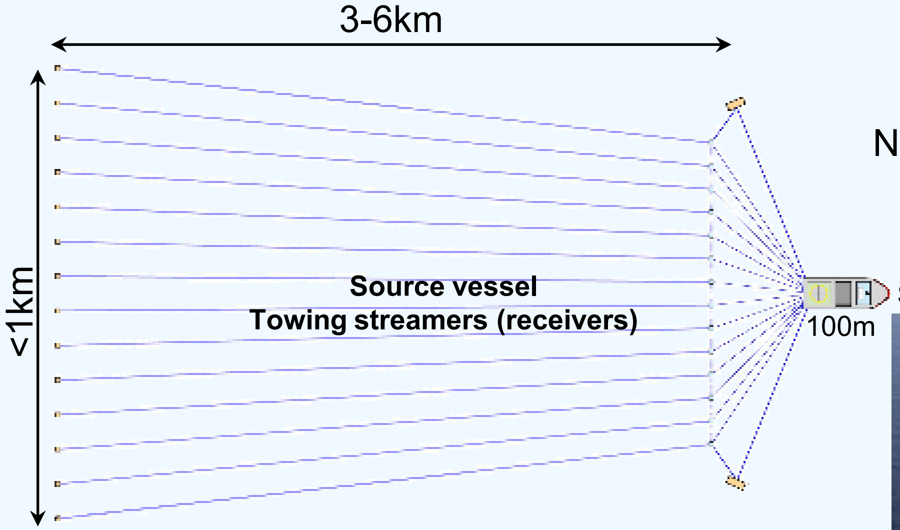
- Semi-Manual unmigrated Processing (1970s).
- Post-stack (1980s) or Pre-stack time (late 1990s) on pcs.
  - Fluid and lithology prediction/ AVO analysis.
- Increasingly highly complex, computer intensive (1990s+) on clusters
  - Pre-stack depth migration and inversion.
  - Pre stack 4D survey matching.

Future Direction: Autonomous vessels or nodes acquisition with increasingly shared space and noise budgets. Processing/Imaging geared towards generating comprehensive synthetic models of rock layers accurately matched to the observed full seismic wavefield (rather than just reflections). More targeted, lower effort geophysical monitoring of carbon stores.

3.3b Comparison of surface and OBN seismic

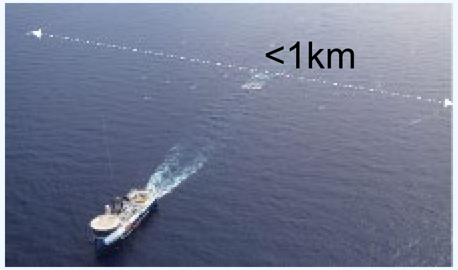
North Sea Transition Authority

Deep 3D Streamer seismic configuration



Not to scale

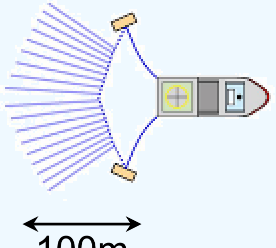
Source vessel



Receivers along length of streamers: hydrophone (measure pressure) and now usually also geophones to measure movement

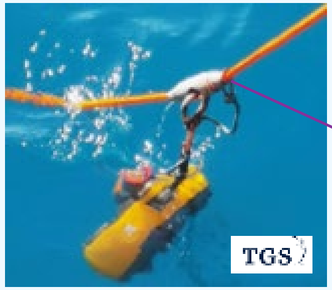
UHR (shallow) 3D Streamer seismic

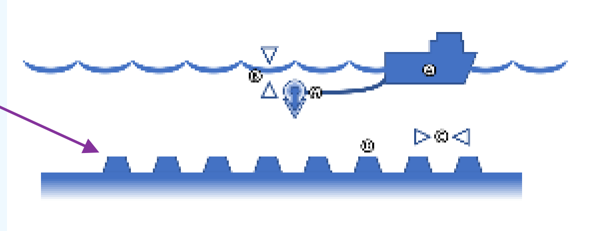
Smaller Source vessel
Towing very short
streamers



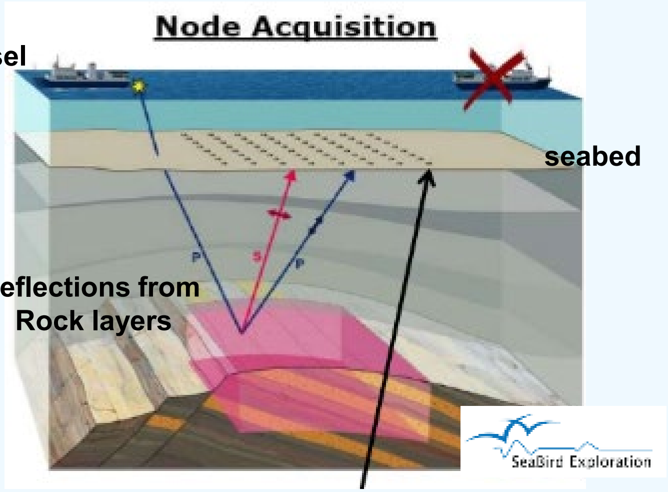
Deep 3D OBN (ocean bottom nodes) seismic

Seismic source vessel & nodes placed on seabed





Source vessel



4 Component Pressure (hydrophone) and movement (x,y,z geophone) sensors
Often 2nd vessel needed for node deployment and retrieval

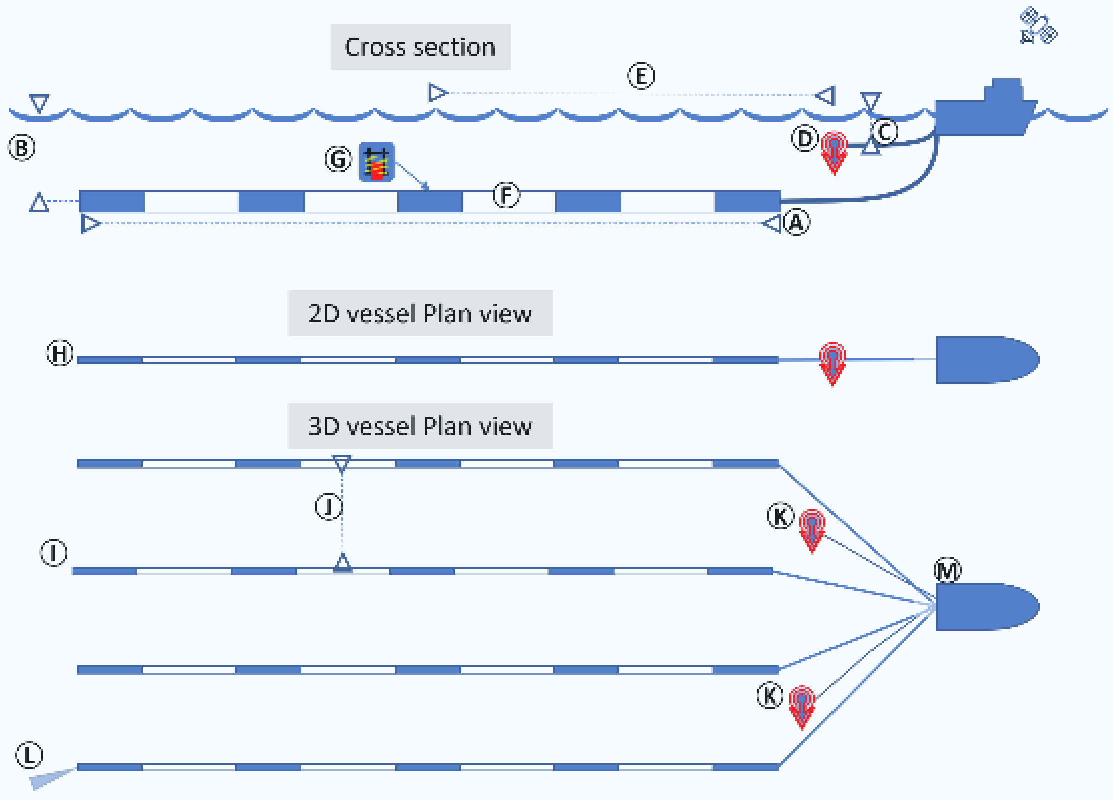
Range of acquisition styles: Deep seismic involves wide & long streamers, HR much more compact. Nodes deployed independently on seabed

3.3c Seismic streamer terminology

North Sea Transition Authority

- Seismic acquisition has many differing variables, depending on objectives, budget and advancements in technologies.
- Variables affect acquisition parameters and quality of recorded signal.

Seismic vessel configuration

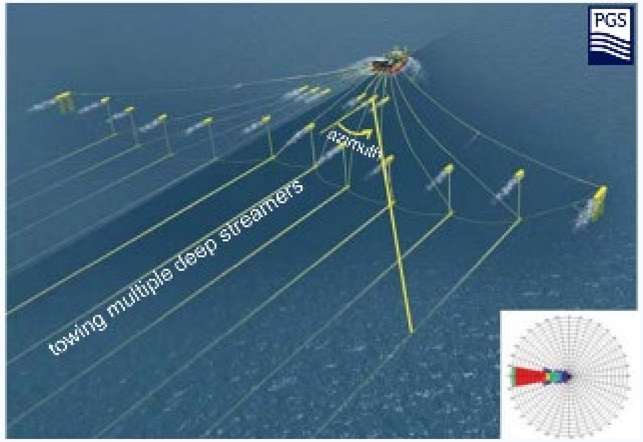


A – Streamer length
B – Streamer Tow Depth
C – Source Depth
D – Source size
E – Source-Receiver offset
F – Solid or gel Streamer, legacy fluid fill
G - Hydrophone or multi-sensor configuration:
    Grouped or single point recording

H - typical 2D survey setup

I – Number of streamers
J – Streamer separation (Cross line resolution)
K – Source configuration (flip-flop)
 & steerable source
L – Steerable streamer
M- Recording sample rate ~ frequency
    (temporal / vertical resolution)

3D seismic vessel equipment schematic



"Rose diagram" = Distribution of offsets and azimuths for typical Narrow azimuth acquisition
(offset = separation distance between source and receiver on the streamer. Near offset = centre of circle, far = outer rim)

(Refs. 3d & 3e)

- A seismic vessel will acquire numerous line - parallel swathes to cover the full extent of the target including migration fringe (section 3.4).
- At the end of each line pass it undertakes a large slow turn. This often takes longer than the active acquisition time.

Key streamer parameter terminology

3.3d The seismic source

North Sea Transition Authority

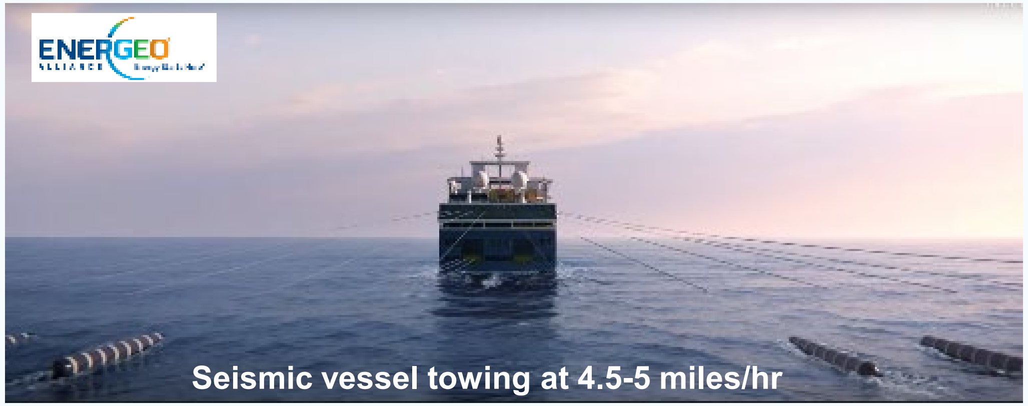
Airgun bubble

This is a picture of the bubble from an airgun off the U.S. Coast Guard Cutter Healy. Image courtesy of Paul Henkart, Scripps Institution of Oceanography.

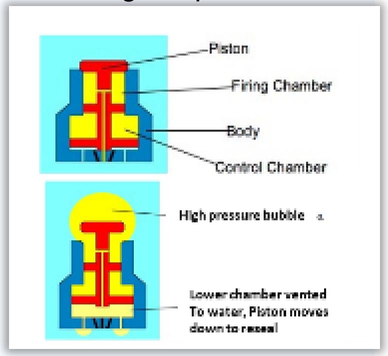
(Ref. 3g)

Analogue
Seismic wave movement (propagation)

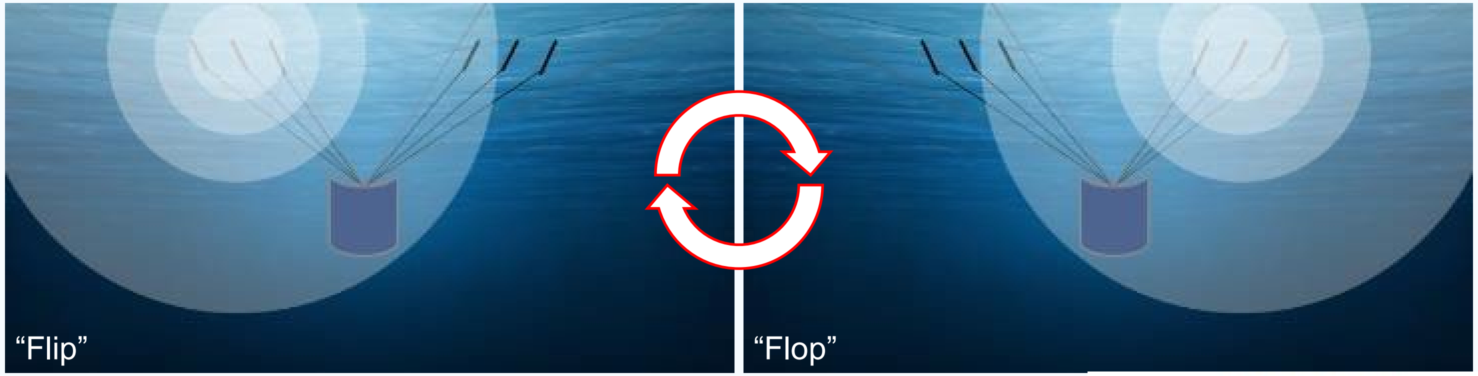
Dedicated seismic vessel: Towed seismic sources



Airgun operation



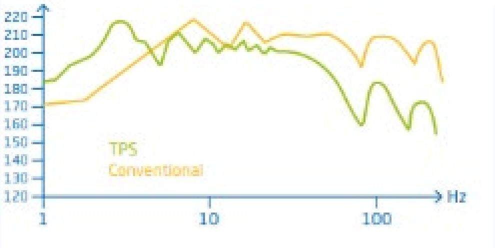
(Ref. 3f)



- Dual airgun source fired alternating every 10secs.
- Seismic pulse lasts 1/10th second.
- Sound pulse expands out through water column at 1450m/sec.
- Sound pulse transmitted from the water column to the rock beneath.
- Low frequency TPS source developed to image deep and complex targets.

(Ref. 3h)

Low frequency source spectra



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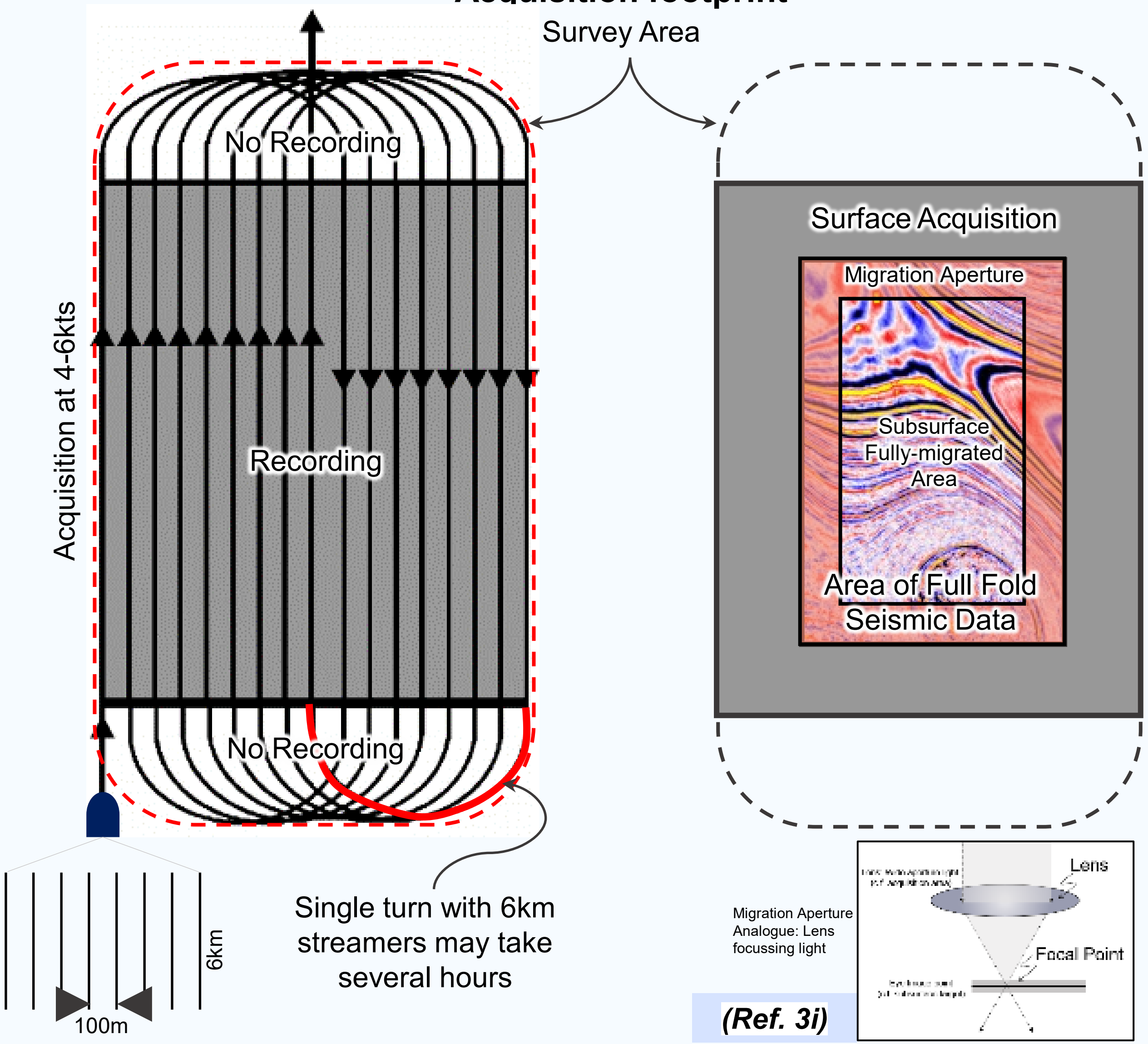
3.4a Seismic Acquisition - Footprints

North Sea Transition Authority

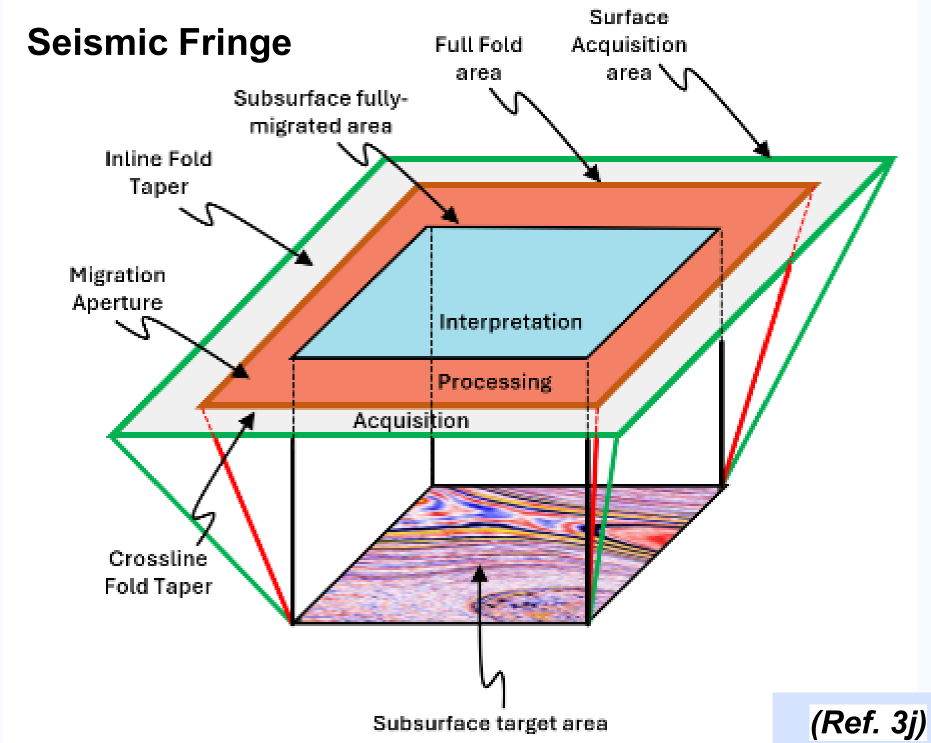
Acquisition footprint



(Ref. 3i)

- Conventional streamer seismic is acquired in a series of straight lines collecting "swathes" of data.
- The vessel then executes very large turns with the streamers still deployed - sometimes termed "racetrack" shooting (e.g., section 4.8 & 5.5).
- The area of acquisition is significantly larger than the final seismic result, due to the requirement to have full fold across the migration aperture.
- The aperture dimensions depend on the geometry of the subsurface and depth to target interval and can be a significant increase in area.

Acquisition area > Full Fold > Migration >Target area



(Ref. 3j)

Seismic acquisition footprints much large than target area

3.4b Seismic Acquisition - Fringe

North Sea Transition Authority

Seismic surveys require a large fringe of seismic data for processing (aperture) and creation of a suitable image of the subsurface target. This comprises a significant increase in the areal extent of the survey, which is not just a cost issue, but also a major consideration for co-location with other marine users.

- Full fold area: ensure a consistently large number of samples are available across the target.
- Aperture to focus & migrate dipping events to their correct position (analogous to a lens focussing light).

Both Streamer and OBN acquisition design must incorporate these elements and it can vary based on acquisition orientation, geology and depth of target interval. There is an option to reduce and optimise this with monitoring surveys.

Seismic Fringe Cost model

Depth of Target (m)	Maximum geologial dip (Degrees)					
	30		45		60	
	Aperture (m)	**Additional cost (%)**	Aperture (m)	**Additional cost (%)**	Aperture (m)	**Additional cost (%)**
1000	600	**19**	1000	**32**	1730	**58**
2000	1200	**39**	2000	**68**	3460	**228**
3000	1800	**60**	3000	**208**	5200	**310**
assuming a 200 sq km (20x10km) survey						

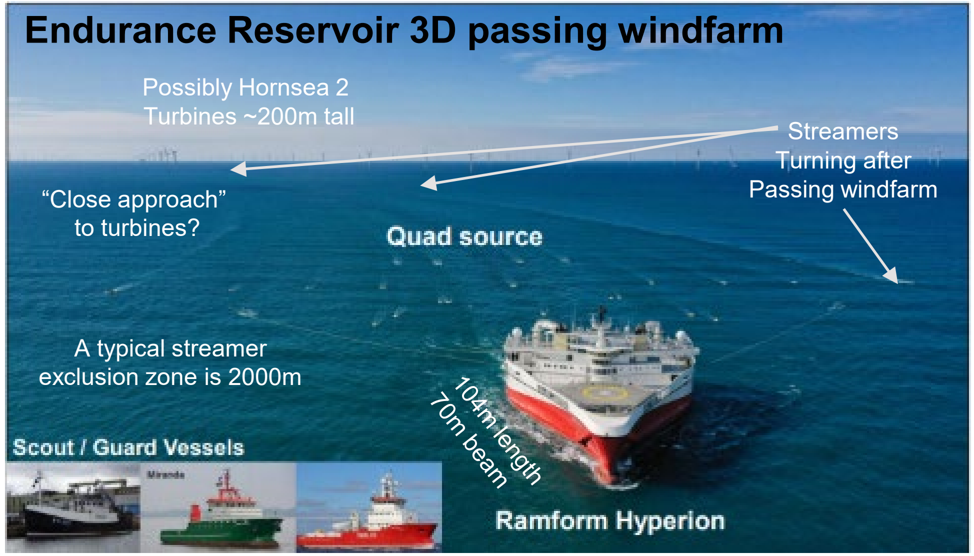
Additional "fringe costs" increase substantially for deeper and more steeply dipping structures

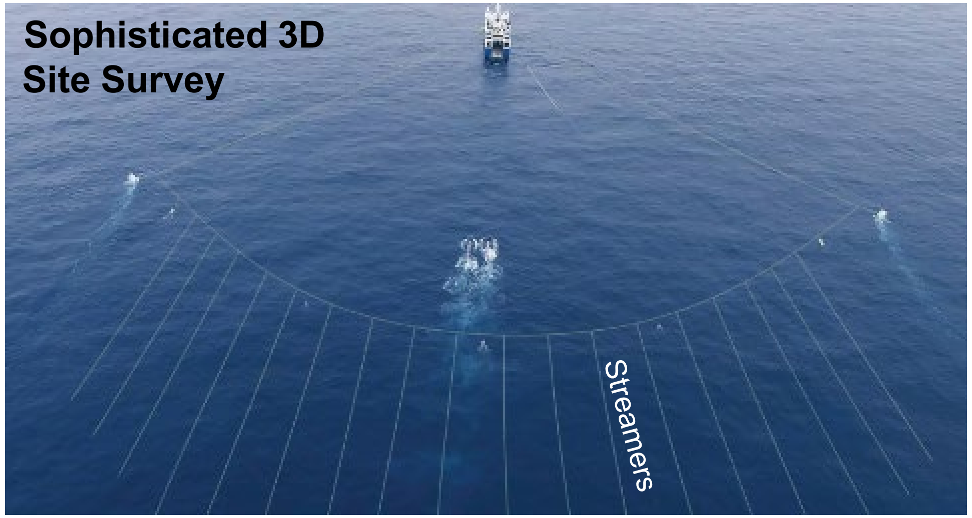
(Ref. 3j)

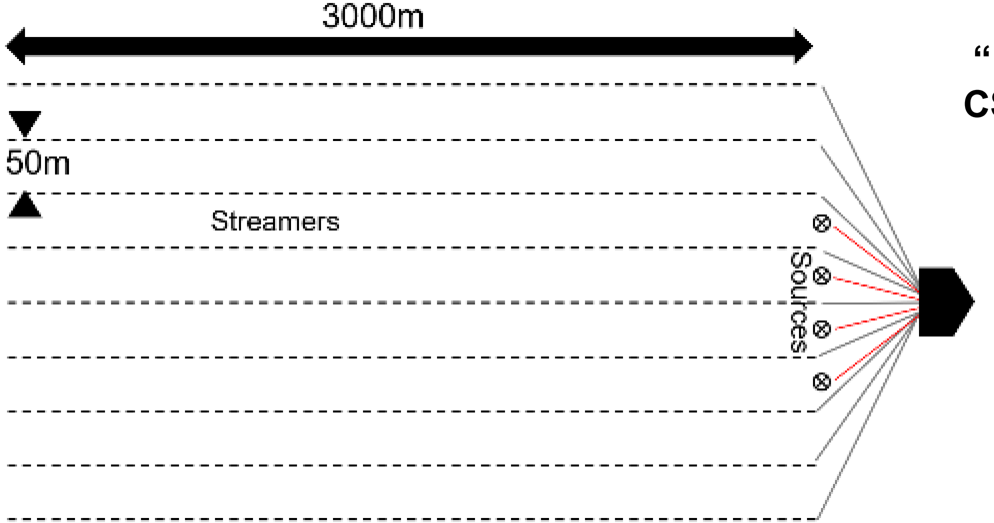
Acquisition fringe is much larger than target especially for deeper targets: Big contributor to overall cost

3.5a Reservoir vs Site Survey Scales

North Sea Transition Authority





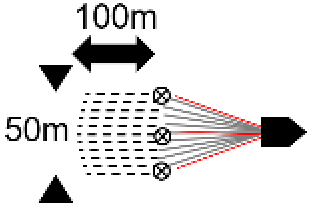


"Deep" seismic for CS & O&G reservoir

Large vessel Endurance HR 3D

NEP CCS 3DHR
4 Sources
9 Streamers

Sampling 2ms,
towed 10-20m, bin 6.25m



Small vessel UHR P-Cable 3D (section 5.12)

3DUHR 3 Sources < 11 Streamers
More typically windfarm UHR 4-7 streamers

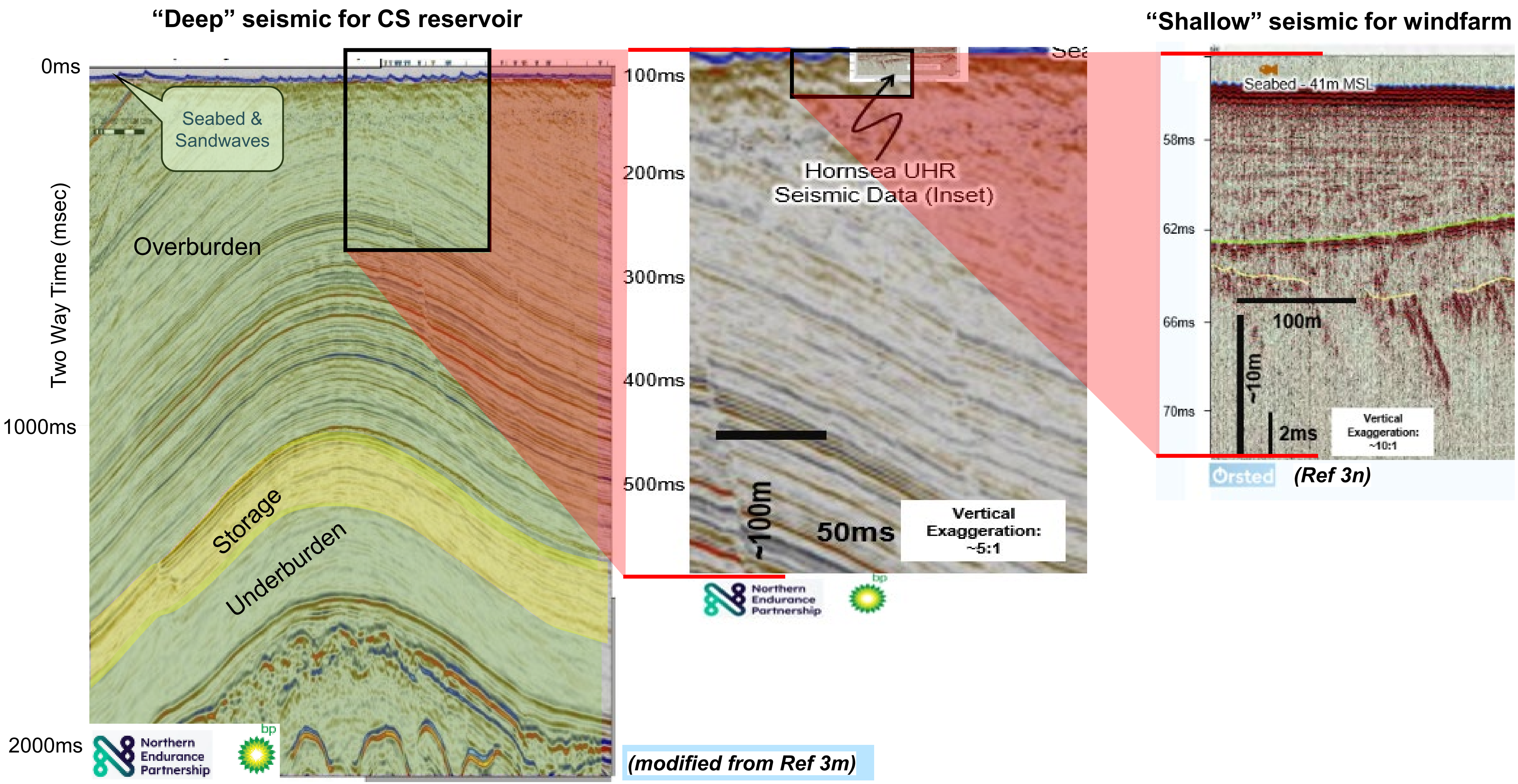
Sampling 0.125-0.25ms,
towed 2-4m, bin <1-6m

(Refs 3k, 3l & 3m)

Vessel scale, parameters & footprint between reservoir "deep" & site survey seismic. Close approach/exclusion zones apply.

3.5b Comparative seismic scales

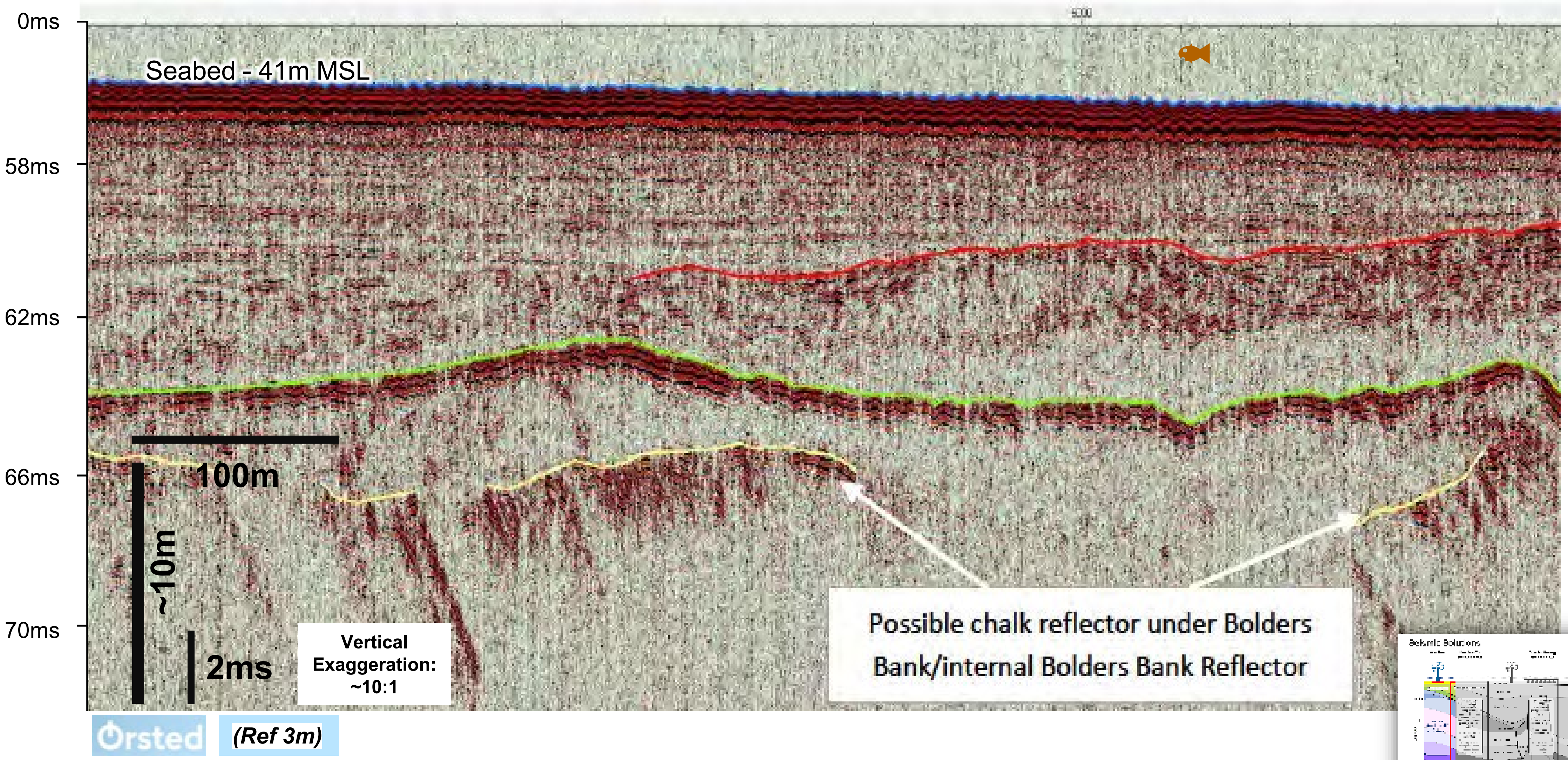
North Sea Transition Authority

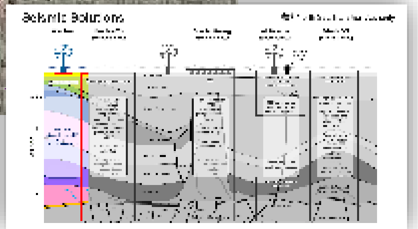


SNS storage complex elements and a comparison of imaging resolution between reservoir HR and windfarm seismic

3.5c SNS Hornsea Windfarm UHR Seismic

North Sea Transition Authority

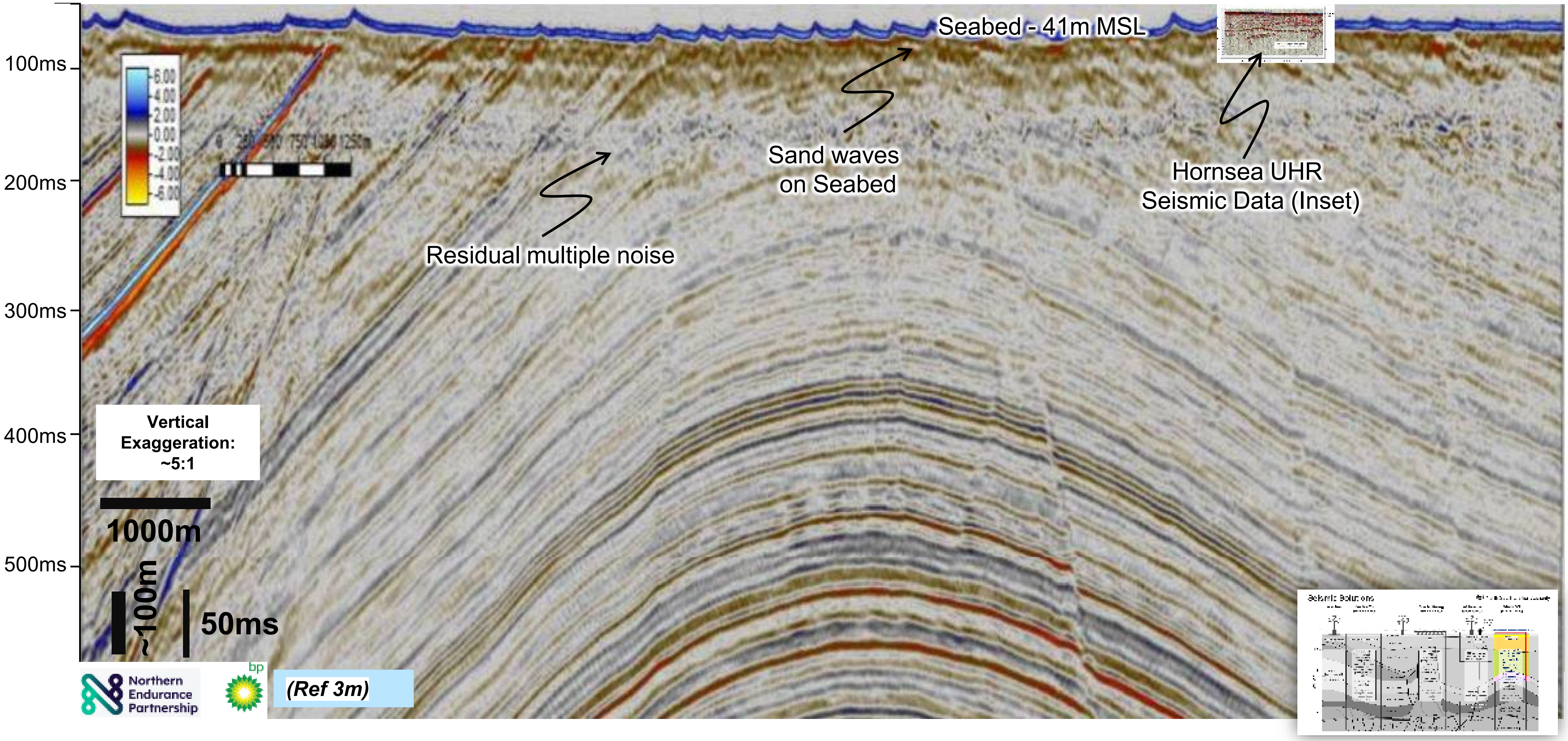




Ultra- High Resolution seismic - high spatial and temporal definition

3.5d Zoom-out Endurance Seismic Scale

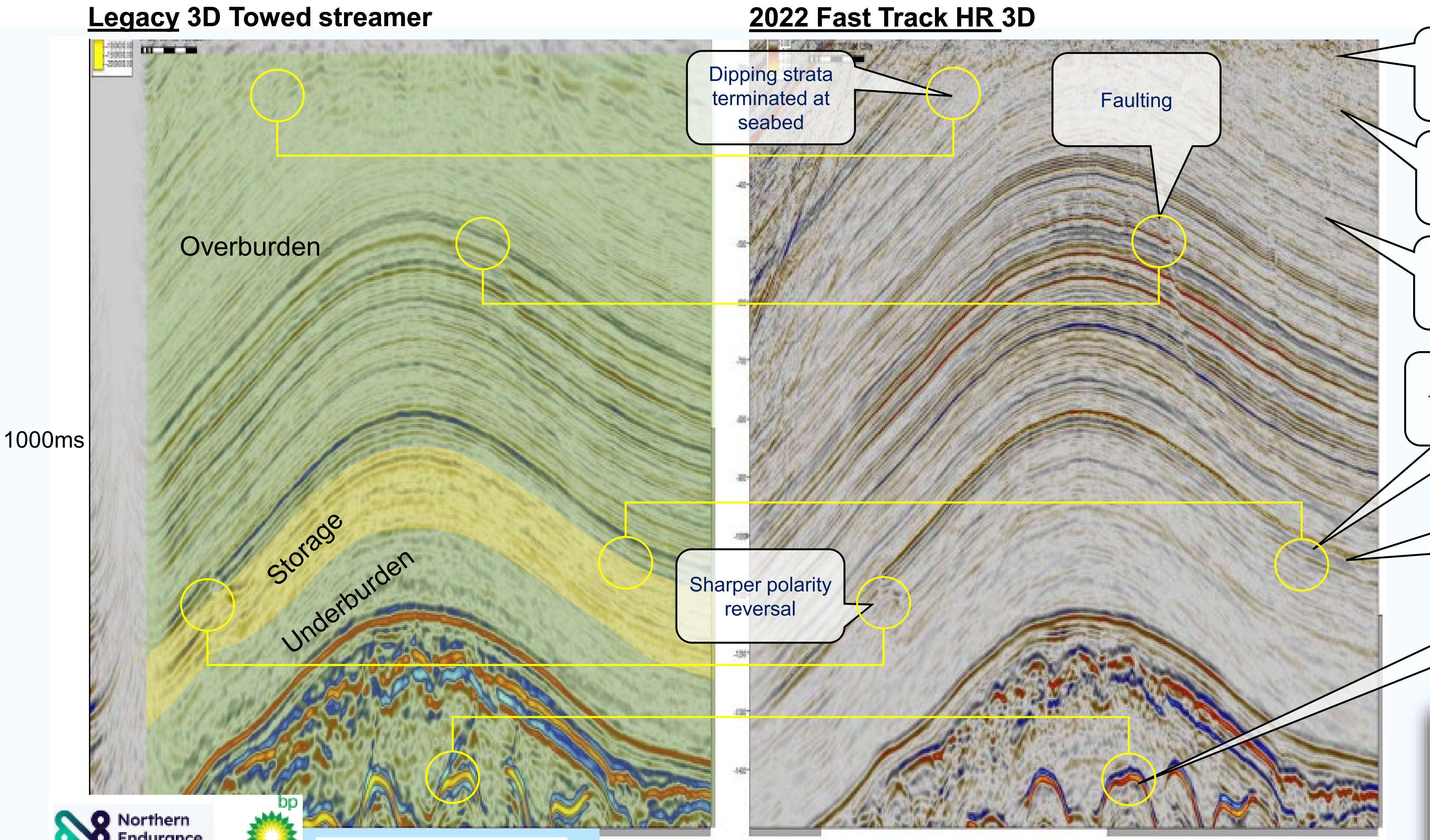
Comparison of Endurance overburden vs Hornsea windfarm seismic



Windfarm / geotechnical seismic results **completely** different level of definition

3.5e Endurance Modern 3D HR seismic

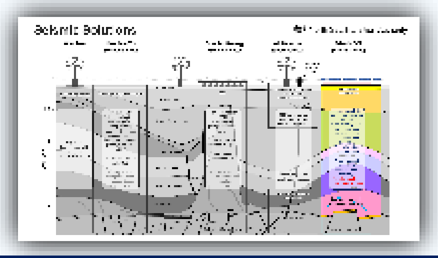
North Sea Transition Authority



Northern Endurance Partnership

bp

(modified from Ref 3m)



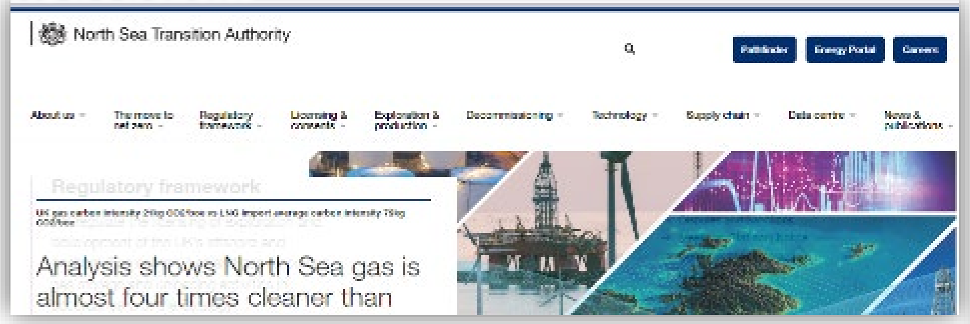
SNS storage complex elements and a comparison of improvements via modern HR seismic acquisition

3.6a Useful links: NSTA

North Sea Transition Authority

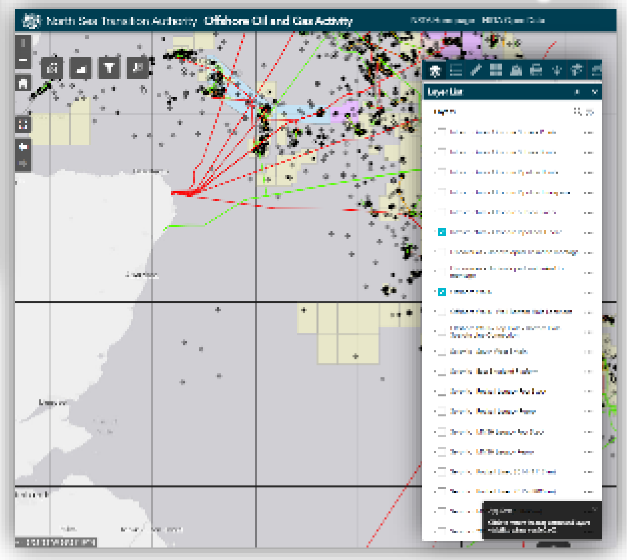
The NSTA website & interactive data centre provides a valuable link into the range of NSTA data download options:

NSTA website



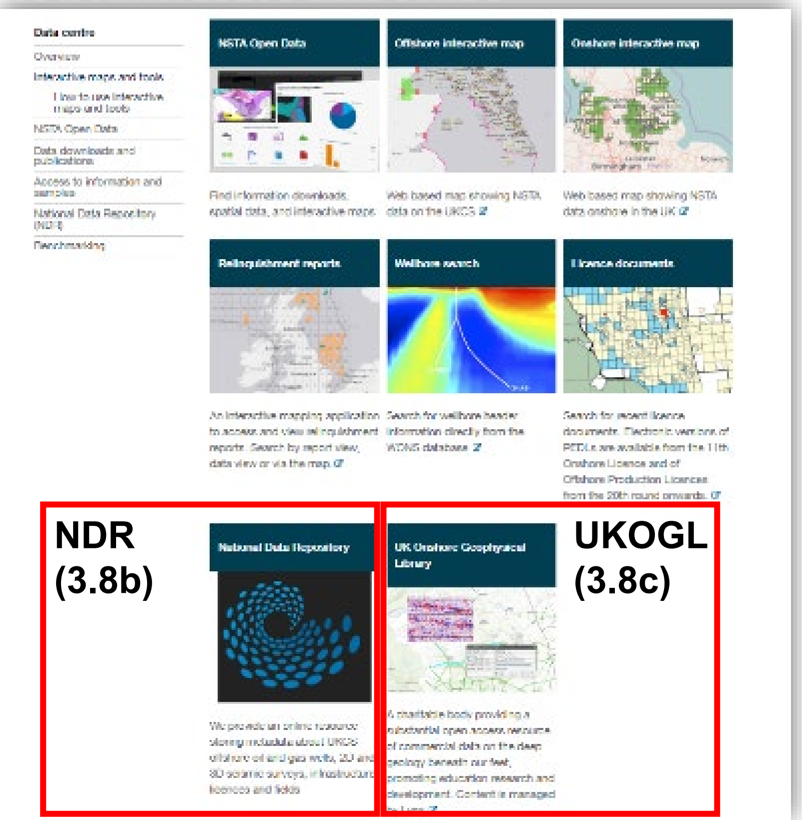
https://www.nstauthority.co.uk/

NSTA Offshore interactive map



Offshore Oil and Gas Activity (arcgis.com)

NSTA Interactive data centre



North Sea Transition Authority (NSTA): Interactive maps and tools - Data centre (nstauthority.co.uk)

NSTA Stewardship Expectations

https://www.nstauthority.co.uk/exploration-production/asset-stewardship/expectations/

Note: there is an ongoing consultation on future date retention, reporting and disclosure requirements for CS licences.

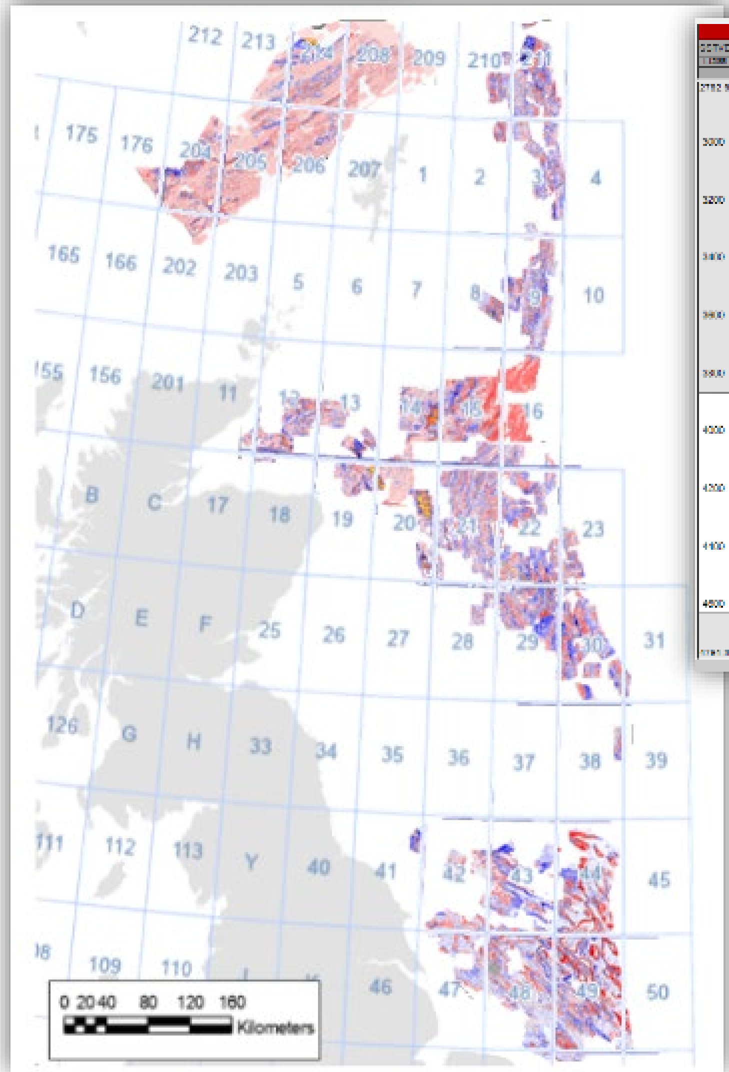
(Refs. 3o, 3p, 3q &3r)

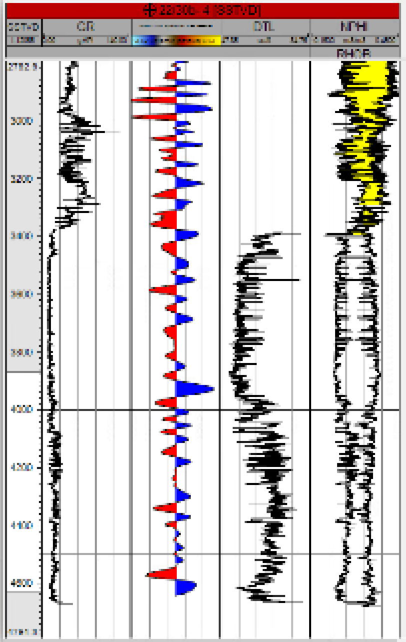
3.6b Useful links: UK NDR subsurface data

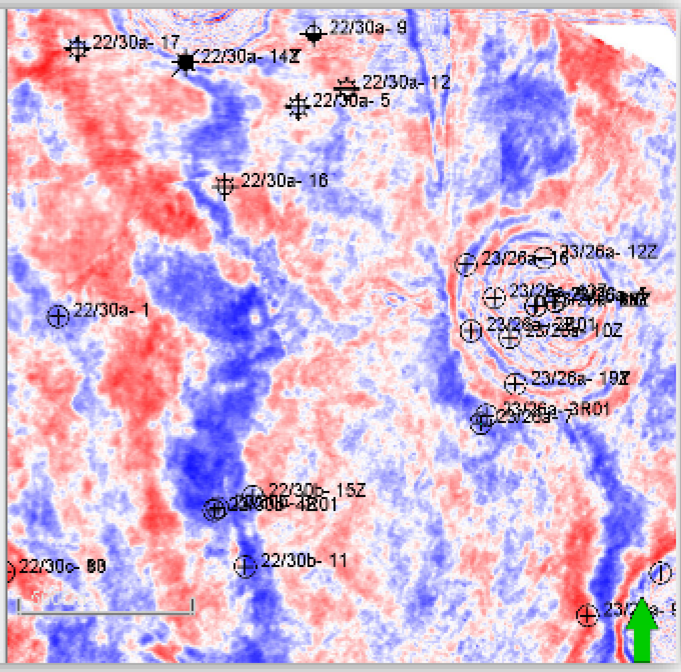
North Sea Transition Authority

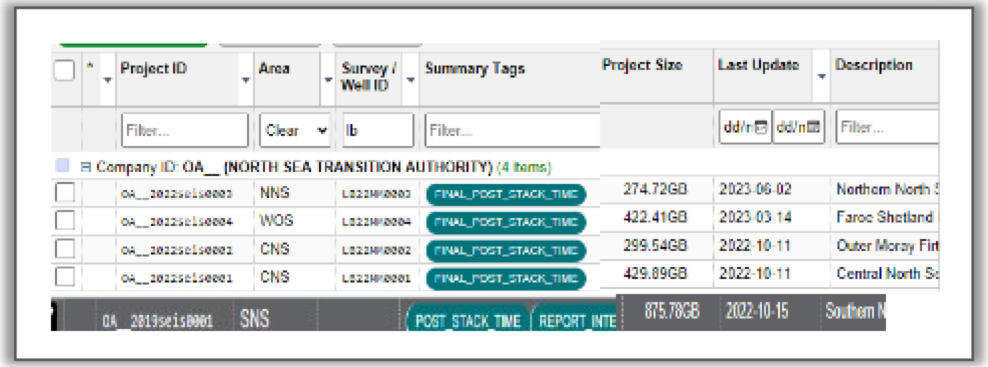
UK National Data Repository

NDR -Regional 3D surveys, comprehensive well log data & reports









Project ID	Area	Survey / Well ID	Summary Tags	Project Size	Last Update	Description
Filter...	Clear	lb	Filter...		dd/m dd/m	Filter...
Company ID: OA__ (NORTH SEA TRANSITION AUTHORITY) (4 items)						
OA__2022seis0003	NNS	L022MP0003	FINAL_POST_STACK_TIME	274.72GB	2023-06-02	Northern North S
OA__2022seis0004	WOS	L022MP0004	FINAL_POST_STACK_TIME	422.41GB	2023-03-14	Faroe Shetland
OA__2022seis0002	CNS	L022MP0002	FINAL_POST_STACK_TIME	299.54GB	2022-10-11	Outer Moray Fir
OA__2022seis0001	CNS	L022MP0001	FINAL_POST_STACK_TIME	429.89GB	2022-10-11	Central North Se
OA_2019seis0001	SNS		POST_STACK_TIME REPORT_INTE	875.78GB	2022-10-15	Southern N

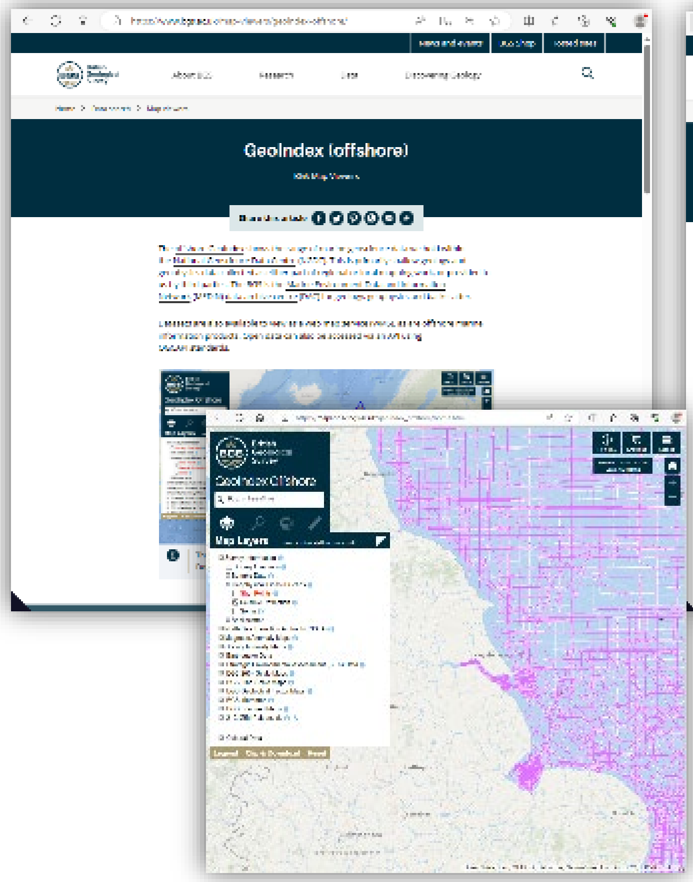
- UK subsurface (well & seismic) data is disclosed across several public and **freely** accessible databases:
- The NDR (National Data Repository) is the principal location for offshore data and is maintained by the NSTA.
- Individual released 2D/3D surveys & 1000's wells, logs and reports are available

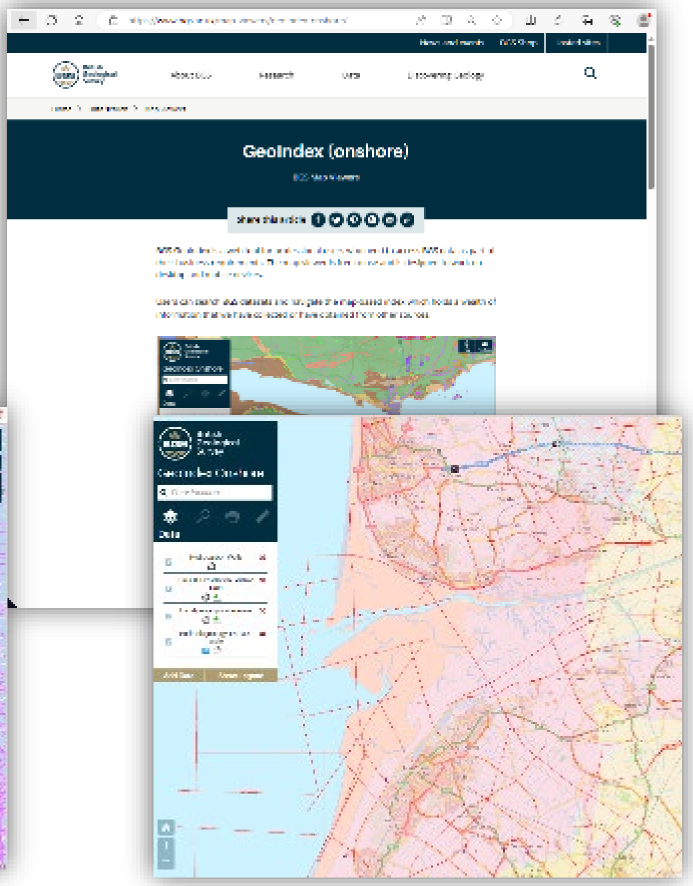
https://ndr.nstauthority.co.uk/

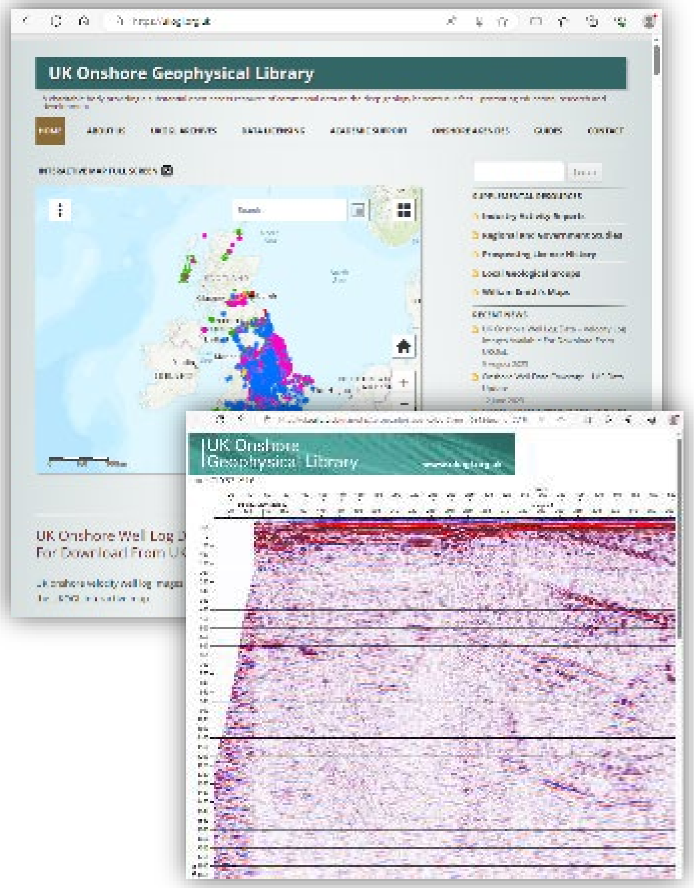
(Ref. 3s)

Extensive sub-surface data available to download from National Data Repository

3.6c Useful links: UK subsurface







https://www.bgs.ac.uk/map-viewers/geoindex-offshore/
https://mapapps2.bgs.ac.uk/geoindex_offshore/home.html

BGS held **offshore** datasets, including survey locations.

https://www.bgs.ac.uk/map-viewers/geoindex-onshore/
https://mapapps2.bgs.ac.uk/geoindex/home.html

BGS held datasets, including **onshore** geological maps.

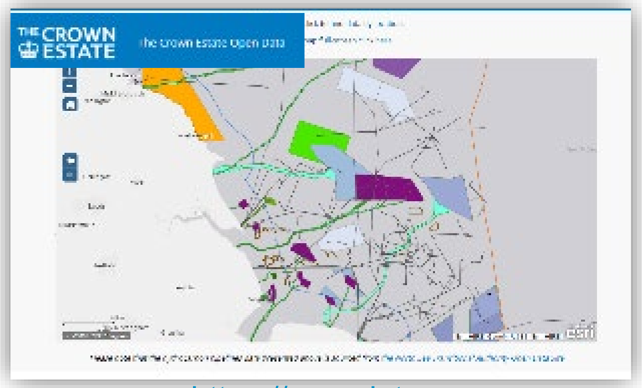
https://ukogl.org.uk/

UK **onshore** well log and 2D/3D seismic data.
Includes some BGS data

(Refs. 3t, 3u , 3v, 3w &3x)

Additional sub-surface data available to download

3.6d Useful links: Crown Estates

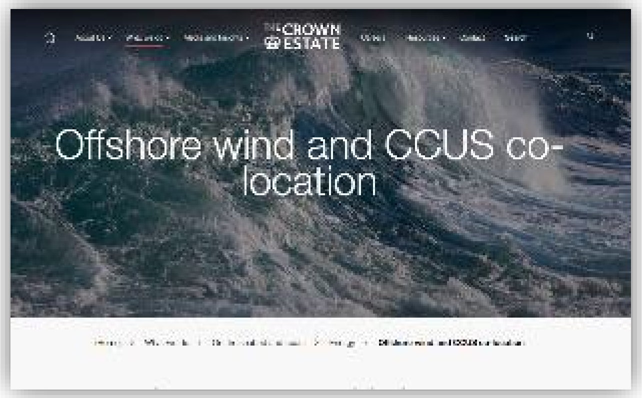


https://opendata-thecrownestate.opendata.arcgis.com/

Offshore wind, carbon store lease agreements (England, Wales & Northern Ireland)

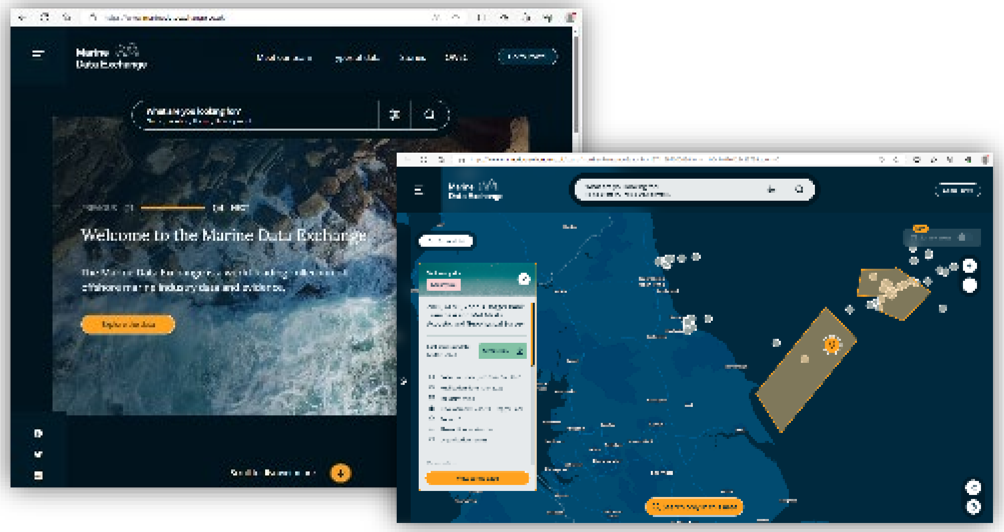
https://crown-estate-scotland-spatial-hub-coregis.hub.arcgis.com/

Offshore wind, INTOG, & carbon store lease agreements (Scotland)



https://www.thecrownestate.co.uk/en-gb/what-we-do/on-the-seabed/energy/offshore-wind-and-ccus-co-location/

Co-Location Forum: challenges & opportunities associated with the efficient use of the seabed



https://www.marinedataexchange.co.uk/

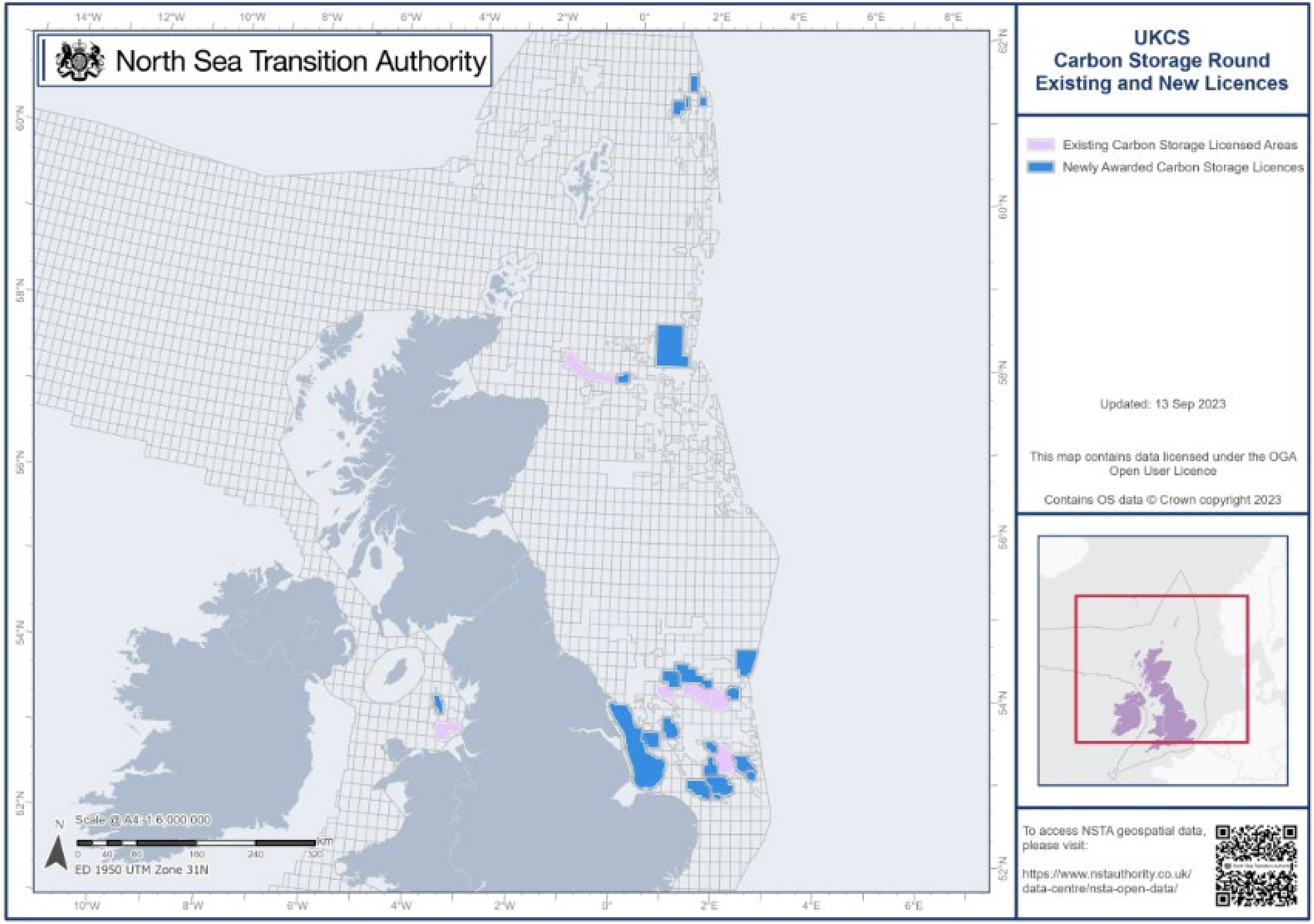
Collection of offshore marine industry data, including site survey information. Operated by Crown Estates

(Refs 3y , 3z, 3aa &3ab)

Additional marine planning and survey data available to download

3.6e 1st Carbon storage licence round awards

North Sea Transition Authority



- 15th September 2023 the NSTA announced the award of 21 CS licences in the UKCS.
- These licences span c.12,000km² and are predominantly within the SNS where competition with planned and active windfarm sites is increasing.

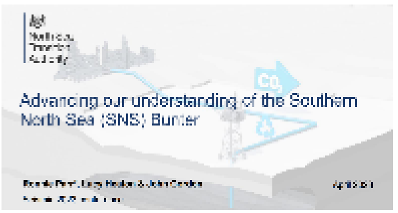
Recent CS licence round awards

4. Southern North Sea (SNS) Seismic Imaging & Acquisition Considerations

Section 4 SNS Seismic Discussion

North Sea Transition Authority

The SNS continues to be an area of focus, as it has the highest concentration of upcoming carbon stores within 2 different reservoir targets within a complex geological environment imaged by a seismic database which is comparatively old. New seismic acquisition is difficult and increasingly constrained by co-location issues with other marine users, and especially windfarms. This section builds upon the SNS regional study conducted & presented by the NSTA.



SNS 1990s 3D are relatively poor compared to modern surveys and comprise: a patchwork of acquisition parameters in multiple orientations obtaining only narrow frequency bandwidth (4ms sampling precluding higher frequencies and low frequency filter), inadequate sea-bottom/ shallow overburden definition and a lack of long offsets for deeper imaging. Furthermore, these surveys will often have some inherent small post 1990s natural gas production related effects.

They cannot be considered as baseline surveys underpinning the next 50 years of basin-wide CS redevelopment. Owing to the proliferation of windfarms, there is a limited timeframe to acquire a regionally extensive streamer/ hybrid 3D in this difficult and congested seaway.

Section 4.1 provides an overview of the issues for seismic acquisition of SNS carbon storage complexes, supported by maps showing the distribution of the 2 principal CCS reservoir stores (Section 4.2). Section 4.3 provides a comparison of typical “easy imaging” planar seismic and complex geology seismic. This helps to distinguish, the majority of areas, which are amenable to typical or high-resolution streamer seismic and contrasting those more limited areas which require high specification (e.g., multi-azimuth OBN – Ocean bottom node) seismic to resolve the complex geological structures.
A chronology of the evolution of 3D seismic is presented by through basin coverage maps (Section 4.4a-c).
Section 4.5 provides a list of progressive improvements in seismic acquisition parameters and then some examples of survey specific design parameters. This shows that the SNS is largely covered by 1990s streamer seismic – generally involving large seismic sources and multiple streamers. **Critically the SNS has seen very little modern “broadband” seismic acquisition over the proposed CS areas**, in comparison to the type of surveys extensively undertaken in other UK basins from ca 2010+. Although 1990s surveys can be reprocessed to modern standards for site characterisation, they are deemed inadequate for CS development compared to a modern standard of broadband or high resolution seismic.
Section 4.6 highlights the issues of co-location between the planned//developed windfarms and the recent CS licences.
Section 4.7a-f highlights the range of marine issues which would affect new seismic acquisition in the SNS waters – focussing on shallow water depth and strong and varying tidal currents and numerous obstructions.
Finally, 4.8 shows an example of the difficulty of race-track seismic acquisition in the Dutch sector of the SNS and 4.9 is a reminder of the type of acquisition required for different targets.

4.1a SNS Geology and Seismic Overview

North Sea Transition Authority

Whilst modern reprocessing of legacy seismic helps support CS store site characterisation, the NSTA expects that modern high resolution or broadband acquisition will deliver significant improvement for CS development phase.

SNS comprises 4 broad reservoirs of which 2 have high potential to be developed for CS:

- Bunter (Triassic) - predominantly aquifer closures → Estimated 10GT CO_2 capacity
- Zechstein dolomites – petroleum play being appraised → Assumed unsuitable for CO_2
- Leman (Permian) - currently producing and depleted natural gas fields → Est 3GT CO_2 capacity
- Carboniferous - currently producing and depleted natural gas fields → Assumed reservoir typically poor quality for CO_2

Legacy/Vintage 3D seismic – Predominantly 1990s acquisition

- Large number/patchwork of surveys
- Each 3D surveys has slightly different acquisition parameters
- Most 3D surveys do not meet modern specifications, especially in main CS part of basin
- Some 3D coverage gaps especially nearshore
- Modern reprocessing always improves the seismic image

Future seismic acquisition will be increasingly challenging

- Shallow water sandbanks & wrecks restrict vessel draft & deep tow streamer
- Strong tides create significant streamer feather or noise on ocean bottom cables/nodes
- Multiple marine users (Fishing/ lobster pots, shipping, leisure)
- Increasing development of windfarms: Preventing all streamer seismic & severely restricting OBN access
- Enhanced HSE (risk to deep tow cables) & environmental (noise budgets, cetaceans, marine areas)

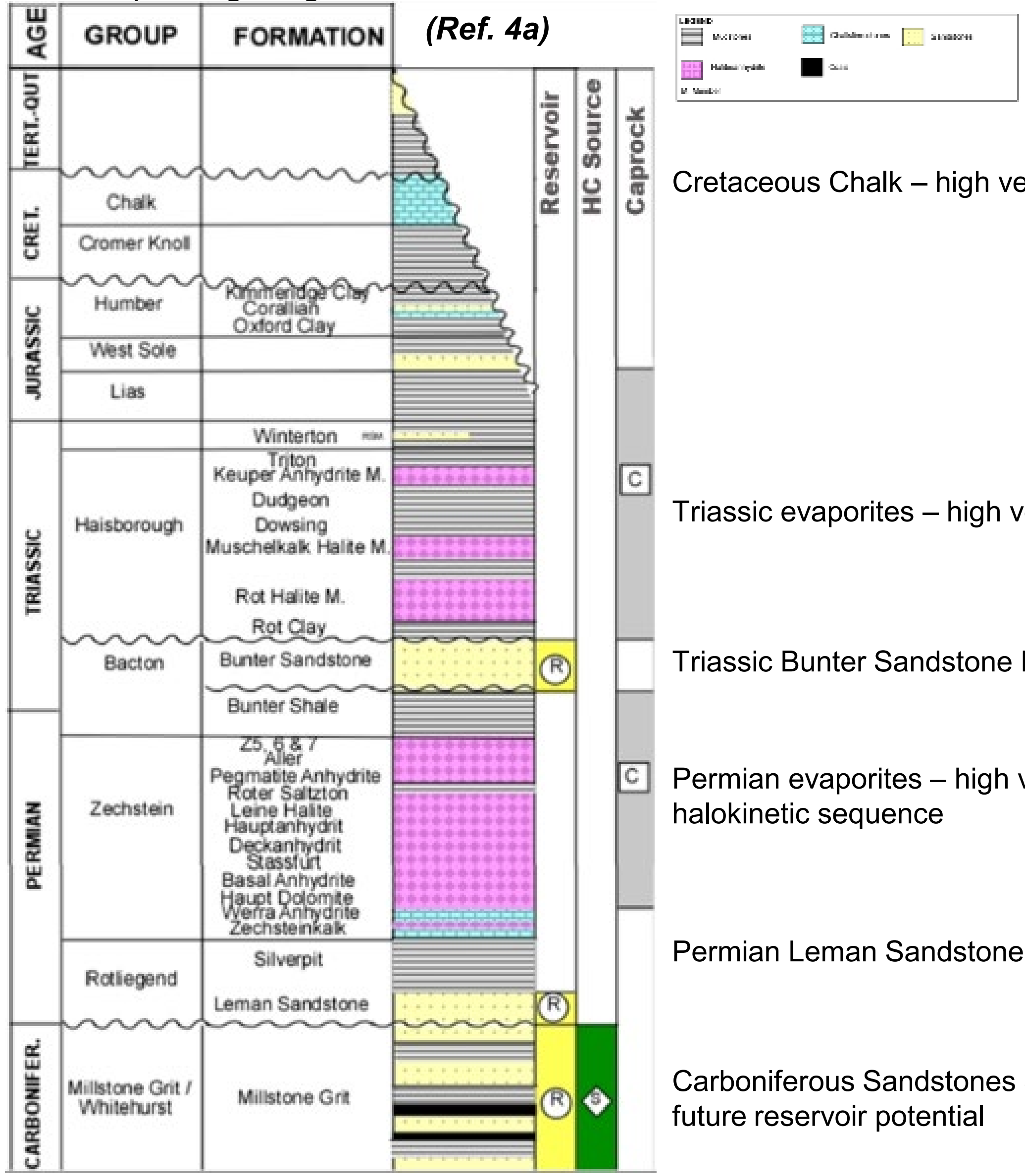
Majority of SNS legacy seismic inadequate for CCS development but new acquisition will be increasingly difficult

4.1b SNS Lithology and Seismic example

North Sea Transition Authority

SNS Simplified geological column

(Ref. 4a)



Cretaceous Chalk – high velocity

Triassic evaporites – high velocity

Triassic Bunter Sandstone Reservoir

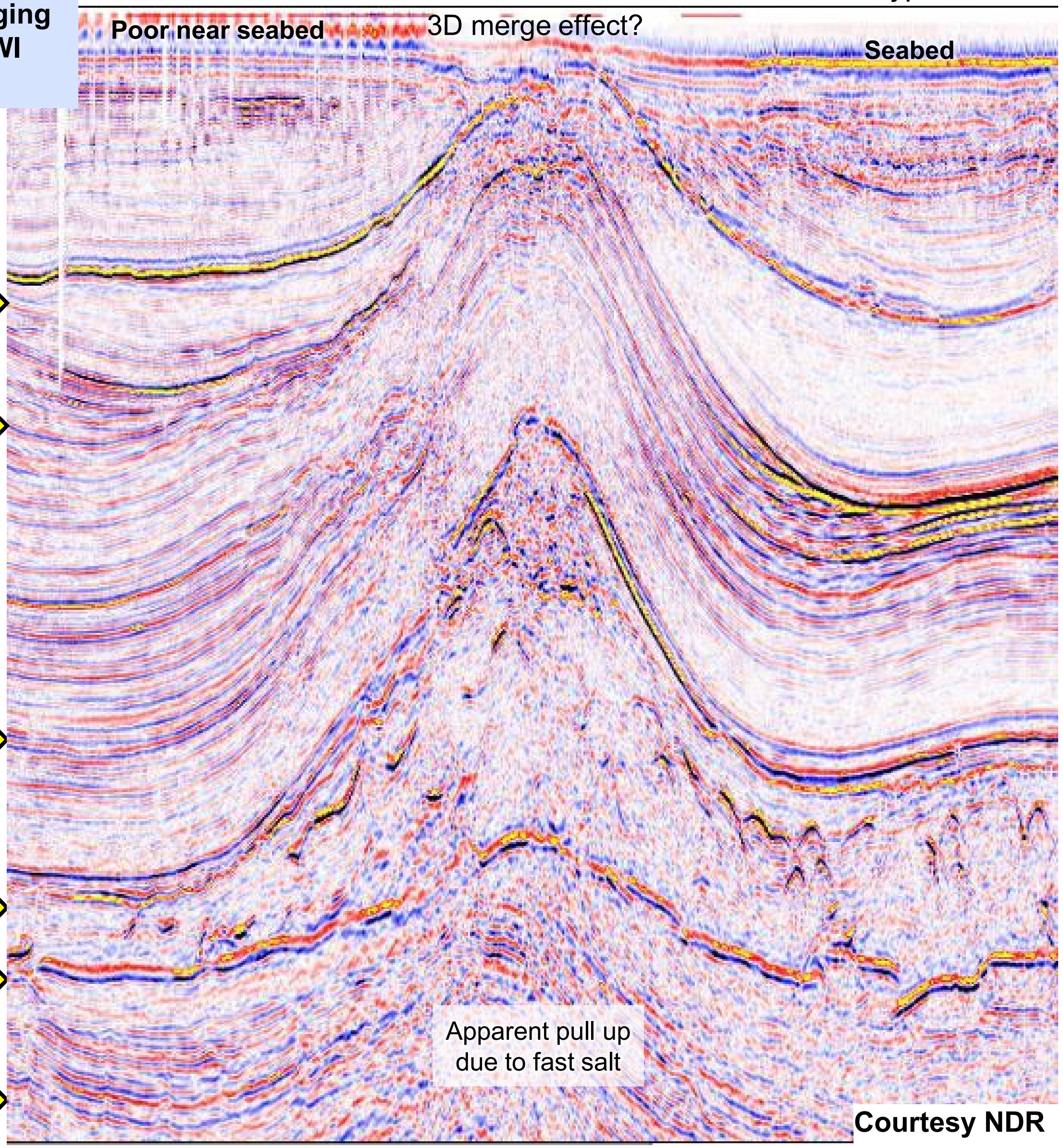
Permian evaporites – high velocity, halokinetic sequence

Permian Leman Sandstone Reservoir

Carboniferous Sandstones & Coals – future reservoir potential

Note: seabed imaging is critical for FWI application

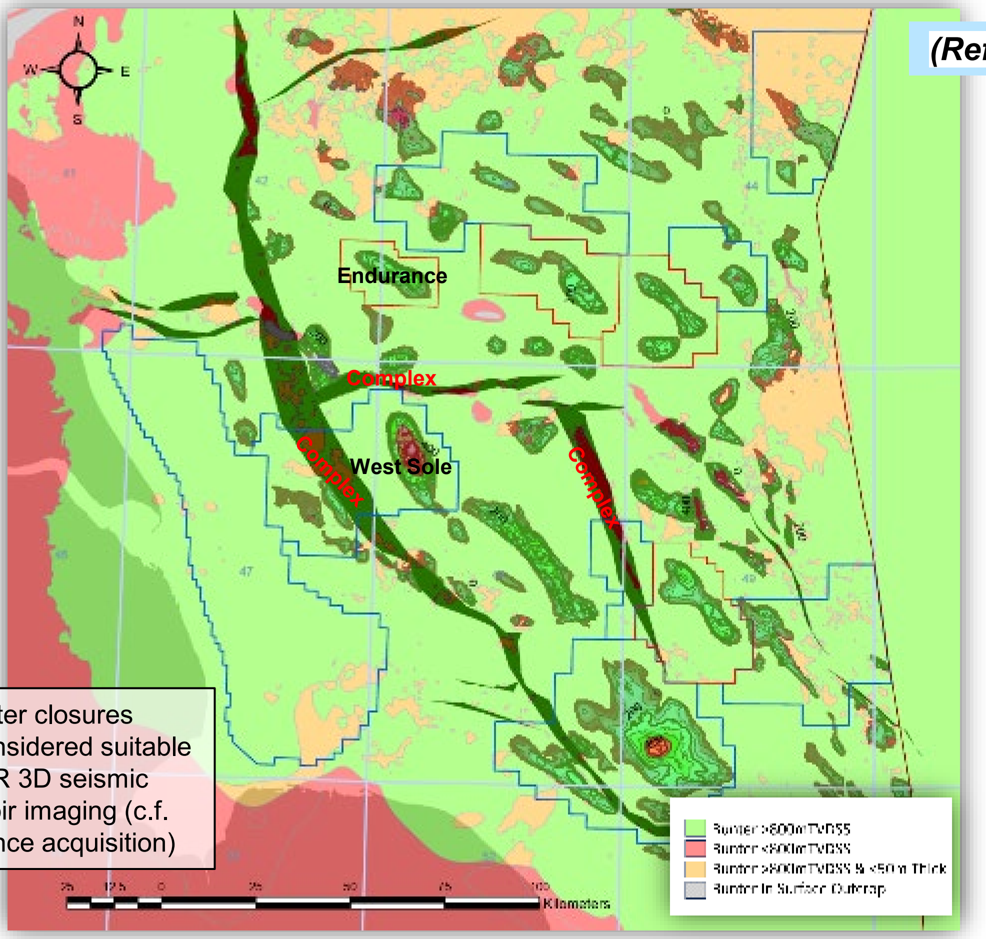
SNS type seismic

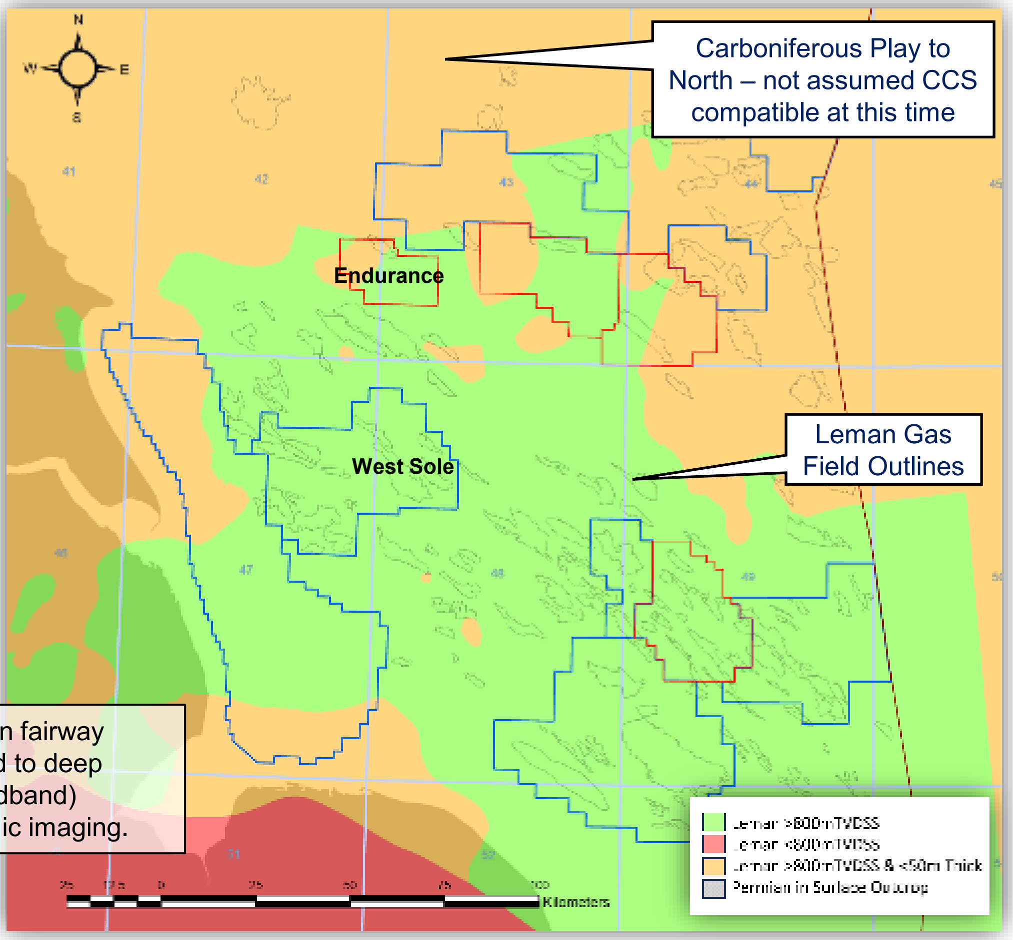


Well established stratigraphy, good imaging down to top salt

4.2 Potential CCS Bunter & Leman reservoirs

North Sea Transition Authority





- The contoured areas within the green polygon are the spatial extents of Bunter closures.
- Bunter covers an area of ~ 30,000km² and the Leman mostly underlies the southern 2/3rds of the Bunter fairway (19,000km²).
- Both the Bunter and Leman outcrop onshore to the west.
- Reservoirs at >800mTVDSS depth (section 2.3) allow CO_2 injection as a super-critical dense fluid. Red fill areas show where reservoir is too shallow (<800m).
- Salt ridges and faulted are areas of particularly complex imaging and require more sophisticated seismic acquisition (see section 4.3).

Maps show the extent of the geological extent CCS fairway in the Bunter and Leman reservoirs

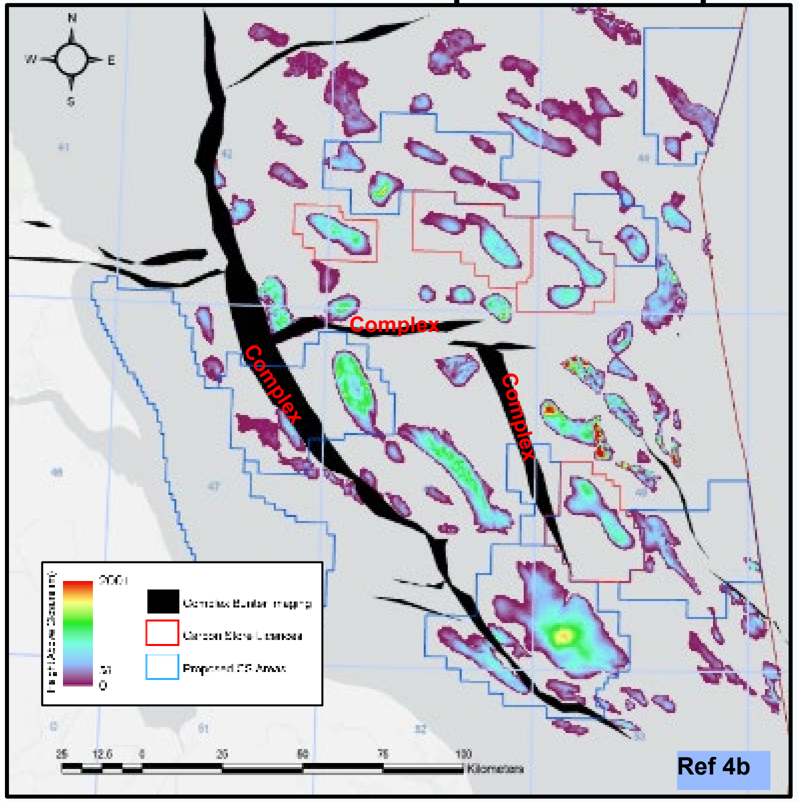
4.3 Complex imaging & OBN specific areas

North Sea Transition Authority

Most of the SNS has typically flat lying reflectivity which is amenable to modern High Resolution or long offset seismic streamer acquisition and processing. A small proportion of the area requires good modern OBN seismic:

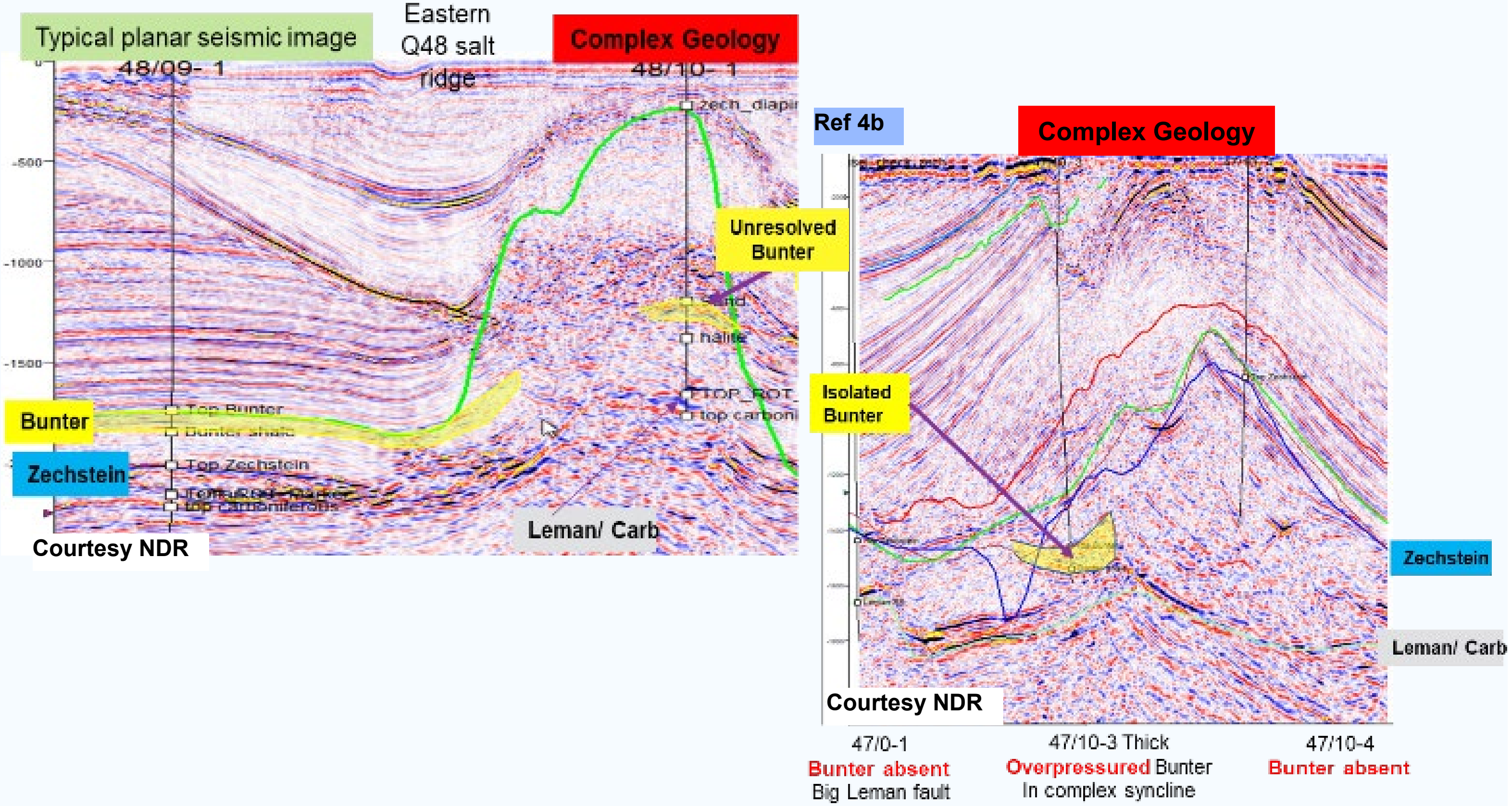
1) ~10% complex geology areas (~3,300 km²) with steeply dipping salt ridges & faulting (shown in black on map).
2) ~7% Very shallow water (<15m) in which OBN is the only acquisition system (section 1.9 & 4.7).
3) ~5% and growing where co-location issue prevent streamer access (below).

Bunter Closures & Complex areas map



Complex imaging usually associated with salt ridges or major faults

Regional complex seismic imaging issues

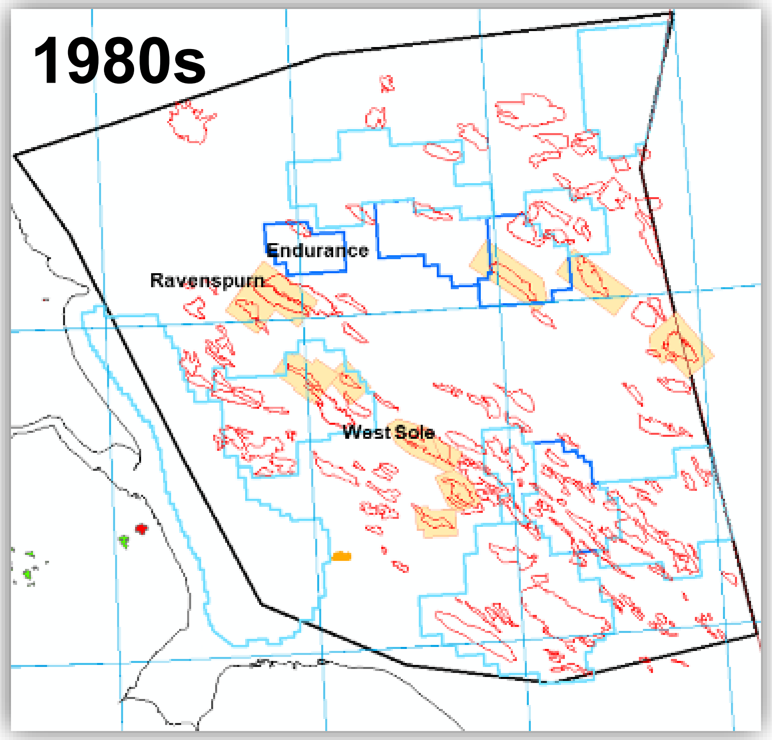


Examples of typical “simple” planar geology compared with extent of areas of complex geological structures

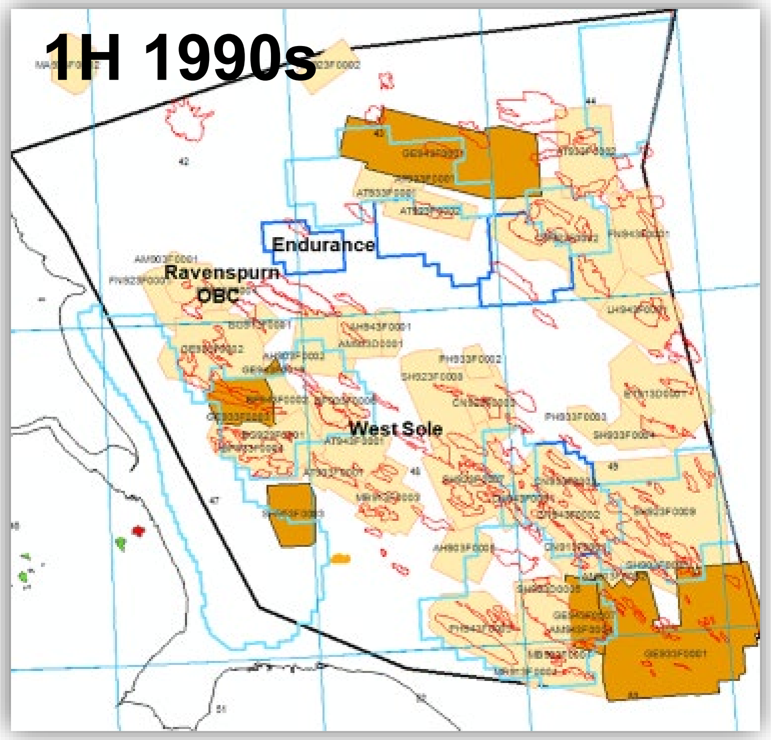
4.4a SNS 3D Seismic Acquisition

This series of panels give the chronology of SNS seismic and highlight some issues regarding the underlying vintage of legacy seismic, which can be tied into acquisition parameters (section 4.5). Specifically broadband seismic re-acquisition which was very common around the UKCS, was comparatively rare in the central part of the basin. This is of importance in understanding the coverage vs quality and informing NSTA expectations for different stage of CS store appraisal and development.

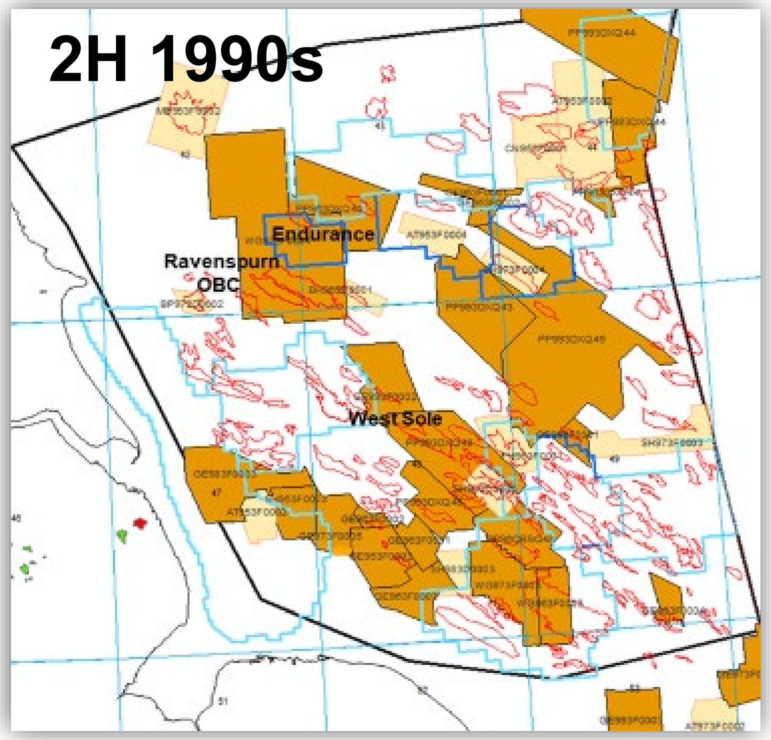
Earliest 3D surveys usually involved moderate sized (40m) single or dual streamer vessels. They comprised analogue signal transmission & limited number receiver groups limited maximum offsets to 3km. Oil filled streamers were noisy so high fold stacking (summing traces) improved signal to noise (section 7.10) and swell noise was removed by low cut frequency filtering, irrevocably limiting the recorded data spectrum. 1990's saw the advent of more typical short offset multi-streamer 3Ds often being replaced by more regional speculative 3Ds towards the end of the decade. Occasional limited OBC surveys generally were sparse with limited technology.



Small focussed proprietary field specific TS 3D surveys



Field specific Proprietary @ basin centre
Larger Speculative testing basin fringes



Fringe Proprietary surveys, West Sole OBC re-acquisition, Resurgent Spec (Cygnus/Breagh)

(Ref 4c)

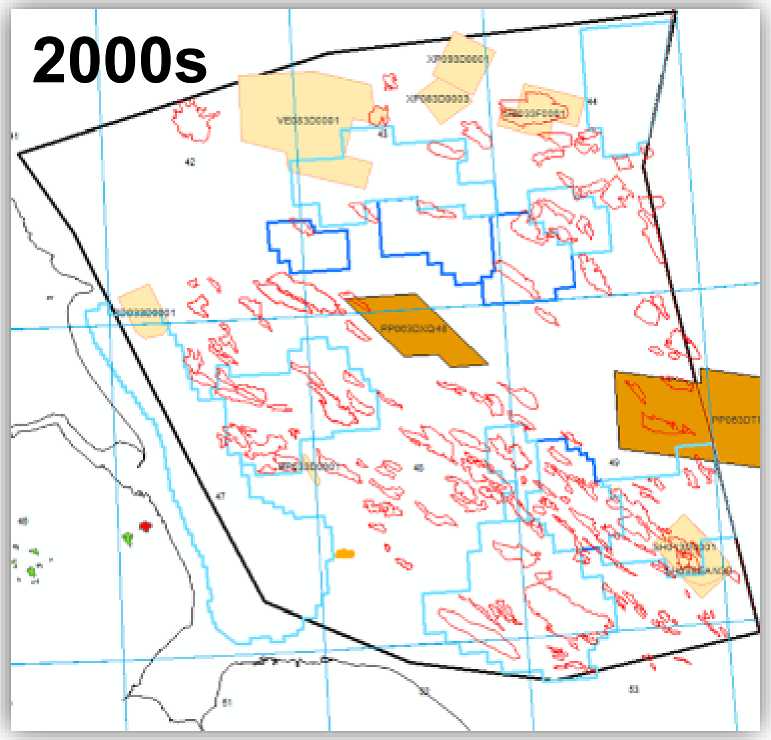
Early growth of 3D seismic, significant increase in coverage through early 1990s

4.4b SNS 3D Seismic Acquisition

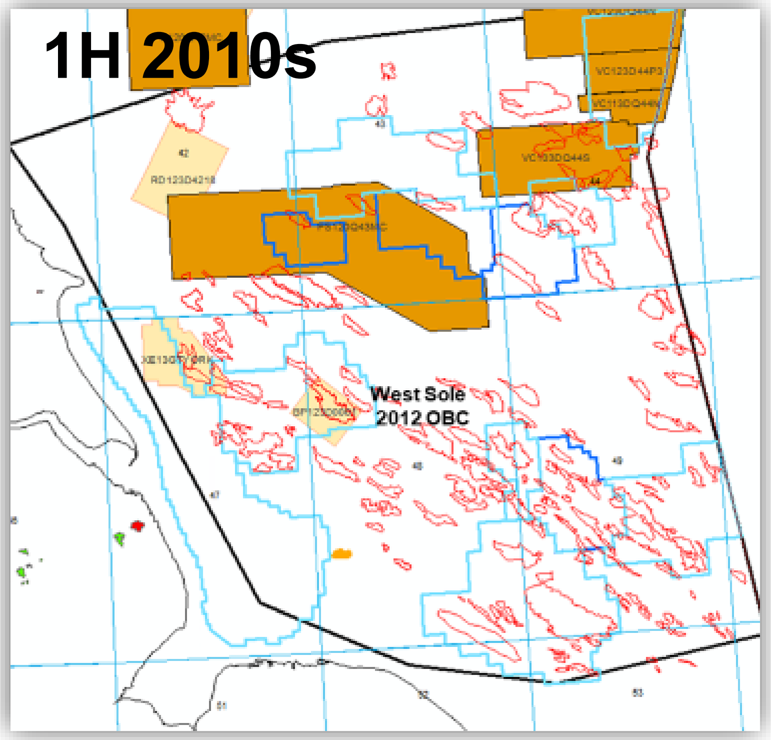
North Sea Transition Authority

By the end of the 1990’s, almost all current CS areas were covered by at least one 3D, with the trend in the 2000’s and 2010’s to new acquisition primarily restricted to the basin margins. These surveys were fully digital, <10 x long solid streamers providing potential for dense inline sampling, but cross line sampling remains an issue.
Most of the CS areas have not benefited from modern broadband acquisition seen elsewhere around the UKCS.

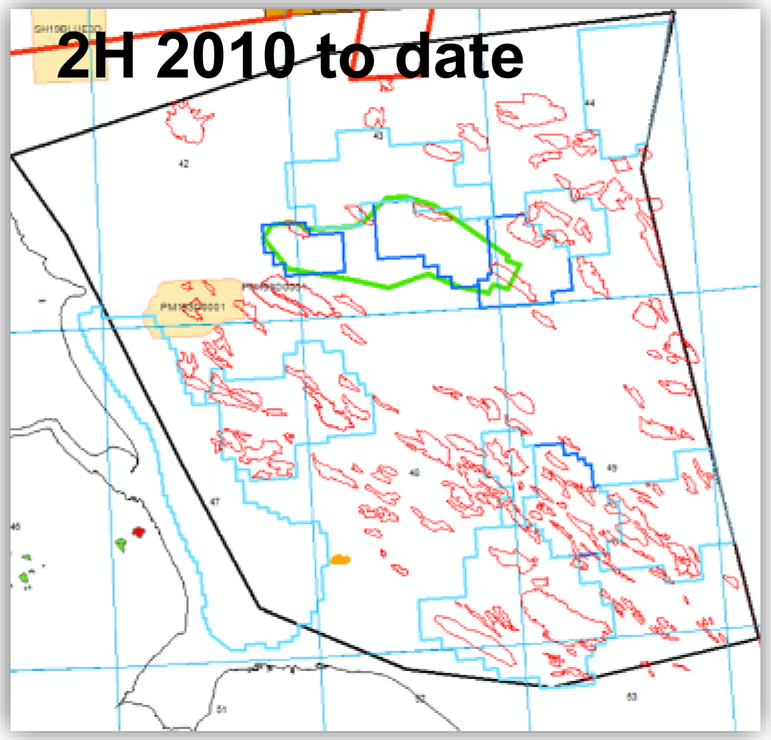
In the last decade, regional long offset exploration has been very limited to the far northern edge and target specific appraisal 3D seismic.
Bespoke surveys include the only HD OBC (West Sole,) Modern Broadband streamer (Tolmount) & High-Resolution CCS specific survey (Endurance).



Limited new 3D Proprietary on N margins
Sean: Basins only 4D monitor. PGS complete Spec gaps



Fringe Proprietary surveys, West Sole OBC re-acquisition, resurgent Spec (Cygnus/Breagh)



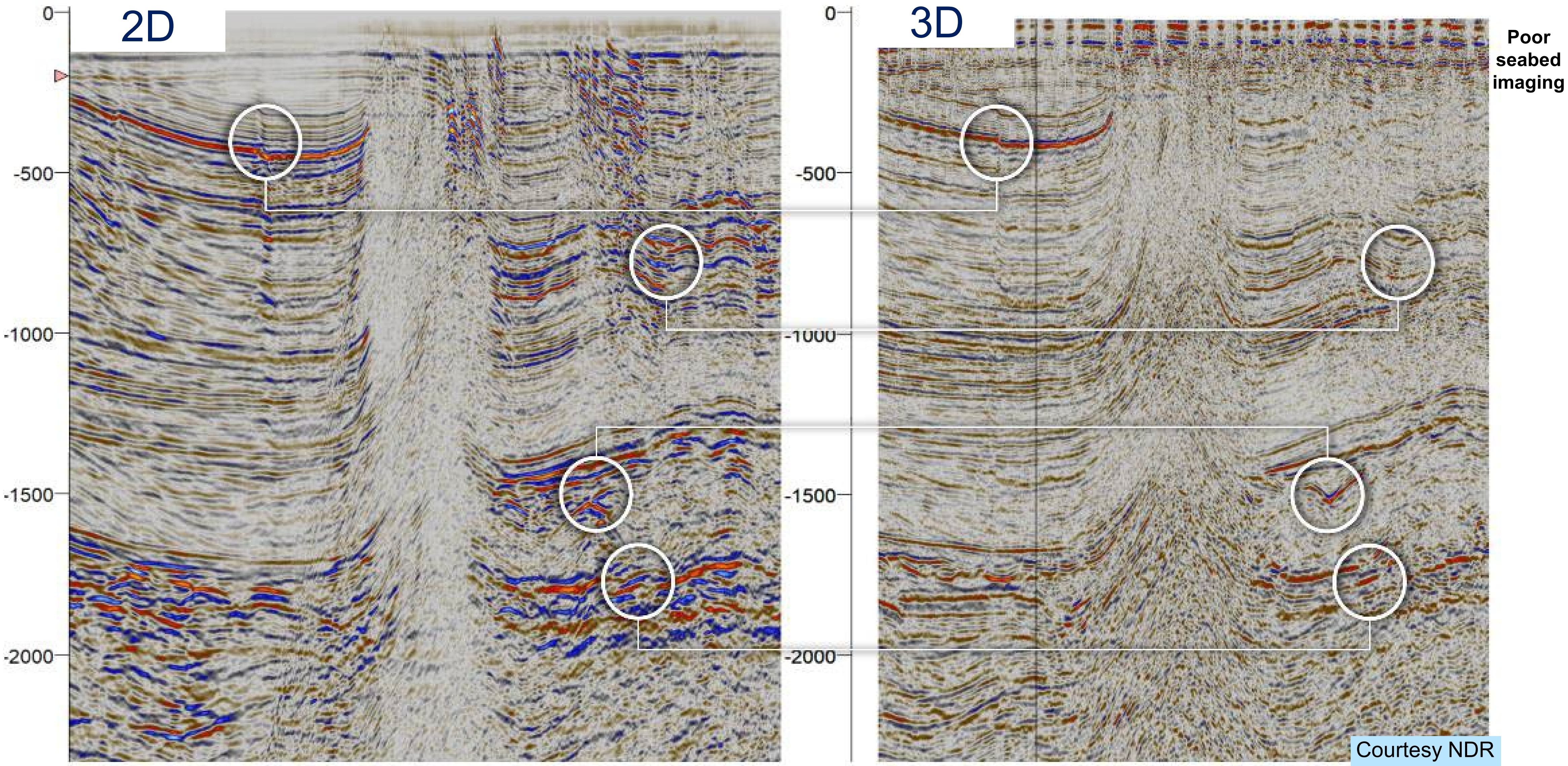
Limited Proprietary surveys. Tolmount long offset & **NEP High Resolution CCS (2022).** Spec/ Large ION (TGS) in North for the Zechstein play

(Ref 4c)

Peak of large regional speculative 3D replacements, waning in 2000s with gas basin maturity, Occasional specialist target acquisition.

4.4c SNS 2D – 3D Comparison

North Sea Transition Authority



3D seismic offers significant imaging improvements over 2D seismic data, but struggles with salt diapirism

4.5a SNS 3D seismic evolution

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Year	Meets NSTA expectations?	Survey style	Streamers	Streamer Length	Streamer type	Sources	Shots	Bin spacing	Fold	On board Filtering	Navigation	4D	Type surveys
1980's	No	2D evolved/ Primitive 3D	1 to 2	<3km length	Kerosene filled	Single Source; commonly water guns		>=25m Xline	Often formed over long arrays	Low-cut applied (remove swell noise)	Very Poor	-	
Early-mid 1990's	Possible reprocessing for site characterisation	Dedicated 3D vessel capability	4 to 6	Offsets ~ 3 km 3km, occasional 3.6-4.5km	Typically 100m separated	2 x Airguns; 50m separation	Usually 25m	25m Xline	<40	Narrow frequency bandwidth	Poor in sea	Surveys occasionally used as 4D baseline; 4D invention aligned with advancements in computing	
Late 1990's/2000's	Possible reprocessing for site characterisation	Increased production & enhanced 4D repeatability		<12 streamers x <6km ,	Steerable streamers & single receiver acquisition	Latterly steerable sources	Shot-by-shot near field signature recording	12.5 or 18.75m	<50	Low cut OUT	Full GPS integration "fully raced" aoustic networks	Major 4D repeatability enhancement	
Early 2010's	Yes; With modern reprocessing for site characterisation or store development	"Broadband" frequency			Dual hydrophone/ geophone sensor Slant hydrophone only cable 3 component streamer (3C Acquisition)	Evolving to use broadband sources (airguns at variable depths)							Tolmount 2019
	Possible for site characterisation	Pseudo broadband			Legacy 3D broadband reprocess								
Late 2010's to Present	Yes; With modern reprocessing for site characterisation or store development	Enhancing lateral/ spatial resolution		Towing closely spaced streamers		Multiple sources Simultaneous shooting & deblending	Shots over streamers (zero offset)	3.125m or 6.25m Xline	~80			4D simultaneous shoot	Endurance 2022

SNS Dominated by 1990's acquisition.

- Poor/no seabed (FWI), Mostly short offset, low frequencies excluded (poor FWI) and 4ms sampling (no high frequencies),
- Whilst other UK basins benefited from 2010's broadband & higher data density, the SNS was relatively left behind.

Modern reprocessing broadly acceptable for site characterisation.

CS site development needs new modern broadband or HR 3D acquisition.

(Ref 4c)

Seismic acquisition parameter evolution summary

4.5b Detailed List of SNS seismic parameters

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It is worth noting that

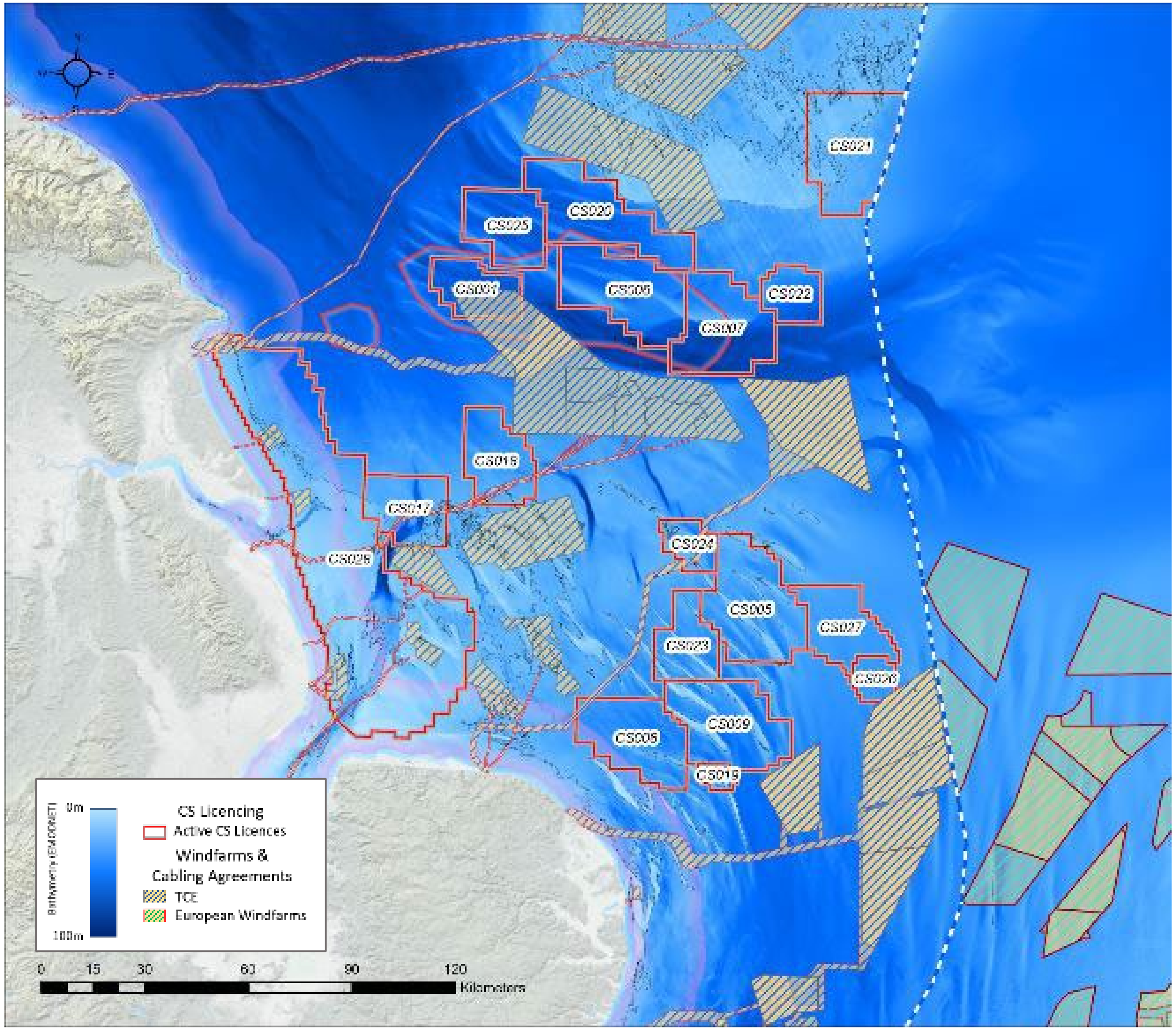
1) every survey has slightly different parameters which are bespoke for specific area, geological target and vessel capability, so generalisations about survey quality should be treated with caution, and
2) The only released modern acquistion surveys in the SNS are the 2019 (Tolmount) broadband streamer and West Sole HD OBC.

Year	Survey	Streamers	Spacing	Streamer Tow Depth	Record Length	Sources	Shots	Bin spacing	Fold
1985	BP853F0002 Hoton	1x 2.7km		8m	5 Sec	2x 1270 cu in, 60m sepn towed @ 6m	26.67		27
1990	Arco AT903F001 (Pickerill/West Sole)	2x 2.4km	150m	7m		2x 3445 cu in, Sepn 75m. Tow @ 4.5m,	37.5m	37.5x37.5m	32
1992	Sean/Inde 1992-93 2 boat Quad-Quad	2x 3km	100m	7m	5 Sec	2x 3162 cu in, 50m spacing	18.75m	25x25m	20
1994	Geco TQ 1994 Blk 47/10	4x2km		7m	4 Sec	2x 2233cu, 50m spacing @6m	12.5		40
1995	PGS Q49- 95	6x 3.0km			4.6 Sec		25m		30
1996	PGS Q43-96	6x 3.6km	100m	4.5m	5 Sec		18.75m	12.5x 25m	48
1996	PGS Q44-96	6x 3.6km	100m	6.5m	6 Sec		18.75m	acqn 25x6.25; proc 12.5x 25m	36
1996	PGS Q49- 96	6x 3km			5.1 Sec		18.75m	acqn 12.5x 25	40
1996	PGS Q44-98	6x 3.6km	100m	6.5m	5.1 Sec		18.75m	acqn & proc 12.5x 25m	48
1999	PGS Q49-99	6x 3.6km		6m	5.1 Sec		18.75m		48
1999	PGS- Silver pit 99	6x 3.6km	100m	7m	7.2 Sec		25m	acqn 25x6.25; proc 12.5x 25m	36
	PGS- Sole pit	6x 2.2km shallow	75m	6m	4 Sec		12.5m	6.25x18.75	45
1999	PGS- Sole pit xtn 99	6x 2.2km shallow	75m	5m	4 Sec		12.5m	6.25x25	45
2002	Sean 2002 4D	8x 3km	100m	6m	6 Sec	2x 3390 cu in, 50m spacing, @5m	18.75		40
2003	York (42/27) Close to shore	4x 4.4km	100m	6m		2x 2890 cu in, 37.5m spacing @ 5m	18.75m	18.75 (XL)x 6.25m (IL)	80
2006	PGS Q48-2006	6x 4.5km		5m	4.1 Sec		12.5m	6.25x 25m	45
2008	VP08 (Cavendish reshoot)	6x 4.5km		7m	6 Sec	2x 1310 cu in		6.25x 25m	60
2009	Sean 2009	6x6km; 100m spacing		7m	7 Sec	2x 3450 cu in, 50m spacing, towed 5m	18.75	6.25x 25m	80
2013	PGS SNS 2013M	6x 6km		6m	7 Sec		18.75	acqn 25x6.25; proc 12.5x 12.5m	80
2019	PM193D0001 Tolmount	10 x 6km	50m	20m		2 x 4100cu in, 25m spacing		12.5x 12.5m xline	
2013 Endurance	Spec 3D for pre-Zechstein	?x 6km		7m		2380 cu in, 7m depth	18.75m flip/flop		
Endurance	Standard HR for shallow hazards	1 x 1.2km		3m		1x 160 cu in, 2m depth	6.25m		
2022	SNS- Endurance 2022 3D HR	9x 3km	50m			4x 400 cu in 62.5m spacing: sources over recievers	6.25m	6.25m xline bin	40

(Ref 4c)

Examples of SNS Seismic acquisition parameter specification:

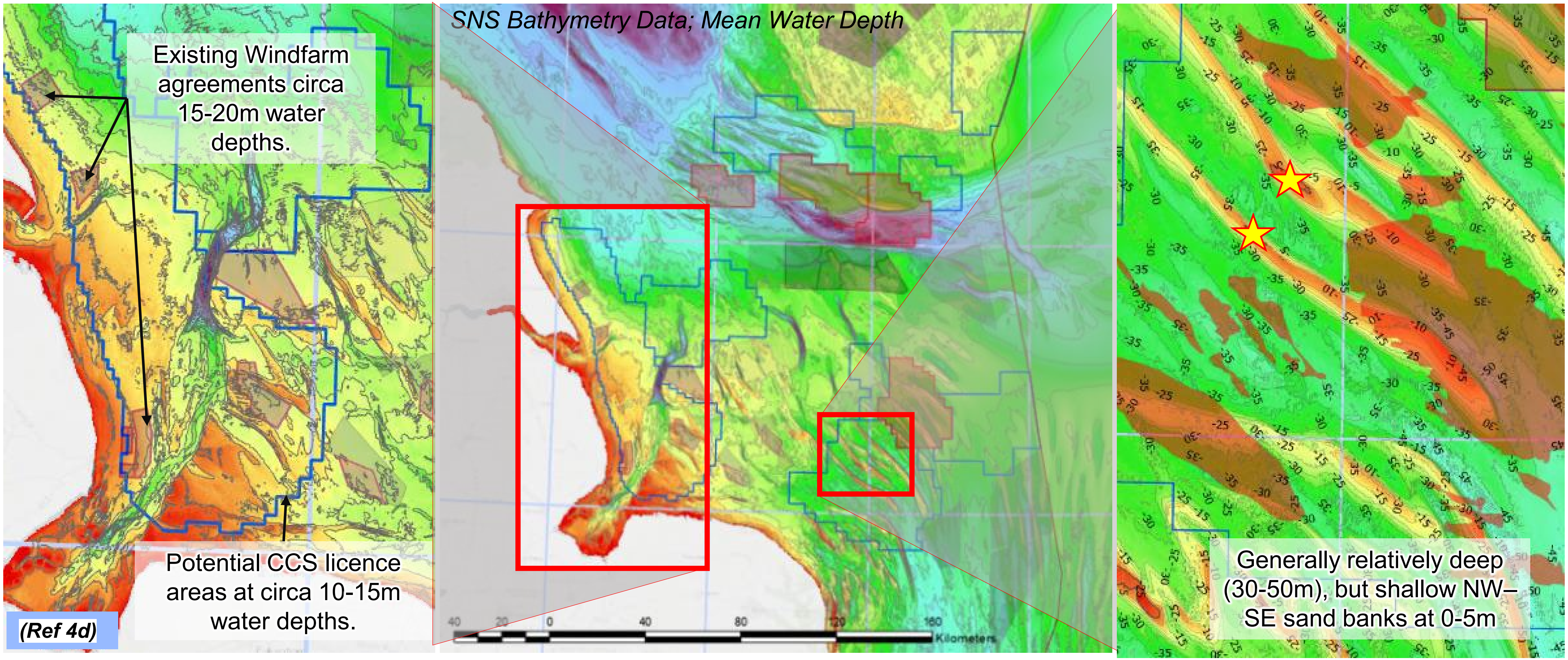
4.6 SNS CS licences and windfarms



- Highly congested area.
- Limited opportunity to acquire new seismic before additional windfarms sterilise the areas from any future seismic acquisition.
- Cross border surveying would optimise typical NE-SW acquisition direction paralleling coast and currents.

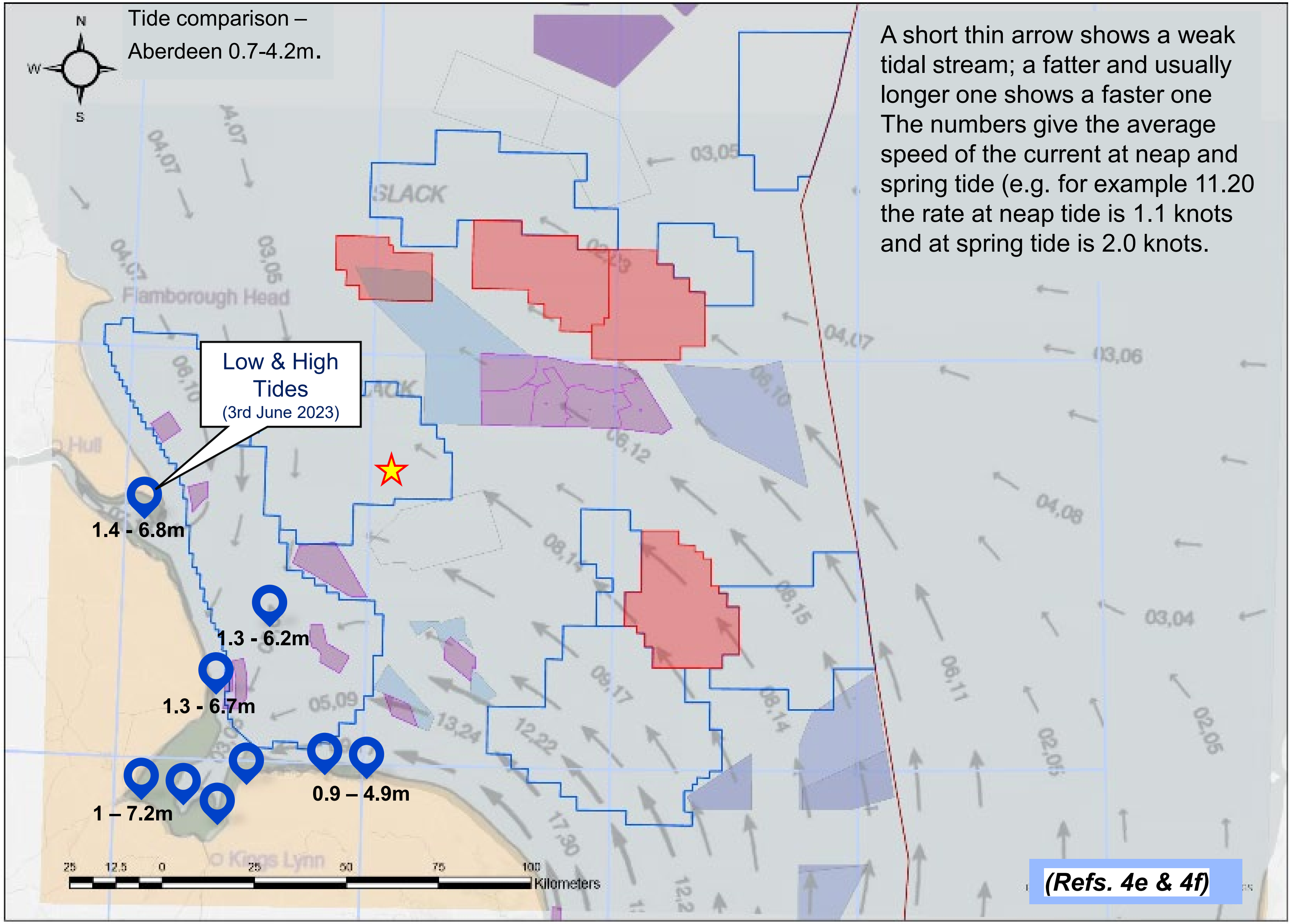
4.7a Bathymetry & Shallow Water Areas

Large parts of the SNS are inaccessible to modern vessel draft and deep-tow streamer seismic surveys. The bathymetry naturally shelves near shore, however a significant number of shallow sandbanks also occur in the middle of the basin.



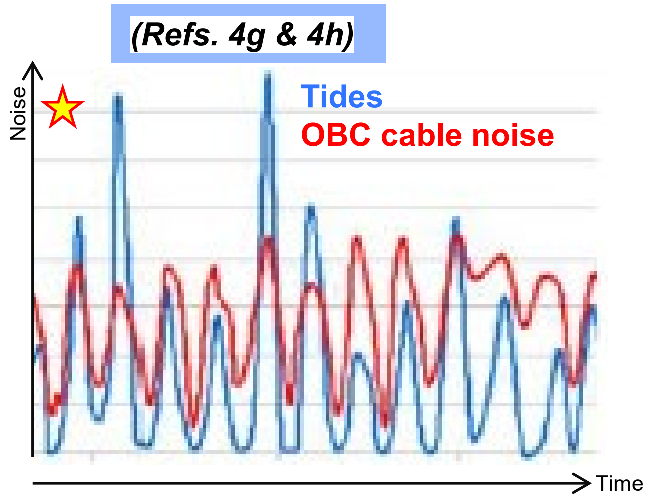
SNS water depth bathymetry can be beyond the limits of deep tow seismic

4.7b Tidal range and streams and OBC noise



The tidal flow at Neep Tides (3hrs after high-water at Dover) is shown in backdrop. Strong flow rates of up to 3kts nearshore, reduce with increasing distance to the coastline.

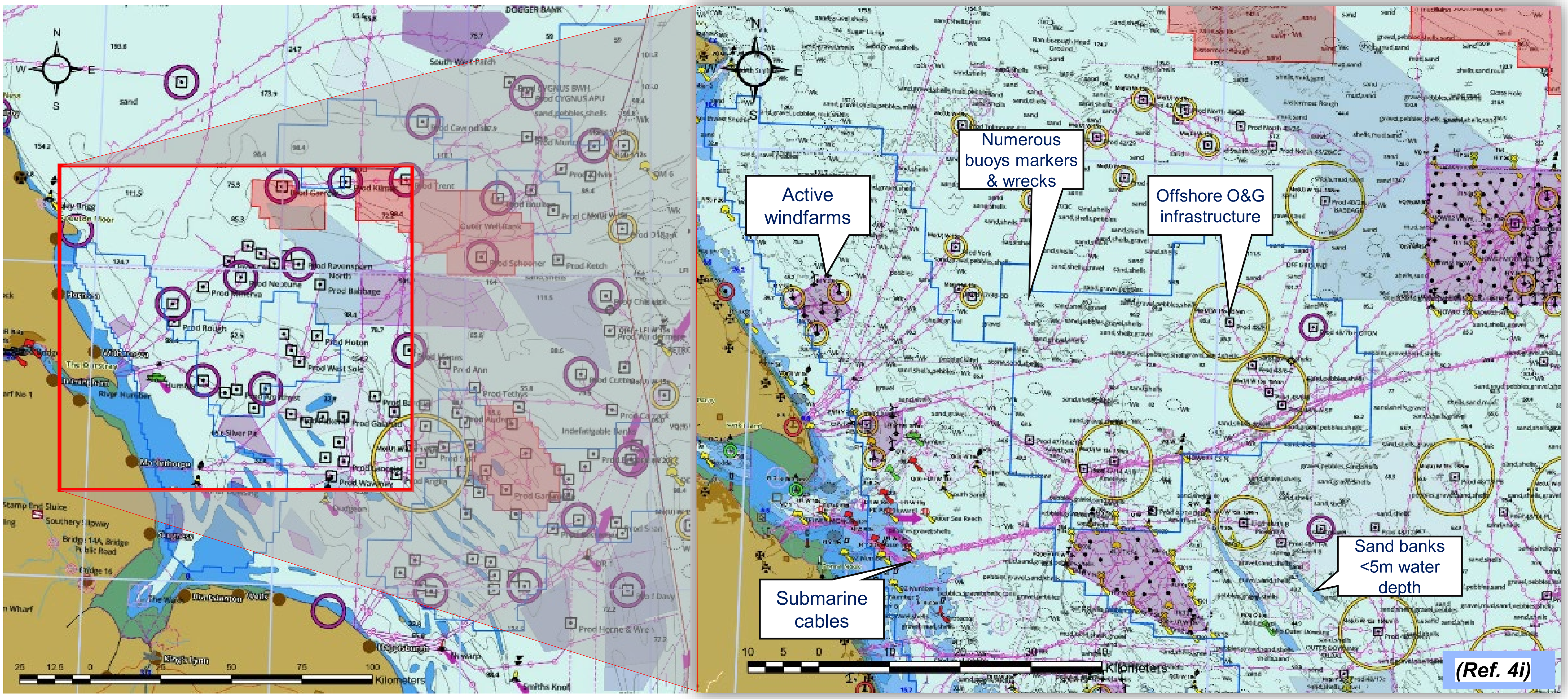
There is a clear correlation between OBC cable noise (strumming) and tidal movement in the SNS (West Sole area (☆)). This is interpreted to be a result of cables being laid NE-SW, perpendicular to the prevailing current direction.



Predominantly NNE tidal direction

4.7c Nautical Obstruction(s)

North Sea Transition Authority

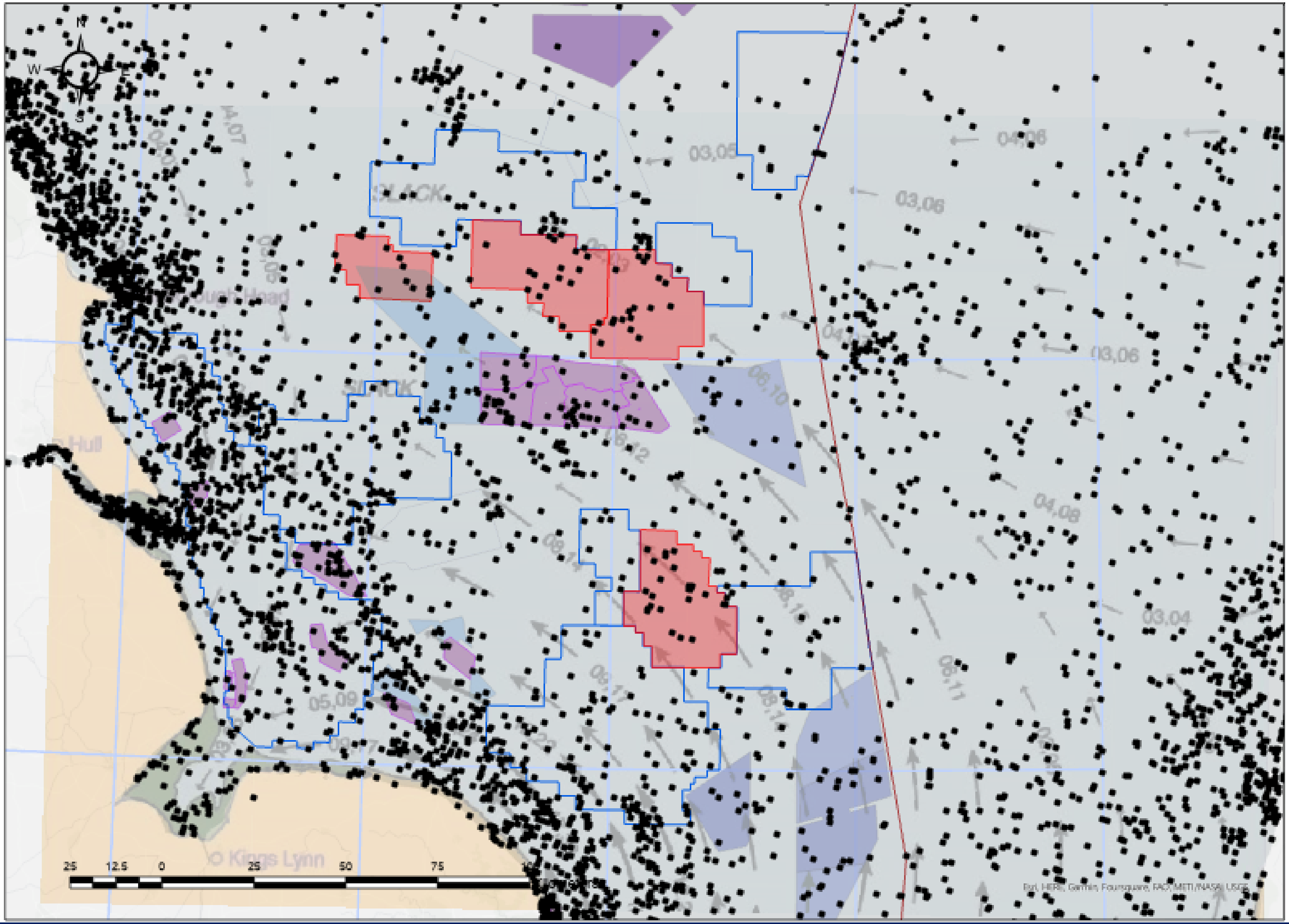


The SNS has a complex network of buoys and wrecks, existing O&G infrastructure (some of which could be re-used for CS purposes) active windfarms and those under development, along with associated cables and gas/potential CS pipelines.

Numerous obstructions throughout the SNS

4.7d Wrecks

North Sea Transition Authority

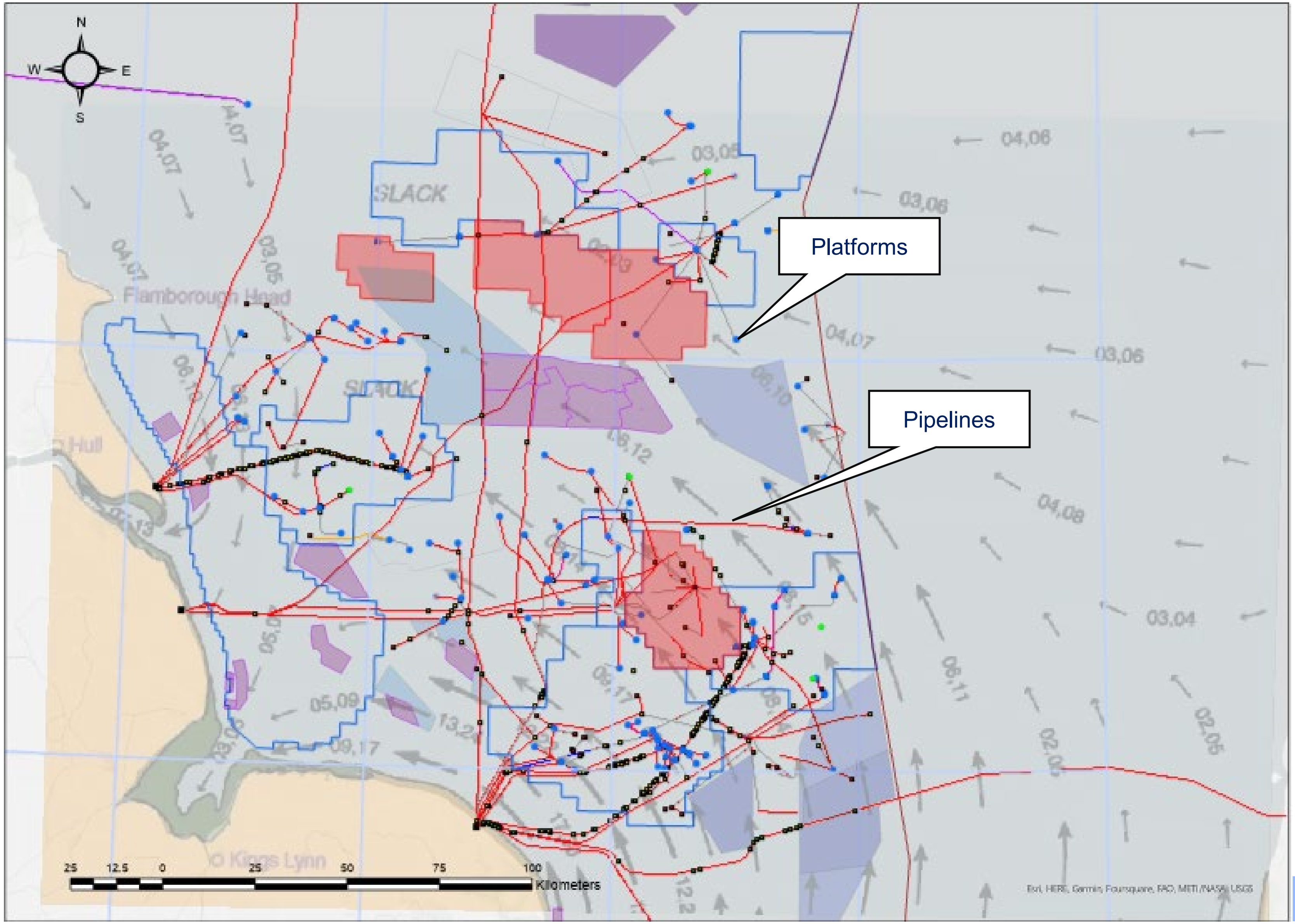


Very high density of potential wreck sites nearshore.

(Ref. 4j)

In more detail, numerous wrecks are known, especially in nearshore

4.7e SNS Infrastructure



(Ref. 4k)

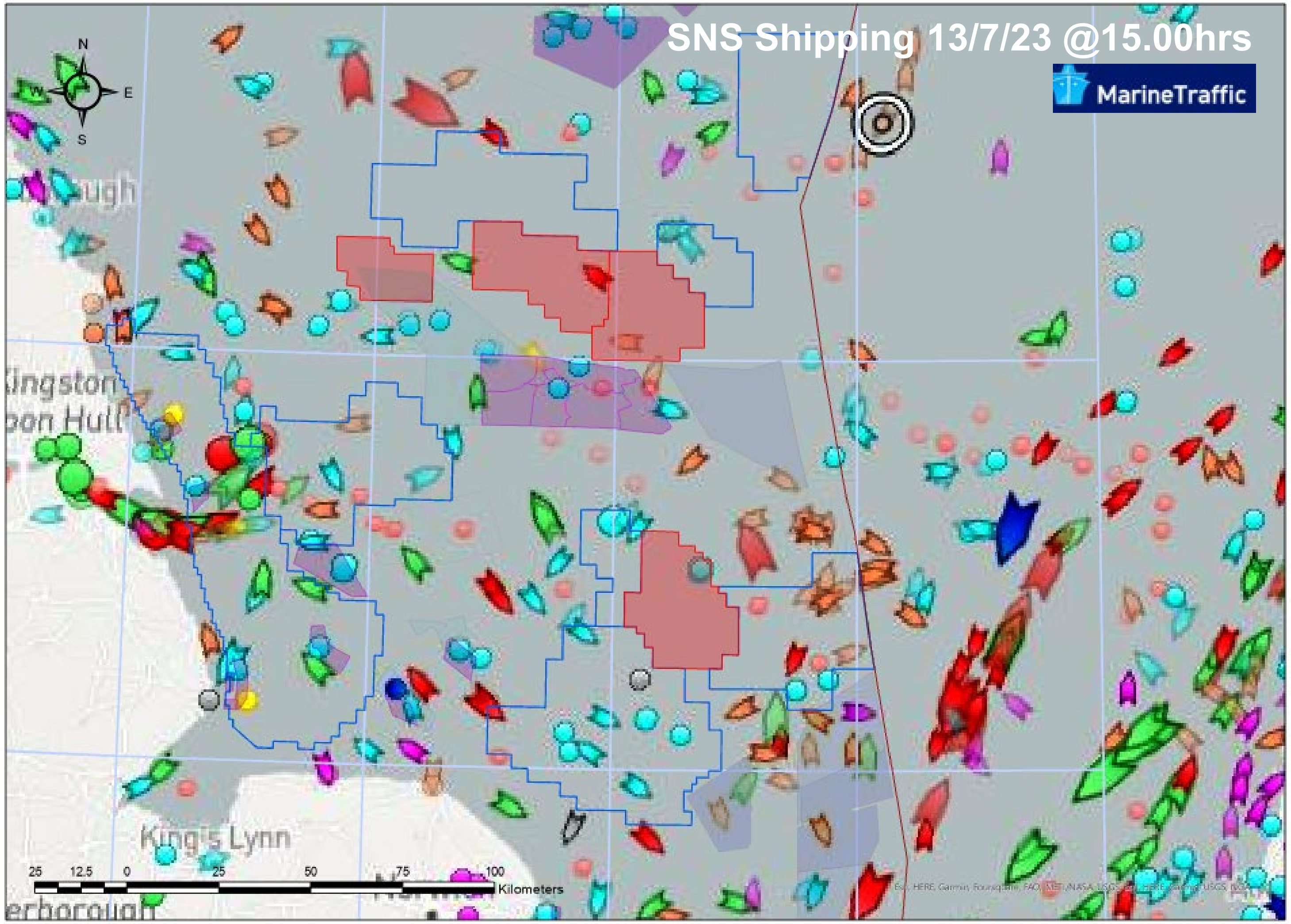
Combination of infrastructure items throughout the SNS including surface platforms as the most visually obvious within the area. All such installations have an exclusion zone surrounding them so as to avoid potential collision events.

In the submarine environment there are subsea manifolds, pipelines, umbilical control lines, anchoring points, rock dumps etc. All are man-made interventions on the seafloor and whilst some would not affect streamer acquisition (water depth dependent), OBC/OBN data acquisition would be affected due to positioning constraints.

Considerable current infrastructure

4.7f Marine vessel activity

North Sea Transition Authority

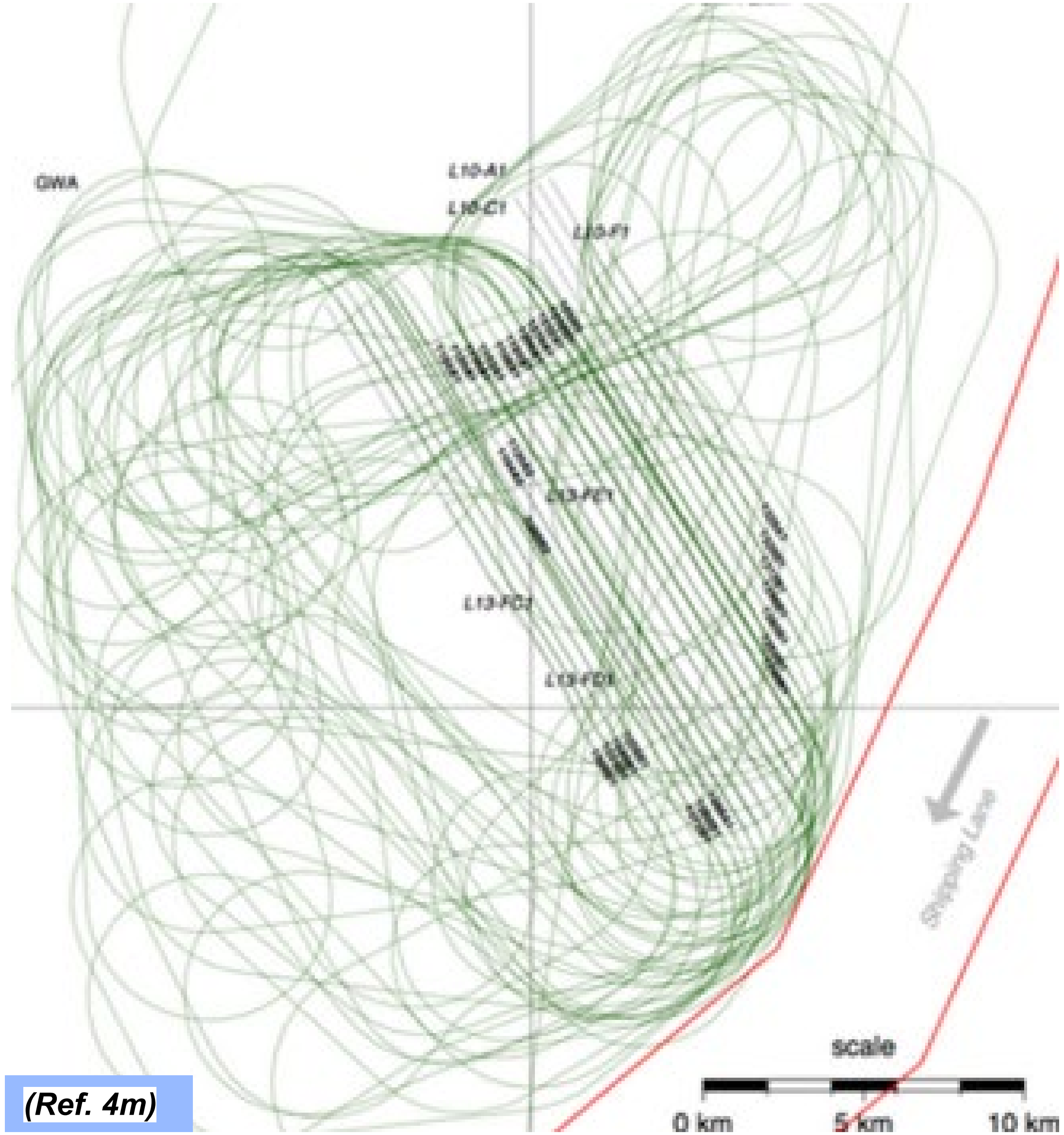


(Ref. 4l)

Whilst busy, especially along the already challenged near shore CCS licence area, it is not as busy as the TSS (Traffic Separation Scheme) along NW/North Europe. Locally the Humber area is busy, but note that not all small craft captured – likely many more than shown.

Marine traffic routing zones and example of level of activity

4.8 Obstructions lead to complex vessel track



(Ref. 4m)

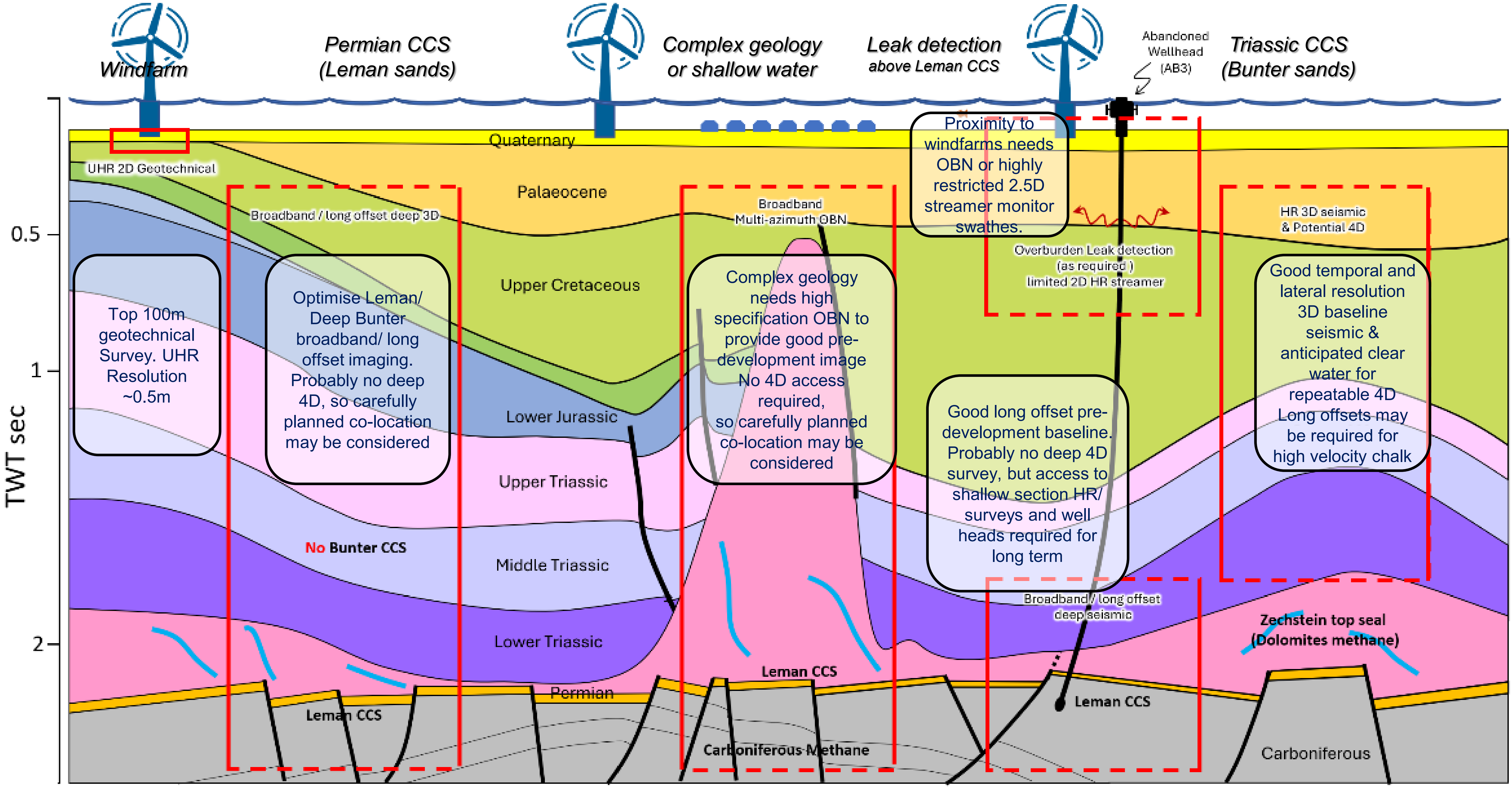
Dutch SNS 4D Survey

- Challenging operations to repeat exactly baseline seismic lines due to the high activity level in the area (shipping lanes, infrastructures, SIMOPS).
- Note the ~26 x 25km (c.650lineKm) acquisition lines requiring far in excess of1000Km of sailing and avoidance of the shipping lane.

High carbon footprint associated with surface obstructions

4.9 SNS developments & co-location reminder

North Sea Transition Authority



Previously shown in 1.7 SNS CS targets & seismic type and co-location access considerations

5. Streamer Seismic Technology

Section 5 Streamer Seismic Discussion

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This section builds upon the SNS parameter review (section 4.5) by overviewing the continuous step-wise acquisition improvements (Section 5.1) for either efficiency or resolution. In more detail, section 5.2 introduces the problem that seismic illumination can vary across a subsurface surface which particularly affect conventional narrow azimuth (NAZ or NATS) seismic. Multi or wide azimuth seismic (section 5.3) provides better illumination, whilst (section 5.4) a long tail streamer seismic design captures the refractions necessary for improved FWI velocity model building.

4D seismic repeatability has been greatly enhanced (section 5.5) by the development of steerable sources (and/or streamers). Section 5.6 provides a greater discussion about the development of broadband seismic which is one of the major technological breakthroughs. Broadband concerns extending the frequency bandwidth (and therefore temporal/ vertical resolution) of the seismic to include lower frequencies (<5Hz), which are valuable for "inverting" the seismic to more geological discernible units and high frequencies (>~40Hz) to improve fine scale interpretations. A type of broadband acquisition usually involves using recording different & multiple types of recording sensors. Multi sensor acquisition also enable shear wave recording (5.6d & 5.6e).

Historically processing focussed on optimising the primary (signal) and suppressing the multiple (noise). Processing these can also allow signal and noise to be separated to extend the extent / aperture of the usable signal (Section 5.7). In addition, a recent development allowing sources to be deployed directly above streamers means that the data is so-called "zero offset" – allowing a much better image of shallow water bottoms. Sources-over-streamers too have brought improvements in near offset/near seabed imaging (Section 5.8). Such "negative offsets" are especially useful for SNS water bottom and near seabed imaging (for CCS).

On the source side (section 3.3d), most surveys have used 2 sources fired synchronously (so called flip and flop) and designed to that the signal from the previous shots has diminished before the next shot occurs. A recent switch to greater number of sources (Section 5.9a) is very efficient but generates overlapping "simultaneous" shooting. This critically relies upon processing of the separation of source signature from the overlapping recorded data. Going to hexa, small, and more closely spaced sources provides higher spatial resolution, when coupled with sources directly over cable acquisition (Section 5.9b) it can produce a very high near trace density, valuable for shallow section imaging and resulting excellent shallow gas hazard detection. Not only multiple smaller sources, but the industry is increasingly looking trending towards smaller and environmentally friendly sources (Section 5.10).
The Endurance HR CCS seismic & bathymetry survey is described in more detail (Section 5.11) and this section concludes with the short-offset P-cable acquisition design (Section 5.12).

(Ref. 5a)

5.1 Streamer Seismic advancements

North Sea Transition Authority

Changes that drive improvements in seismic technology can be categorised by productivity and imaging:

Significantly improved productivity

Cost per square mile of 3D was reduced a factor of five from 1990 to 2000).
Substantial increase in number of streamers per vessel,
- from ~2 up to 10 in the SNS and 20 worldwide

Wide swathe tow (<~1km) are efficient, but at the loss of near offset and poor cross-line shot sampling

Shallower target specific imaging

Provided by High Density/HR - closely spaced streamers
High lateral & in-line resolution with bins down to 3.125m and less.

Longer streamer (up to 6km in SNS and 10km worldwide)

Capture more far offset data for complex ray path imaging
Better velocity model building (e.g. FWI)
(when currents & water depth permit)

Broadband acquisition & processing: Major breakthrough

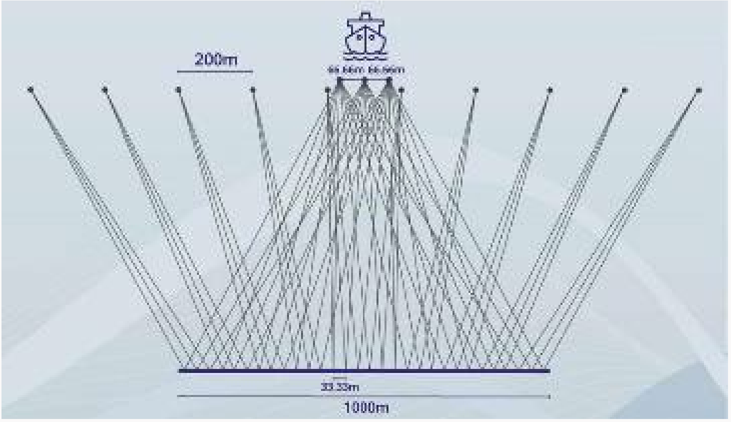
Improving temporal resolution (if water depth permit).
Meanwhile processing-based de-ghosting can work on all cable acquisition geometries to produce a pseudo-broadband result (section 10.6).

These factors are accommodated by:

- Larger & quieter purpose-built vessels up to 110m in length.
- Multiple (<10) smaller sources.
- Better and denser in-sea positioning networks.
- Quieter streamers (gel/solid) with High channel count & single sensors.
- 24bit continuous recording: noise attenuation, lateral resolution & simultaneous shooting.
- Near uniform zero offset with sources over streamers allowing seabed/shallow imaging.
- Legacy surveys ~ 160m from source to first (near) offset receiver.
- Near field hydrophones for shot-by-shot designature.
  - Dual hydrophone per gun/cluster for more accuracy.
- Low-cut filters "out" so more low frequencies.
- Very long streamer tails, on a subset of streamers, for velocity model building.
- 4C streamers enabling wavefield reconstruction.
- Increasing 4D seismic repeatability (especially Steerable streamers and sources).

(Refs. 5b, 5c,5d & 5e

Triple source streamer in cross section



Prior to 2000, the North Sea was dominated by standard "short" offsets (3-4km) streamers, with "long offsets" (<6km) appearing in early 2000's. Many multi-sensor/ broadband and ultra short (P-cable) streamer developments (2008-2013) and source over cable (TopSeis) later in that decade. Little had changed on the source side until triple sources & deblending emerged in mid-2010's. Whilst Ocean Bottom Seismic has been around for a long-time, high-density programmes transformed from being field-specific to a regional exploration tool in late 2010s.

Considerable number of step-wise advances in streamer technology

5.2 Illumination- not all points are equal

Seismic wave propagation through the Earth becomes complicated when rapid lateral variations in the geological (velocity) model exist above or near the target.

In UKCS these occur in high velocity Upper Cretaceous chalk or salt (halite), especially adjacent to, or below complex diapir structures (section 1.7).

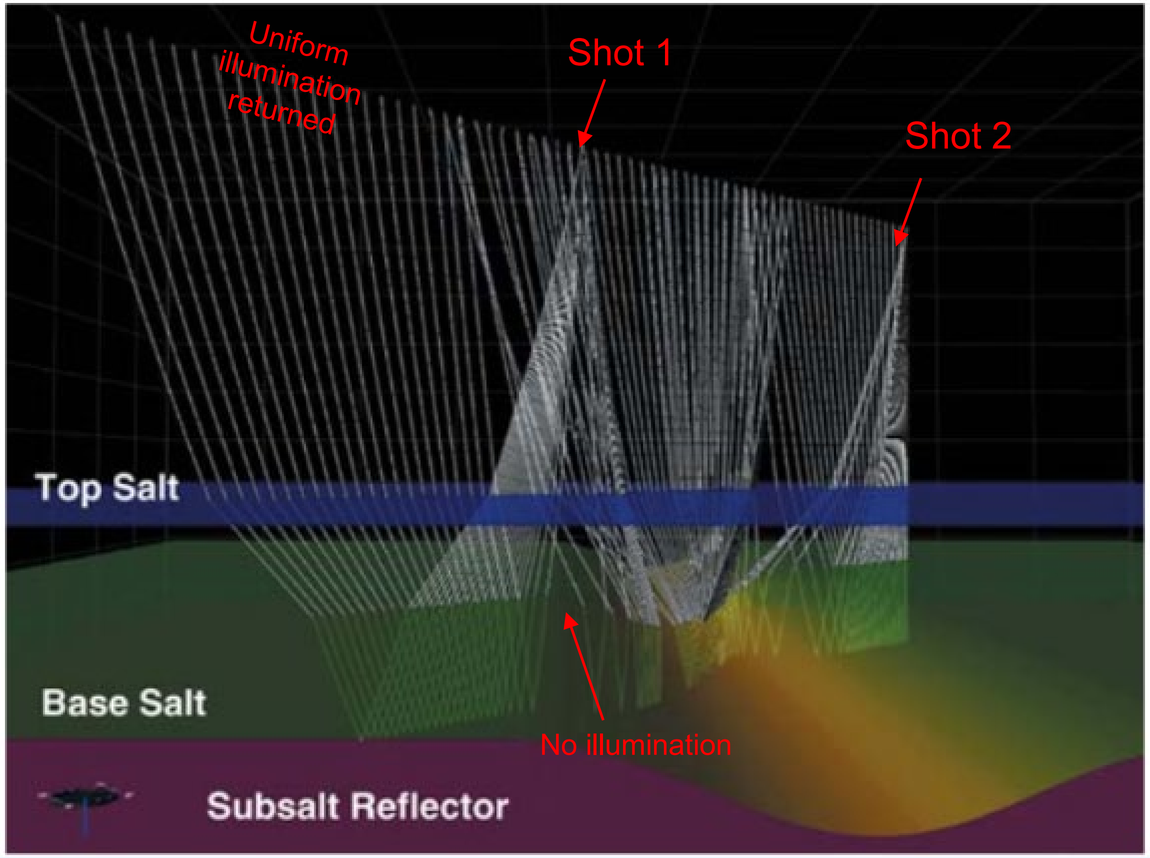
In the worst scenario "multi-pathing" occurs: several seismic arrivals from the same interface are recorded at coincident surface locations, causing:

- Degraded image quality, resolution and interpretability.
- Parts of target interface correspond to holes in seismic illumination.
- Causes weak or scattered seismic energy may be reflected back to the surface.
- Resulting in poor or useless seismic images.

Poor illumination is most common in the single vessel streamer because of NAZ narrow range of source and receiver distributions for any given shot.

Azimuth explanation:
A conventional narrow azimuth (NAZ) 3D acquires seismic where source and streamer are virtually in a straight line.
Dual azimuth is where a second straight line (NAZ) survey is acquired in a different orientation and co-processed in improve illumination.
Rich Azimuth is usually obtained via an OBN survey where many more source-receiver vectors can be acquired (e.g. 27).

3D perspective of synthetic GoM seismic wave path modelling



2 Simulated shots and resulting distorted reflection ray paths as (2) traverses more complex high velocity salt

(Ref. 5f)

Synthetic example of different ray paths and illumination issues

5.3 Multi-Azimuth seismic

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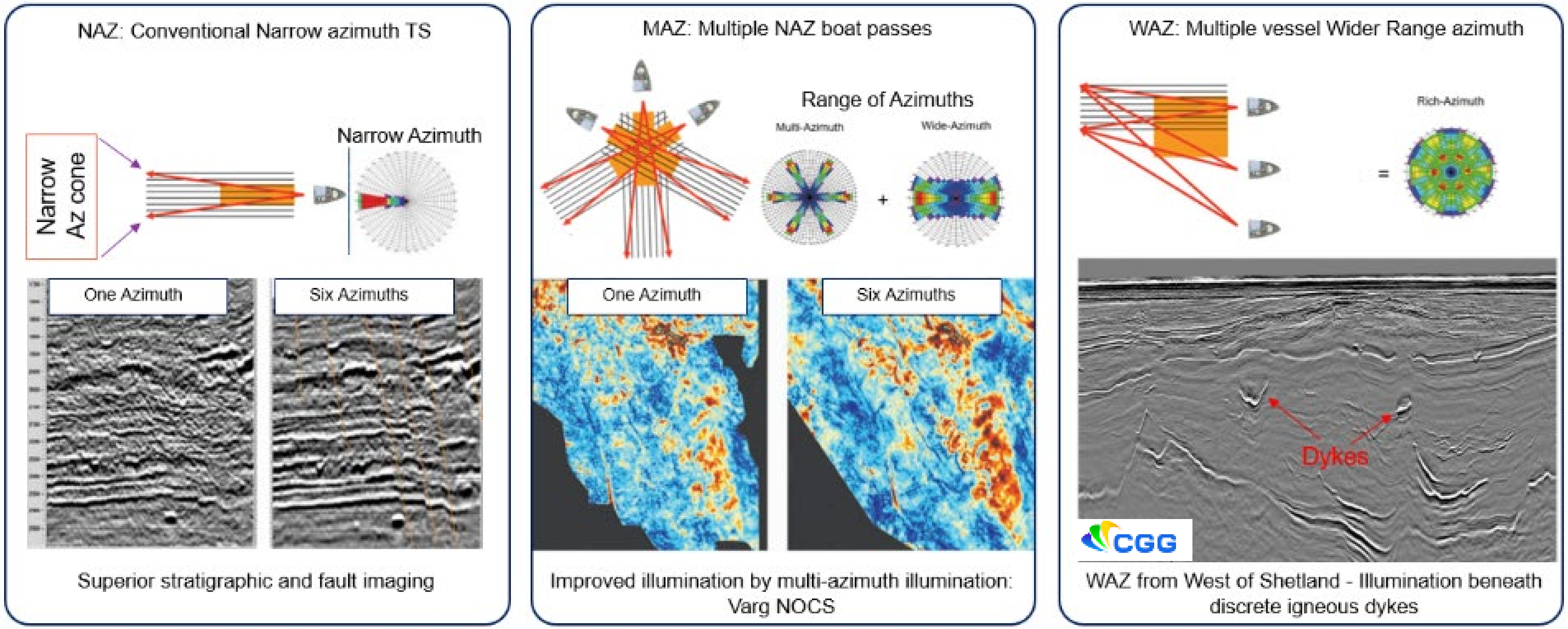
Complex geology and highly refractive (fast) layers cause ray bending that can leave portions of the subsurface untouched by seismic waves or poorly illuminated. A range of acquisition options are available which are typically described as being wide azimuth in compared conventional single vessel narrow azimuth. Each has a different operational niche, but they all benefit from the principle that high wide-azimuth fold is better than narrow azimuth to alleviate problems of illumination, signal-to-noise (S/N) ratio, and multiples.

Azimuthal seismic options



(Refs. 5g, 5h, 5i, 5j, 5k, 5l)

Much of the UK-CNS is covered by Multi-Azimuth (MAZ) streamer surveys involving extra pass(es) of NAZ acquisition to improve image quality by adding additional value to legacy single azimuth 3D. Wide azimuth streamer seismic became popular for "undershooting"/ discrete complex structures. OBN/OBC deliver the most comprehensive "Full Azimuth" seismic. All options come with higher costs associated with more vessel time than NAZ.

Variants of multi-azimuth seismic are applied for complex imaging

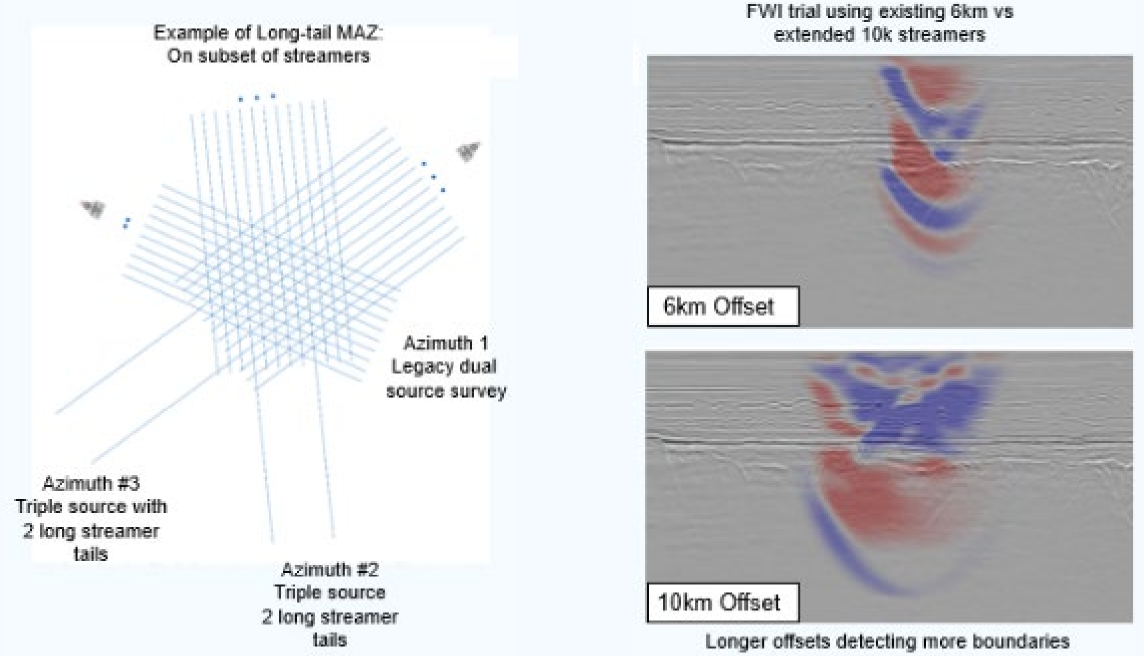
5.4 Long Streamer Tails

North Sea Transition Authority

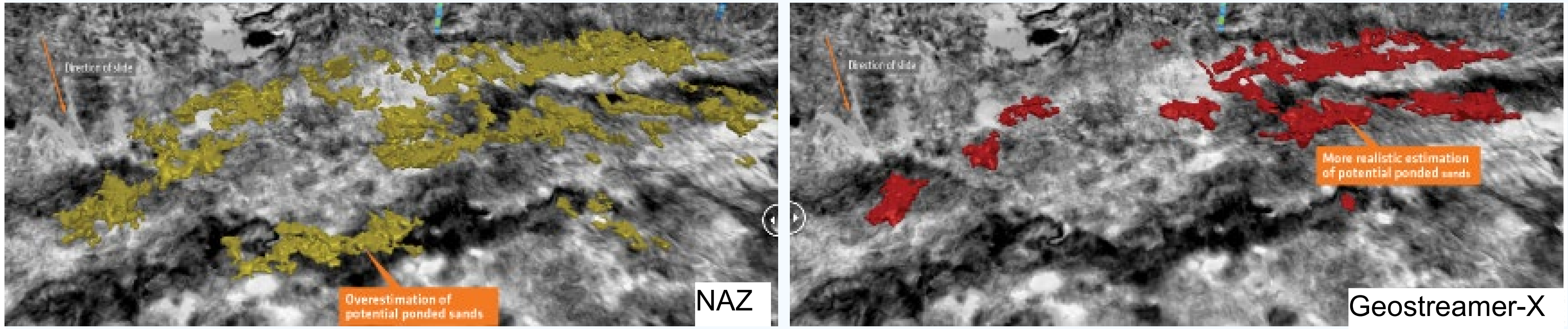
An option to have long tail streamers assists FWI & velocity model building. This example from the Viking Graben includes isolated cemented injectites that have historically resulted in shadow zones at target level. It is claimed that single seismic vessel enables multi-azimuth acquisition at a much lower cost compared to OBN operations.

Multi-azimuth acquisition design with 2 new azimuths comprising wide-towed triple sources, 12 streamers including 2 extended 10km offset-tails (2-in-1) to provide a simultaneous velocity survey. The velocity trial shows that FWI can be applied down to the target interval of 3km with the longer offset cables.

Long tail seismic and impact on velocity model



Viking Graben Geobody: sand prediction



The NAZ seismic image is noisier, less coherent and potentially over-predicts the ponded sand distribution compared to PGS's multi-azimuth Geostreamer-X image

(Refs. 5m, 5n, 5o)

Longer offsets by extending streamer tail, improves velocity field to detect more boundaries and ultimately image reliability

5.5 Steerable sources and streamers for 4D

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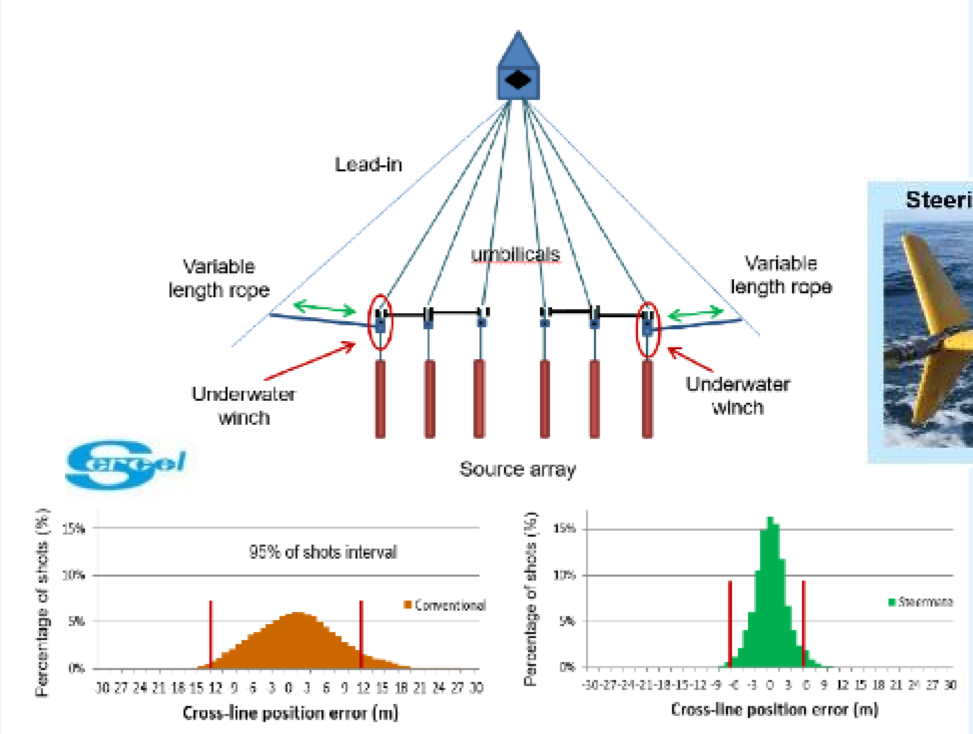
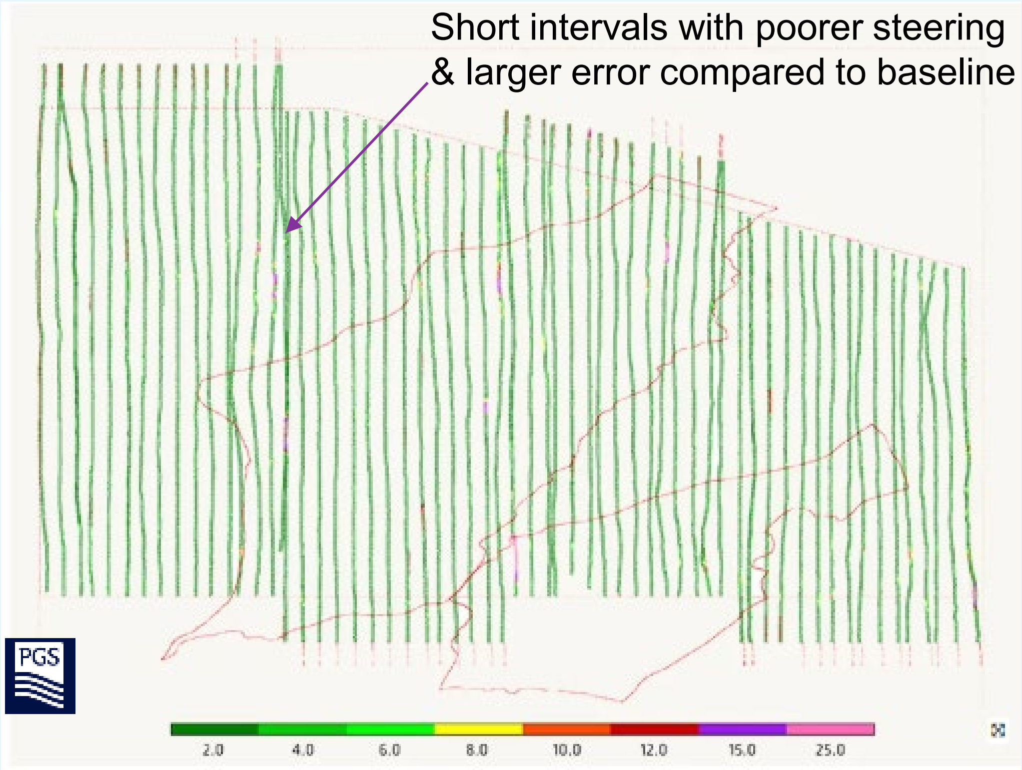
Steerable sources and streamers can improve 4D repeatability by reducing the effects of variable currents on acquisition geometry. Computer controlled winches on the sources reduce difference from original baseline survey position, by a maximum of 4m correction. Meanwhile wings on the streamers can provide lateral steering and depth control to reduce the impact of feather mismatch automatically to within +/- 3 degrees.

Vessel and source steering for 4D diagram



Steerable sources reduce repeatability position error

4D survey acquisition track map



Colour bar is source position error (m) compared to baseline 3D

(Refs. 5p,5q,5r & 5s

Source and receiver repeatability is a major factor in reducing mispositioning “noise”/ enhancing 4D signal reliability

5.6a Broadband Seismic & interpretation

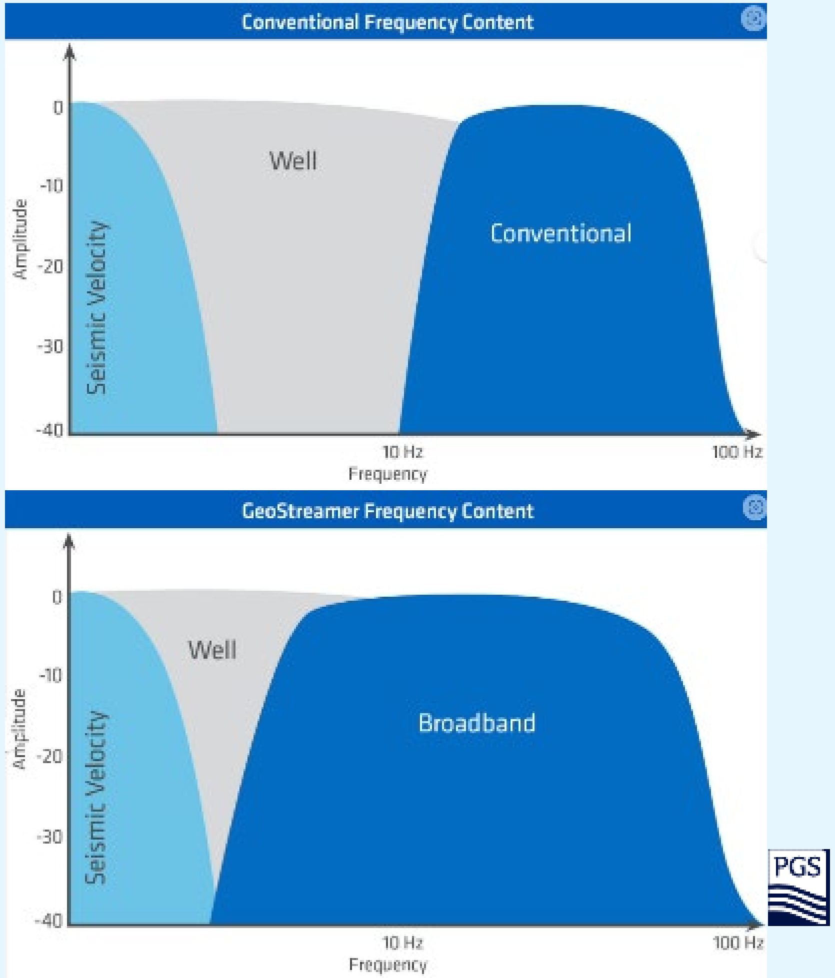
North Sea Transition Authority

‘Broadband seismic’ describes an acquisition and processing system with source and receivers which enhances and preserves the bandwidth at both low and high frequencies in a pre-stack amplitude and phase-compliant manner. The lack of low frequencies has a detrimental impact on processing (less compact wavelet), seismic imaging (weaker resolution of deeper targets), inversion (missing long wavelength trends) and reservoir characterisation (weaker thin bed resolution). Usually broadband seismic has a much lower frequency bias.

Broadband frequency spectrum

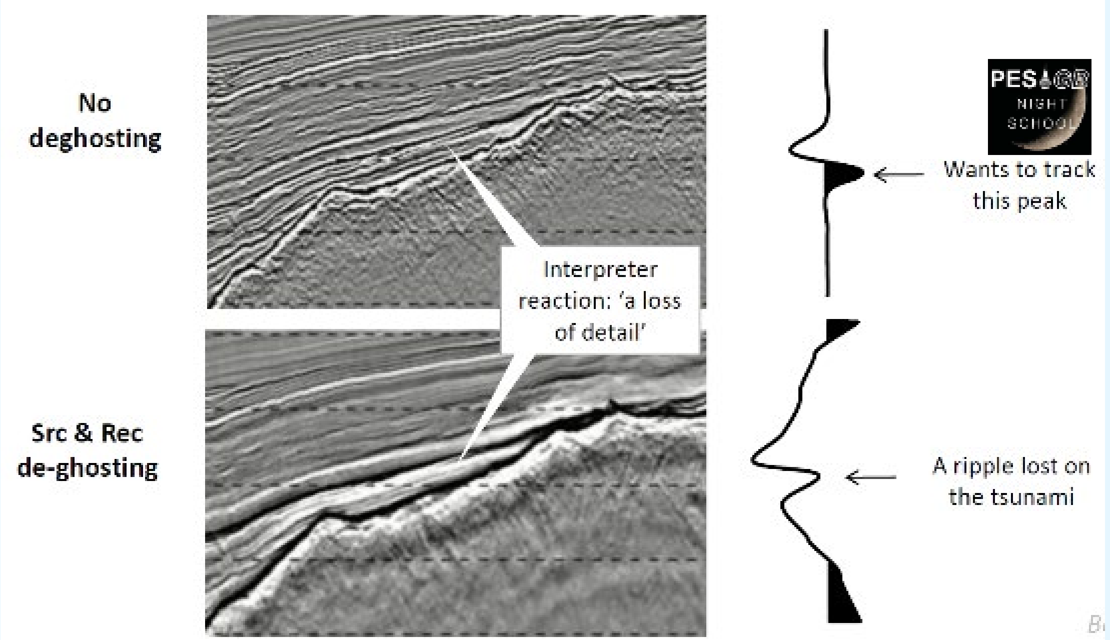
Narrow band seismic would invoke well based data to infill the low frequency spectrum

Broadband data focussed on improving low frequencies



(Refs. 5t,5u & 5v)

Impact of deghosting on seismic image



- The deghosting process improves the bandwidth but can give an *apparent* loss of high frequencies.
- Interpreters’ initial reaction is often that the vertical resolution (fine scale imaging) is missing.
- In practice, there is more information in the broadband seismic and mapping; “ripple on the tsunami” provides a more accurate subsurface description of the event.

Multi-sensor streamer seismic transformed broadband seismic acquisition

5.6b Multi-sensor Broadband acquisition

North Sea Transition Authority

Mapping seismic reflections interfaces inherently relies upon a large contrast in either the sonic (velocity) and/or density. Conventional seismic relies upon P-waves recorded on single component omni-directional (1C) hydrophones. Streamers incorporating both pressure and particle motion sensors are now co-located along the length of modern streamers. Reflected P-waves travelling upwards have a strong vertical component at the surface receiver. The pressure and velocity sensors record each upgoing seismic event with equal polarity, while the time-delayed downgoing seismic event is measured with opposite polarity.

Method:

- Up going wavefield has not been scattered off sea-surface,
- Whilst the downgoing has been reflected off the sea-surface,
- Hydrophone only recording is contaminated by these “ghost” notches in frequency spectrum
- Wavefield separation can be achieved in streamers using 2 component (P- hydrophone and one geophone/ velocity sensor) or 4 component (additional 2 horizontal geophones) to improve the overall processed signal.

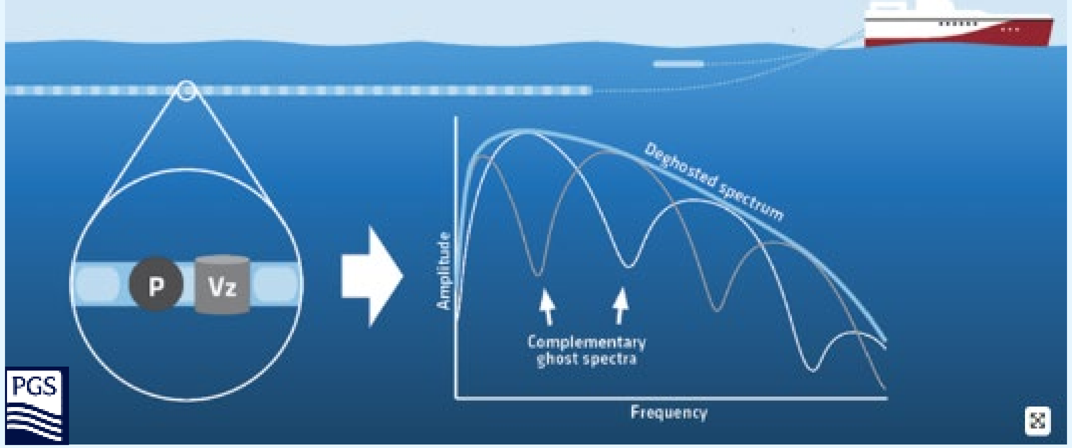
4 component sensors within cable

WesternGeco Isometrix Comprising Hydrophone (P) & accelerometer particle movement in Z and cross cable (y) direction

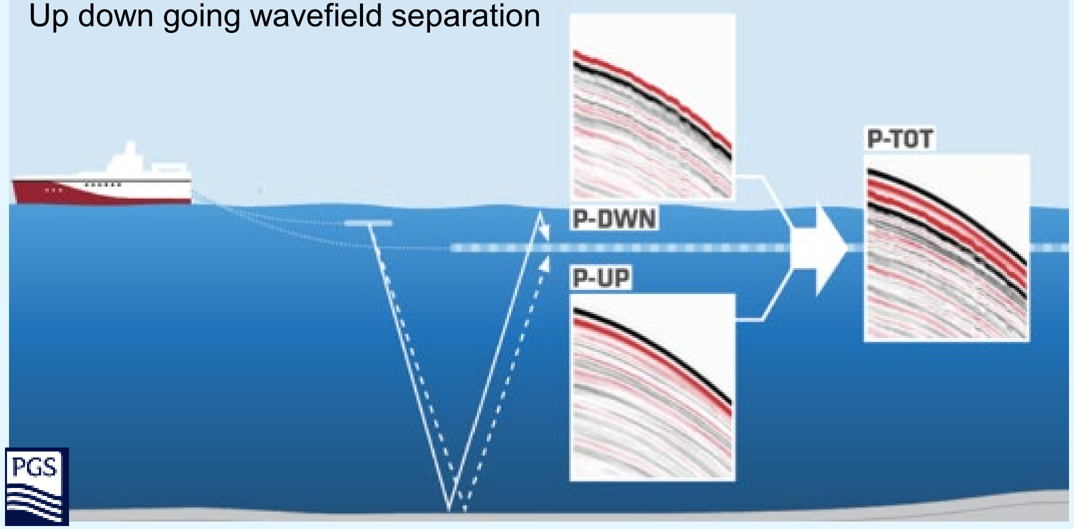
(Refs.5u & 5v)

Multi sensor seismic implications

Removal of “ghost” notches in broader frequency spectrum



Up down going wavefield separation



Multi-sensor streamer seismic transformed broadband seismic acquisition

5.6c Wavefield separation (OBS application)

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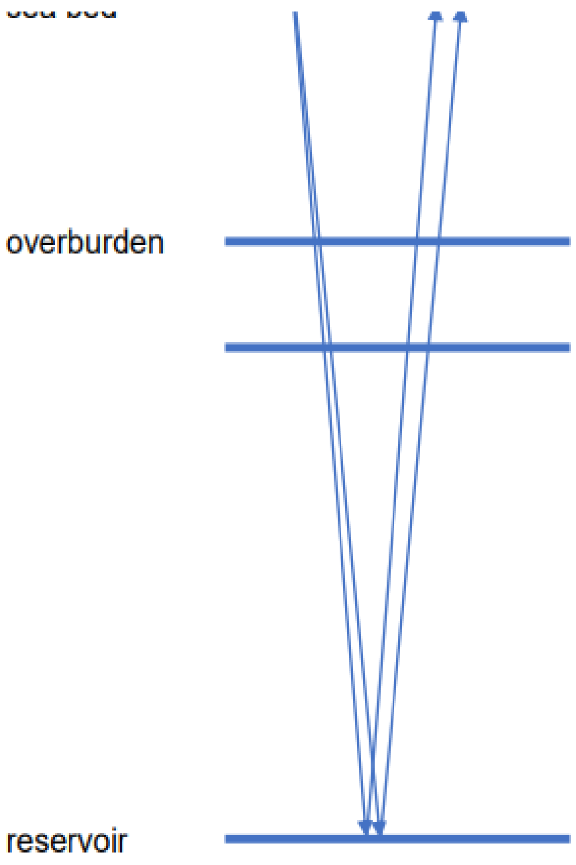
Wavefield separation can be undertaken with either 2 or 4 component streamer or OBC/OBN data. This description was written from the OBN perspective:



insensitive to the direction of propagation of the seismic energy.

A 3-component geophone measurement is **directional** – delivers a **vector** with (x, y, z) component.

One of the key advantages of OBN seismic is that we can identify and remove certain modes of seismic multiple energy by exploiting the different characteristics of hydrophones and geophones.

We separate the recorded signal into **upgoing** and **downgoing** wavefields from which a third wavefield, the **reflectivity**, can be estimated by up-down deconvolution.

At Golden Eagle we observed that while the 4D

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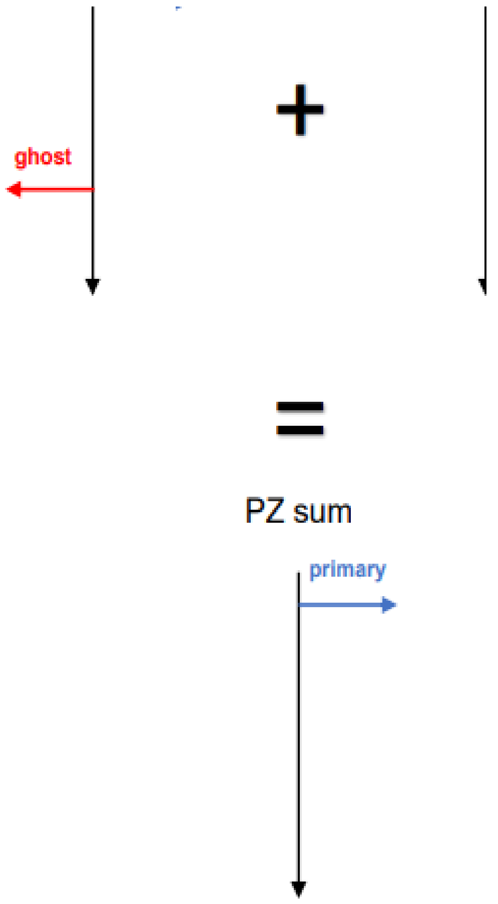

(Ref. 5w)

Up and down going wavefield separation

5.6d Multi-component /Shear wave Seismic

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Seismic energy is partitioned into both upgoing (reflected) and downgoing (transmitted) waves (both P and S). This occurs at every interface in the subsurface.

S-waves are transverse sound waves that have particle motion perpendicular to the direction of travel. Shear is only recorded in OBS or land seismic as the geophones are coupled to the ground/seabed and as a result can measure ground movement; this is not the case for streamer data.
However, most of the observed S energy is mode-converted PS energy (i.e., wave that travels down to a geological boundary as a P wave, gets partially converted to S energy at the boundary and then travels back to the surface as an S wave). Compared to P-waves, the (converted) S-waves are less affected by fluids. PS-wave arriving at the surface will have a strong horizontal component of particle motion. Multi-component seismic recording is needed to measure both the vertical and horizontal components of ground motion.

(Refs. 5x, 5y, 5z,

Schematic of P and S wave seismic

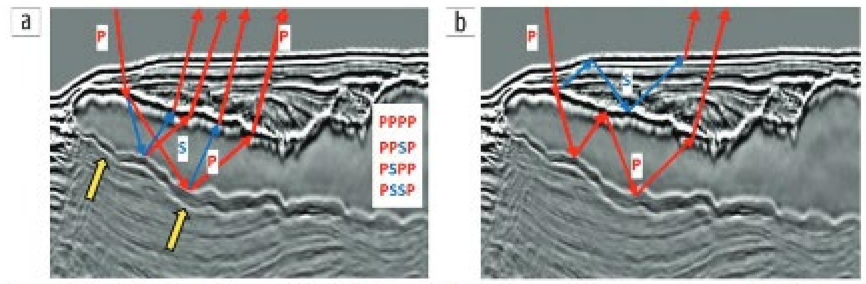
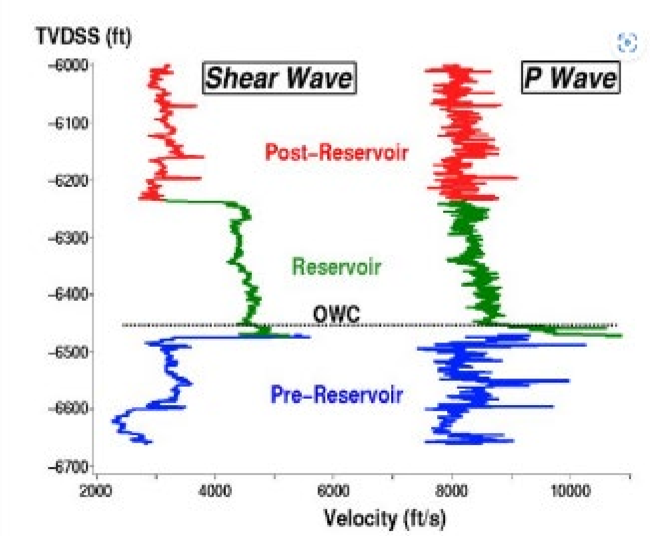


Figure 1. (a) Four different arrivals for a single incident P-wave to the top of salt raypaths of some mode-converted reflections at the salt boundaries. (b) Raypaths of interbed multiples between salt boundaries and water bottom.

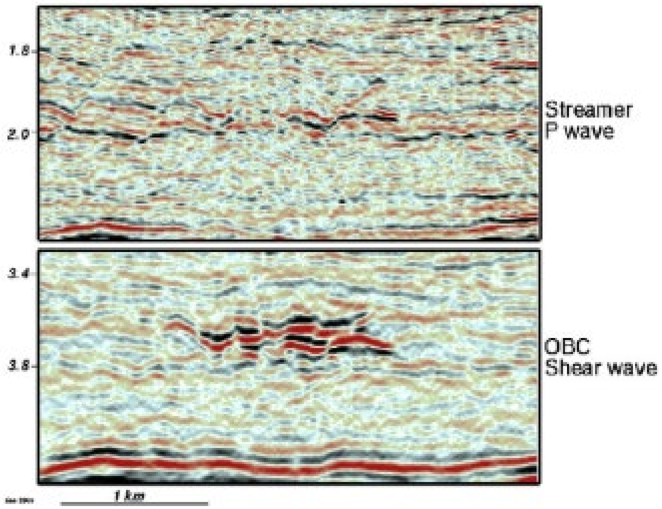
Converted seismic waves (specifically, downgoing P-waves that convert on reflection to upcoming S-waves) are increasingly being used. Streamer data only records P-waves

(Ref. 5aa, 5ab)



Alba Dipole (P & S) log

The well logs show very little P-wave contrast at both the top and base of the Alba Eocene. A large (S) shear wave contrast at top reservoir, which could be successfully identified with multi-component (OBC) seismic and mapped.



The reservoir can be clearly identified using shear wave data derived from the multi-component (OBC) seismic (see also section 5.6e)

Application of shear wave seismic

5.6e Multi Component Shear wave imaging

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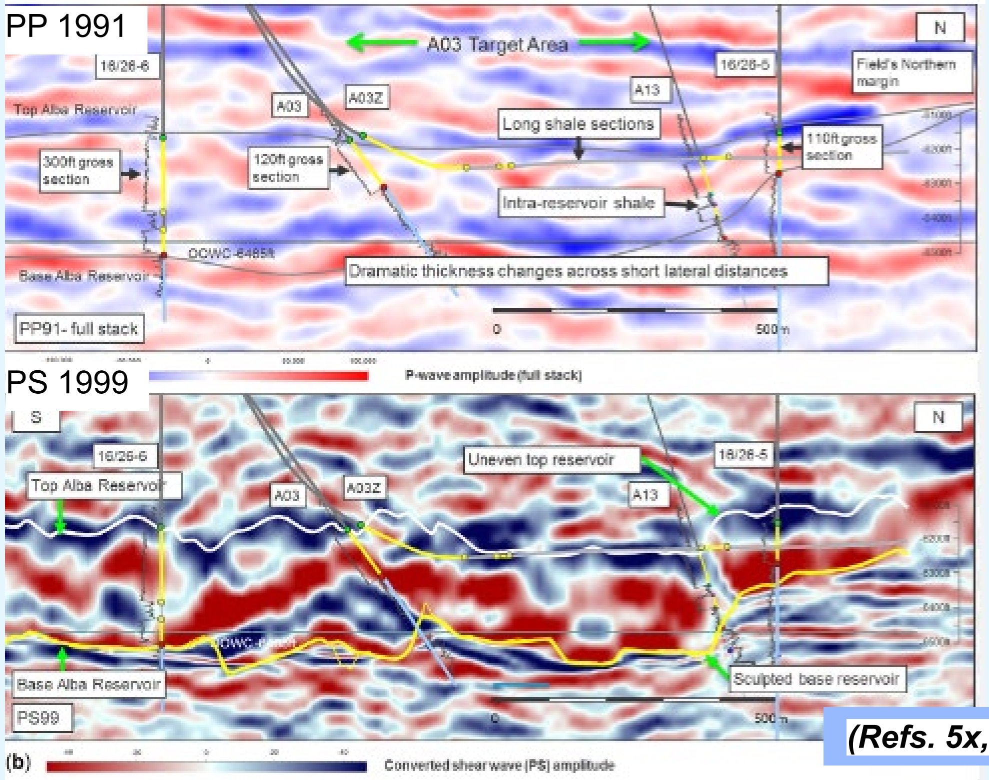
One of the additional imaging benefits of multi-component data is the calculation of shear wave imaging via either streamer or OBN. Multi-component data combined with the 3D seismic facies analysis provides significant added value for reservoir characterization and delineation in a complex setting such as in the Grane Field. PP-data reveal both geological and fluid information, whereas PS-data contribute extensively to a better definition of the sand body geometry. PS-data allows a detailed analysis of the internal deformation features, structure, and mapping of the sand injections above the main reservoir sands connected to a polygonal fault network.

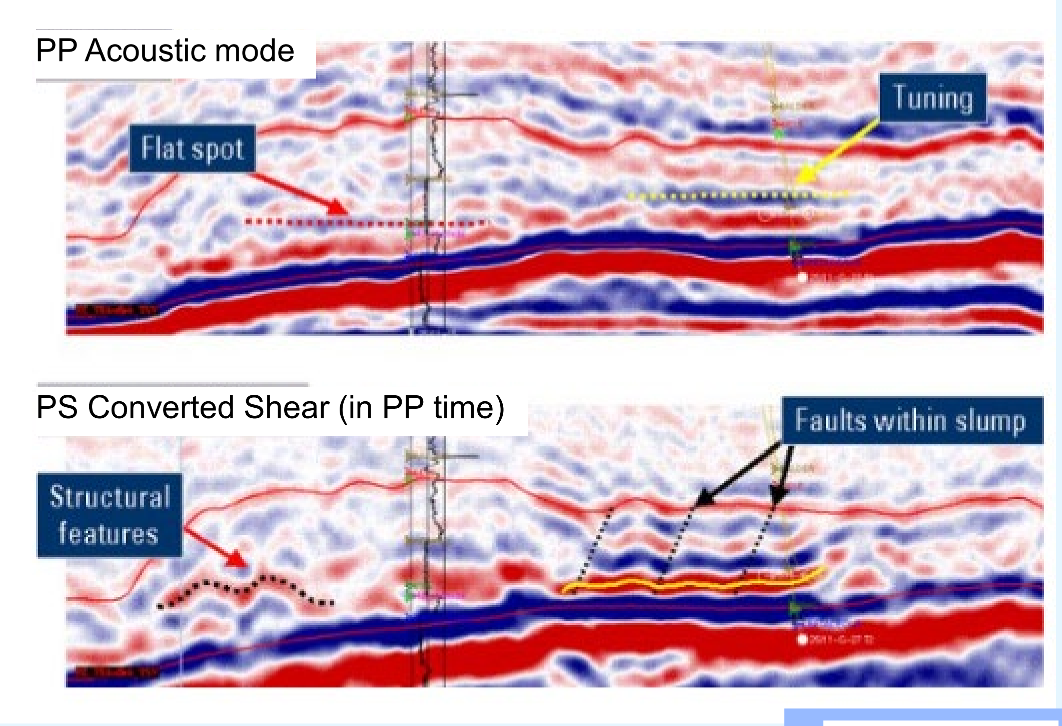
PP-PS OBC imaging Alba Field, UKCS.



(Refs. 5x, 5y, 5z,

Building on the Alba example in 5.6c) the PS also provides a broader band / low er frequency image which fits the sand distribution more closely, compared to legacy PP.

PP-PS imaging Grane Field, Norway.



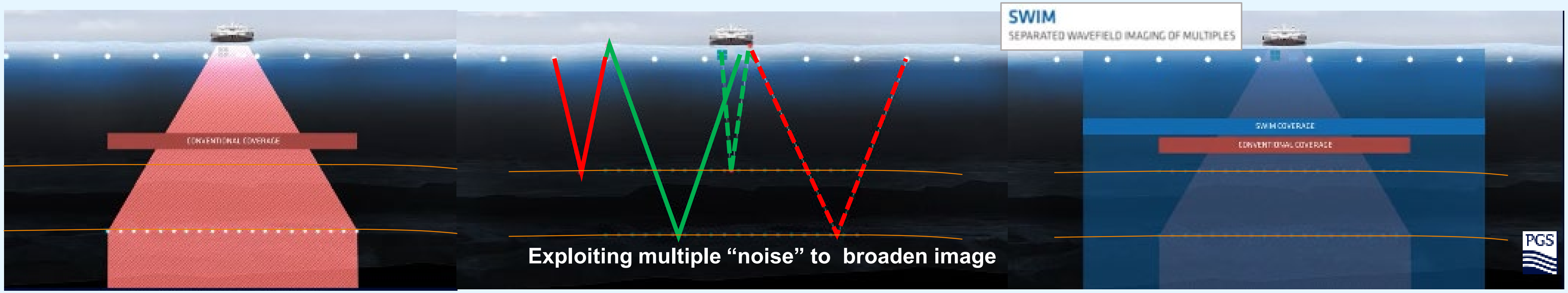
(Refs. 5ac, 5ad)

PP: both geological and fluid information; PS: better definition of the sand body geometry (internal deformation features, structure, and sand injections)

Shear wave seismic examples

5.7 Extending illumination with multiples

Traditionally multiples are treated as ‘noise’ within seismic processing and are removed to improve the overall signal-to-noise ratio. New approaches with multi-sensor streamers exploit the multiple as a signal, allowing for shallower and wider imaging. The technique requires multi-sensor streamer or OBC/OBN to separate the up and down going waves.

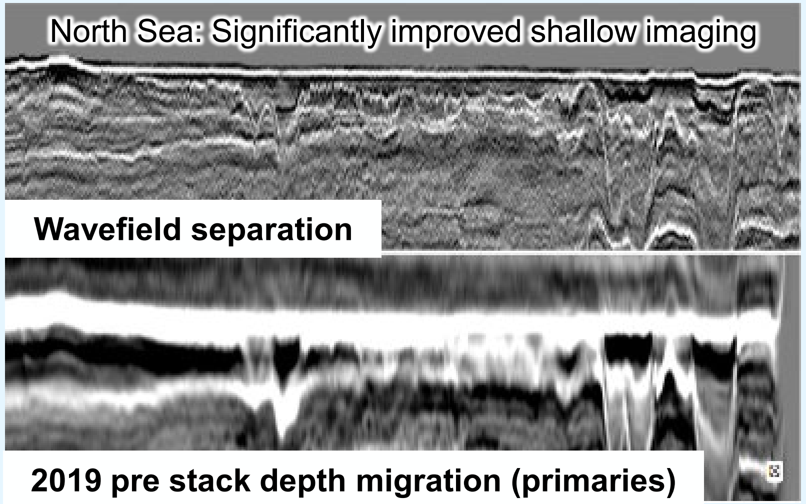


Traditional primary processing
Produce narrow swathe

Multi sensor streamer allows Primary and multiple “wavefield” separation

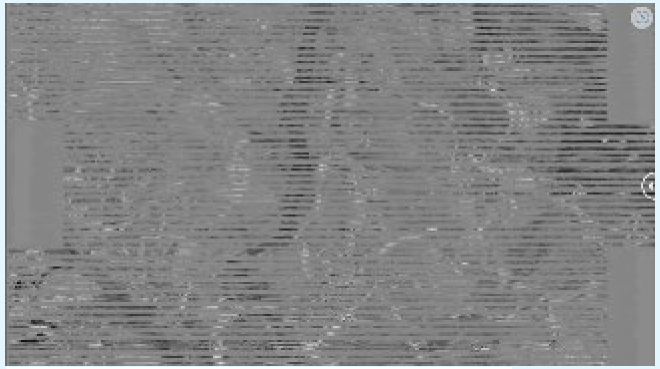
Broadens illumination & allows improved near seabed imaging

(Ref. 5ae)



Enhanced near seabed imaging

Malaysia 70m water depth, 3D slice @ 35m depth below mudline



Primaries processing leaves stripes

Wavefield separation illuminates shallow channels

Extending seismic and improved near seabed imaging by multiple “noise”. Works best in deep water.

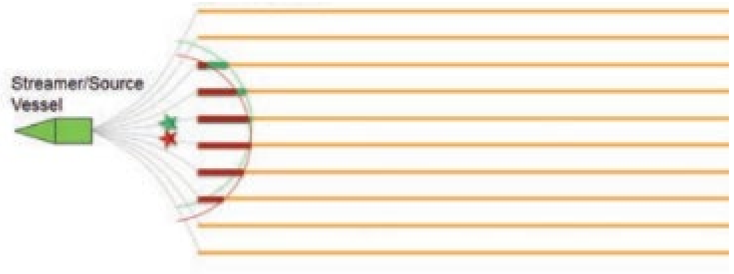
5.8 Source over cable

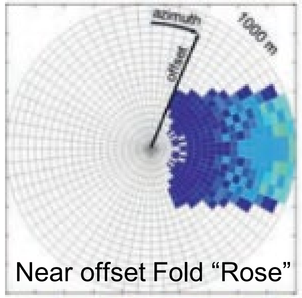
Conventional marine seismic surveys are typically a single vessel towing two airgun source arrays in front of a spread of 10+ streamers. This gives a relatively narrow-azimuth and lacks near offset data. The distance between the sources & streamers of 100-200m for the inner cables and up to 500 m for the outer cables. Near-offset and zero-offset data are especially critical for imaging shallow geological targets and of great benefit for multiple attenuation and improving the processed seismic result. TopSeis involves a source vessel positioned vertically above the middle of a slanted/deep tow cable and offers a substantial improvement in azimuthal illumination.

Source over cable seismic

(Ref 5af)

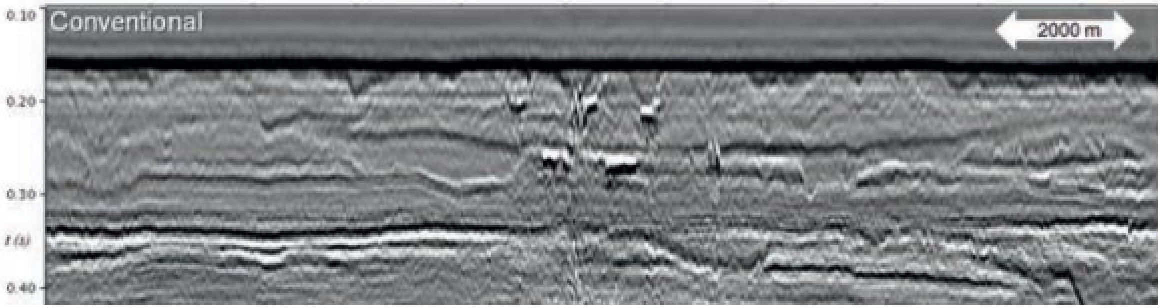
Conventional 2-Source "Flip-Flop"



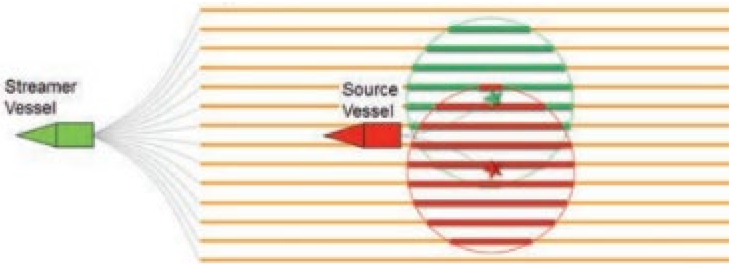


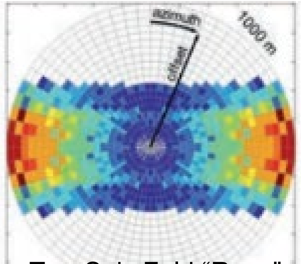
Near offset Fold "Rose"

Low & narrow azimuth spread



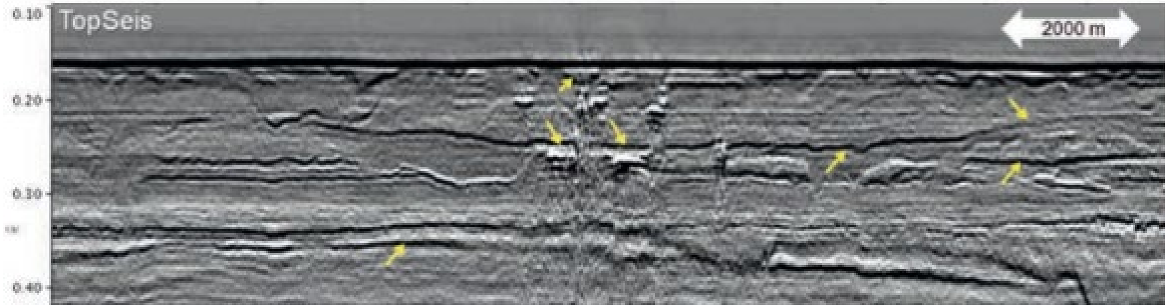
TopSeis: "Flip-Flop" Source Above Streamer





Top-Seis Fold "Rose"

Streamer vessel in front and source vessel sailing directly above and middle of all streamers. Higher near offset fold and broader azimuthal illumination



Complex shallow geological comparison with post-glacial Neogene channels several gas water bottom pockmarks. Both images show shallow structures, but TopSeis provides better definition.

Sources located over the receivers, provides greater near offset fold & better near surface imaging

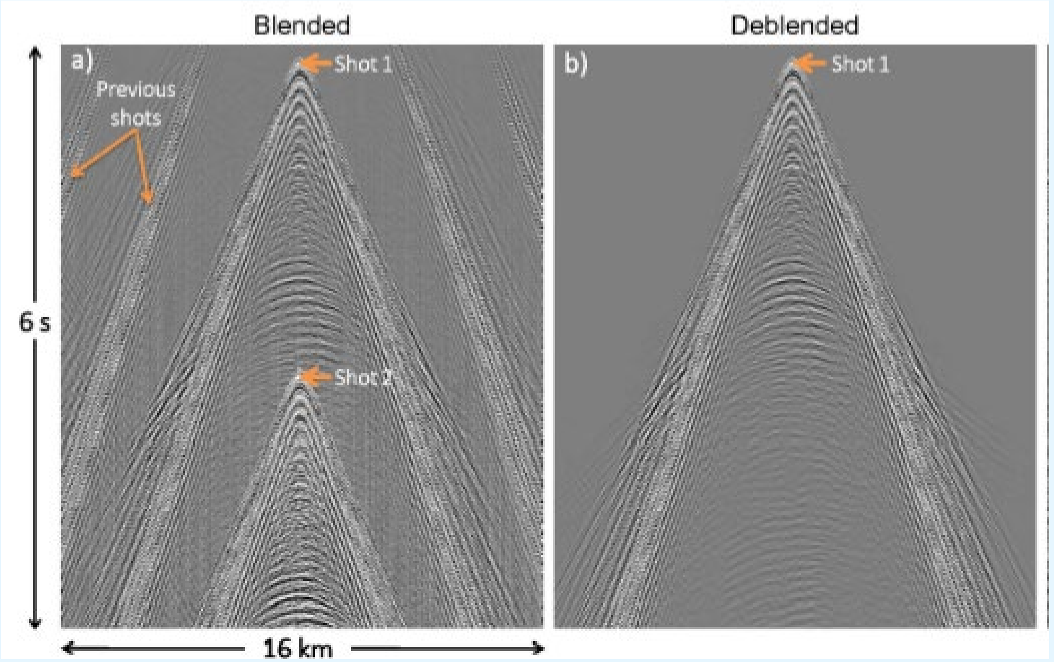
5.9a Multi-source - Simultaneous Acquisition

Most legacy 3D surveys have 2 sources (“flip flop”- section 3.3d) located in narrow tow mode positioned between the 2 innermost streamers.
The record length in time is dictated by duration the vessel takes to move from one source position to the next – to provide clean records.
Multiple airgun source arrays allow 4 sources (“flip flop flup flap”) or more sources are being used:

- Reduce average shot time creates overlapping shots.
- Improves efficiency by simultaneous shooting.
- Options to separate source from main streamer vessel.

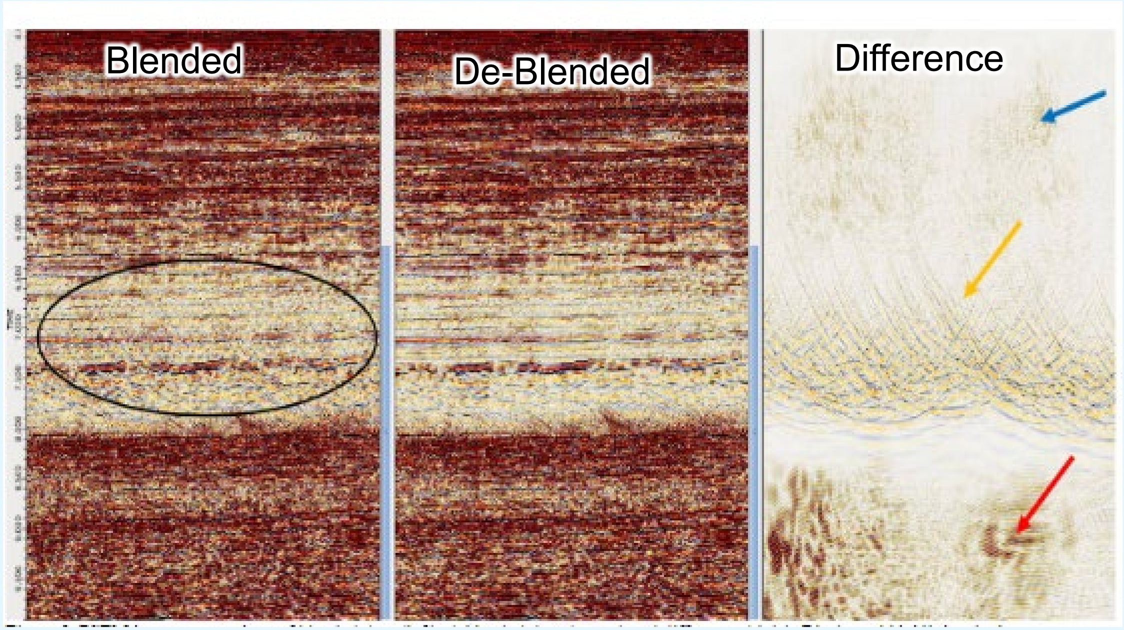
However, overlapping sources creates residual noise from previous shots which require "deblending" during processing.

Seismic shot gathers before and after separation



2nd shot appears with previous shot record ***(Ref 5ag)***

Simultaneously acquisition triple source OBN Migrations



Deblending removes most of previous shot noise

Simultaneous shooting with deblending now routinely adopted to improve efficiency

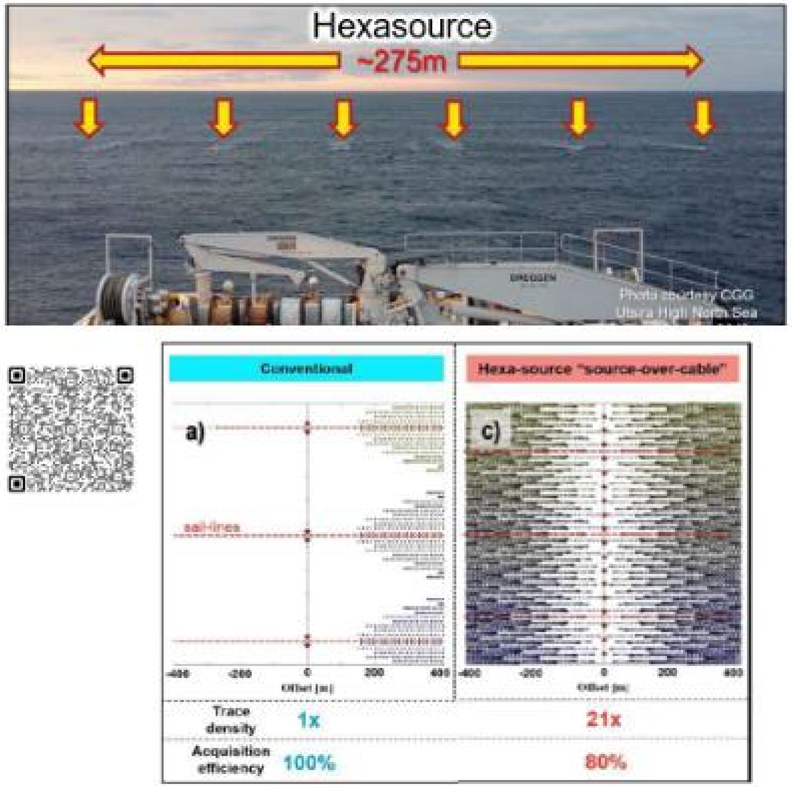
5.9b Hexa source with source over streamer

Hexa-source, and reduced volume sources can provide high resolution bin size 5x 6.25m.

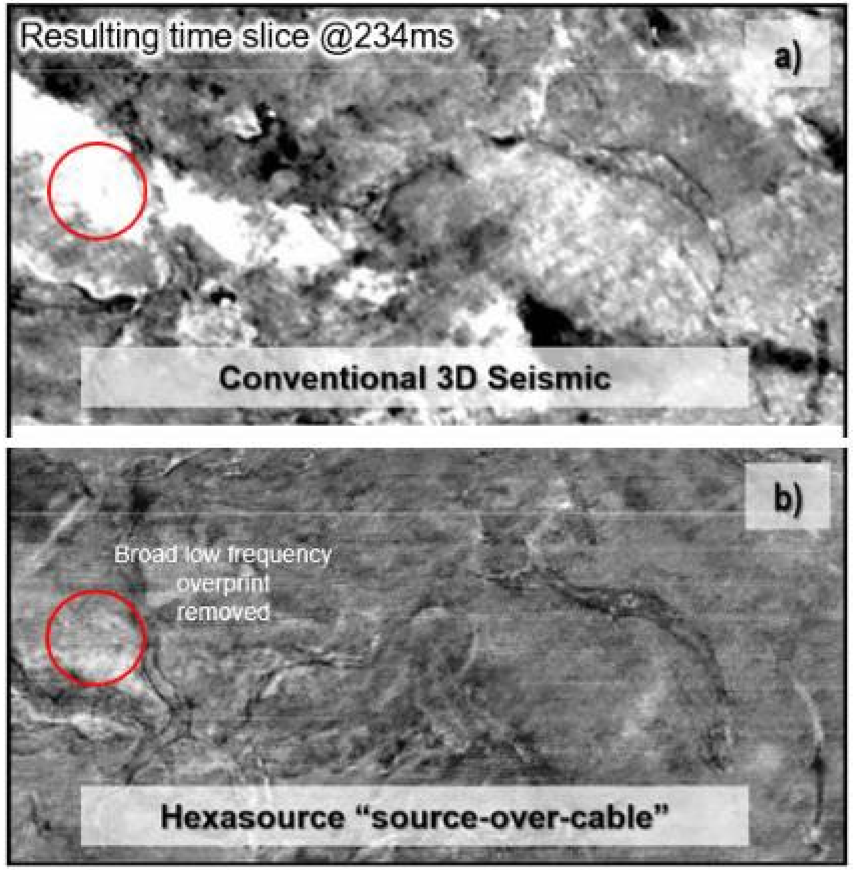
- Towed between innermost 2 streamers to decreasing cross line separation & increase lateral resolution.
- Or towed wider/ larger lateral separation (<250m) to improve near offset coverage distribution for shallow water/ shallow targets.

Combined with source-over cables provides very high near trace density.

Hexa source over streamer



Traditional 3D spread leaves large near offset gaps which can be infilled with larger number of sources atop the cables.



Greater spatial resolution- better channel definition

(Ref 5ah)

Hexa source provides higher spatial resolution (see also section 6.9)

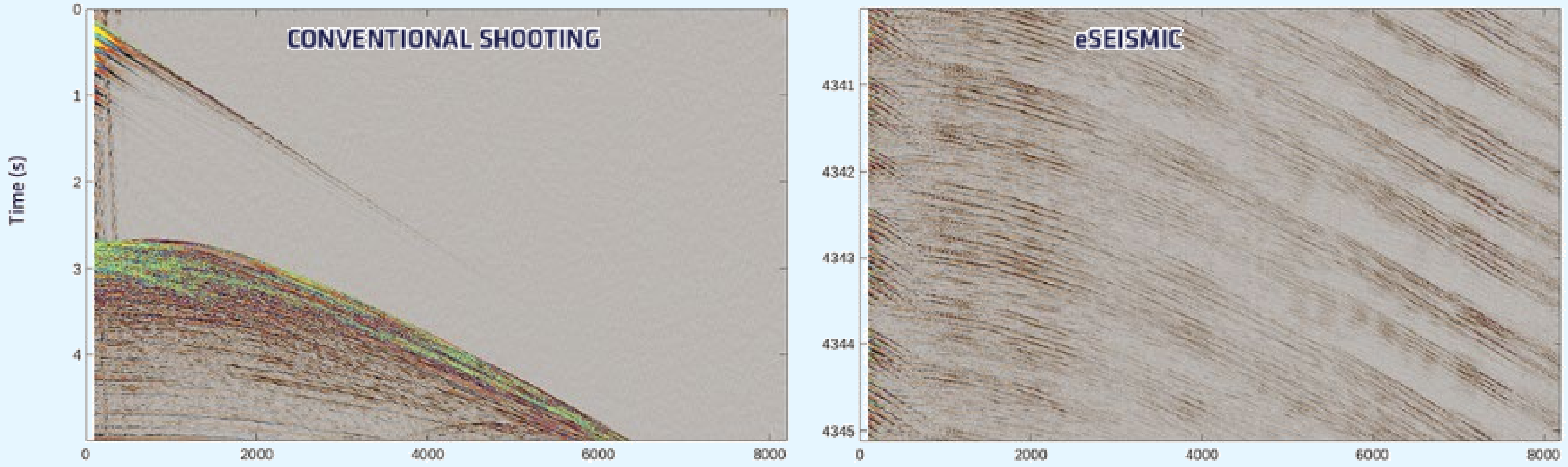
5.10 Reducing source output

- Historically the trend has been to increase the strength of the marine seismic sources:
  - Aim was to maximize the signal-to-noise ratio, therefore increase the peak pressure levels of the emitted energy.
  - Resulted in large arrays of air-guns triggered simultaneously.
  - High sound pressure levels increasingly result in environmental restrictions for seismic acquisition.

- Increasing recognition that airgun sources do not need to be so big for environmental reasons.

- Continuous E-source energy spread overtime to minimise emitted environmental sound levels:
  - Individual guns triggered randomly and recorded as continuous sail line.
  - Can supress high frequencies outside seismic bandwidth.
  - Results in a 65% reduction in sound output at 500m compared to standard 4130 cu in gun array.

Comparison of traditional shot gather with continuously emitted source



(Refs 5ai, 5aj)

Individual guns firing

5.11 Example of HR Survey (Endurance SNS: recall 3.5a)

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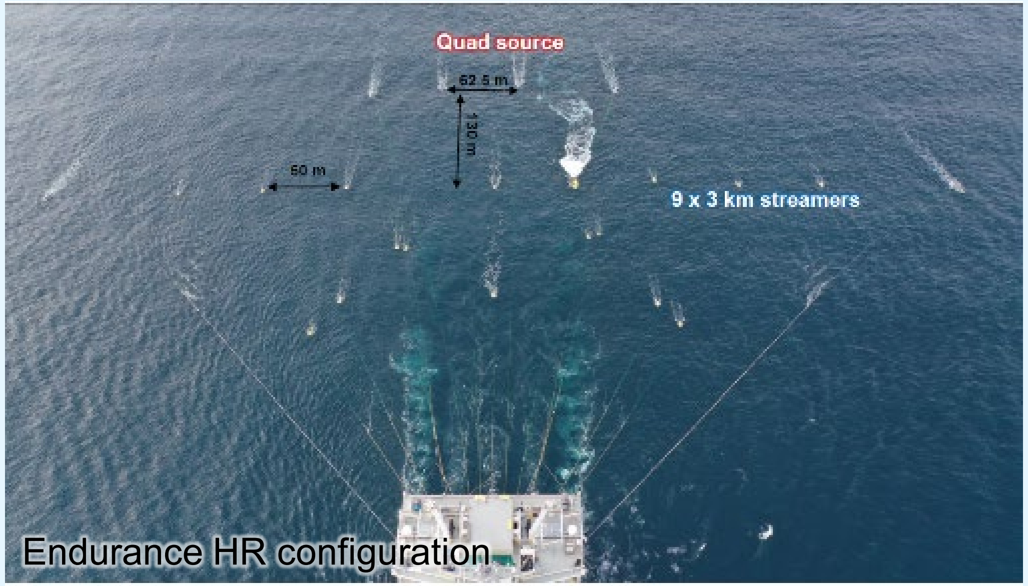
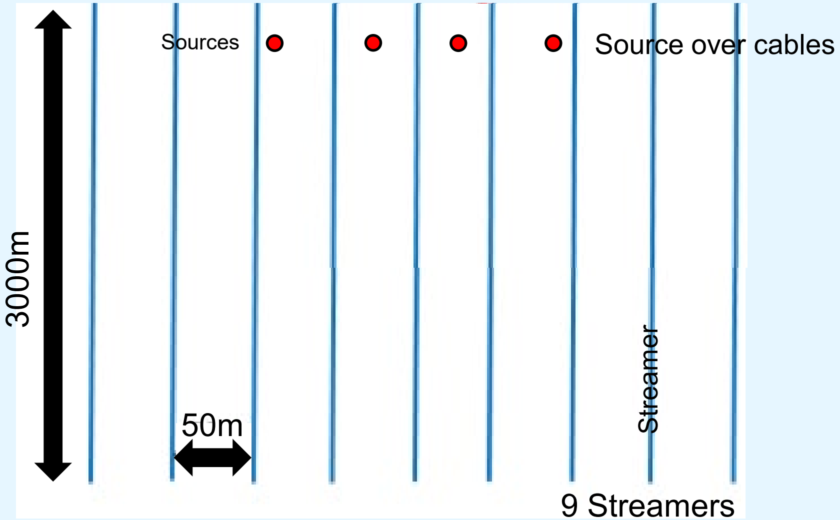


(Refs 5ak & 5ai)

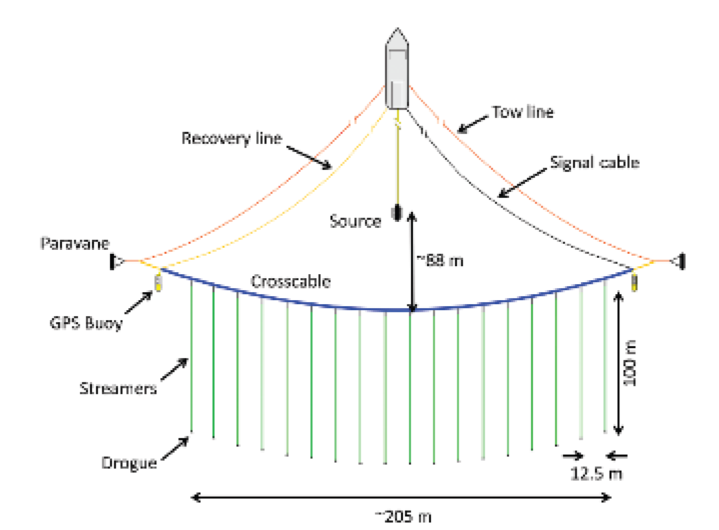


- Designed to image both targets:
    - Shallow seabed (20m)
    - Deep target (1000-2000m)
- Much larger area (1600 sq. km) compared to traditional HR (few sq. km).
- Wide tow / Multi-streamer sensors with 50m separation.
- Quad source (400 cu in) towed over front end of streamer spread.
- Acquisition bin size 6.25x6.25m, 40-fold.
- USV (Uncrewed Surface Vessels) used to de-risk shallow water areas.
    - Sandbanks <20m Water depth.

Modern 3D survey with preparatory bathymetry survey operation

5.12 Short offset P-Cable acquisition

Single source P-Cable configurations



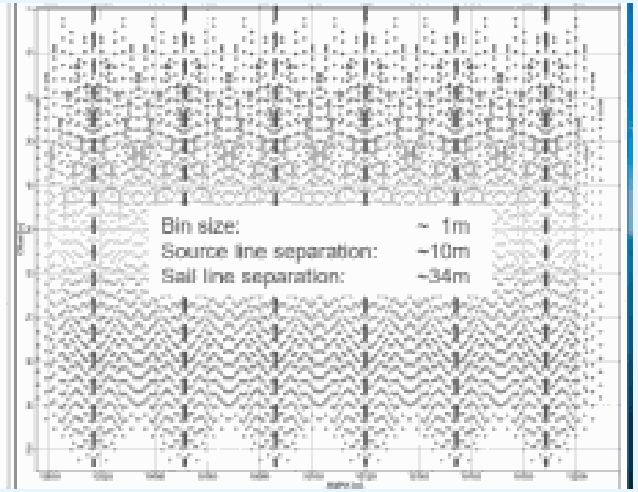
- Ultra short 100m cables designed for shallow UHR imaging.
    - Cross-connecting cable that links several short streamers.
- <18 streamers, 12.5m separation @ 2m depth for high frequencies (<600Hz).
- Sampling: 0.125- 0.25ms sampling.
- One source (210 cu in) @3m depth, 12.5m shot point interval.
- Acquisition bin size 3.125 × 6.25 m, 4-fold.
- Uniform trace density of 4 million traces/ sq. km (c.f. section 7.10b).
- Short cables mean that:
    - Feathering has a minor impact.
    - Velocity analysis poor.
    - Amplitude vs offset (AVO) analysis impossible.
    - Shallow cable is more weather sensitive.
- Possible for time lapse 4D in shallow reservoirs (~1km), near offset changes expected.
- Relatively low cost, flexibility, and safety in restricted areas.

Aerial view of P-cable 18x100m cables

18x100m cables with tow width of ~200m

(Refs 5am, 5an & 5ao)

Near offsets with triple source



Provides 1m bin size for windfarms

6. HR Seismic for Windfarms & CS

Section 6 Discussion

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This section provides a comparison of the role of high resolution seismic for CS/ hydrocarbon subsea/ well shallow gas detection vs ultra-high resolution seismic technologies used for geotechnical site surveys both in the windfarm and hydrocarbon industries.

This highlights some of the technologies and demonstrates that whilst the methods appear superficially similar, the spatial and vertical (temporal) resolution requirements are quite different.

Whilst the (HR) site surveys and reservoir seismic industries have developed separately, the authors note are some signs of convergence via legacy seismic re-purposing, multi-channel reprocessing, some increasing use of 3D via Ultra-high resolution short offset 3D (aka P-Cable section 3.5a & 5.12) and multiple wide towed sources (6.9) allowing for greater lateral reservoir HR resolution. This could be an important co-surveying factor in future (Section 1.10).

In the CS scenario geological paths are natural routes from the storage complex to the surface. In the current CS licenced areas, these are less likely than mechanical leak paths (i.e. poorly abandoned wells).

High Resolution (HR) Seismic Data:

- To ~1000mTVDSS.
- Reservoir focussed.
- CCUS use.
- 4D seismic compatible.

Ultra-High Resolution (UHR) Seismic Data:

- To ~100mTVDSS.
- Geotechnical site survey focussed.
- Offshore construction.
- UXO, Geohazard assessment.

(Ref. 6a, 6b & 6c)

Section 6.1 starts by providing an overview of windfarm site characterisation techniques and summarises the range of geophysical tools (6.2) and provides some examples of acquired data (section 6.3). Section 6.4 provides an overview of borehole/well based data types and outlines the differences in borehole/well-seismic integration. After highlighting some of the 2023 activity (6.5), section 6.6 shows the type of uplift possible with reprocessing multi-channel UHR data.

Section 6.7 provides examples of site survey seismic used in the O&G industry and trials conducted for the CS industry. Some of the huge legacy O&G dataset is being repurposed and example of targeted reprocessing seismic can provide an uplift for the shallow section (Section 6.8). This can be used for first pass wind site evaluation. Finally (6.9 & 6.10) re-visits the way in which high specification "deep" reservoir seismic can be optimised for the shallow section.

6.1a Windfarm surveying

Windfarms undertake a series of surveys
1) Characterisation: surface and sub-surface soil conditions and the integration of geophysics and geotechnical data for foundation design.
2) Hazard: Anything to obstruct installation? (UXO survey, surface boulders, sub-surface boulders)
3) Construction: Bathymetry and Sidescan for pre and post cable lay surveys, post construction (as-built) surveys.
4) Operation: Bathymetry and scour monitoring.

Surveys comprise 2 parts:
1) geophysical surveys of seabed and bathymetry.
2) geotechnical/ soil surveys of seabed characteristics to inform support optimal wind turbine generator (WTG) location:

- WTG & Substation siting, design piles & foundations (type/size).
- Cable crossing design.
- Horizontal Directional Drill design and siting.
- Cable design, burial and protection plans and siting.
- Scour protection requirements.
- Boulder clearance requirements.
- Sandwave clearance requirements.
- Unexploded Ordnance (UXO) clearance requirements.
- Ensure safe placement of jack-up vessel legs on the seabed during construction.

Shallow windfarm siting issues

(Refs.6d, 6e,6f & 6g)

Windfarm site survey rationale and requirements

6.1b Windfarm surveying

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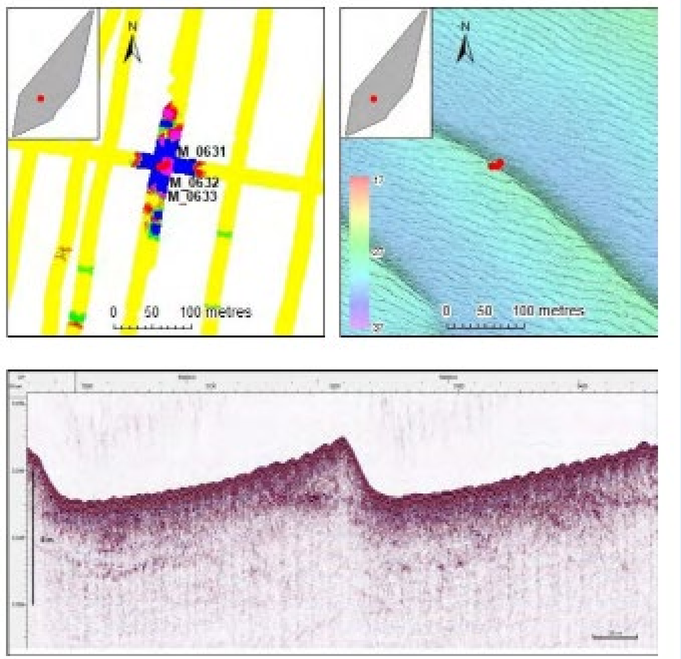
Geophysical techniques used consist of bathymetry (water depth) mapping with conventional single or multibeam echo soundings or swathe bathymetry, sea floor mapping with side scan sonar, magnetometer for UXO, acoustic seismic profiling methods and high-resolution digital surveys.
General surveying requirements are to obtain images 100m below seabed down to <1m with a very fast turnaround.

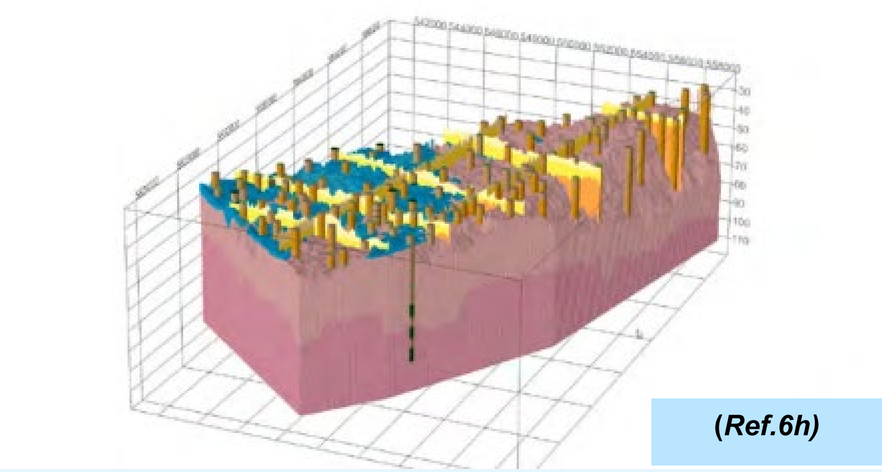
- Traditionally acquired in 3 phases sequentially:
  - Near surface high-resolution sub-bottom profiling currently still relies mainly on single-channel 2D method.
  - Mainly based upon 2D screening, then
  - Possible 3D micro-siting: Windfarms ~1000 km^2, Micro-siting 50-100 km^2
    - To date, 3D UHR surveys have typically deployed 4-7 streamers and rarely larger P-cable spreads.

Geotechnical studies are predominantly intrusive and include such methods as boreholes with soil/rock sampling, and cone penetration testing (CPT).
More recently P & S wave logs are collected – and sometimes sonic can be justified.

An interesting emergent technology involves using 3D UHR seismic attributes to better understand the unconsolidated near seabed rock strength, to help predict turbine stability. This is a potential cross–over technological subject with the hydrocarbon/ CS imaging seismic.

Magnetometer anomalies & SBP reflections



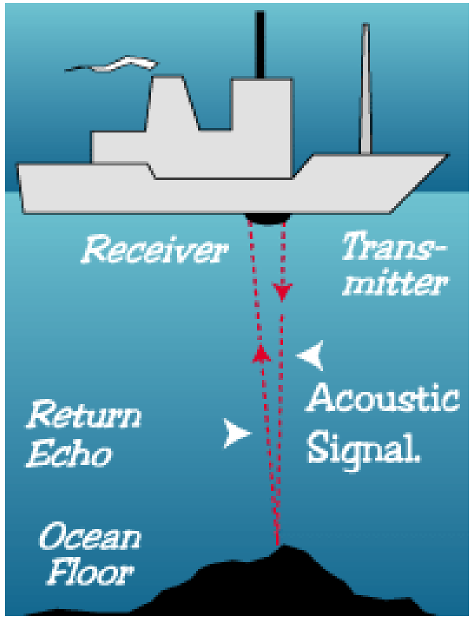


(*Ref.6h*)

6.2 Shallow geophysical techniques

- Acoustic (seismic) techniques give different penetration depths.
- Bathymetry: single-beam / multi-beam echo sounders (SBES and MBES) & side scan sonar (SSS) focussed on spatial resolution, rather than vertical resolution.
- Sub-bottom profiler (SBP) achieves resolution <10cm and comprises:
    - Pingers (2-20Khz), Penetration limited to 10m.
    - Chirp (1.3-13Khz): Produce long, low frequency pulses made of multiple higher frequencies: penetration depth 20-50m.
    - Boomers (500Hz-5Khz. Penetration <100m).
    - Innomar have more recently developed a range of SBP's with penetration depths of between 70m -250m.
- Sparkers: vaporise water, with low frequency down to 50Hz, and penetrate down to 1000m.
- Less commonly now: Single channel seismic: SCS short mini streamer (3 -15m with <15 summed hydrophones).
- Multi-channel seismic (MCS) e.g.
    - Southampton university: 60 hydrophones 25cm x25cm, allowing processing or commercially.
    - Slant or flat tow gel hydrophones with split set-up: first 24 channels @ 1m, last 24 channels @ 2m.
    - Emphasis on processing for deghosting and statics.
- Usually, shallow tow depth to capture higher frequencies but can be a noisier (wave action) environment.

Echo sounders



Comparison of acoustic site survey technologies

	HR	UHR	UUHR	SBP	Echo sounders	SSS
Dominant Frequency	75-300Hz	250-800Hz	750-2000Hz	1Khz-20Khz		~12kHz
Vertical resolution	1-7m	0.5-2m	0.2-1m	<0.5m	0.1m	0.05m

- Magnetometer for metallic objects (e.g., UXO).

(Refs. 6i, 6j, 6k, 6l, 6m, 6o, 6p & 6q)

6.3 Examples of windfarm survey seismic

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Multi-beam echo sounder Bathymetry

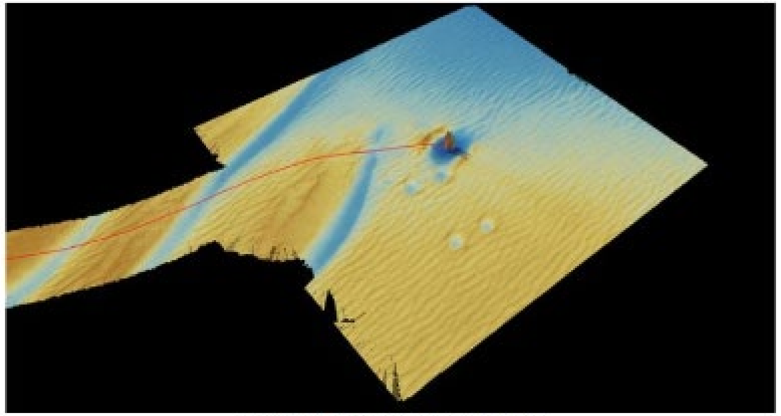
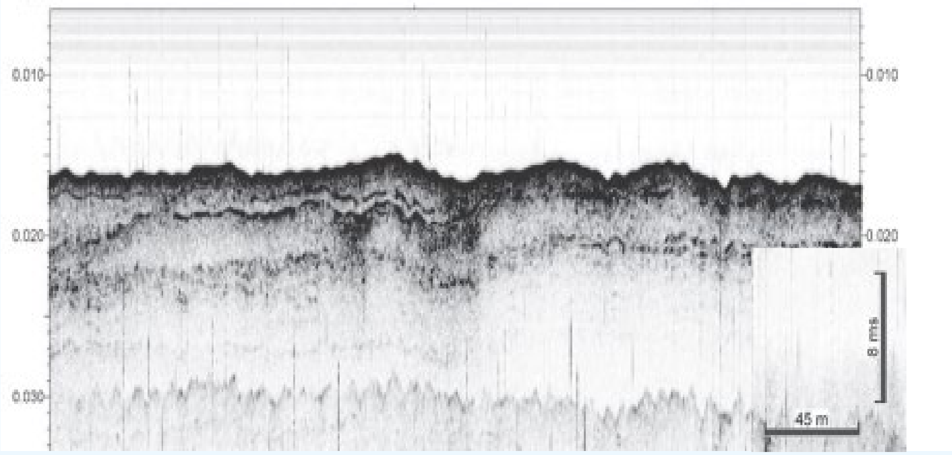


FIGURE 6: BATHYMETRY GRIDDED AT 0.2M RESOLUTION

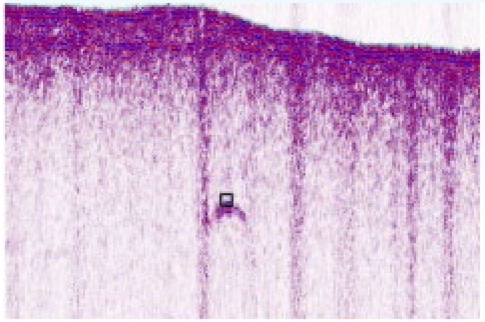
0.2m resolution
Sand waves and “spud-can” depressions from jack-up rig operations

Sub- Bottom profiling



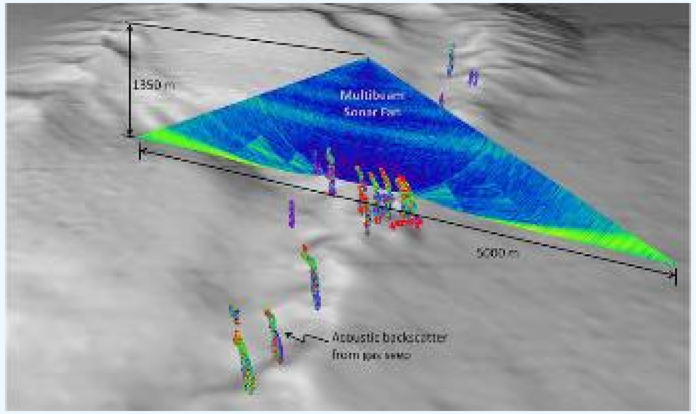
Very High resolution, but no useable data below 8ms (6m below mudline)

Sub- Bottom profiling @ 12Khz



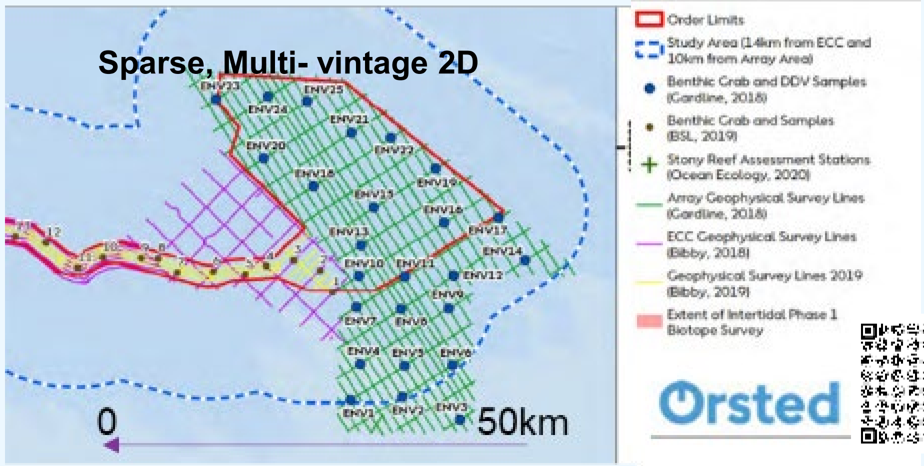
Buried cable detection

Multi-beam Backscatter data



Gas seeps imaged as coloured plumes

Hornsea 4 Preliminary site survey



Ørsted

(*Refs. 6f, 6n, 6o, 6p, 6r &6s*)

6.4 Geotechnical Borehole/Well Data

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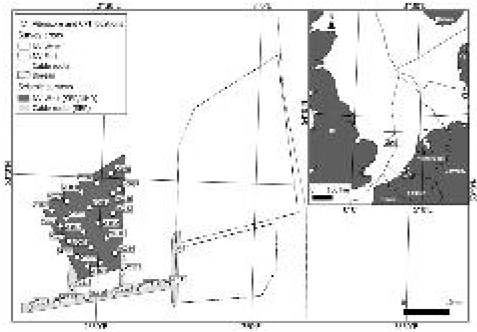
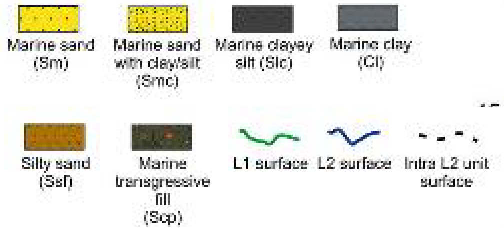
Windfarm borehole data includes cone penetration/ soil strength test (CPT):
- High vertical resolution Sampling @ 2cm, soft soil resolution ~1m.
- No direct linkage to seismic.
- Limited use of seismic to interpolate CPT data.
- Seismic methods and CPT represent very different soil properties that correspond to very different levels of strain.
- PS logs acquired to calibrate some of the lab testing. Occasional sonic (DT) acquired

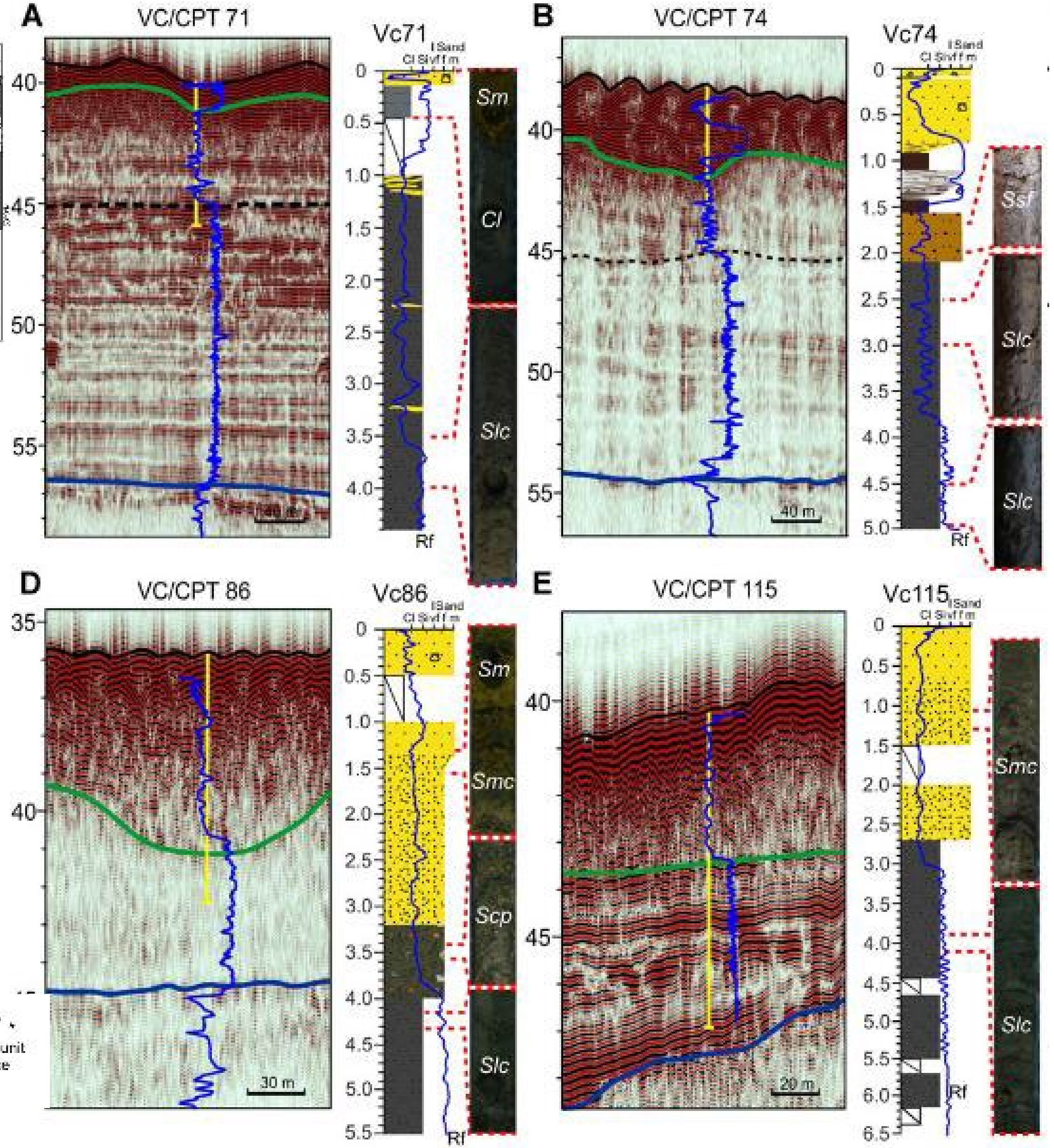
For comparison:

O&G/ CCS wellbores rich in range of log data types
- Minimum overburden Lithology, Gamma Ray, ROP (rate of penetration).
- More typically also sonic and resistivity.
- Usually sampled at 2 points/ft = 14cm vertical resolution.
- Additional reservoir logs density/neutron, checkshots/ VSP, image, core, pressure, etc.
- Sonic & Density & time-to-depth (checkshots) allow direct well based synthetic to real seismic tie.



(Ref. 6t)





J Quaternary Science, Volume: 35, Issue: 6, Pages: 760-775, First published: 13 July 2020, DOI: (10.1002/jqs.3230)

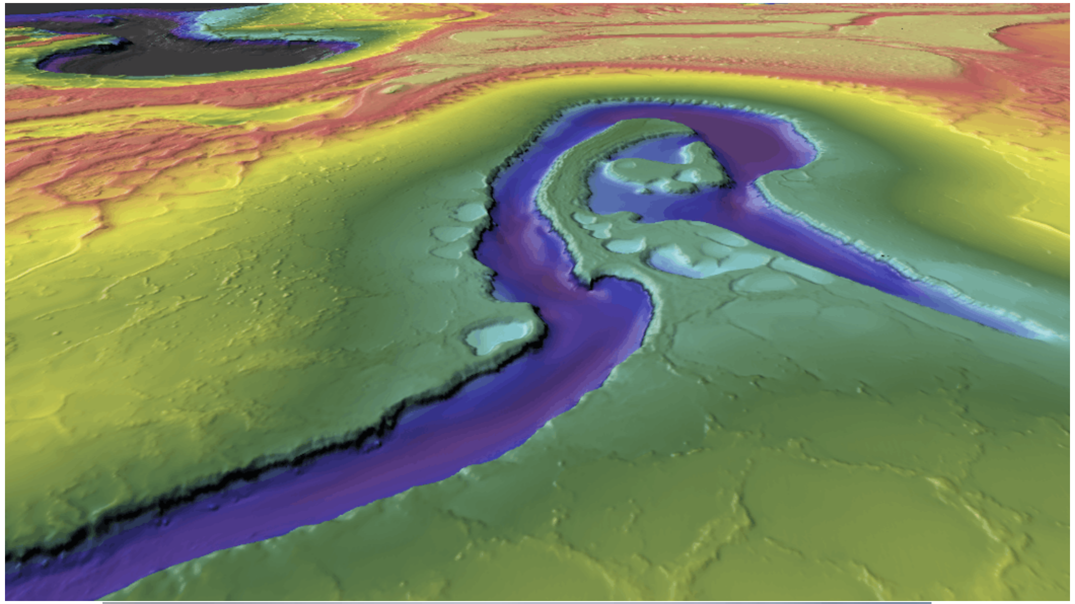
6.5 Current UK activity

North Sea Transition Authority

There is currently a high level of windfarm site survey activity, with some of the press releases summarised below:

“Construction of a 2GW high voltage direct current subsea transmission cable, stretching from Peterhead in Scotland to Drax in England”.

“Geophysical survey about to begin for ‘world’s longest HVDC subsea cable’…will follow the proposed cable corridor for the Xlinks Morocco-UK Power Project, routing along the North Cornwall coast to make landfall in North Devon…. The activities will consist of a multibeam and sub-bottom profiler and side scan sonar (SSS) with a piggybacked magnetometer”.



“Flotation Energy Awards Survey Contract for 1.4 GW Cenos Floating Wind Farm... Rovco’s scope of work involves the acquisition of benthic and geophysical information to provide detailed data to inform environmental impact assessment (EIA) consents and the engineering processes”.

“The survey vessel Horizon Geodiscovery will collect data from different locations within the Morecambe array area".

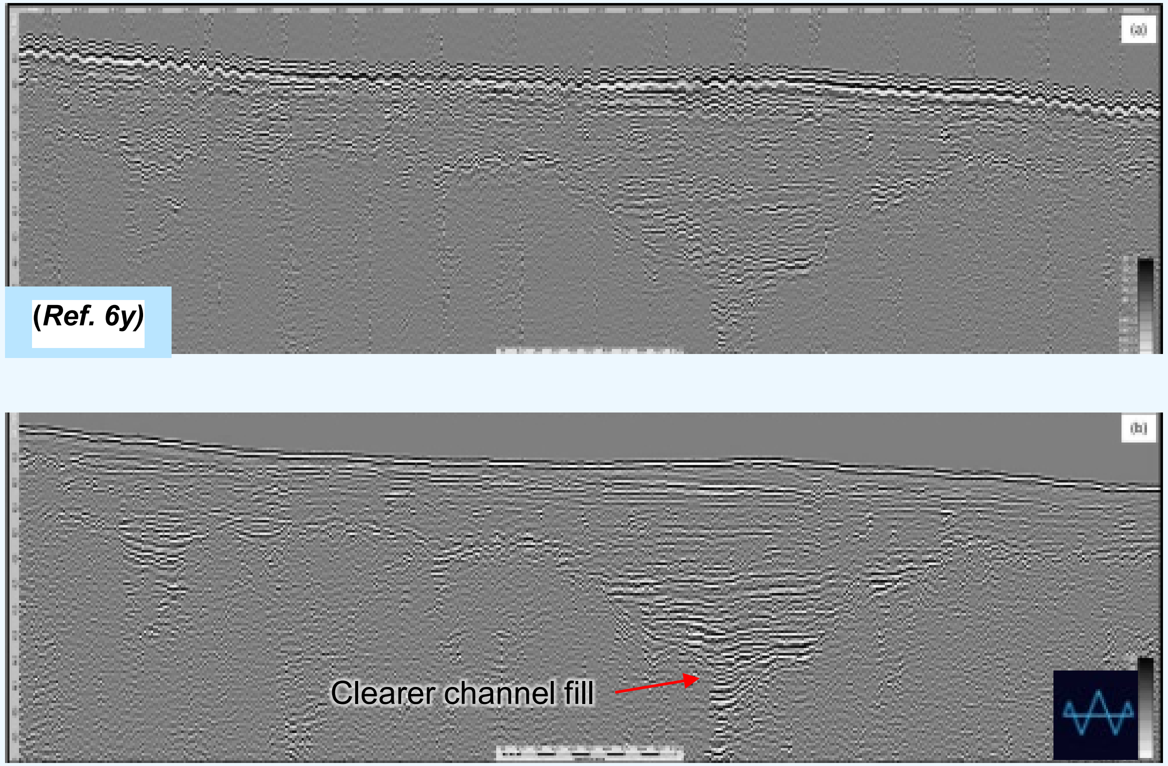
This is thought to be a P-cable 3D.

(Refs., 6u 6v, 6w & 6x)

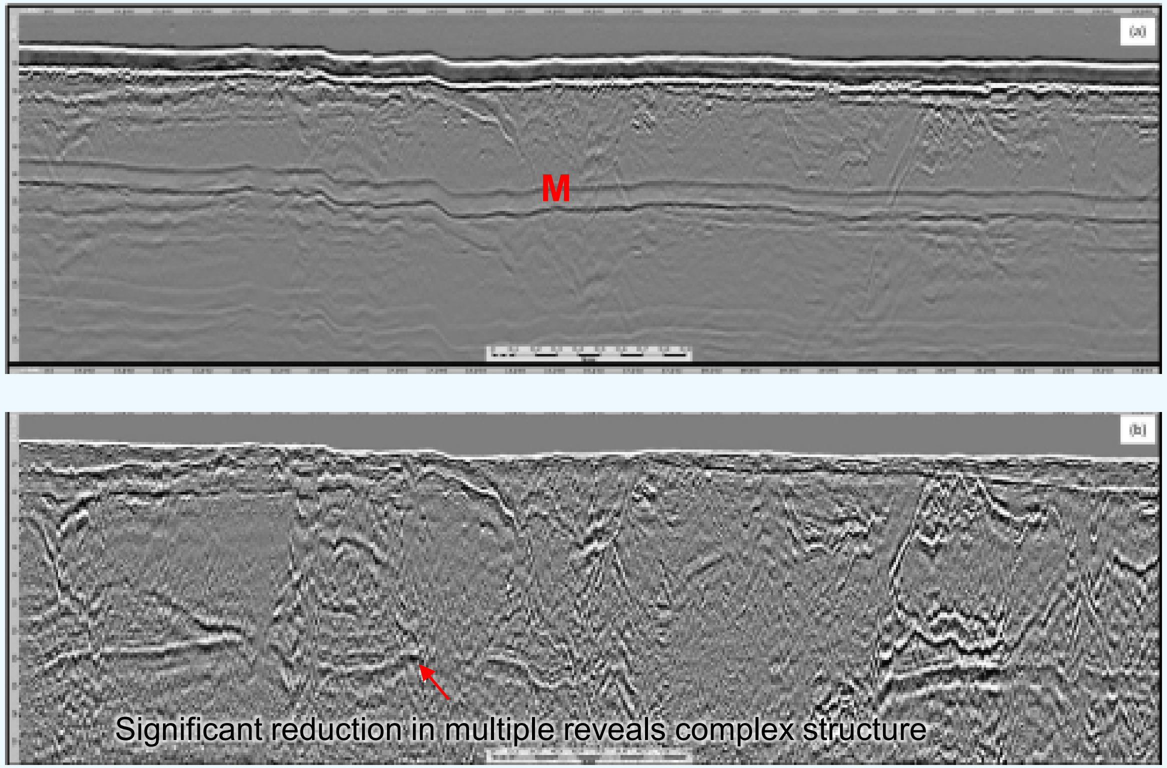
Current UKCS site survey activity

6.6a UHR & UUHR seismic reprocessing

Sub bottom profile (SBP) before and after reprocessing



Ultra-High resolution Sparker before and after reprocessing

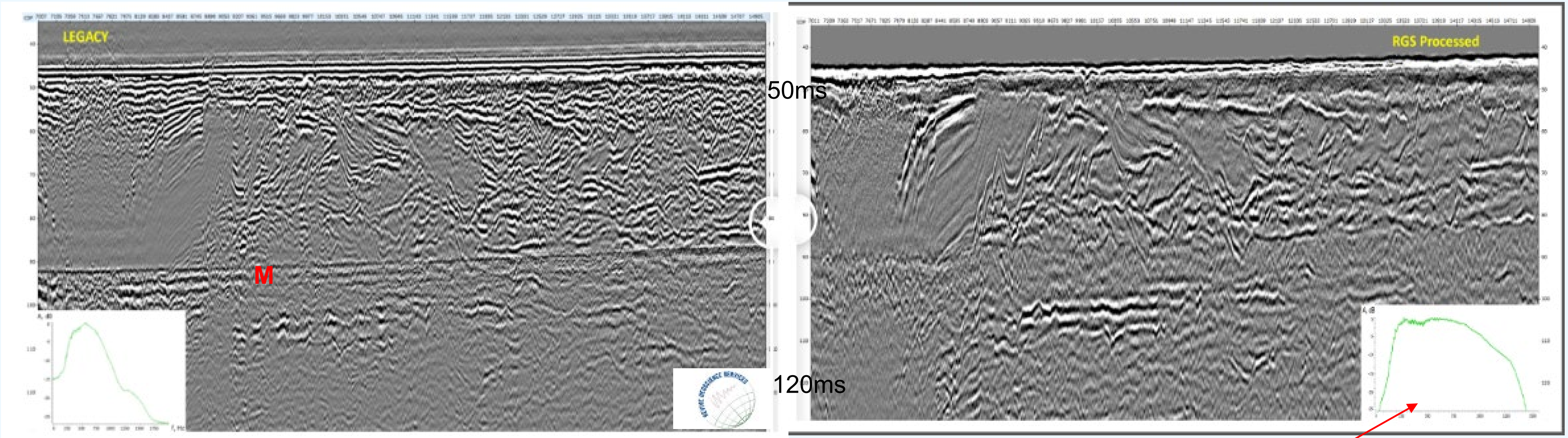


Like deep seismic, multi-channel processing of UHR seismic can greatly reduce noise (M multiple) & enhance signal.

6.6b UHR seismic reprocessing

North Sea Transition Authority

UHR reprocessing removing multiple and improving bandwidth

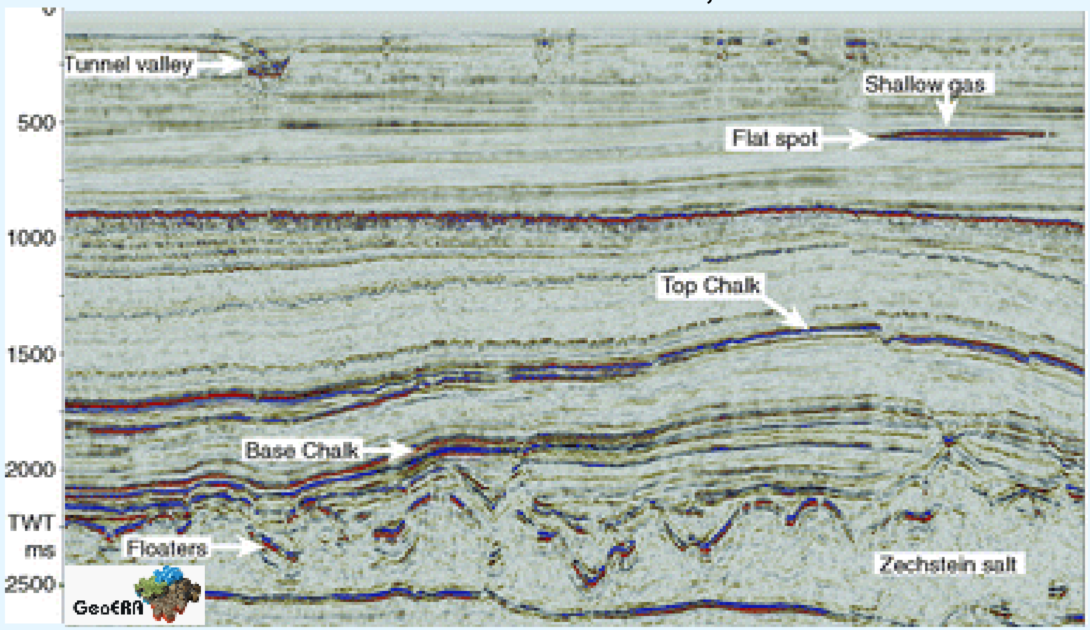


Improved frequency bandwidth

(*Ref. 10h*)

6.7 Oil and Gas/ CS site survey applications

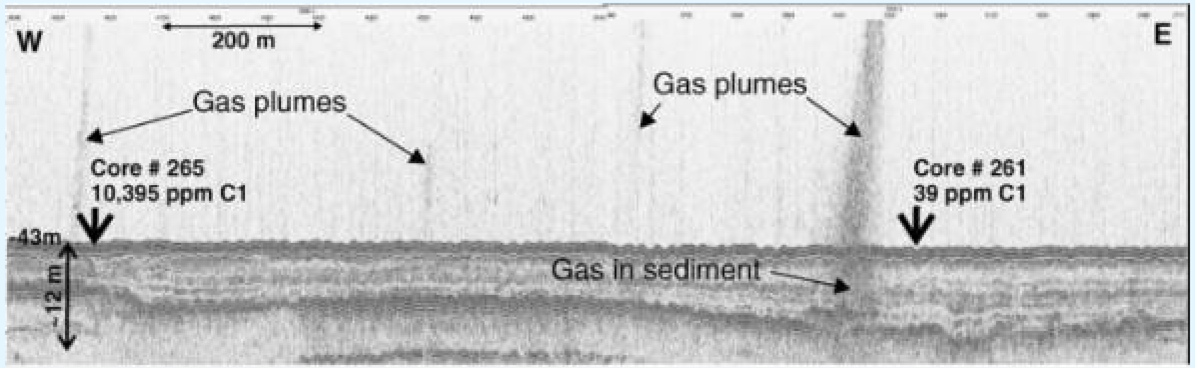
Drilling hazard identification
Reservoir seismic: Dutch sector, North Sea



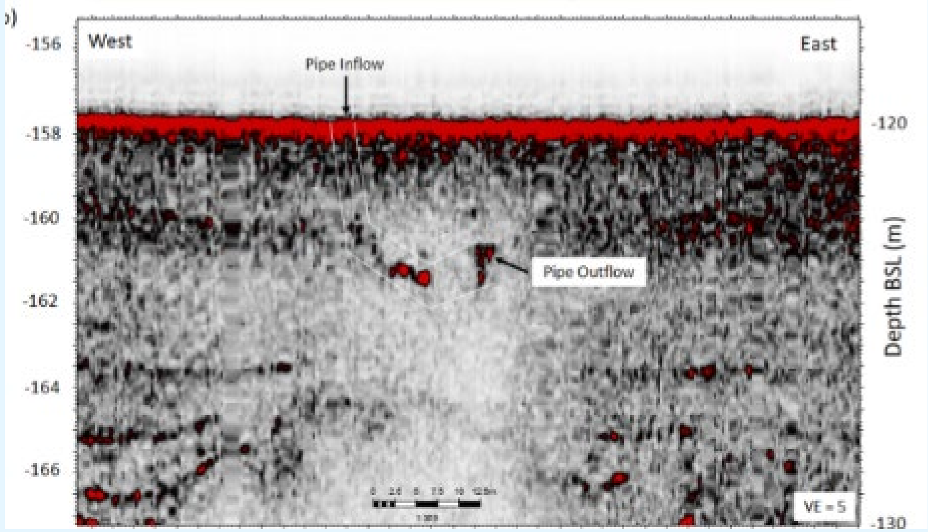
Glacial valley & shallow gas (probably biogenic methane)

(Refs. 6z, 6aa, 6ab, 6ac & 6ad)

Gas plume leakage detection UHR seismic: Dutch sector, North Sea



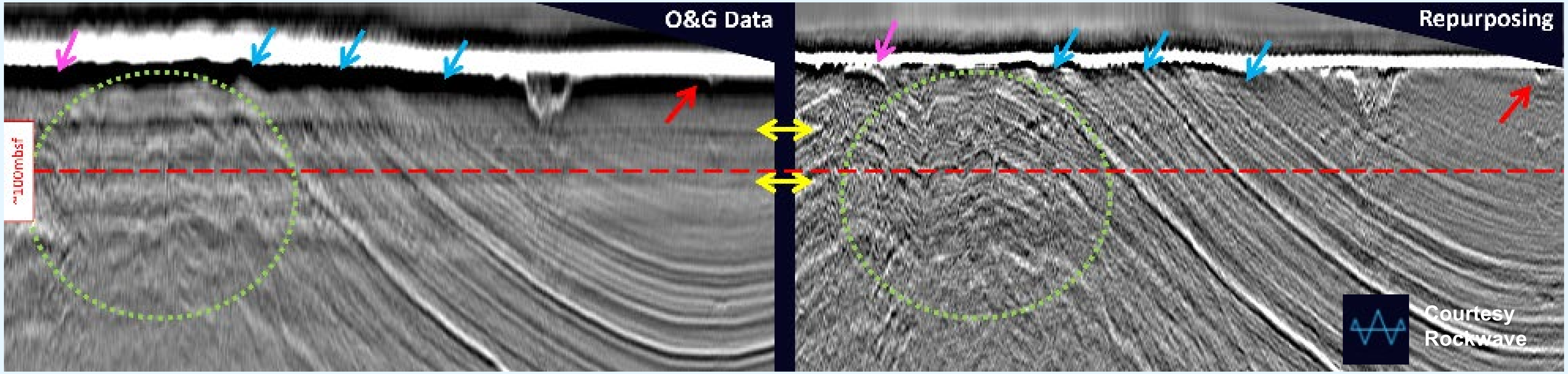
Buried CO_2 pipe experiment: Chirp data



Detects pipe outflow but limited below.

6.8 Repurposing legacy reservoir seismic

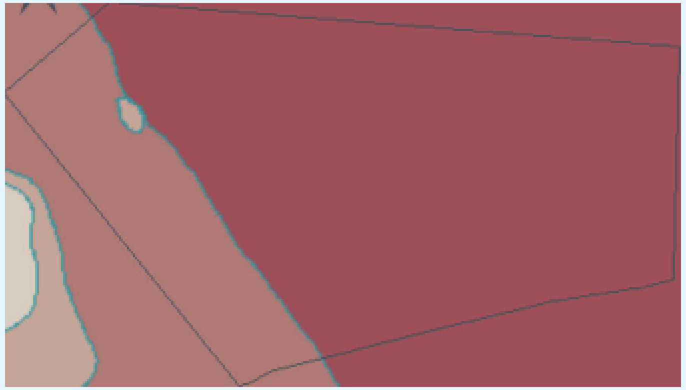
North Sea Transition Authority



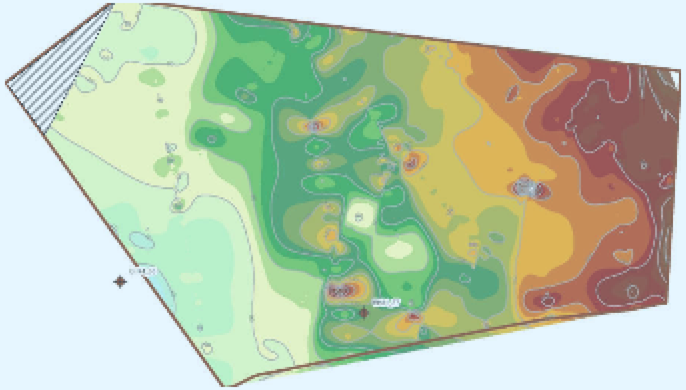
Reservoir seismic reprocessed for shallow imaging: Celtic Sea

Shallow Quaternary remapping based on repurposed seismic

Mid North Sea High for O&G exploration (OGA released seismic package)
Reprocessed from raw shot gathers for uplifting quality in top 500m



Thickness of Quaternary Deposits from BGS



Top of Bedrock (mbsb)/Thickness of Quaternary Deposits re-purposed O&G data

ATKINS
Courtesy Rockwave & Atkins

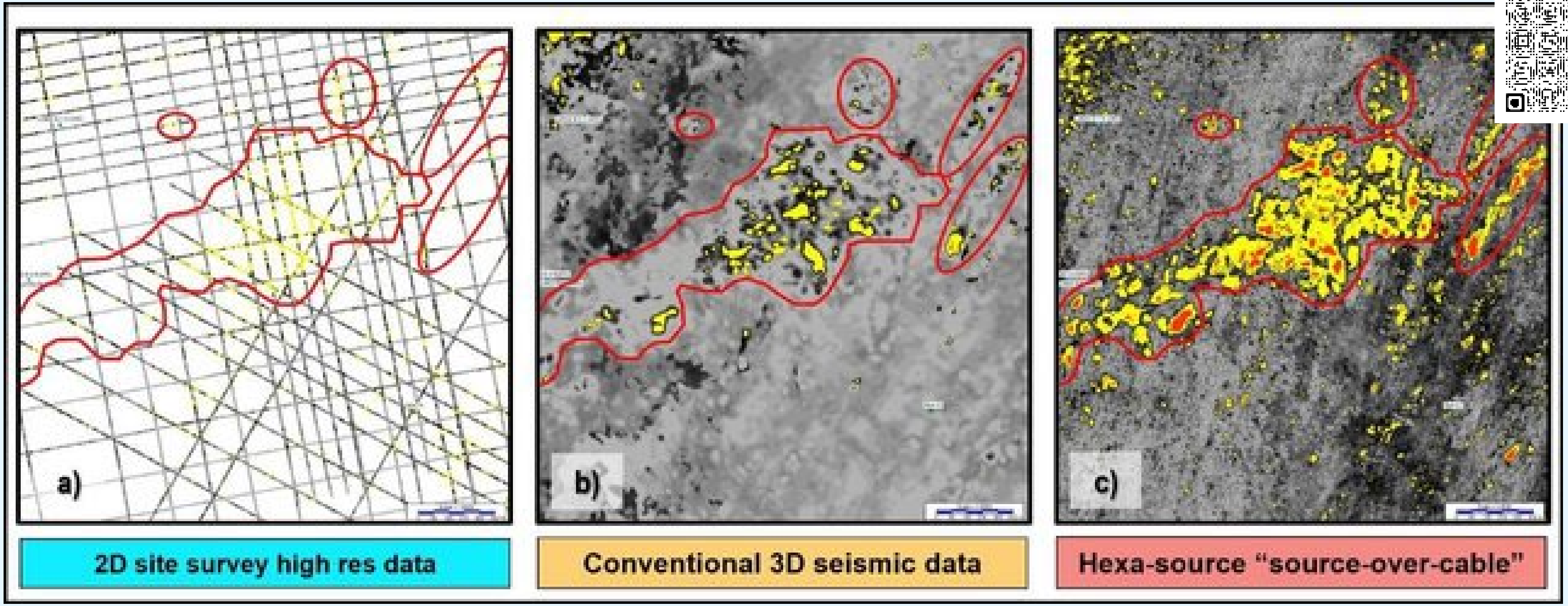
(Ref. 6ae)

Legacy Oil and Gas seismic reprocessed and repurposed for shallow imaging

6.9 High-density streamer for HR imaging

North Sea Transition Authority

Evolution of shallow gas detection: 2D to Multi source 3D seismic (timeslice at 500ms ~450m depth)
(see also section 5.8).



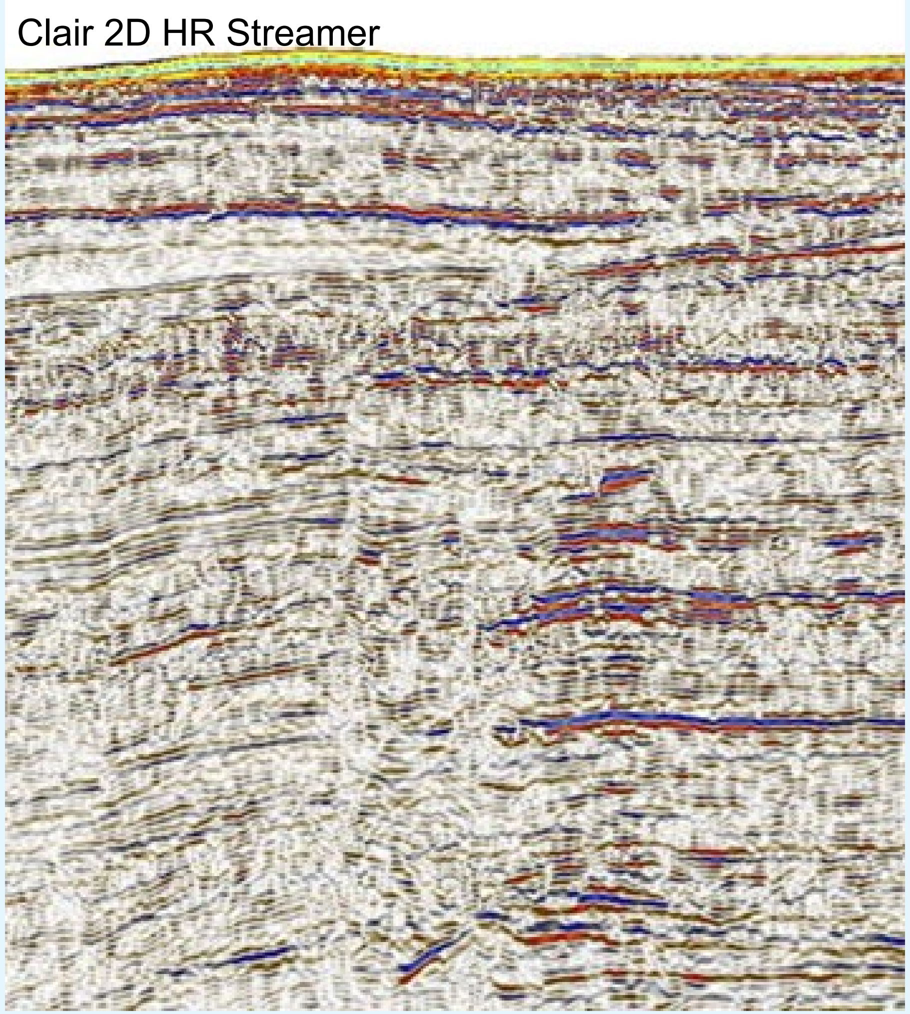
(Ref. 6af)

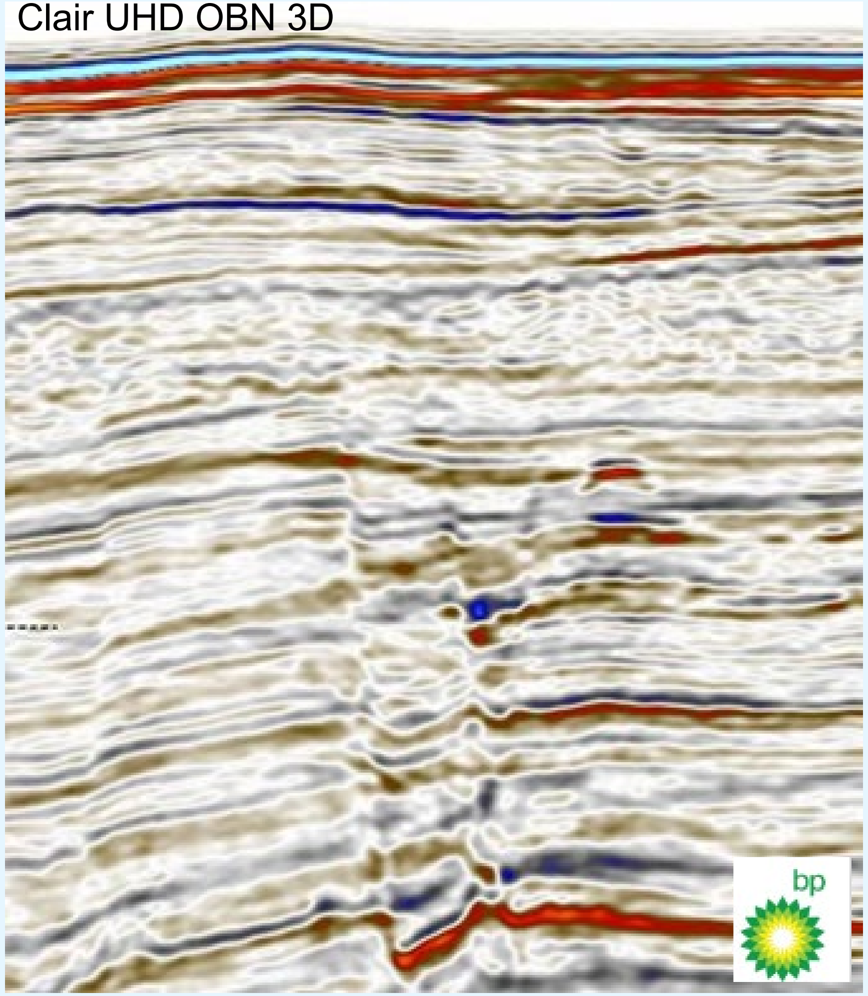
6 (Hexa) small source with source over cable (near zero offset) provides very high spatial resolution for shallow gas detection

6.10 Shallow imaging - Ultra high density OBN

North Sea Transition Authority

Clair Legacy 2D HR vs 2017 Ultra high definition (UHD)OBN





(Ref. 6ag)

In contrast to typical sparse OB seismic (7.9) data gaps, **Very dense** Ultra HD (section 7.12) recovers excellent near surface image(receivers 50x50m, shot 25x25m, an order of magnitude higher than previous 2010 OBC).

Very dense, Ultra-High resolution OBN can provides good shallow imaging

7. Ocean Bottom Seismic

7 Ocean Bottom Technology Discussion

This section introduces the OBC/OBN technology and summarises its technical benefits. The primary motivation for acquiring seabed or so-called "ocean" bottom seismic is that provides:

1) Proven superior geophysical image mainly through high fold & multi-azimuth imaging for complex geological targets or overburdens.
   i.e. Horizon continuity, reservoir property prediction, fault imaging, salt body mapping & 4D reliability.
2) Provides flexibility around surface obstacles, especially for multiple obstructions such windfarms and,
3) Allows acquisition in shallower water compared to deep tow reservoir streamer seismic.

(Refs. 7a & 7b)

This is summarised in 3D schematic is section 1.8.

Geophysicists are universally convinced of the **technical** merit of high density, rich azimuth seismic. There are many good UK & worldwide examples of the uplift OB seismic can provide in complex imaging situations. However, complex geology is very basin specific, but in general is the exception rather than the rule.
The main commercial constraints remain the cost multiplier compared to streamer seismic (section 9), high demand/ limited crew availability. The NSTA believes that OBN will remain more expensive than streamers owing to relatively slow deployment/retrieval, so that streamers remain the cost-effective solution in most situations.

Background- to recent rapid advances in OB seismic
A decade ago, a 1500 node survey was considered ground-breaking, but the rapid expansion now means 10,000 node operation now being deployed most often by Nodes-on-a-Rope (NOAR), ROV or gravity drop. Meanwhile automation has helped to drive a 50% reduction in costs. A modern quality OBN design typically delivers many times more data (fold/trace density) than a streamer survey. Whilst existing ocean bottom cable (OBC)/ node (OBN) / seismometers (OBS) technologies are mature in the Oil and Gas (O&G) sectors, there are still developments which could significantly improve its cost of flexibility.

This section highlights the advantages/ disadvantages of ocean bottom seismic (Section 7.1), the industries evolution from OBC to high density OBN (7.2 & 7.3). Section 7.4 presents an overview of OBN parameters, followed by an outline of the nodes, deployment and source vessels (7.5 & 7.6). Section 7.7 considers the size of an obstruction gap and shows a platform 'close approach' examples. Hybrid OBN streamer examples are presented (7.8) and a useful reminder of the near surface illumination with typical node spacing (7.9). The role of very high trace density (7.10) and subsequent receiver line decimation. Several examples of the role of OBN are given (7.12-7.18). Followed by new technology developments for sparse (7.19) or autonomous nodes (7.20), there is a reminder of permanent reservoir monitoring (7.20). Some seismic business context (7.21) concludes this section.

In summary:
To re-iterate the NSTA expectation is that streamer seismic is expected to the default characterisation & monitoring tool for most O&G and CS sites:

- **Hybrid streamer & limited OBN may be a good cost compromise, when necessary.**
- **OBN remains in the midst of major developments and new & potentially game changing tools.**
- **Lower cost AUV/ SUV game changers are untested.**
- **On demand nodes are an interesting option.**

OBN developments continue apace

7.1 Summary Pros & Cons of OB acquisition

North Sea Transition Authority

For target optimised Ocean Bottom and Broadband Streamer acquisitions, the following general statements can be made:

Ocean Bottom Acquisition	Broadband streamer
Pros	
Close approach to facilities/ infill, shallow water or ecological sensitive areas	Lower survey effort/ **Lower Cost**
Used in heavy traffic areas: pop-up buoys make large footprint "invisible"	Deep Tow (quietish environment)
For complex reservoir or overburden: Full azimuth (illumination, imaging: scattering & multiple attenuation)	
Broad bandwidth/ Rich in Low frequencies	Broad Bandwidth, Multi-component receivers
Very long offsets (when possible e.g., Utsira 20+km) – imaging, multiple attenuation	Long offset (when possible) typically <6km
Single point recording/ continuous recording	
Better 4D repeatability (section 11.3)	
Receivers are stationary in x,y,z space	
Usually Quieter environment (SNS strumming see section4.7b)	
Very high Trace density (high fold), Better signal to noise	Hybrid with OBN possible (dense infill or sparse velocity)
Imaging through Gas	
Access to PS (primary- Shear wave data	
Fracture detection	

Cons	
Higher Cost	**Single azimuth/ Poorer illumination**
Survey effort	
Turnaround time	

(Refs. 7c,7d & 7e)

7.2 Evolution OBC to High Density OB Nodes

The term "ocean bottom" is now used to encompass any seismic in which equipment is placed on the seabed – irrespective of water depth. OBN are the modern development from ocean-bottom seismometers (OBS), with the First Ocean bottom seismic survey in 1936.

In OBS acquisition, each individual receiver (autonomous or embedded in a cable) consists of 4 sensors- one hydrophone measing pressure (P) and 3 orthogonal geophones (Z- vertical and XY- horizontal). This allows recording of the full elastic wavefield as well as separation into up and down going parts (section 5.6b).

OBC was developed for difficult acquisition areas e.g., water depth too shallow for streamers (near shore or transition zone) or near facilities and the PZ (hydrophone/geophone) summation to broaden the frequency spectrum.

In comparison:

Ocean bottom cables: OBC: Sensors linked by cables that transmit raw data back to the central recording unit:

- Cumbersome cables.
- Increased time for deployment.
- Limits distance between sensors.
- Cable break or electronic short could functionally shut down the entire system.
- Early systems were just a single hydrophone (OBH) or hydrophone/ geophone pair.

Ocean Bottom nodes (OBN):

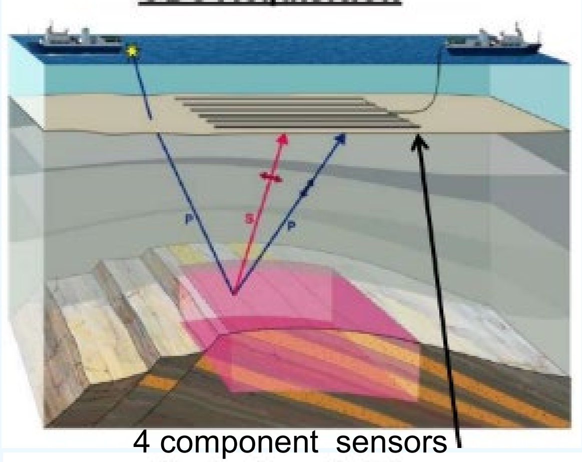
- No cable requirements, removes operational limitations.
- No sensor spacing limitations.
- No requirement for interconnectivity, to capture the raw data).
- Advanced battery life technology.
- Retrieved/ data download at end of swathe acquisition.
    - no real time QC.

(Refs. 7f, 7g, 7h, 7i & 7j)

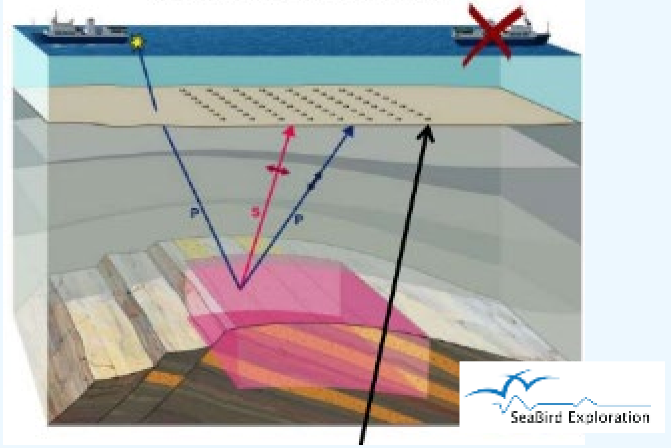
In the past, node clock-drift and battery lifetime were issues in the past but becoming less so with modern equipment and technologies.

Schematic comparison of OBC vs OBN

P vs S wave arrivals



4 component sensors



4C sensors: (3 geophones (x,y,z) – also MEMS or optical for OBC + 1 hydrophone
Often 2nd vessel needed for node deployment and retrieval

Evolution from sparse OBC to HD OBN

7.3 Ocean Bottom trends

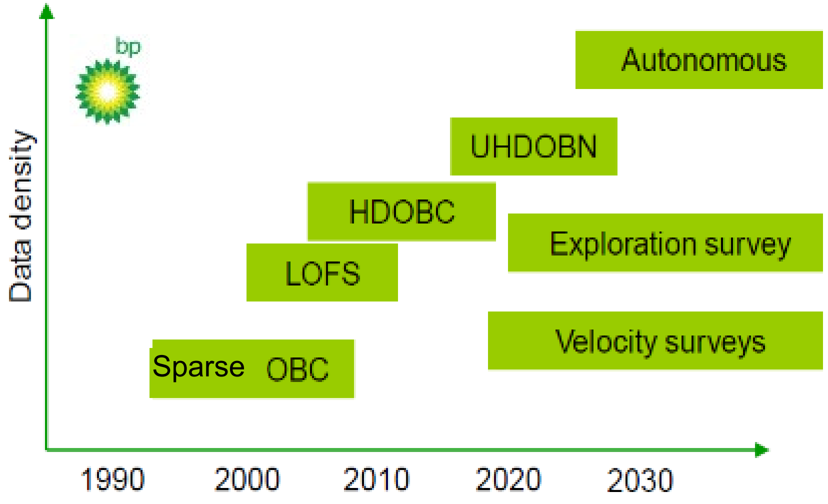
North Sea Transition Authority

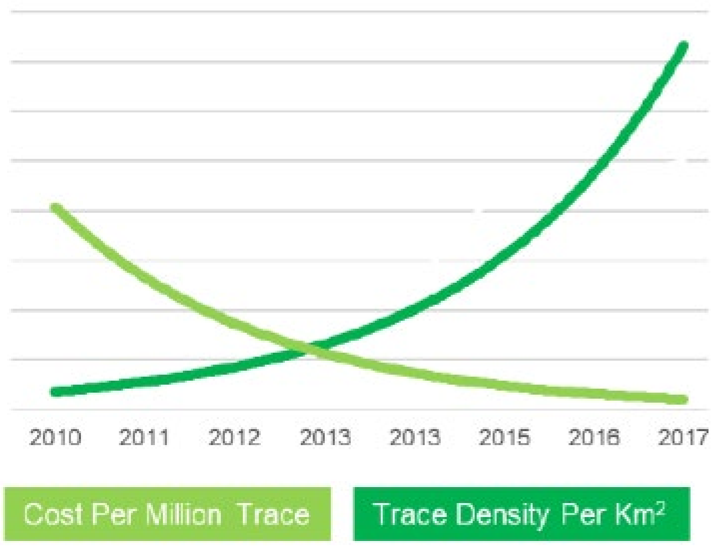
The perfect situation is that source and receiver are densely sampled. In reality – modern surveys are usually acquired with sparse nodes (400-1000m separation) and dense shots (50x50m grid).

- Early "Sparse" OBC surveys were shot (mostly) with orthogonal shot and receiver lines and later progressed to wide shot carpets.
- HDOBC increase the shot carpet density, retaining large cross-cable separation.
  - e.g. West Sole, SNS; Mungo salt diapir in CNS – field specific acquisition.
- Life of field seismic (LOFS) is a permanent OBC array for frequent 4D monitors.
  - Valhall is one of the best established installed in 2003:
    - 13 cables: receivers: 50m spacing x 300m separation. 10,000 sensors
    - shot carpet 50x50m grid.
    - 20 repeat surveys by 2018.
- Exploration HDOBN surveys have much larger areal coverage:
  - CNS Cornerstone (CGG) nodes 300X100m and 50x50m shot carpet
  - Utsira High : TGS/ AXIS geosolutions (hexa-source).
    - >1500 sq. km. 300x 50m 140k node deployments, 3.8 million sources.
- UHDOBN: densely sampled in both shot and receiver domain.
  - Clair Field 100x50m nodes and 25x25m shots.
- Velocity surveys: Ultra long offsets/ sparse nodes (800m+ separation) to derive velocity model (FWI).
- Future potential high density Autonomous nodes with aspiration of a full inventory of nodes single survey.

Whilst trace densities have been significantly increasing, the cost per million traces has provided a dramatic fall (computing power increase being a notable contributor).

(Refs. 7k to 7r)



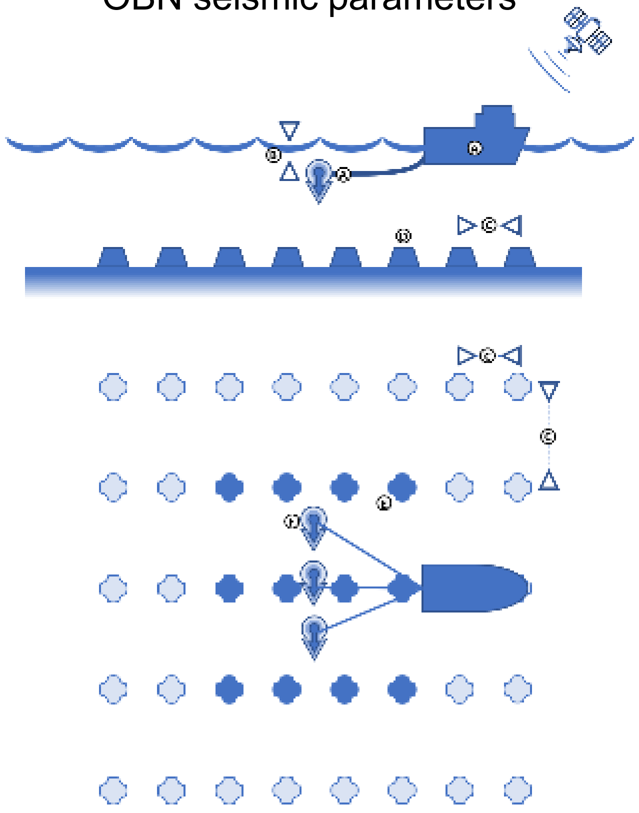


Evolution from Sparse OBC to range of ocean bottom deployments

7.4 OBN schematic seismic parameters

North Sea Transition Authority

OBN seismic parameters



A – Source Type & Size
B – Source Depth
C – OBN Receiver spacing (Grid/Ad hoc)
D – OBN Receiver type
E – Active Nodes
F – Source number/size

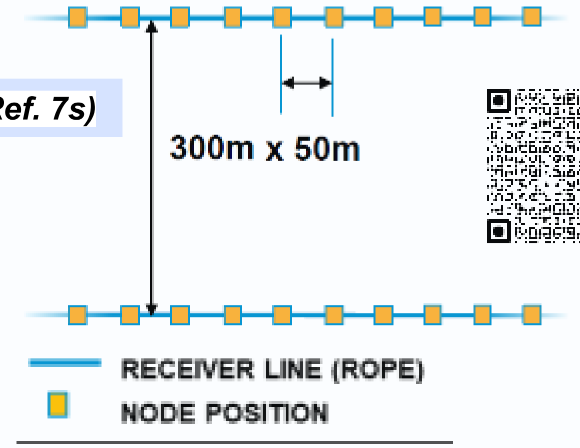
Receiver density: Are usually less well sampled:

- Inline spacing typically 25-100m.
- Crossline separation range 300-400m to 100m (UHD).
  - Has the largest impact upon the processing and final image quality.
  - Significant levels of receiver-specific noise.

Shot carpet: Typical high density 25 - 50m.

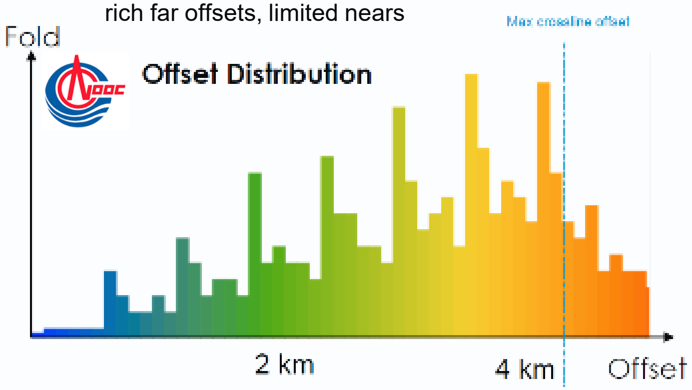
NOAR: CNOOC Golden Eagle

(Ref. 7s)



Golden Eagle offset distribution

COV: Common offset Vector fold, rich far offsets, limited nears



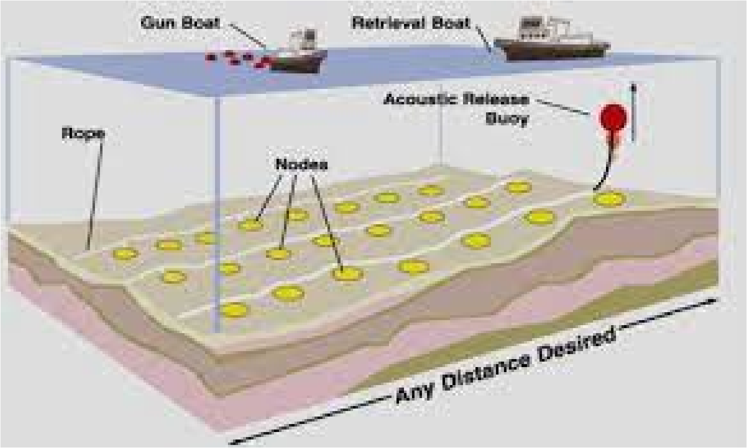
Good mid/far offsets, poor nears

OBN seismic parameters limited near offset, excellent mid & far offset fold

7.5a Some Node deployment options

North Sea Transition Authority

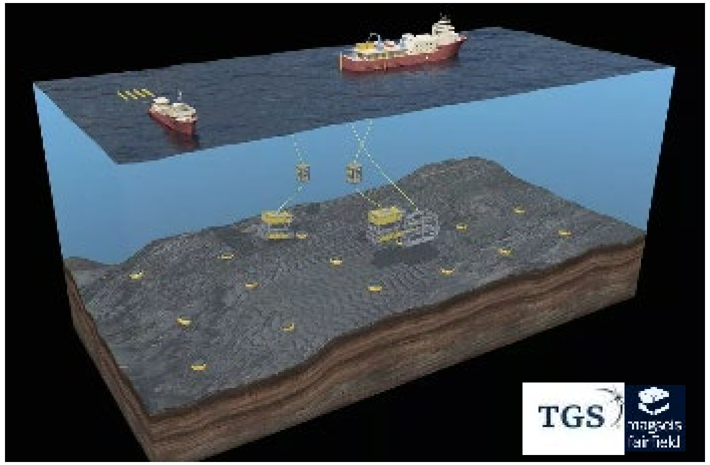
Nodes-on-a-Rope (NOAR)



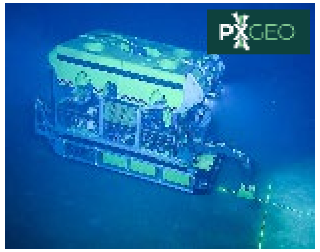
Nodes are anchored to a cable at a pre-defined spacing. Deployment and retrieval relatively simple and time efficient. This is the most frequently used technology.
The cables hold sensors with no electronics in cable. A mature technology with >100 deployments worldwide.

Nodes on a wire (NOAW) also possible

ROV Deployment

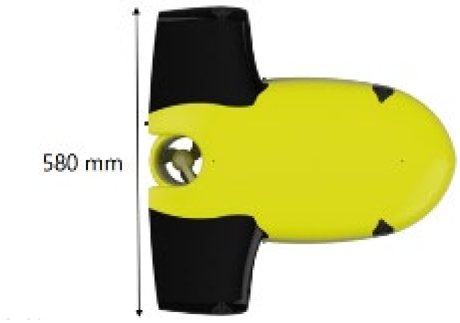


Nodes are deployed by ROV across seabed. Allows some flexibility in deployment pattern, especially if working close to existing infrastructure.



Usually, it take a long time to deploy nodes, but the regional hybrid survey (section 7.8c) deployed a combination of free drop and ROV pick up.

Automated Flying Nodes



Largely automated node deployment, surveying and retrieval. The key advantages of 'Flying Nodes' are in the reduction in survey costs – expected to be less than half the cost of ROV deployed nodes, combined with excellent positioning accuracy and data quality. See also Section 7.20

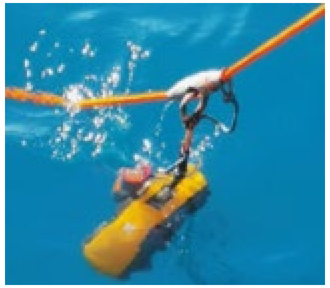
(Ref. 7t)

More recently, nodes can now also free-dropped and picked up from the seabed by either ROV or released and then collected at surface. Free drop & sea surface collection may provide opportunities to improve efficiency, assuming node positional accuracy is less of a consideration.

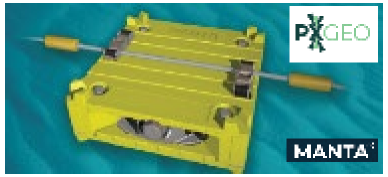
Comparative node deployment technologies

7.5b Nodes

NOAR: Node & deployment on a rope



4C Node

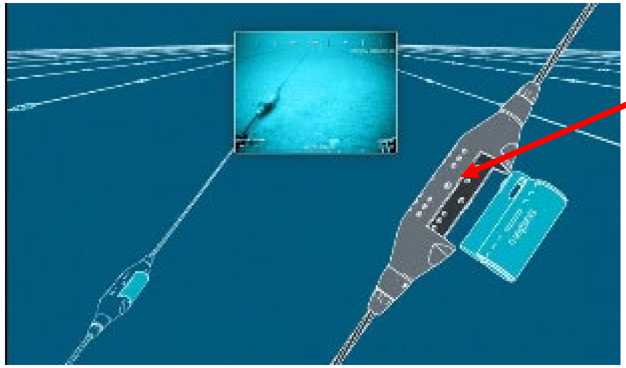


3 omni directional geophones & hydrophone Inclinometers to check orientation

MV Ocean Pearl - Potential Node Handler

- Lays/Picks up nodes in very controlled fashion.
- Can/does go close to installations.
- Redundancy of propulsion/steerage.
  - Not necessarily DP.

High-Capacity NOAR



- Vessel holds several hundred kms of cable.
- Robotic back deck speeds up deployment/ removes manual handling.
- Automatic data transfer.

(Refs. 7u, 7v, 7w)

Typical nodes: existing design were ~ 25kg, but newer ones smaller and more light weight (7kg)

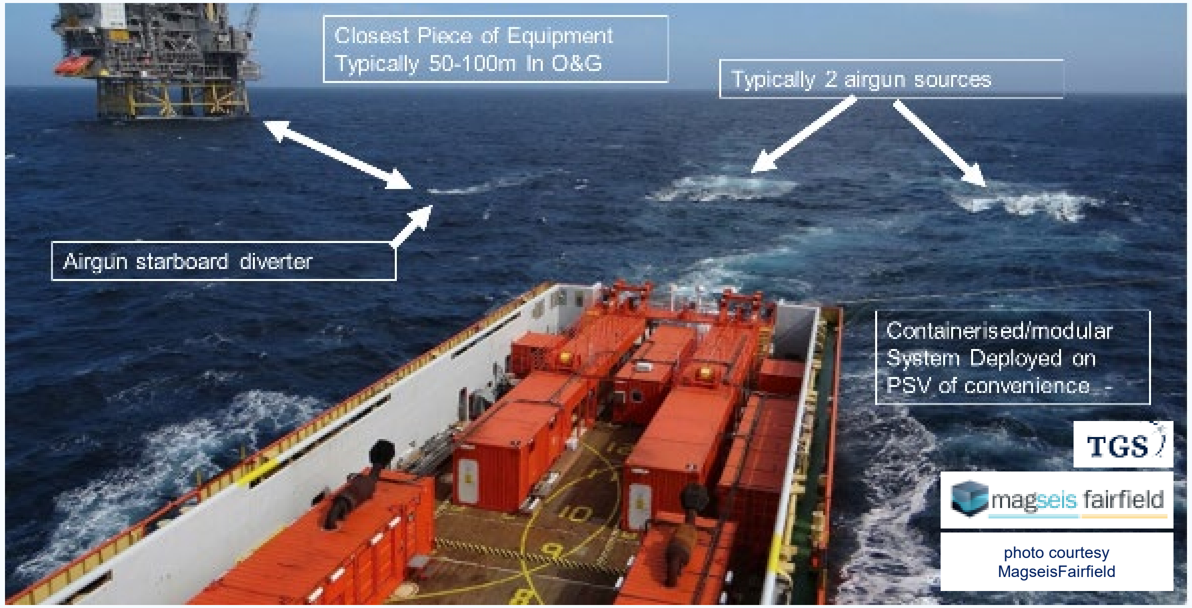
7.6 OBN vessels & Source

- Deployment ranges from:
  - Full dedicated seismic vessel & crew.
  - Modular containerised system on local platform support vessels of convenience.
    - (e.g., Platform supply vessel PSV).

- Ships are combination of ownership, long term lease & "asset light" rental.

- Crews are combination of permanent staff and agency.

Containerised Source System on PSV



Potential source vessels

- Both vessels formerly streamer vessels.

- Can/do go close to installations.
  - Unlikely to possess formal DP2.

7.7a Mind the obstruction gap

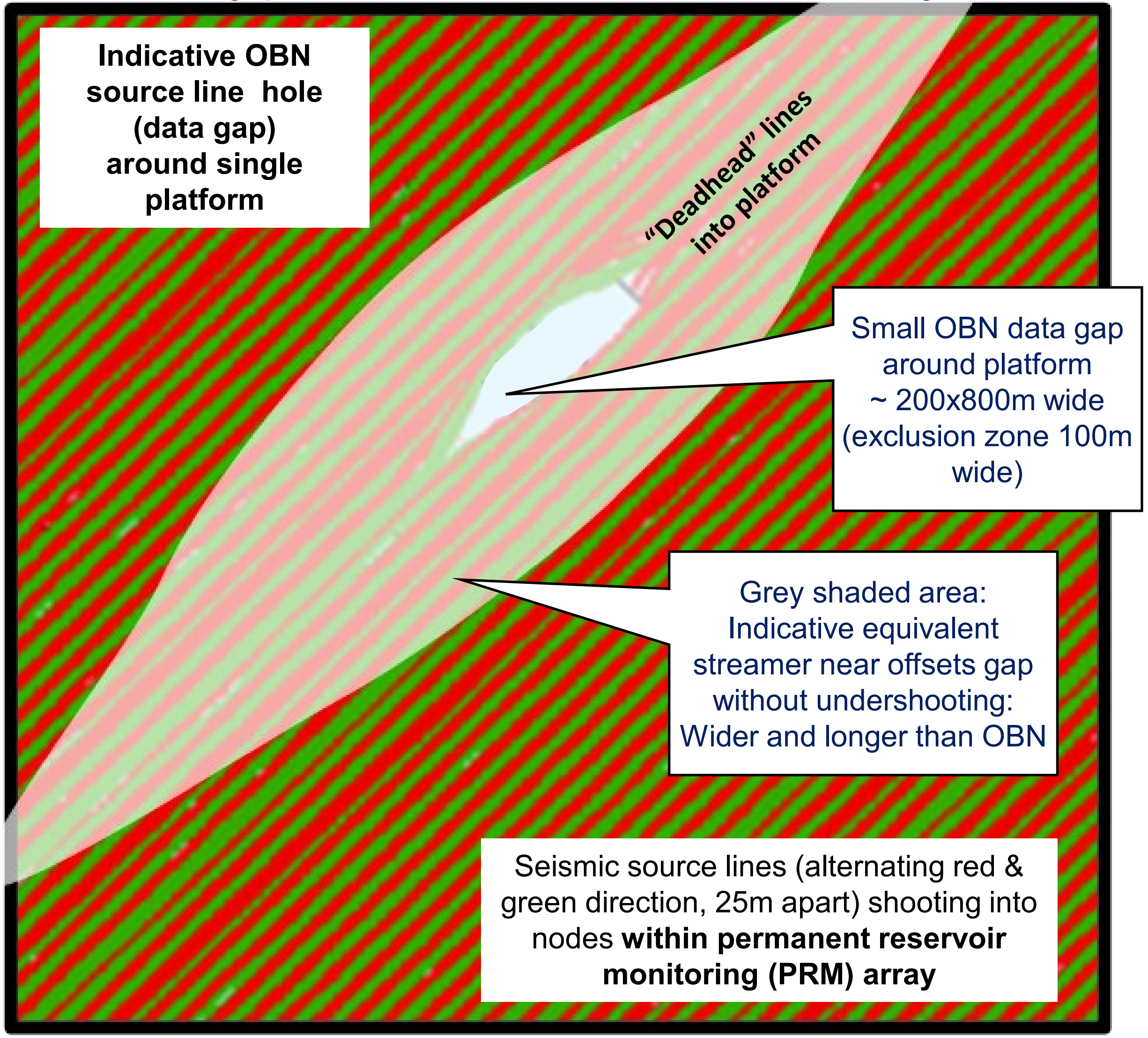
A seismic streamer data gap is significantly larger data hole than OBN

Whilst Ocean Bottom seismic was developed to be acquired around complex infrastructure (7.7b) & sensitive ecological environments (7.7c). Examples have included NOAR being carefully laid close to surface infrastructure and over some subsea infrastructure.

However, multi - obstruction wind turbines/ substations and associated subsea equipment are a new and very difficult challenge for the industry (section 1.9).

<u>If</u> such data could be operationally acquired in & around the tightly knit array of wind turbines (see also section 8) it would still lead to large 3D data gaps or even in worst case just a limited number of 2D lines.

Indicative data gap between streamer and nodes around single obstruction



Ref. 7x

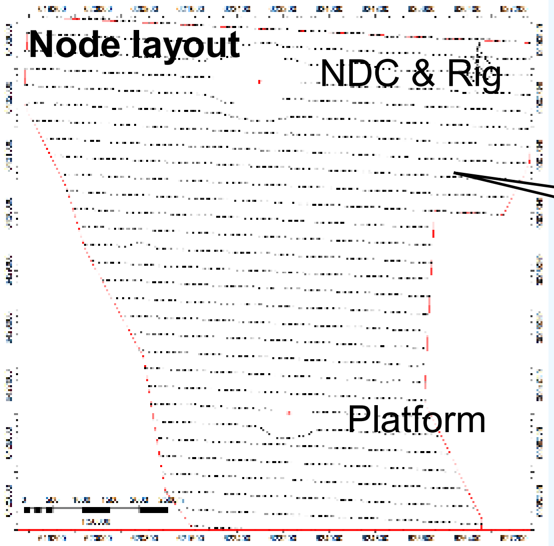
Comparative streamer vs OBN acquisition gap

7.7b OBN around obstacles (Golden Eagle)

North Sea Transition Authority

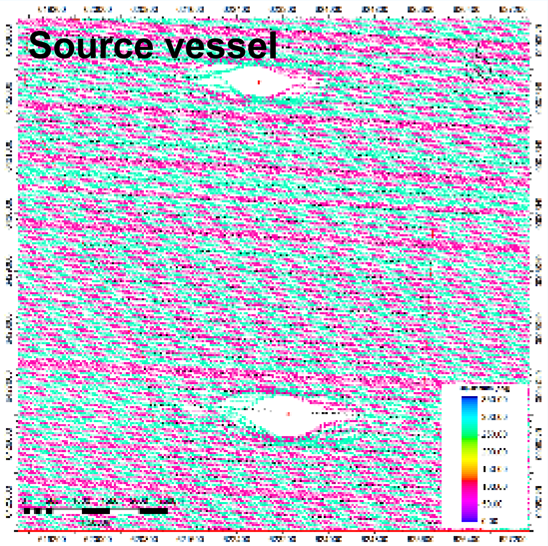
Golden Eagle HDOBN survey

cnooc



Black circles show OBN receiver locations.

(Ref. 7y)



Vessel is either sailing
West to East or East to West
Approaching an installation the vessel deviates early, then moves back onto line as soon as possible after passing the installation.

This results in an asymmetric pattern of missing shots around an installation.

The NSTA gratefully acknowledges these unpublished image is shown with permission of the GEAD coventurer group

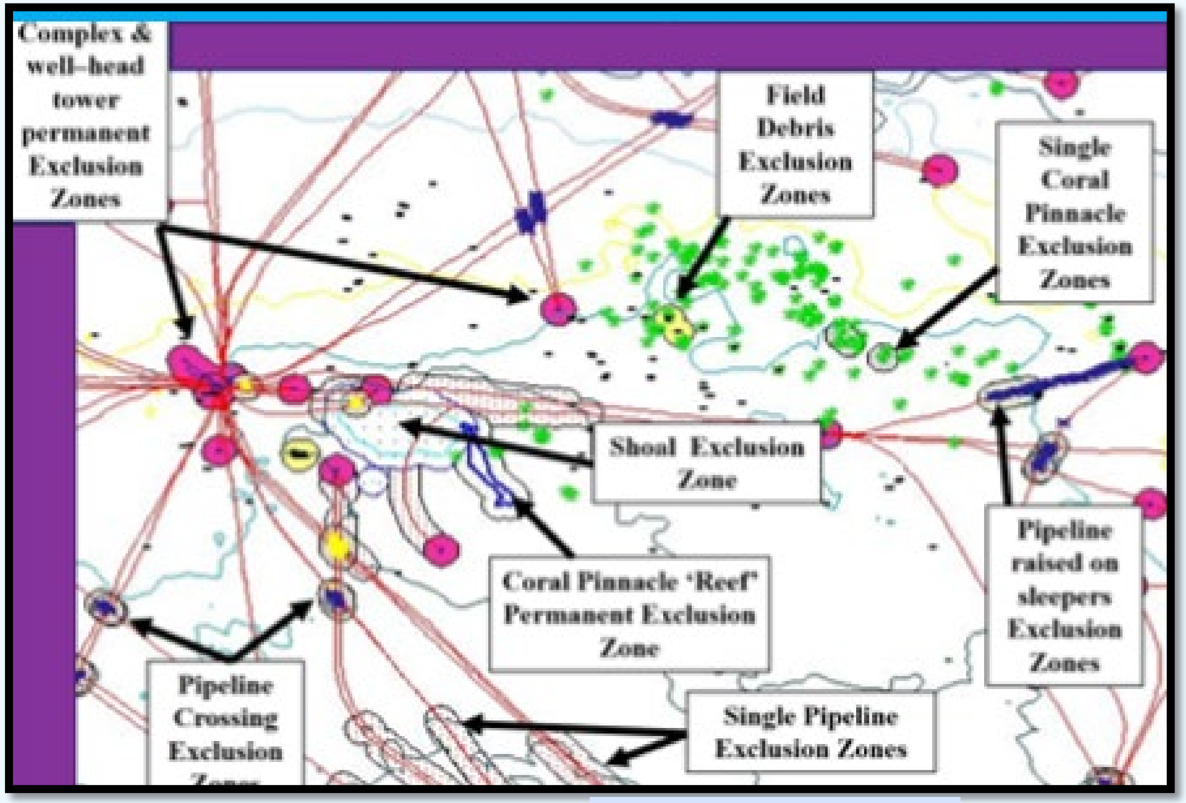
HDOBN acquisition complexity of close approach to 2 obstructions

7.7b Abu Dhabi; Large Multi-obstacle OBC

North Sea Transition Authority

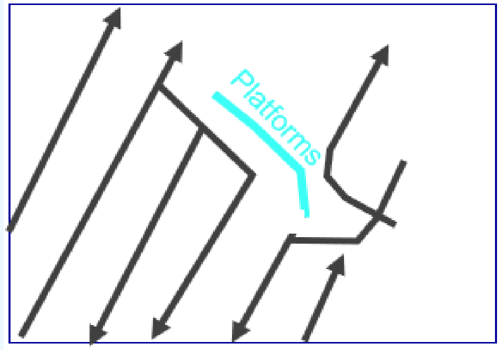
In the early 2000's, the world's largest 3D OBC survey of its time, was undertaken offshore Abu Dhabi. Extreme field complexity >210 surfaces obstructions, pipelines & coral reefs all had to be accounted for. This was a dual sensor OBC, but the recent major reshoot included 4C sensors and multi-well 3D DAS VSPs.

Examples of Abu Dhabi obstructions and exclusions



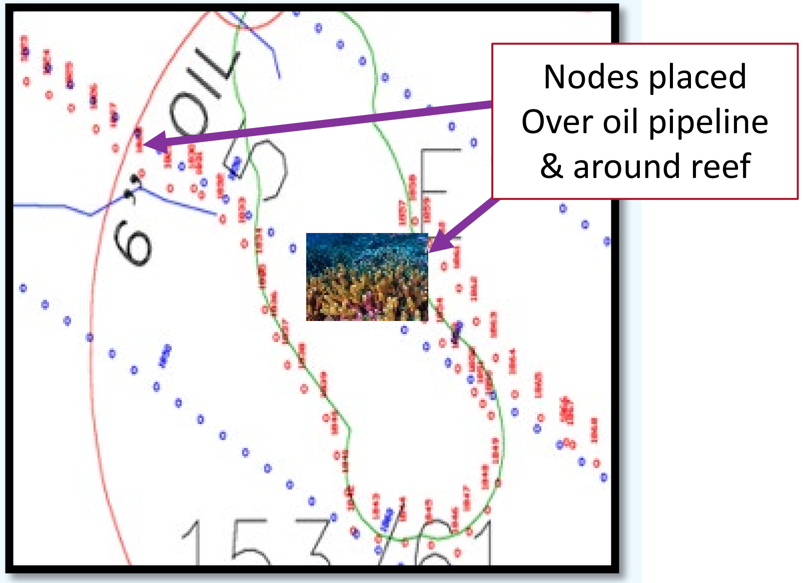
(Refs. 7z, 7aa & 7ab)

Source vessel track map



Carefully planned close approach around linked platforms obstruction

Node layout around reef



Carefully planned seabed seismic can be undertaken around very many obstructions and sensitive areas

7.8a Hybrid: HR Streamer & OBN patch

In the Middle East/ UAE another offshore hybrid survey combining streamer and OBN deployed under infrastructure to produce a seamless and contiguous 3D.

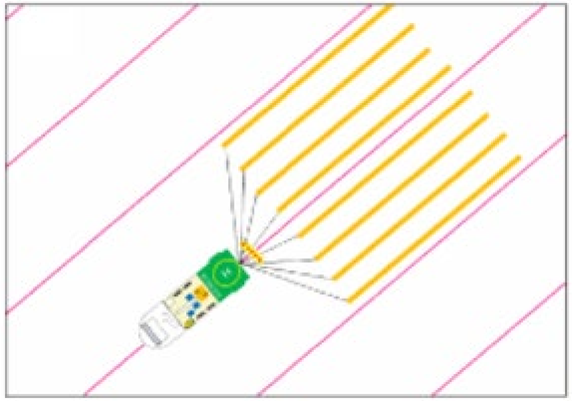
In this case, a penta-source configuration delivers a very high-density source carpet and increased spatial resolution compared to conventional streamer acquisition. Increasing spatial resolution not only aids processing routines such as noise attenuation, demultiple and velocity analysis, but the fine sampling means improved illumination of geological features, and enhanced imaging of shallow targets & dipping events.

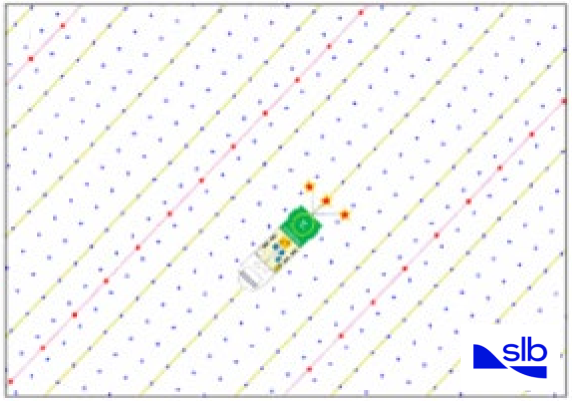
This provided a high trace density (~fold) and high spatial resolution survey.

	Conventional dual source HR Streamer	OBN
Bins	6.25 x 12.5	6.25 x 6.25
Traces/km²	1.024M	1.84M

Compare with graph in section 7.10b

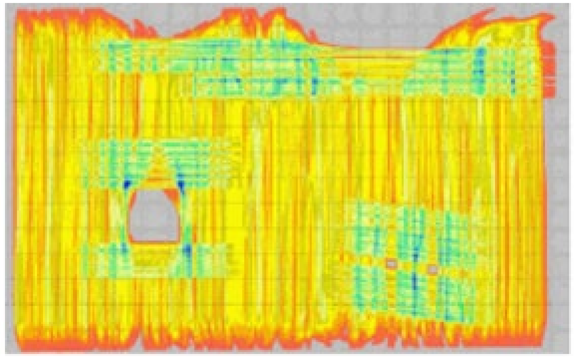
Conventional dual source HR Streamer	OBN Triple-source (SX 25x25 RX 50x225) OBN (red) Source (Blue) Receiver Lines (Pink), Source Vessel lines (Yellow)





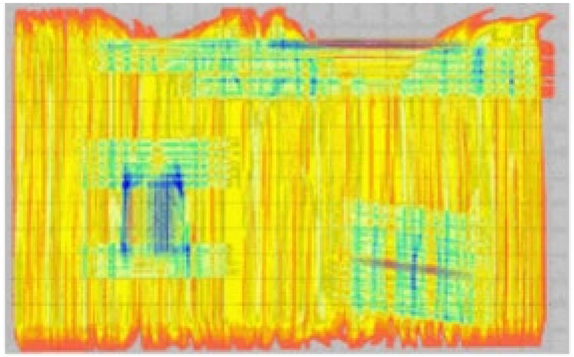
(images courtesy of Western Geco)

Streamer Fold coverage map



Counts of number of traces that fall between the midpoint bins).

Fold coverage map for Streamer + OBN.



Gaps infilled. All data restricted to main acquisition azimuth

(Ref. 7ac

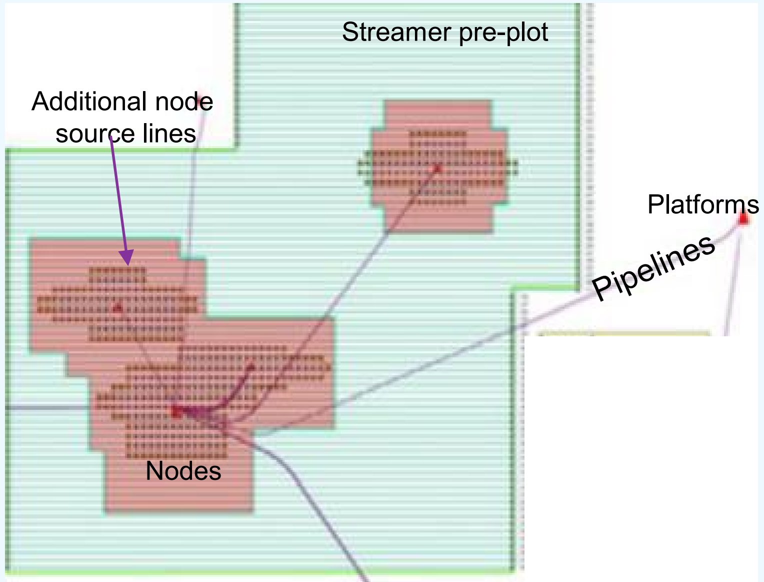
OBN complementing Streamer for high resolution in 'inaccessible' areas

7.8b Hybrid Streamer / OBN obstruction

North Sea Transition Authority

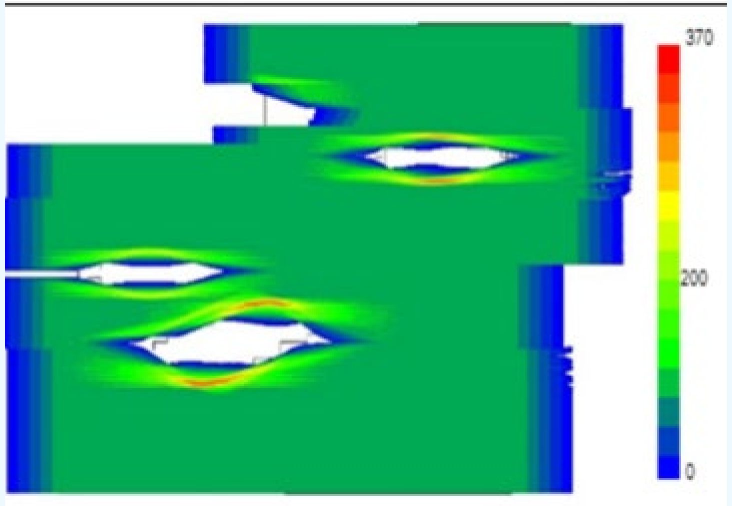
OBS was used in offshore Malaysia to improve imaging under shallow gas and provide illumination due to high dips and data gaps from facilities. A hybrid survey involving a simultaneous conventional streamer, where possible and OBN to fill the platform data gaps. This was undertaken with a multi-purpose vessel: deploy nodes, tow streamers and deploy triple source airguns. It is claimed hybrid was circa 25% of cost of full survey by OBN.

Hybrid pre-plot (340 sq km)



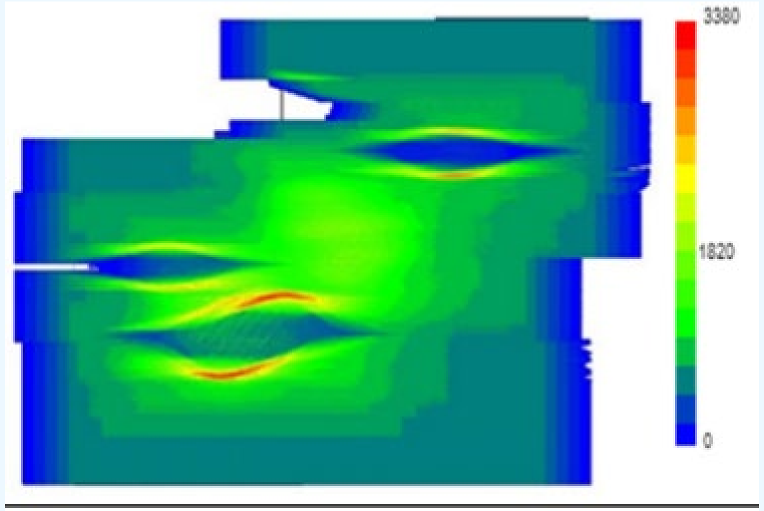
Nodes 300x300m grid

Streamer fold coverage



- Streamer data gaps around installations.
- Gaps < 2kms wide by several kms long
- 6x 5.1km streamers with 75m separation

Hybrid fold coverage



Much higher folds with good sampling in undershoot areas

(Refs. 7ad & 7ae)

Hybrid streamer and OBN is a good cost compromise in co-location situations

7.8c Hybrid streamer & Sparse nodes

North Sea Transition Authority

Previous examples of hybrid surveys were primarily concerned with obstructions. When ultra-long offsets are required for FWI velocity model building (e.g. salt province) or converted wave data would be beneficial (PP-PS characterisation), combining hybrid streamers and sparse nodes is possible.
Shallow image resolution is optimised by the streamer data and because the source vessel is decoupled from OBN receivers, the maximum offsets recorded can be as large as logistically reasonable and as large as the signal-to-noise (SNR) of recorded diving wave events allow. The OBN spacing is typically not dense enough to enable standalone OBN imaging.

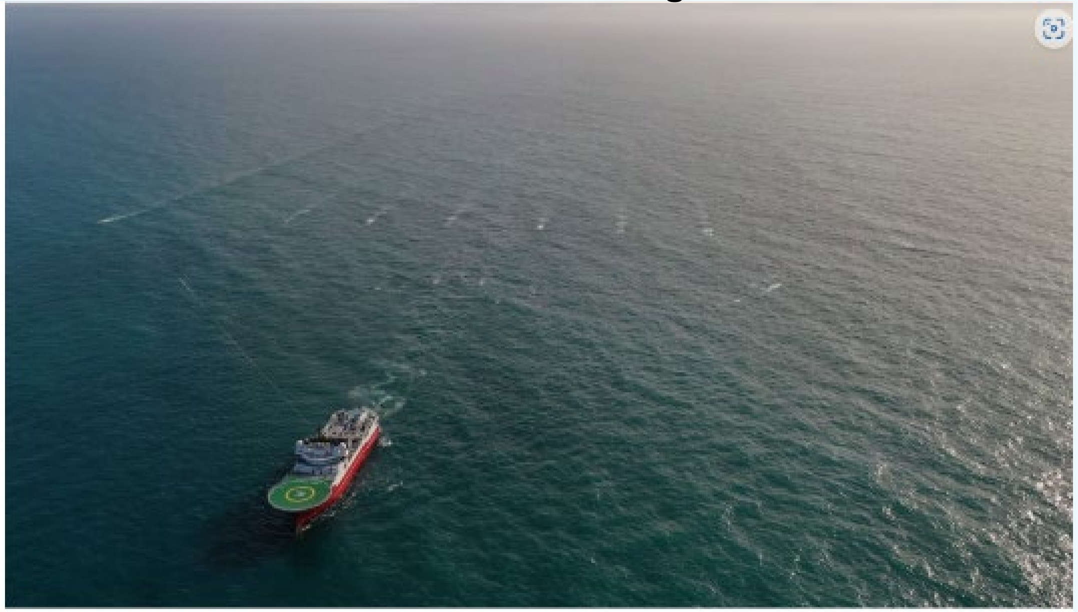
In this case, in the Barents Sea, a very wide Hexa-source configuration towed behind the *Sanco Swift*, on top of a massive, high-density 3D Geostreamer spread that was towed behind the *Ramform Hyperion*. A substantial portion of the survey area was also covered with a sparse grid of 1000 ocean bottom automated free drop nodes and retrieved from the seafloor using an ROV.

(Refs. 7af, 7ag, 7ah)

Ramform towing 18 cables

Ramform Hyperion towing 18 x 75m x 8 025m GeoStreamer spread.

Source vessel towing hexa -source



Sanco Swift towing 437.5-meter wide Hexa-source.

Sparse nodes can be deployed to improve streamer survey velocity field prediction

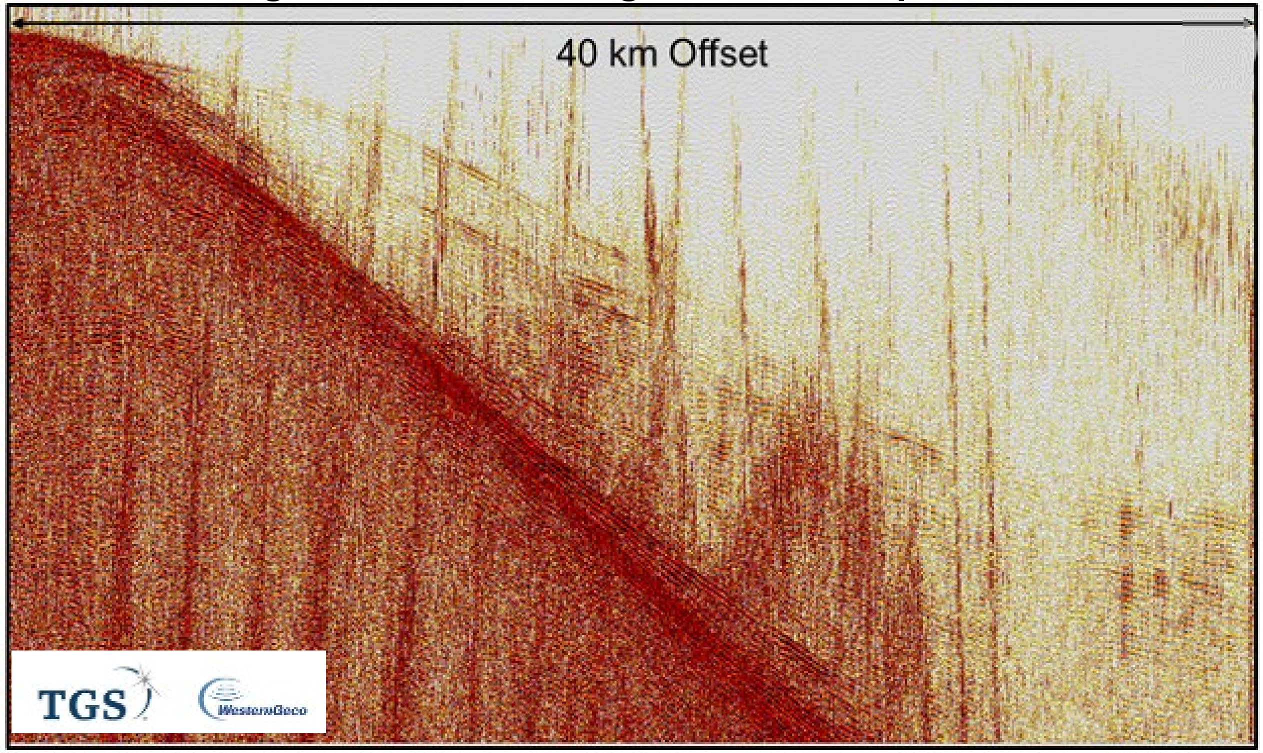
7.8d Very long offsets

Decoupling the source and streamer can result in some very source – receiver long offsets.

In this Gulf of Mexico sub-salt survey sparse nodes (1x 1km) & 50x100m shot carpet provided long offsets for a reflection-refraction FWI (level 2 – section 10.11) to provide improved velocity field for a WAZ streamer survey.

(Ref. 7ai

Shot gather with ultra long offsets from sparse nodes



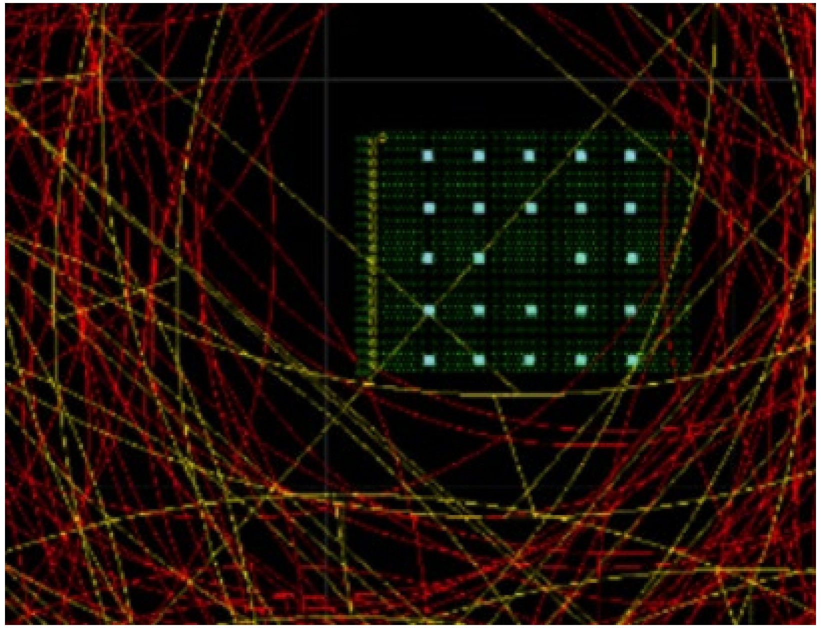
OBN allows very long offsets which can be used for velocity field

7.8e Hybrid coil streamer and autonomous nodes

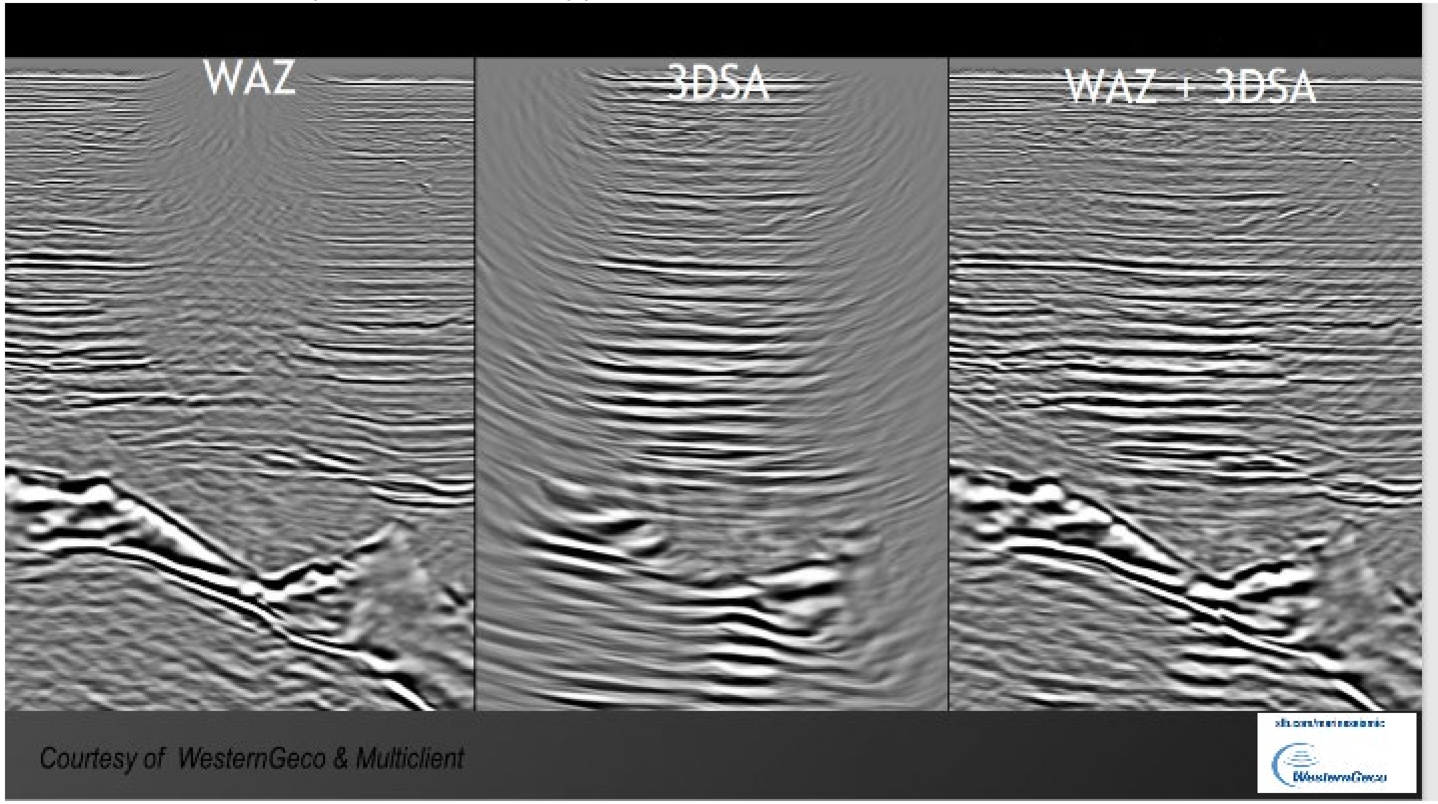
North Sea Transition Authority

Autonomous nodes acquisition (section 7.20) has been conducted in an area (blue squares) where a surface obstruction created a gap in dual coil shooting (blue and yellow lines). The resulting limited aperture image has then been used to infill a wide azimuth streamer survey.

Coil seismic acquisition track & obstruction nodes



3DSA (3D sensor array) incorporated below WAZ obstruction



(Refs. 7aj & 7ak)

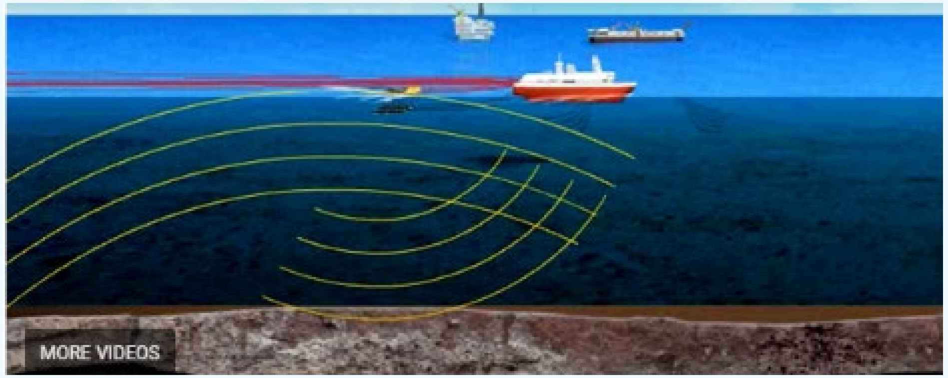
Small scale Autonomous marine vehicle trials promising

7.9 OB Poor Shallow illumination

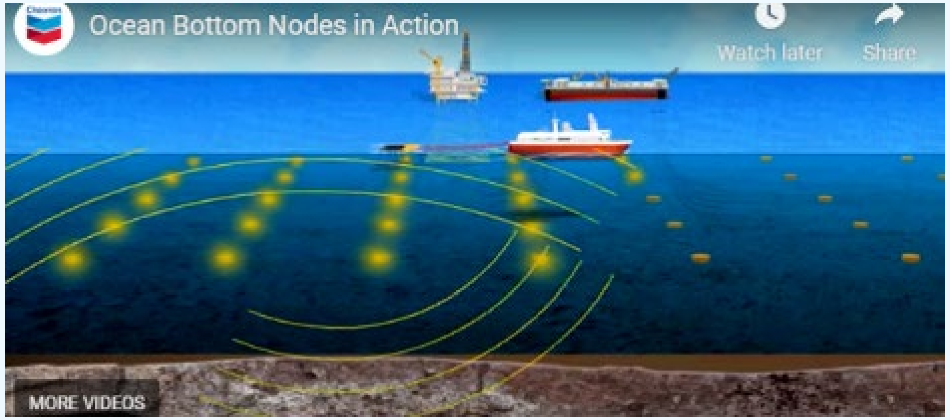
North Sea Transition Authority

On its own, the relatively wide separation of nodes on the seabed inevitably leads to data gaps and low fold, especially in shallow water.

Schematic of streamer vs OBN near surface coverage

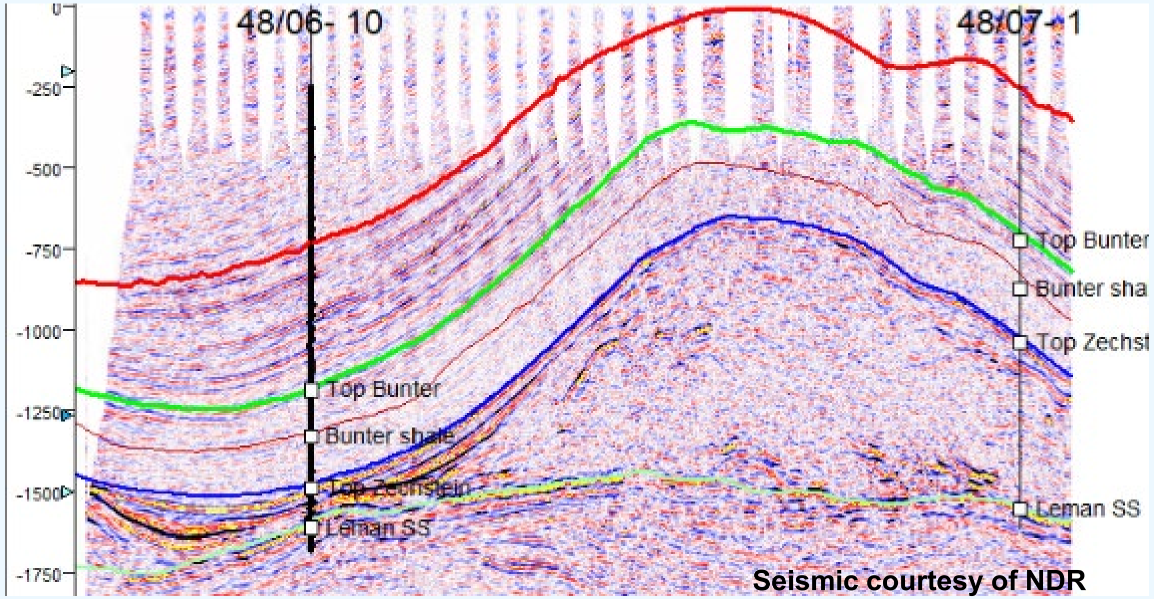


Streamers: continuous coverage of shallow and deep

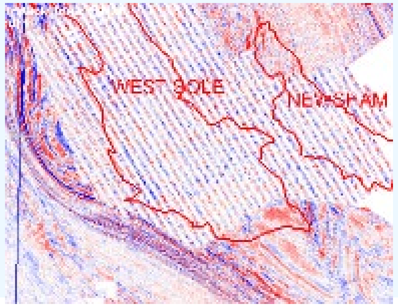


OBN gives continuous deep imaging, but leaves near surface gaps

SNS/ West Sole 3D OBC seismic



West Sole 3D streamer OBC merge timeslice



Near surface data gaps/ low fold evident on cross section and timeslice

(Refs. 7al & 7am)

Very limited near offset data is apparent even on <u>**HD**</u> OBN surveys (Golden Eagle 7.4). Seabed can be imaged with very dense (and expensive) <u>**UHD**</u> OBN and seismic imaging technologies (section 6.10 & 7.12).

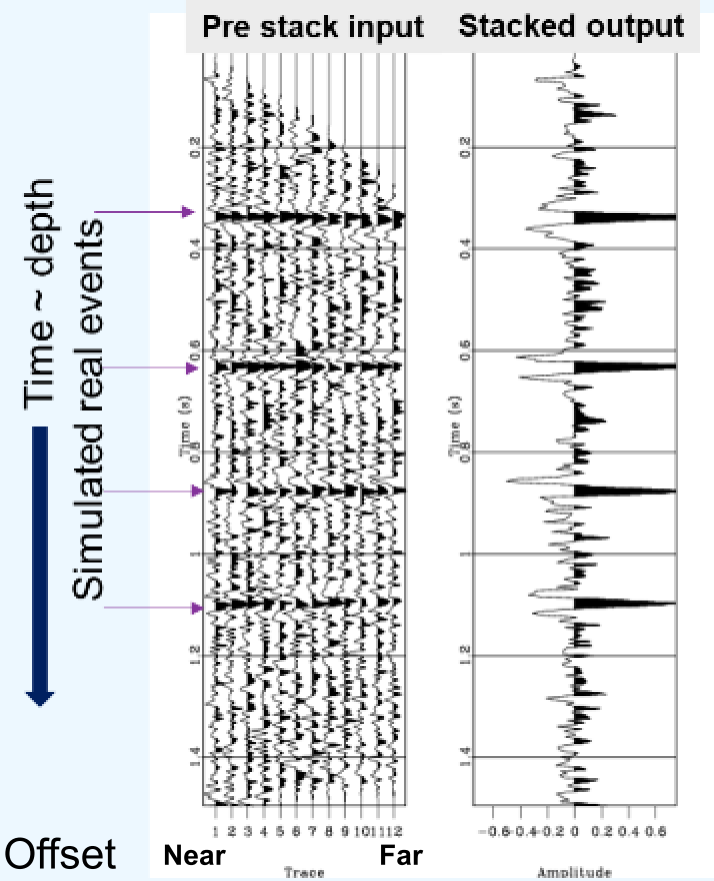
Large cross line node separation typically leads to inadequate near surface imaging

7.10a Fold matters

North Sea Transition Authority

Each subsurface position is sampled very many times with different source and receiver distances (offsets). The number of traces binned and ultimately summed together (stacked) to produce each single output trace is known as the fold. The higher the fold, not only improves processing ability to suppress both random and coherent noise, but the "power of the stack" means noise can be better cancelled out by utilising the data redundancy. A simple example shows the impact:

Synthetic example of stacking



Signal to Noise (enhancement of repeatable signal and suppression of random noise) improves by of the $\sqrt{\ }$ fold,

.

12 traces "fold" with simulated real reflections signal & significant added random noise.
Summing (stacking) improves signal/ noise
Enhancing the "target" reflectors and supressing the noise in between.

(Ref. 7an)

Stacking several traces from the same subsurface point (fold) directly reduces the background noise and enhances geological signal

7.10b Seismic trace density

North Sea Transition Authority

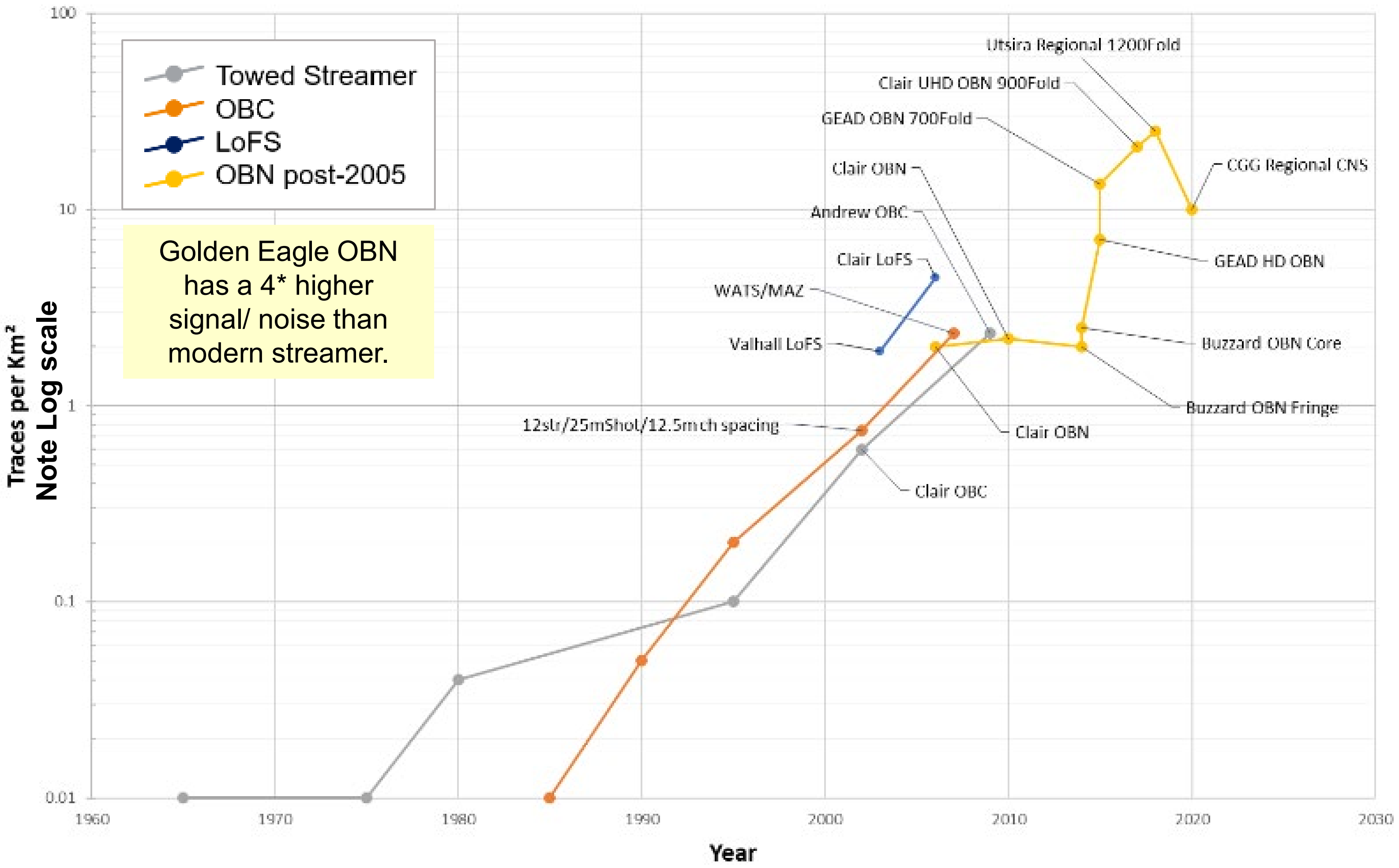
Trace density (approx. equivalent to fold) has been rapidly increasing throughout the 1990's/ early 2000's for both towed streamer and OBC.

Seabed seismic, also including permanent reservoir monitoring installations (PRM: section 7.21) such as the Valhall Life of Field Seismic (LoFS) further increases this trend. Now large complex fields undertaking increasingly higher trace densities and even regional exploration surveys adopting high density/fold where necessary, but at greatly increased cost.

The cost of this trace density clearly is subject to careful optimisation.

The world record for an onshore survey has a trace density of 257million traces km².

Illustrative data density



Note the methods and parameters used for calculating fold and trace density are study dependant.

(Refs. 7ao, 7ap, 7aq , 7ar & 7as)

Substantial year on year increase in data density (fold)

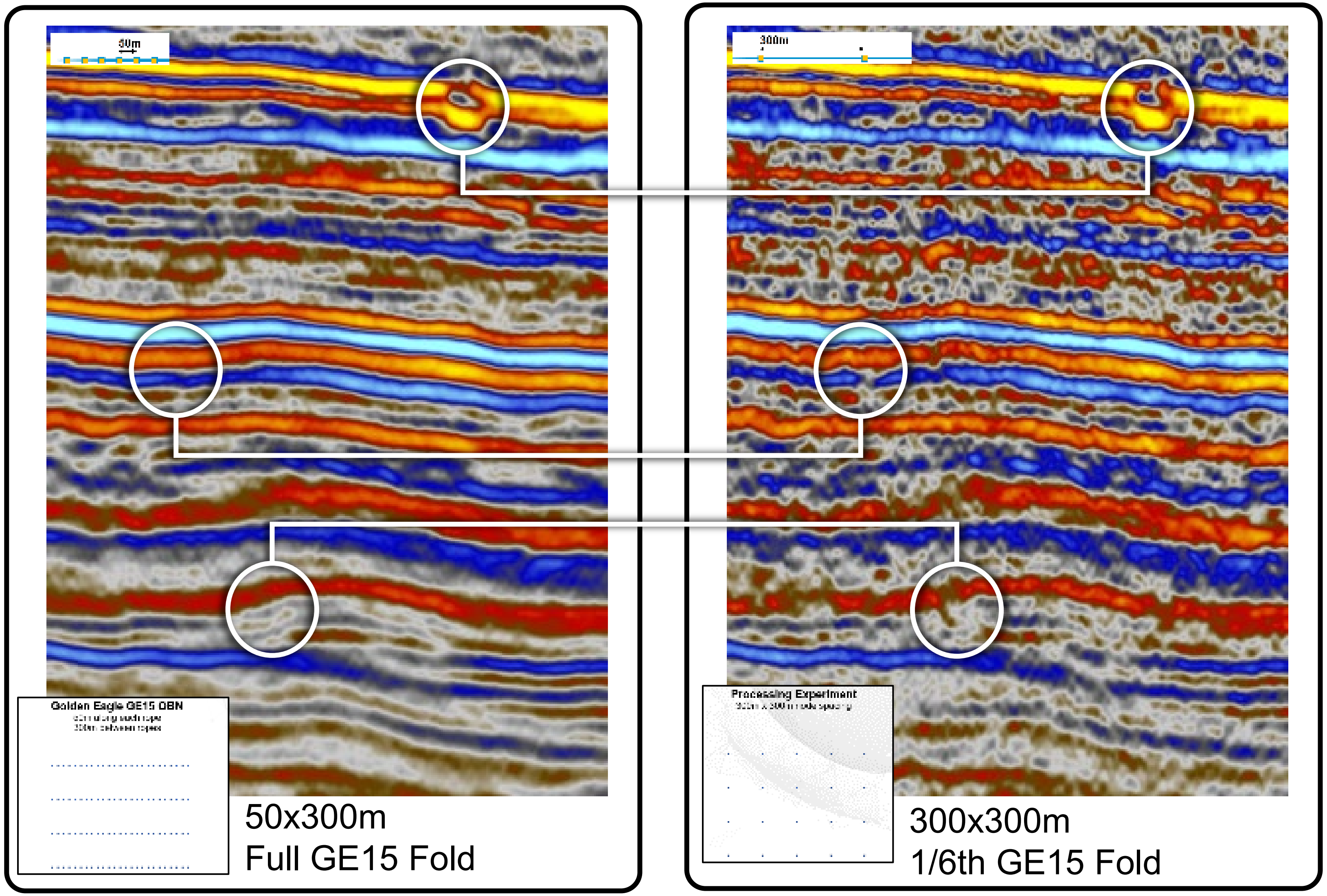
7.11a Golden Eagle OBN decimation: 3D

North Sea Transition Authority

The cost of high-density (HD) nodes is a major consideration, so CNOOC undertook a decimation trial of their Golden Eagle OBN survey.

- Golden Eagle Dense Nodes Decimation Trial on 3D imaging.
- The trial tested the reduction in inline receiver sampling from 50m to 300m and the effects on the output data.

- There is a clear increase in 3D noise with the reduction in receiver sampling.
- General form, structure and 1st/2nd order features preserved.
- Loss of seismic interpretability.
- 3D Noise is not necessarily repeatable, so a sub-sampled survey may not be a suitable baseline survey.



50x300m
Full GE15 Fold

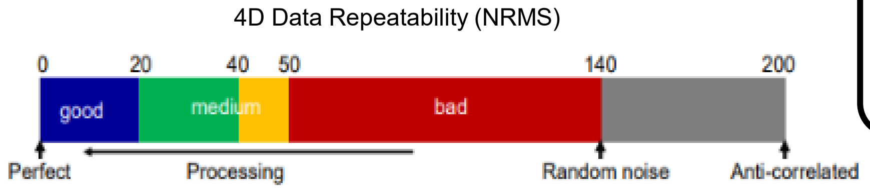
300x300m
1/6th GE15 Fold

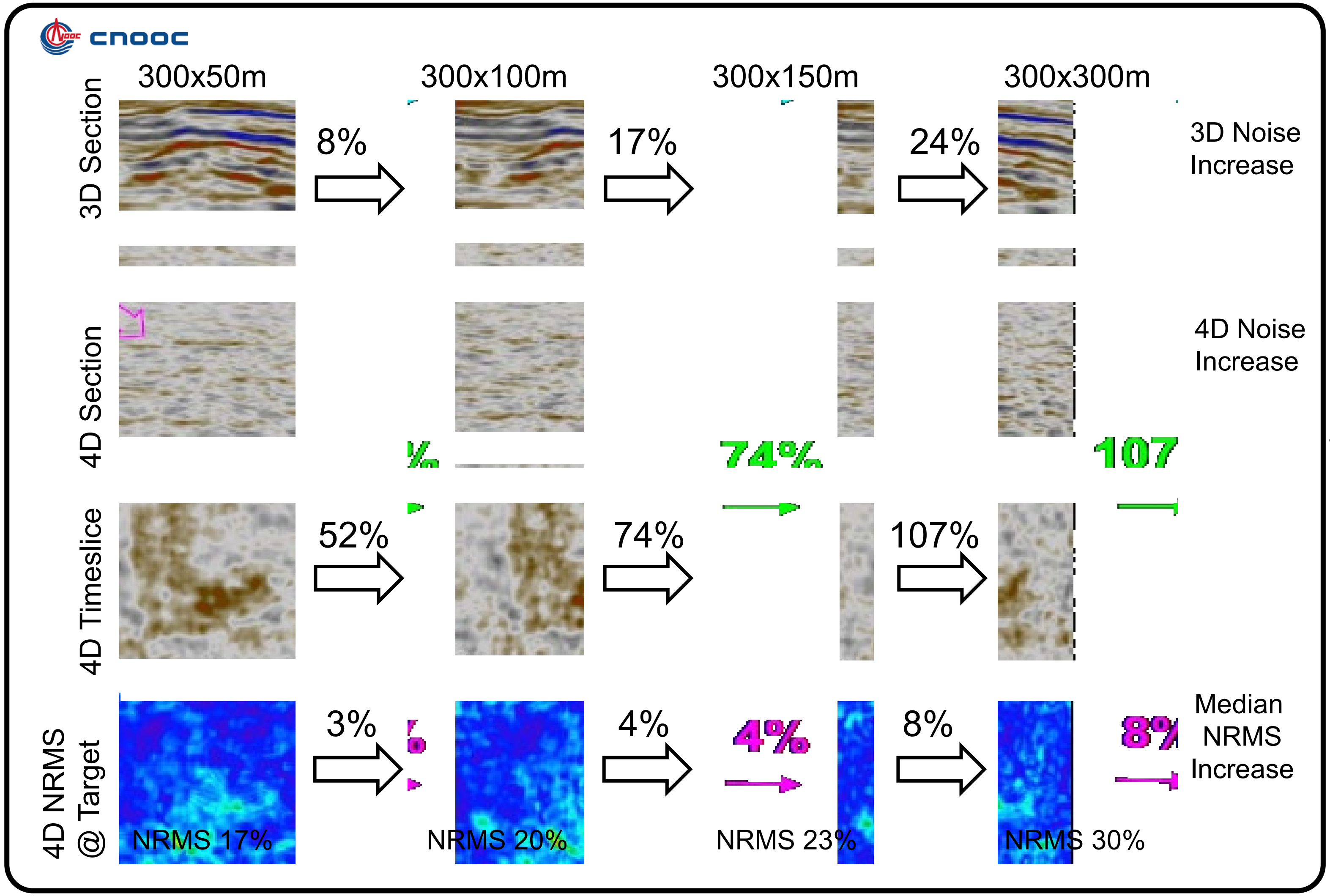
(Ref. 7at)

High density vs sparse receiver has major impact on 3D signal. This is likely to be target depth specific.

7.11b Golden Eagle OBN decimation: 4D

- Golden Eagle Dense Nodes Decimation Trial on 3D imaging & 4D difference (seismic monitoring).
- The trial tested the reduction in inline receiver sampling and the effects on 4D output data.
- There is a clear increase in 3D noise and 4D noise.
- General form, structure and 1st/2nd order features preserved throughout.
- Conclusion that a minimum node spacing of 300x100m required for Golden Eagle from a quality-cost perspective.
- This conclusion appears consistent with other OBC decimation studies, beyond which the image suffers from lack of continuity and resolution.



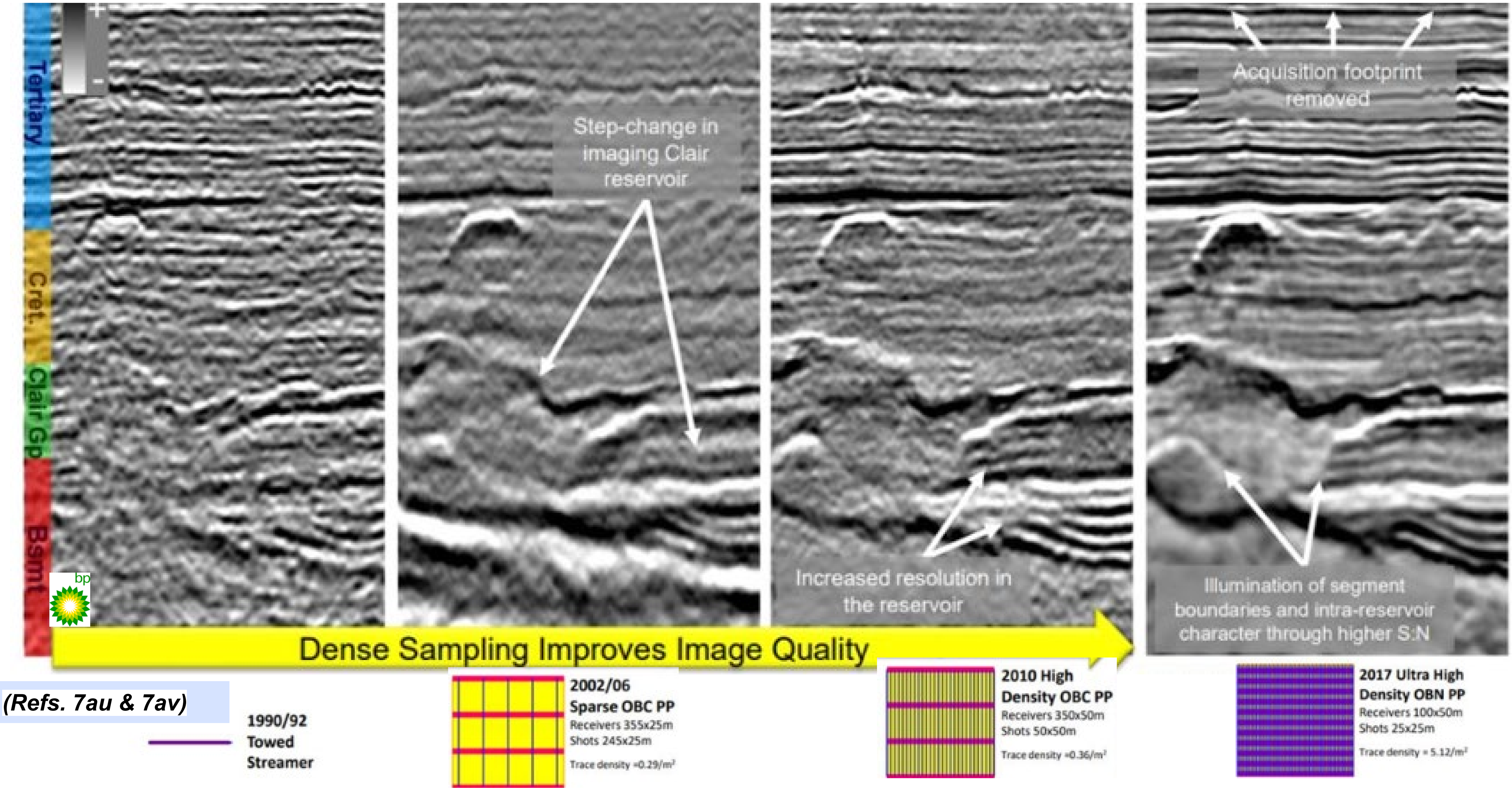


(Ref. 7s)

7.12 Clair 3D imaging Streamer to UHDOBN

North Sea Transition Authority

Multiples (noise) and complex and fractured geology has meant that Clair imaging has been challenging. Increasing spatial resolution and trace density has created a significant reservoir uplift.



(Refs. 7au & 7av)

Clair 3D evolution: from streamer, sparse OBC to ultra-high density OBN

7.13 Complex Salt Diapirism

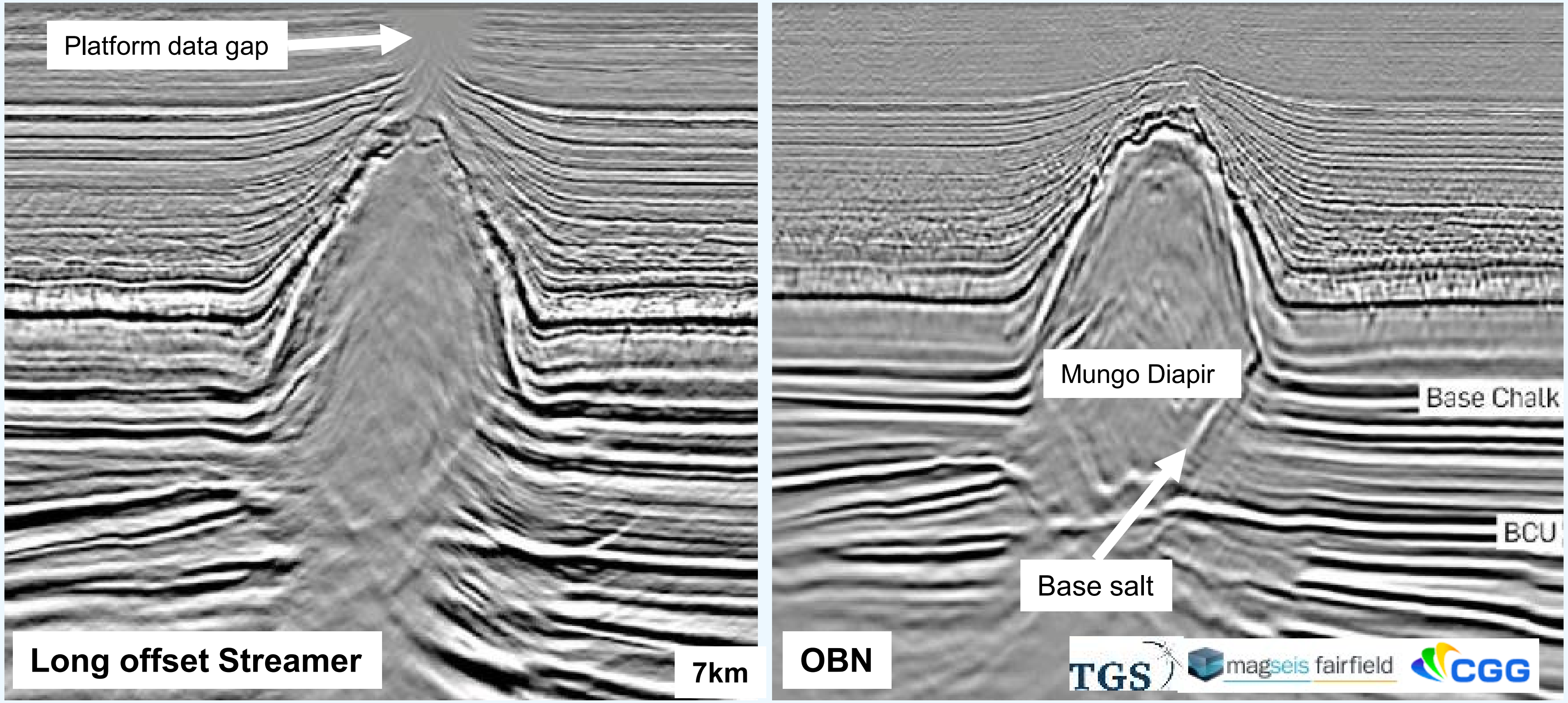
North Sea Transition Authority

OBC/OBN found early success in the Gulf Of Mexico (GoM) salt fields. Similarly, in the UKCS, a typical OBC/OBN complex structures imaging:

- High velocity salt is uplifted into classic diapir shapes and juxtaposed against much slower Tertiary sediments.
- Leading to complex ray paths.
- Originally the CNS Mungo diapir was imaged by restricted aperture OBC for the Tertiary/Cretaceous section above the diapir.
- Exploration attention has now switched to the sub-salt play with longer offset OBN.

(Refs. 7aw & 7ax)

CNS Long offset streamer vs OBN comparison across Mungo Field

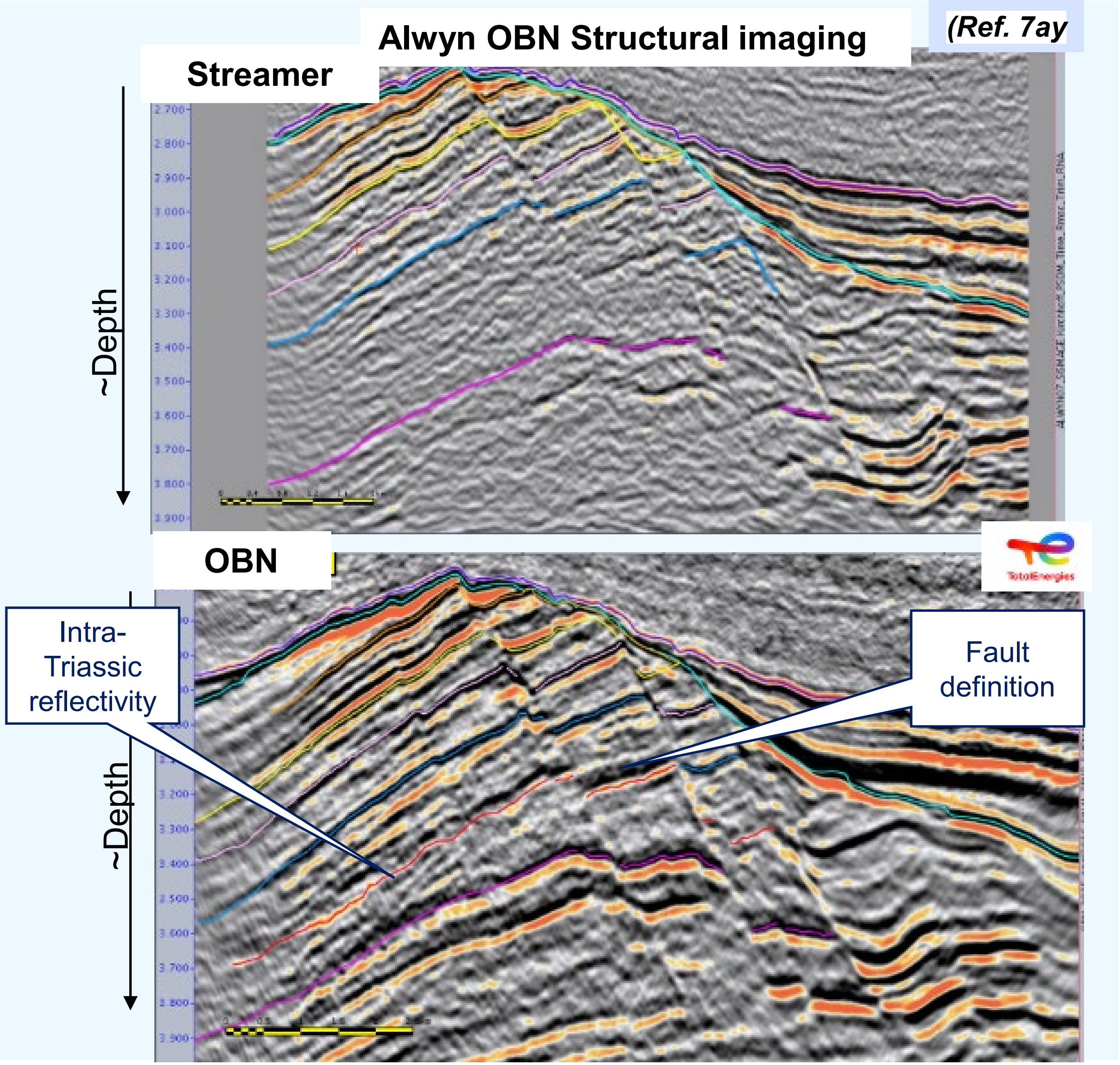


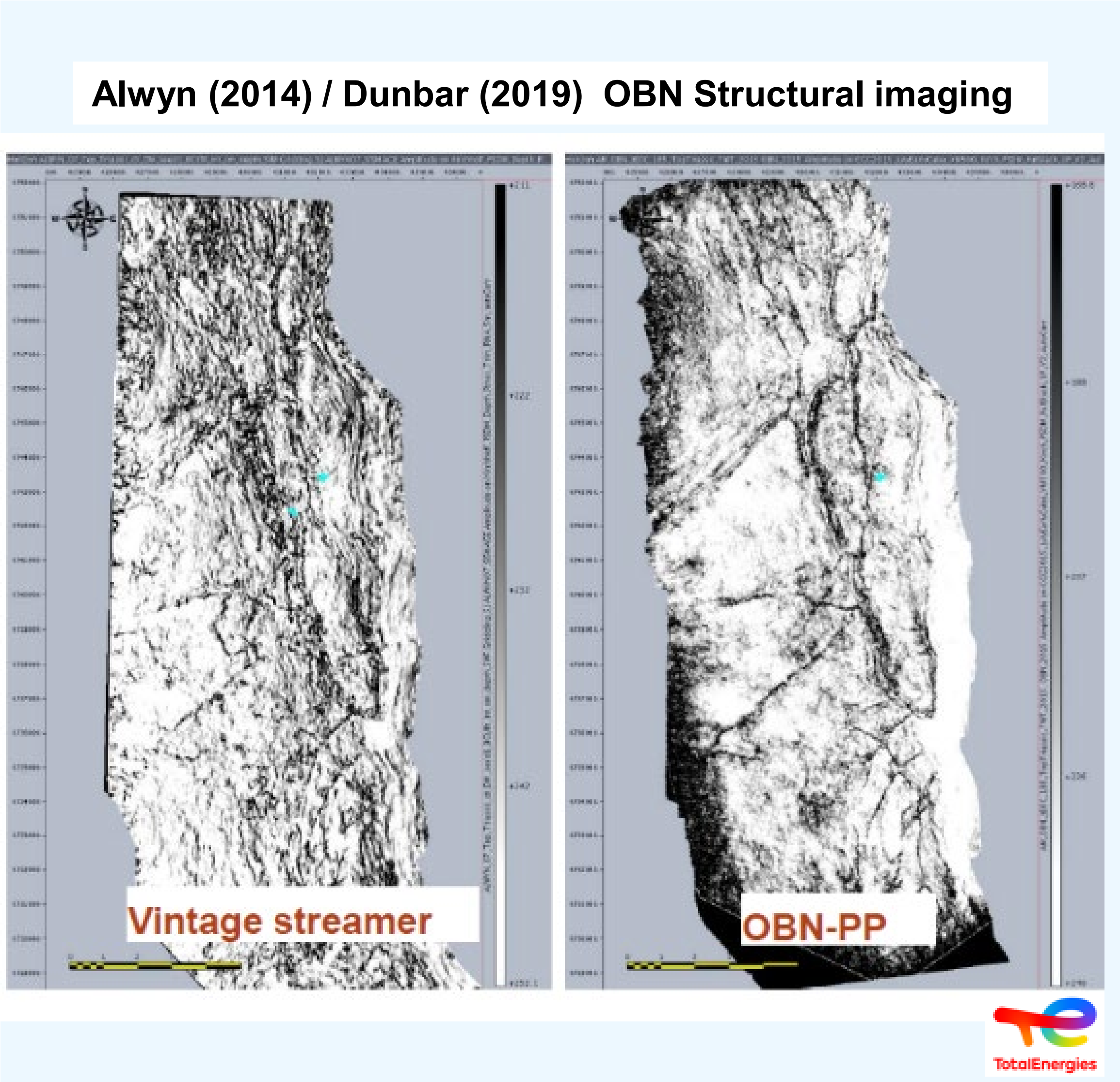
Depth slice through Fram Field

Radial faulting segmenting field

Traditional complex structure OBC/OBN salt diapir target

7.14a Alwyn Fault Block OBN Imaging

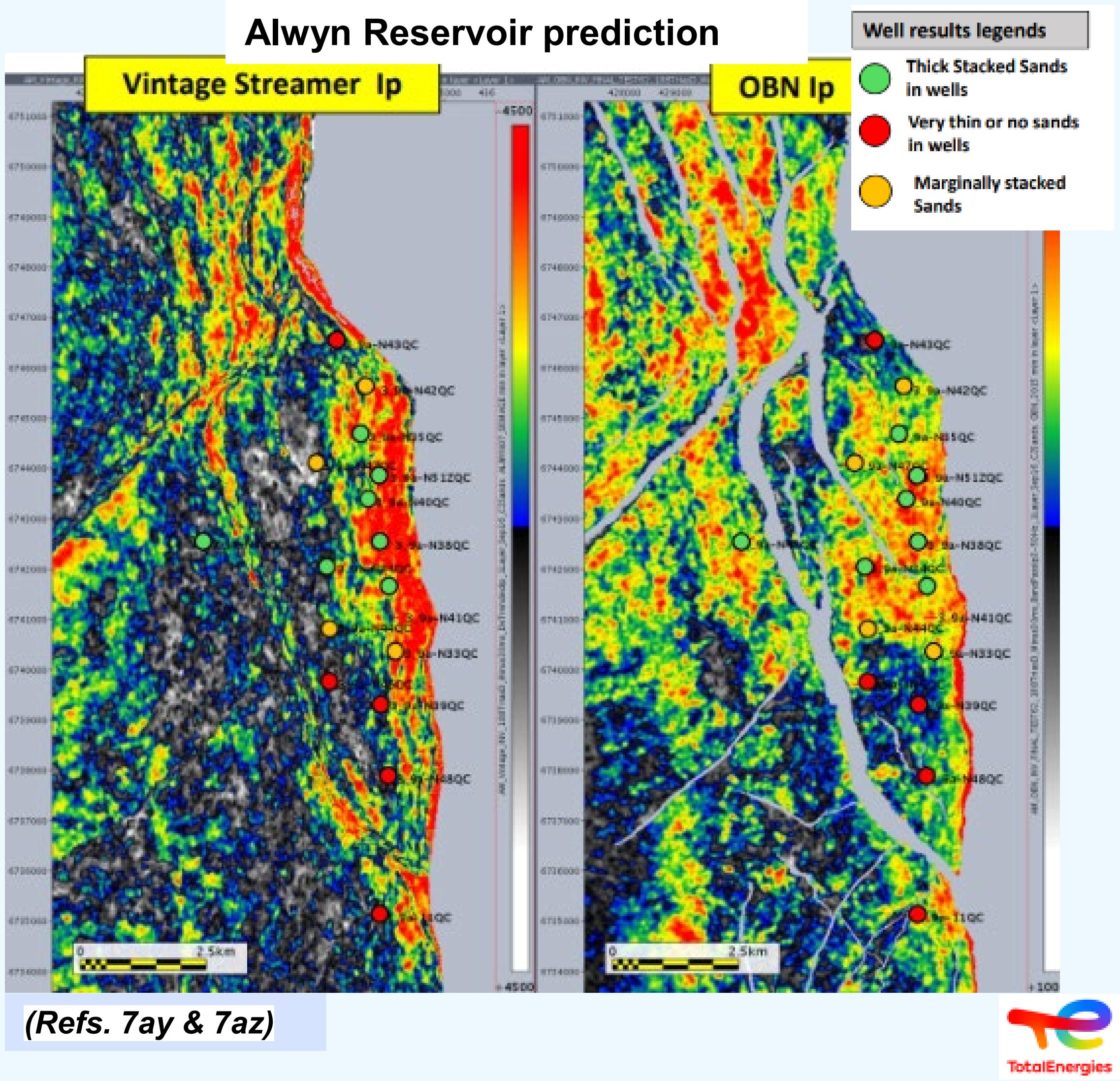




OBN: step change in image quality and fault definition

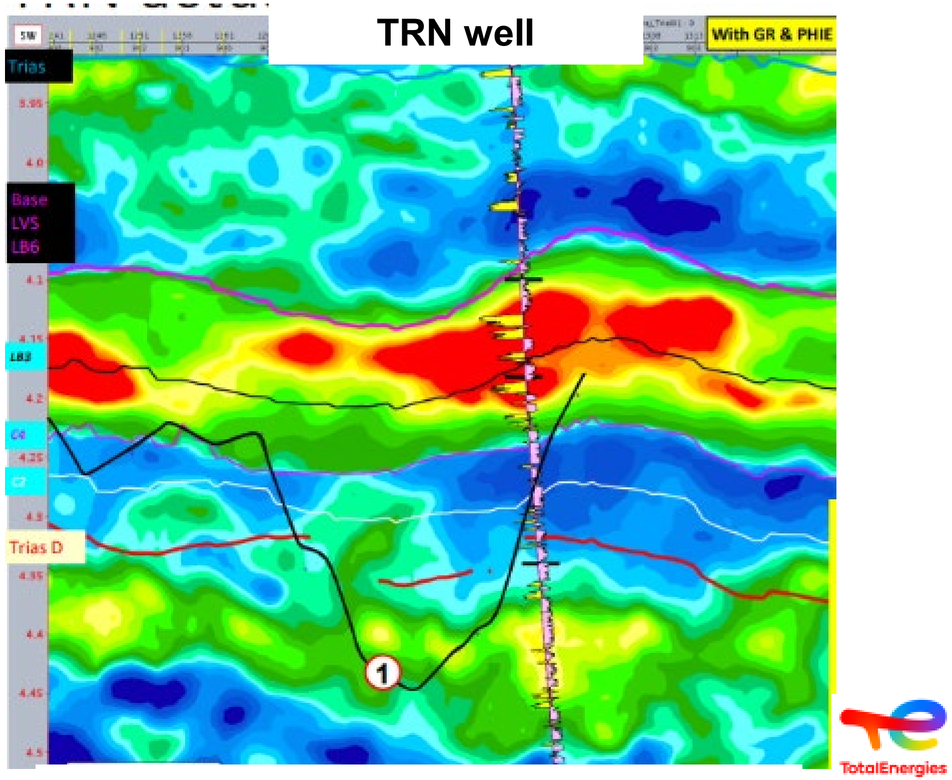
7.14b Alwyn Reservoir Prediction with OBN

North Sea Transition Authority



(Refs. 7ay & 7az)

- Previous seismic inversions had limited success owing to seismic data quality.
- Sparse OBN acquired with full azimuth, PP and PS datasets.
- Resulting elastic PP inversion together with seismic interpretation resulted in improved 3D mapping of Triassic sands, confirmation of regional sedimentary trends and better coherence with dynamic information.



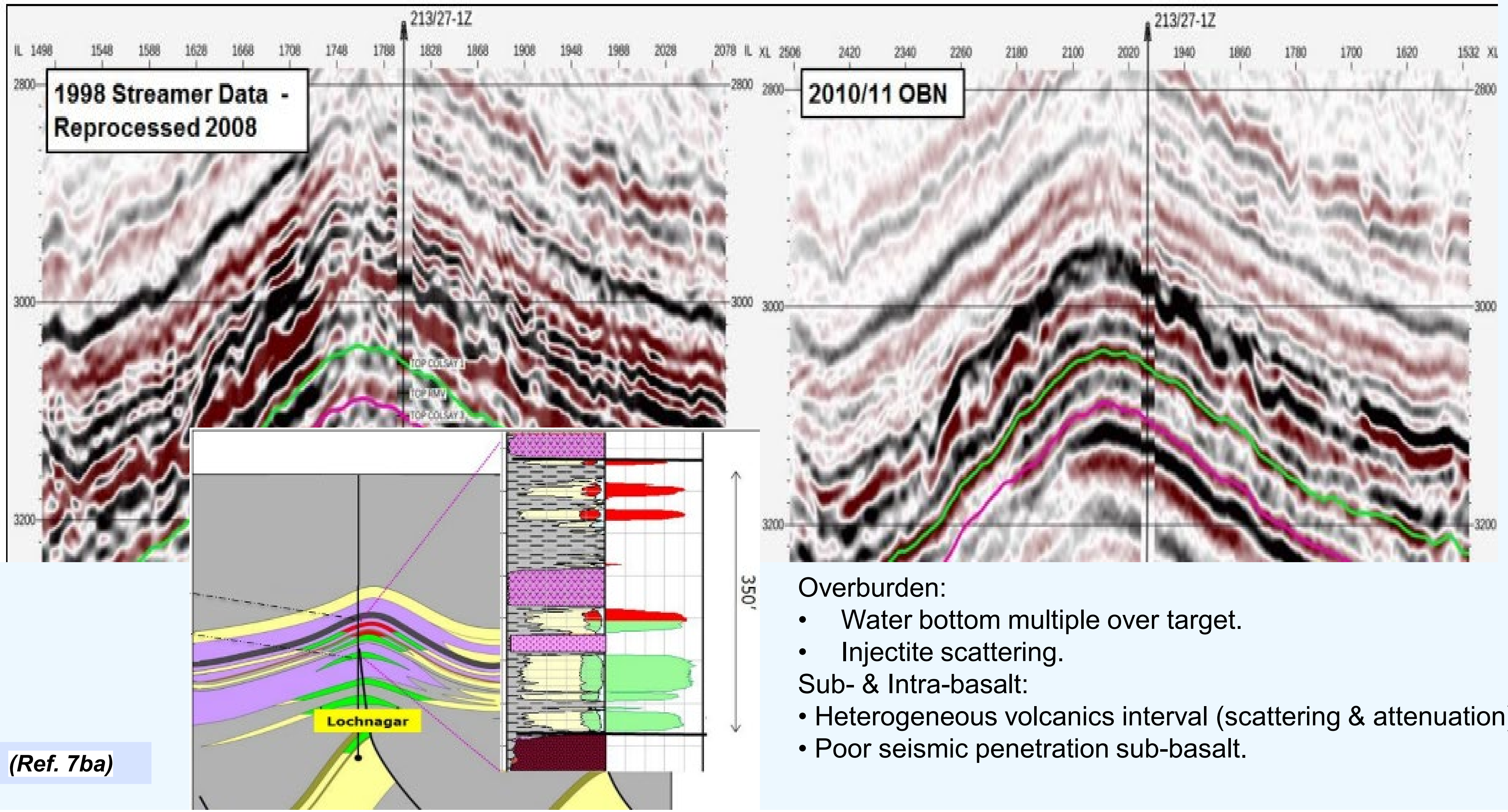
Demonstrated OBN reliably predict sand

OBN: step change in reservoir characterisation & prediction of porous sands

7.15 Intra Basalt Reservoir imaging; West of Shetland

North Sea Transition Authority

Intra and sub- volcanic reservoirs



Overburden:
- Water bottom multiple over target.
- Injectite scattering.

Sub- & Intra-basalt:
- Heterogeneous volcanics interval (scattering & attenuation).
- Poor seismic penetration sub-basalt.

(Ref. 7ba)

OBN: significant improvement in structural definition and velocity model. Individual basaltic flows and sand fairway confidence

7.16a Complex overburden imaging: Kinnoull

North Sea Transition Authority

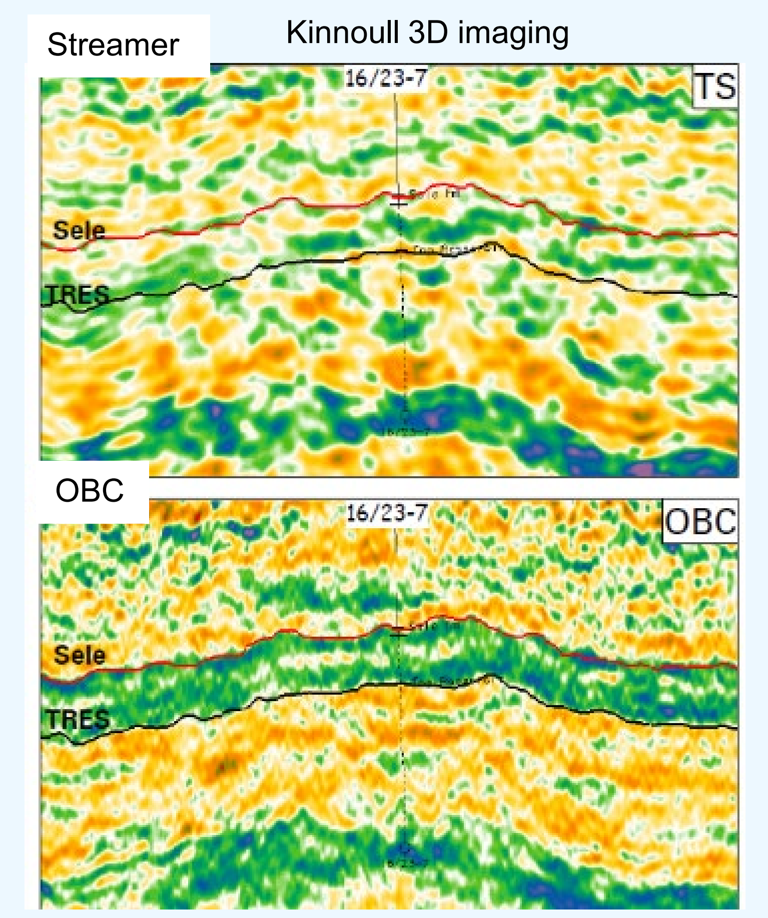
Traditionally, OBS was used for areas of complex reservoir structures, but it was found also to be valuable for imaging complex **overburdens.**

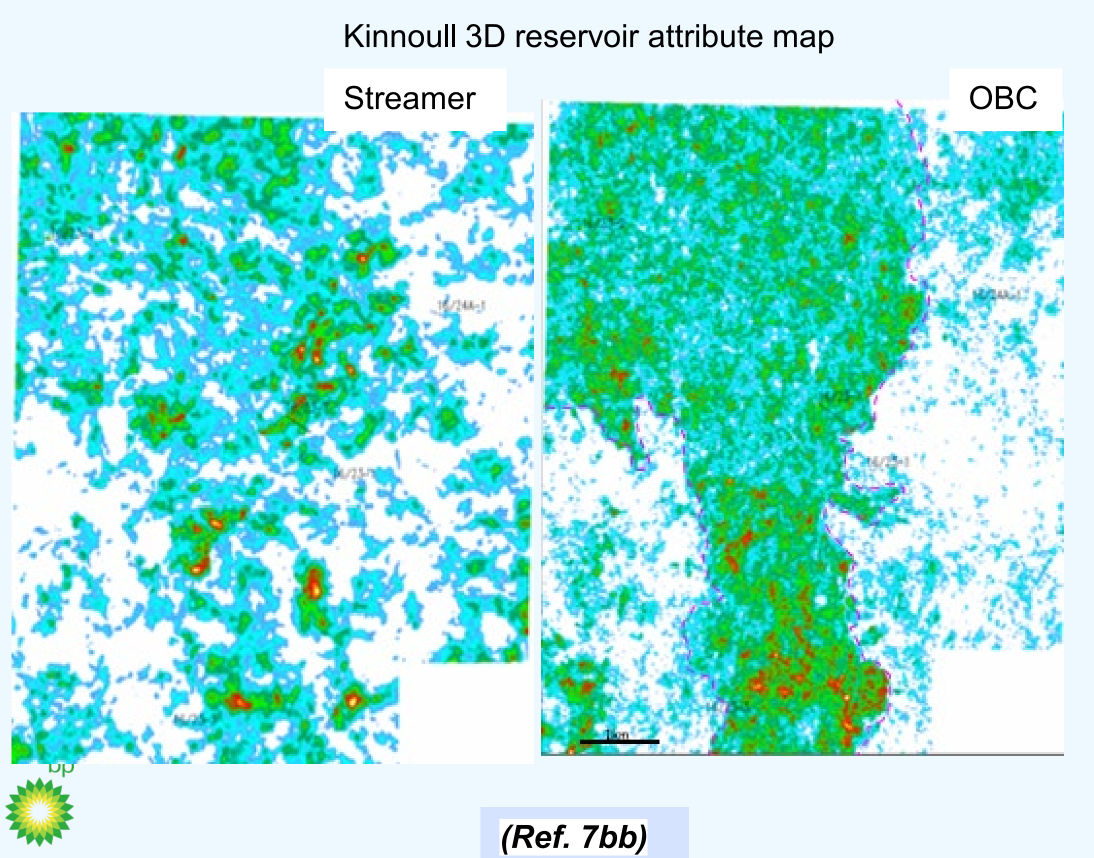
UKCS Kinnoull field OBC/OBN

The original poor quality streamer image at Kinnoull was due to the because anomalously fast Eocene sands overburden which attenuate the primary and produce strong multiples.

The level of uplift provided using 2010 HDOBC was a surprise. This allowed for a better mapping of the top reservoir and consequently definition of the reservoir fairway attributes which closely tied to the well data. This step change has been attributed to using Wide azimuth OBC and high shot density.

The results of 2019 4D HDOBN are provided in section 11.4





(Ref. 7bb)

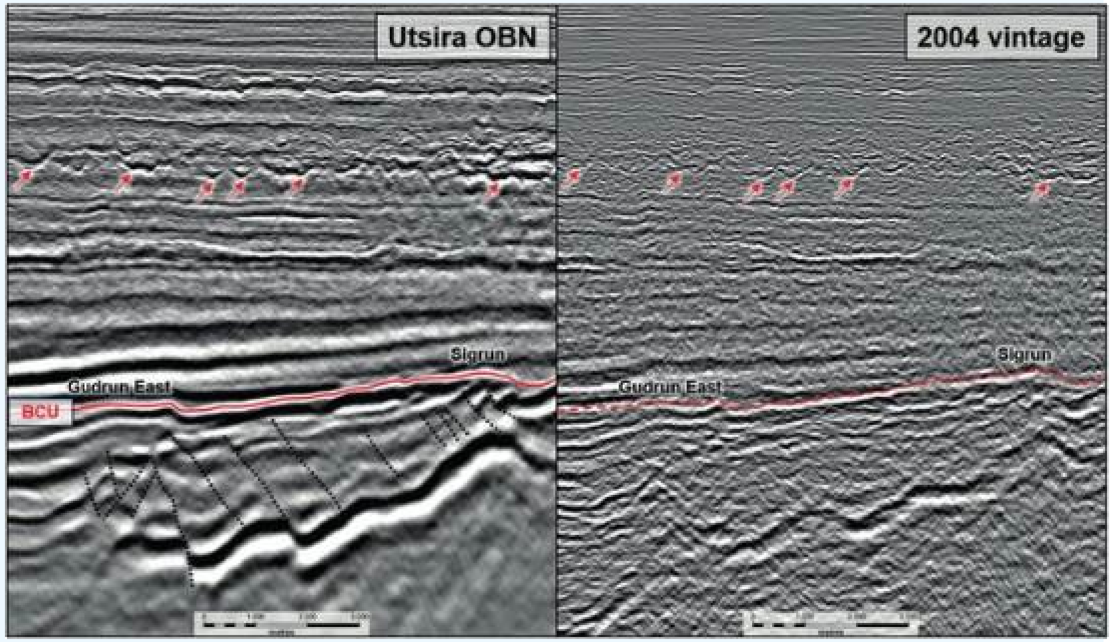
OBC/OBN significantly improves shallow Eocene injectite imaging

7.16b Complex overburden imaging: Utsira

North Sea Transition Authority

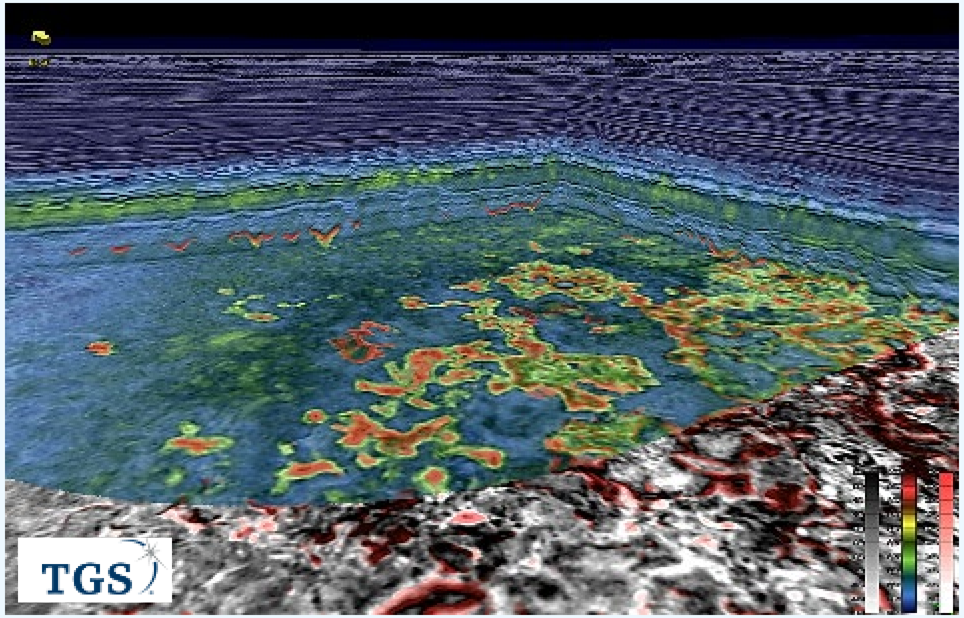
An ultra long offset (>17km) regional HDOBN survey provided both excellent deep imaging and detailed velocity models for Eocene injectites.

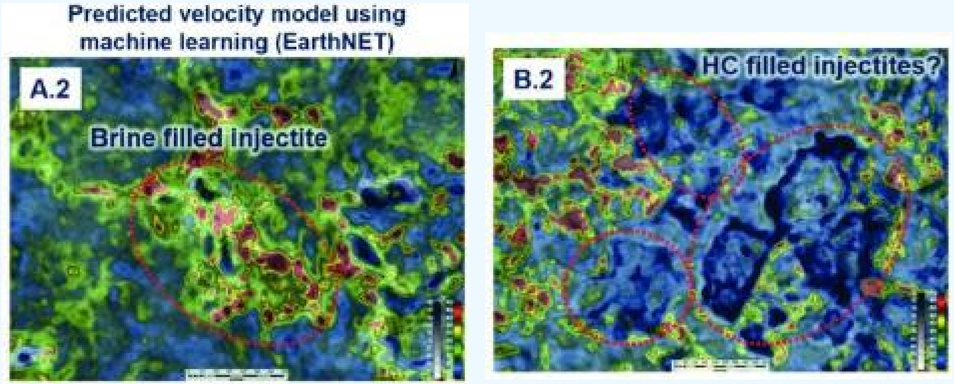
Utsira (NOCS) OBN imaging



Building on earlier injectite experience (e.g., Alba – section 5.6d& 5.6e), fine scale imaging has been provided in the regional Utsira HDOBN survey. OBN illuminated from all sides and sampled up to 25 times better than with a narrow azimuth streamer 3D.

(Refs. 7bc & 7bd)





High resolution FWI and machine learning velocity models can be used to characterise the potential fluid fill of injectites

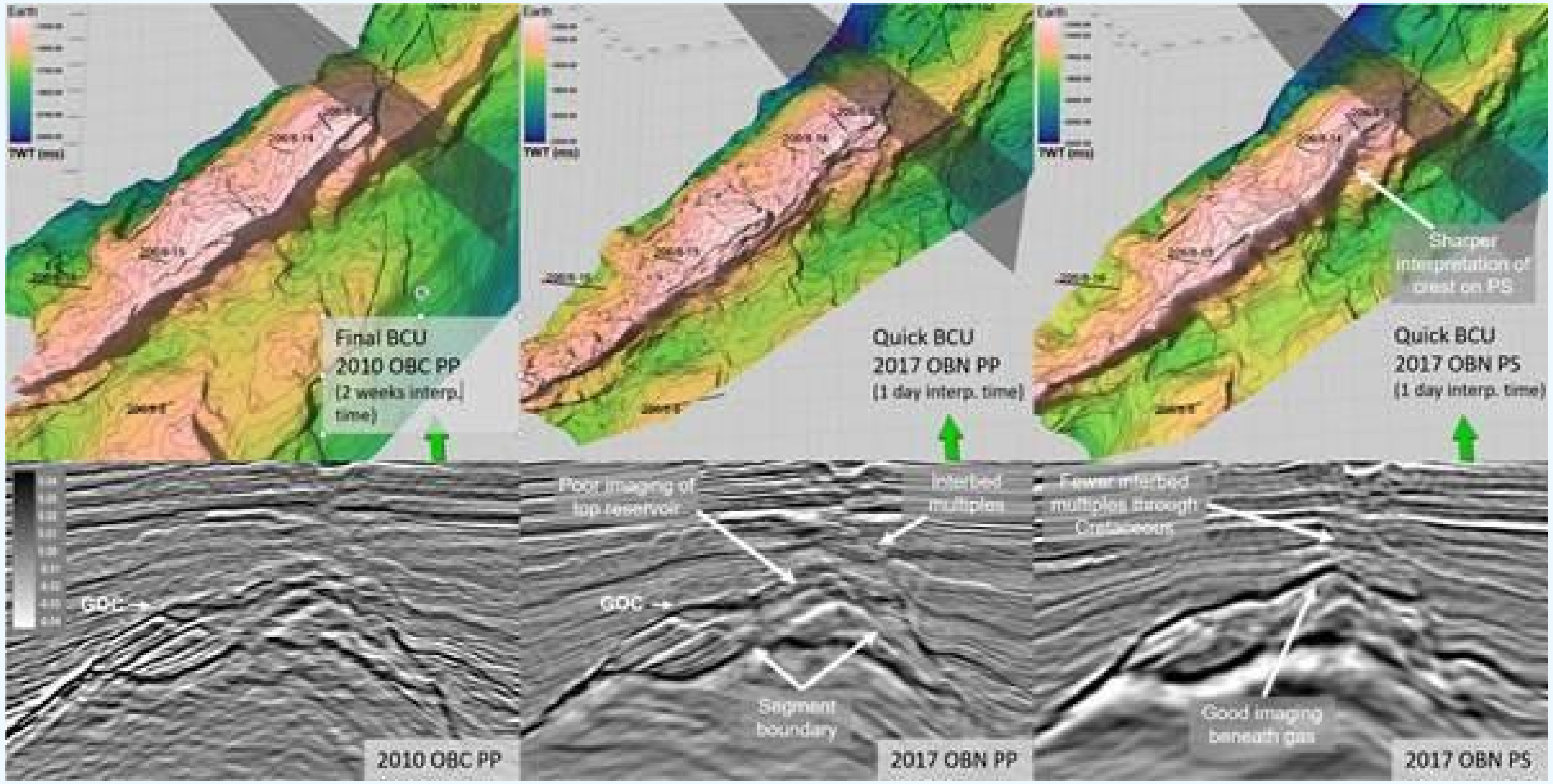
Dense OBN provides major uplift in both deep imaging and fine scale velocity models for shallow injectites

7.17 Shear wave imaging

North Sea Transition Authority

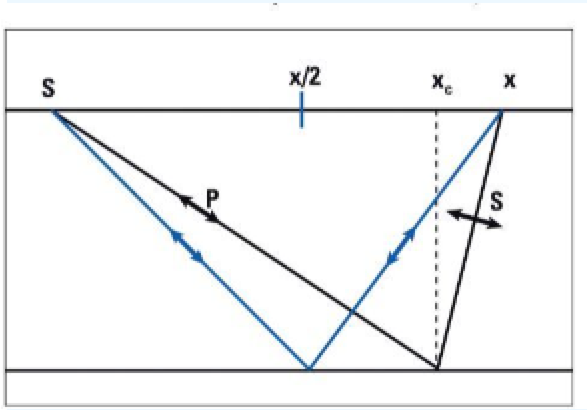
P-Wave imaging is by far and away the main seismic reflection tool. However, naturally leaky gas reservoirs can release a gas plume which makes conventional imaging and characterization of the reservoir very difficult. S-waves, on the other hand, are generally less sensitive to rock saturants and can be used to penetrate and "see through" gas-saturated sediments, so Shear (S) waves collected by OBS can be particularly valuable for imaging through shallow gas. There are many other applications for shear data (fault imaging, near surface resolution, lithology estimation and anisotropy – fracture estimation.

Comparison of Clair legacy OBC and recent OBN P and S wave imaging.



This comparison builds on Clair HDOBN imaging description (section 7.12) differences in both cress section and Base Cretaceous Unconformity (BCU) mapping.

Asymmetry of raypaths makes PS imaging more difficult



PP reflection point can be determined geometrically, PS depends upon the medium parameters

(Refs. 7au, 7be, 7bf, 7bg)

Shear wave imaging can be beneficial in specific imaging environments

7.18 Testing the limits of sparse nodes?

North Sea Transition Authority

Decimation trials in deep water Brazil for the Jubarte field (Campos basin) have exploited high-order multiple sea-surface reflection using down-going wavefield & mirror imaging. Node separation has been tested out to 500m but will only work with the minimum fold to assure sufficient image resolution is respected i.e. the number of receivers is still essential for signal-to-noise but their position on the seabed is less important.

Another decimation trial in the ultra-deepwater Santo basin in Brazil, showed the velocity estimation results from sparse node surveys in general produce poorer velocity models than relatively denser ones when deriving the model from FWI with primarily diving wave energy. However, a relatively coarse source-receiver distribution is still able to produce a high-quality velocity model.

The conclusion here was that receiver sampling of 1km by 1km and a shot geometry of 100m by 300m spacing is a viable alternative to denser node surveys.

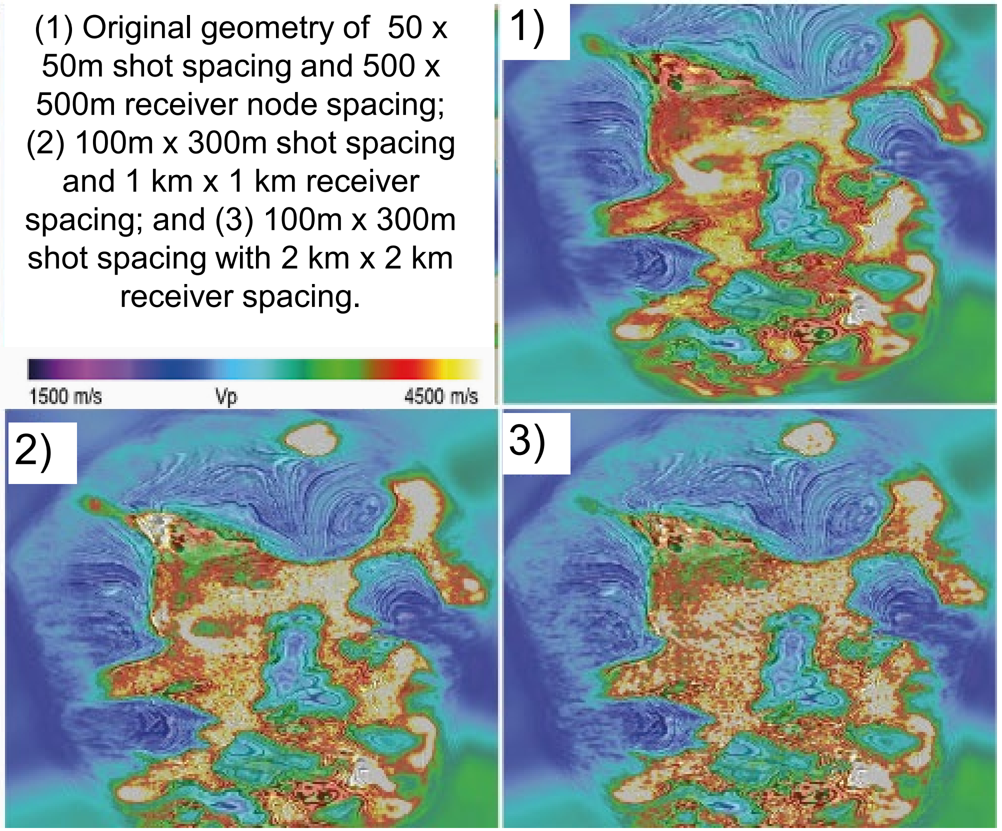
(Refs. 7bh & 7bi

This technique potential ability to drastically reduce the node sensor spacing can have a major impact on OBN deployment costs as it enables a stretched layout over a larger area.

The outstanding question is how applicable this approach is given the much shallower waters around the UK.

Velocity coloured Depth slice through salt bodies (red-white)

(1) Original geometry of 50 x 50m shot spacing and 500 x 500m receiver node spacing; (2) 100m x 300m shot spacing and 1 km x 1 km receiver spacing; and (3) 100m x 300m shot spacing with 2 km x 2 km receiver spacing.



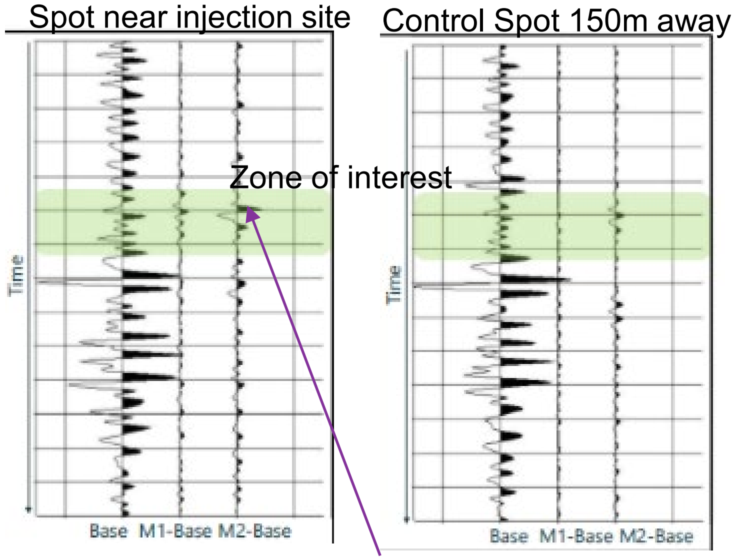
Salt bodies and min-basins delineated.

7.19 Spotlight / Targeted 4D acquisition

In 4D seismic, only a tiny proportion of the overburden and reservoir is expected to change, so it is reasonable consider full field 4D re-acquisition as "overkill". In theory, improvements in seismic structural images combined with reservoir dynamic simulations could provide more accurate predictions areas to target & image. It is then possible to consider lighter and more focused seismic monitoring to provide more frequent observations at strategic subsurface locations to rapidly validate or invalidate flow simulations. The concept is the spot is defined from the simulation and the seismic spread designed from existing 3D data, to target that specific location. Acquisition involves single-source-single-receiver location with repeatedly stacking the reflected seismic energy in one seismic trace over time and analyse the differences in the reflected seismic waves that were originated from the same reflection point.

The method does not result in subsurface maps but in individual seismic traces containing information about the presence or absence of CO_2 in this spot location.

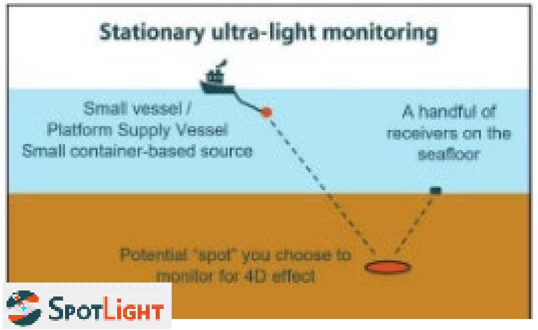
This technique was originally trialled onshore. This showed that with continuous recording, noise filtering and weekly stacking reduces the NRMS from 0.62 to 0.12 (compare with section 11.3). The small-time shift varies with day & broadly matches the gas pressure injection/depletion cycle.

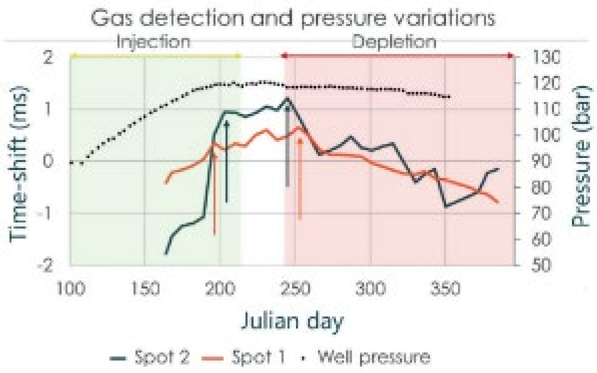


More recently (2023- section 12.10b) Spotlight has been trialled on the Project Greensand CCS test area in Denmark. This involved a baseline and 2 monitor surveys using 25 nodes deployed throughout and 80 shots at 7 stationary locations. The shots typically achieving 1m repeatability.

The examples shown are from 2 spots:

- The near injection site recording a polarity inversion
- Intra-reservoir event during the second monitor and the control spot showing low differences throughout.





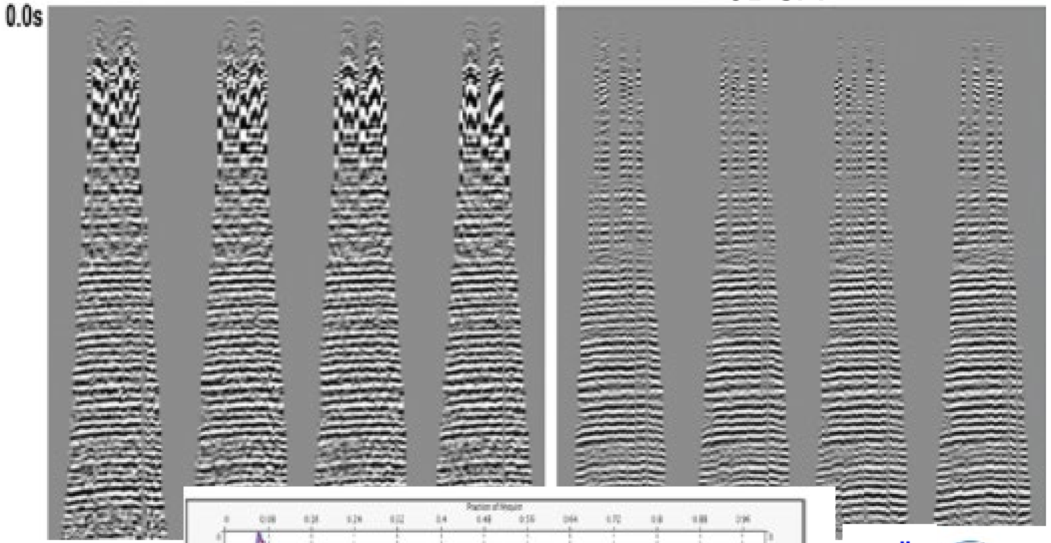
(Refs. 7bj, 7bk, 7bl, 7bm & 7bn)

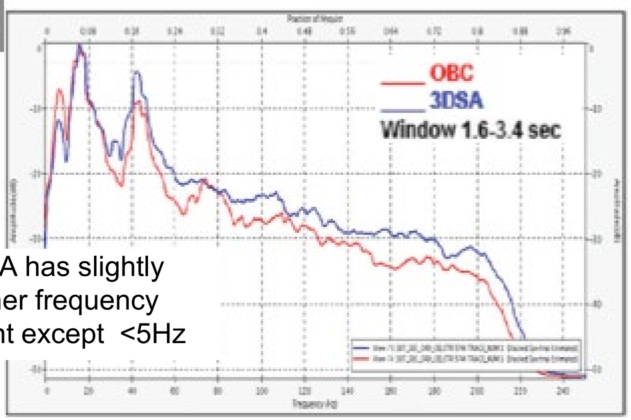
7.20a Autonomous nodes development: AMV trials

North Sea Transition Authority

Autonomous systems are being increasingly tested in marine environments. In 2017, SLB announced small trials conducted by the 3DSA (3D sensor array) system attached to an autonomous marine vehicle (AMV) undertaking small circular acquisition patches. This was developed to help infill near offsets around obstructions or congested areas but could well have applications for well based 3D VSPs, acquiring ultra-long offsets decoupled from the source vessel, shallow water and rugous seabed where OBN coupling is difficult (see also section 7.8e).

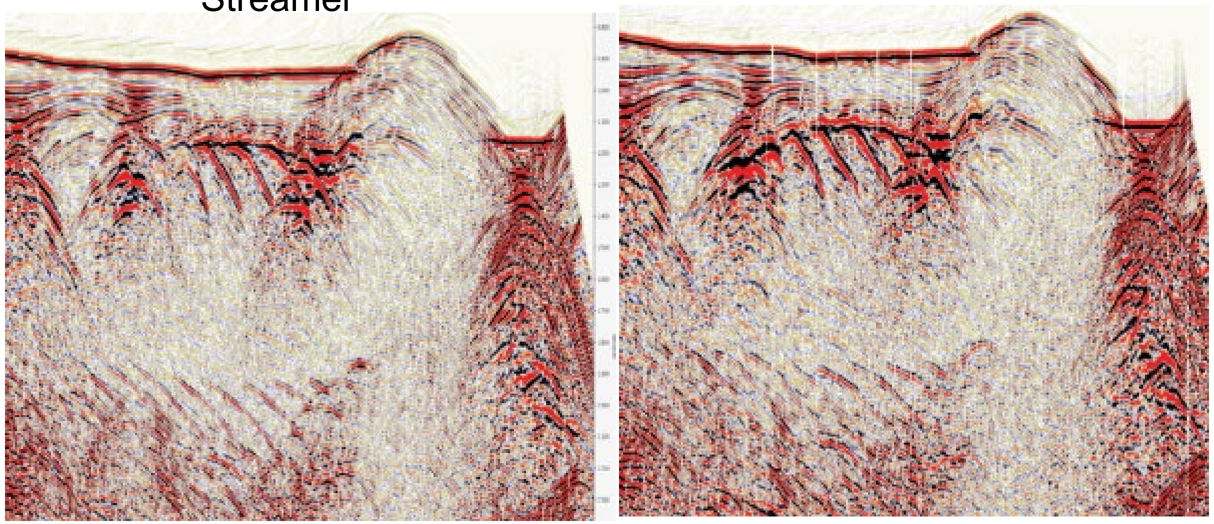
Partial stacks: Small 3DSA trial within OBC source spread





3DSA has slightly higher frequency content except <5Hz

North Sea 2D line Stacks with same offsets range



3DSA has similar frequency content and signal to noise to streamer
3DSA not affected by crossline strumming

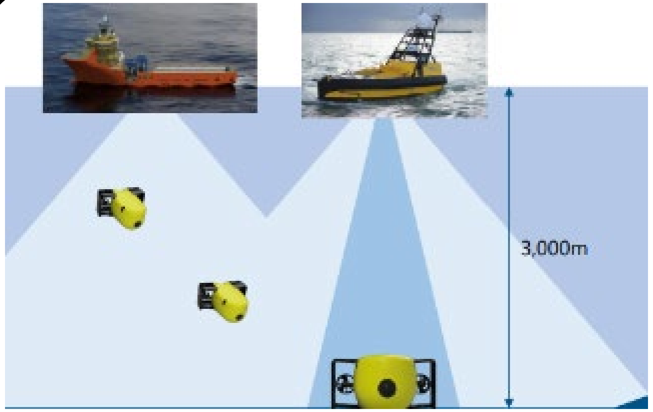
(Refs. 7bo & 7bp)

Small scale Autonomous marine vehicle trials promising

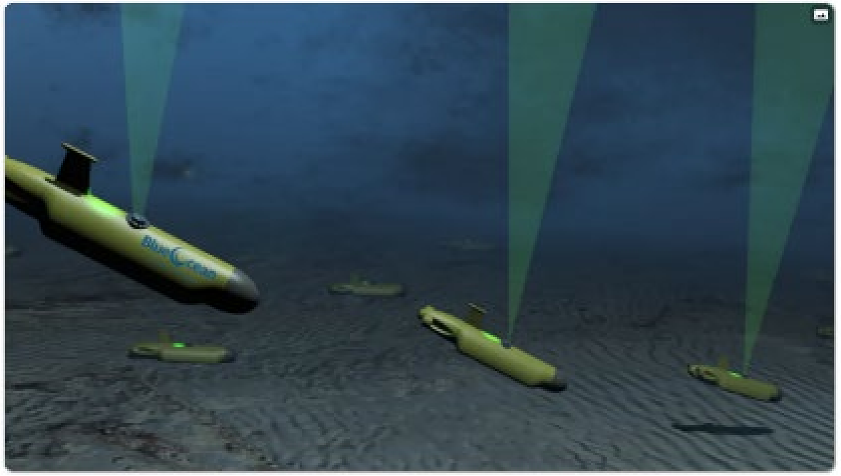
7.20b) Autonomous Flying nodes development

North Sea Transition Authority

It is predicted that flying nodes may mean than seabed seismic more affordable, faster, safer, more environmentally friendly and significantly less carbon intensive. They are designed to be deployed in swarms of up to 3,000 into water depths of up to 3,000 meters.



Positioning enabled by 2 acoustic positioning systems:
One on node & second on uncrewed surface vessel (USV).
USV positioned over the node at touchdown to give accuracy.



Fleets of autonomous, self-positioning subsea nodes could soon be acquiring ocean bottom seismic data

In a 2023 proving trial in a Scottish sea loch, it is reported that the flying node:

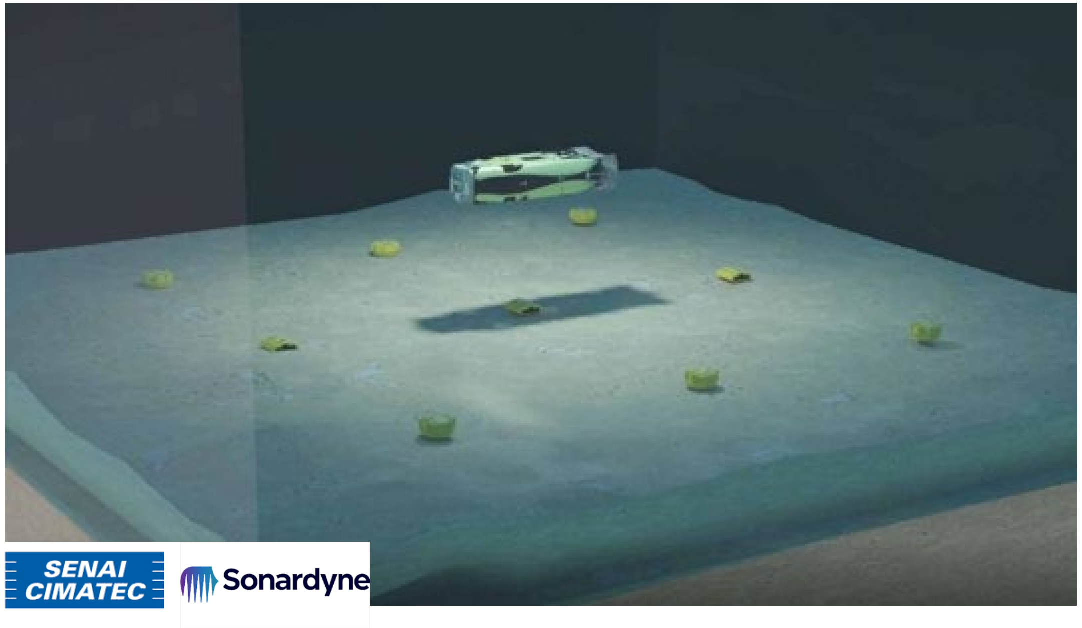
- Efficiently navigated and accurately located to a target location on the seabed.
- Landed, increase their weight to couple to the seabed & recorded seismic data.
- Took-off and navigate to a new location multiple times.
- Returned to the surface in difficult tidal conditions: often pushed off course but consistently and autonomously corrected to complete operations.
- Outperformed a ROV positioned Ocean Bottom Nodes.
- Recorded an unexpected earth tremor which occurred during the trial.

(Refs. 7bq, 7br, 7bs, 7bt & 7bu)

Autonomous flying nodes may be a significant development especially in shallow or co-location areas, if they can be deployed at sufficient scale

7.20c 4D- On- demand nodes

In Brazil, a semipermanent system which 4-component nodes can be deployed for up to 5 years and be activated for surveying and data harvested by an AUV.



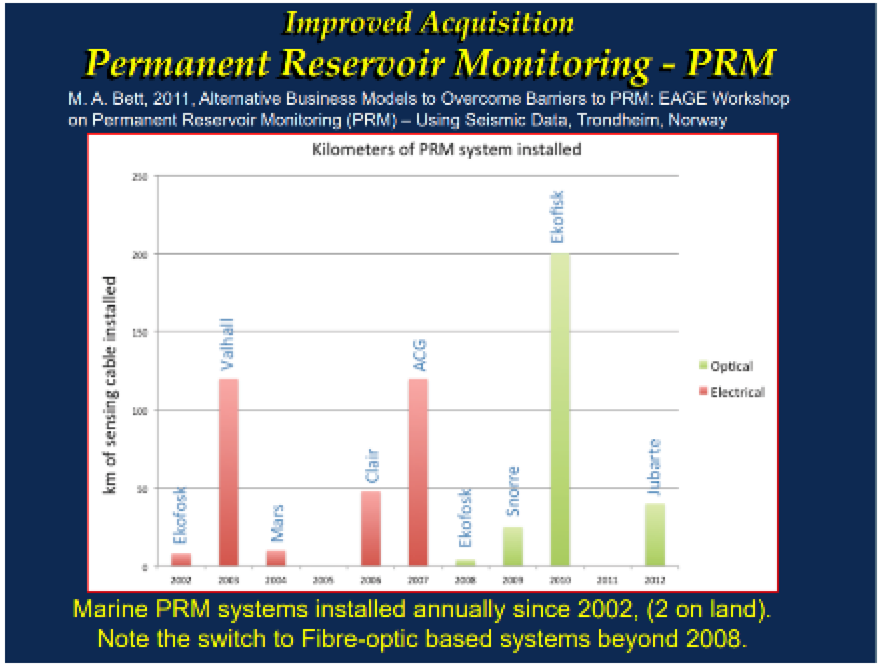
It is a possible concern that in a strongly dynamic & tidal environment semi-permanent sensors could become lost or buried under shifting sand waves.

(Refs. 7bv, 7bw, 7by)

Semi-permanent node acquisition- could provide an interesting development

7.21) Permanent reservoir monitoring (PRM)

PRM involves permanent installation of seabed receivers for highly repeatable time lapse (4D) seismic. Initial 1996 trials only involved a small patch of OBCs with hydrophone receivers on the UK's Foinaven field (FARM project), whilst more recent LoFS (life of field seismic) systems used 4 component sensors (Valhall & Ekofisk & Jubarte (section 7.18)).



Primary expected benefits are to be:

- 3D and 4D imaging uplift due to PZ summed, wide-azimuth high-fold illumination.
- Improved geometric repeatability due particularly to fixed or similar positioning of seabed cables and the generally more accurate repeat positioning of seismic sources on a shooting vessel;
    - Use of identical or similar sources is also beneficial.
- The opportunity for frequent 4D or "seismic-on-demand"

- The permanent cable systems have the following additional primary benefits:
- Improved cycle time (automation of much of the Valhall LoFS processing and interpretation workflow has dramatically reduced first data and basic interpretation delivery from months to days).
- Ongoing shooting is simplified, with lower cost, and with lower HSE risk.
- Further benefits can include:
    - Azimuthal P- and S-wave attributes
    - Passive monitoring potential (particularly for permanent arrays)
    - PS converted-wave image potential
    - Overburden characterization (e.g., for drilling hazard analysis).

The initial phase of Clair used a 5 survey PRM, but the subsequent phases of field development opted to UHDOBN (sections ?) with potential for re-deployable OBS, as required. The 2007 ACG (Azeri-CARSP) survey acquired OBC equipment but unlike FARM, Clair & Valhall, they are not trenched and can be redeployed around the field as required.

The cost and commitment to PRM deployment has always been restricted to a small number of giant hydrocarbon fields, where frequent & accurate 4D seismic monitoring is justified. The rationale for permanent deployment may be further questioned with the advent of long-term deployable nodes (7.20c).

(Refs 7bz, 7ca, 7cb, 7cc & 7cd)

PRM seismic provides highly accurate 4D, at cost. Full field deployment unlikely to be required CS stores, but may be useful for local obstructions

7.22 OBN Business context

North Sea Transition Authority

For general context the seismic acquisition companies have suffered from a significant downturn over the last 5 years. In 2017 there was a worldwide downturn in streamer acquisition, but more OBN vessels were being commissioned. In 2020 & 2021, immediately post-Covid pandemic the UKCS OBN activity remains at an all-time low. Only ~10% by number of 3D surveys were OBN, representing ~2-10% of 3D coverage. In 2022 there were a series of seismic liquidations and takeovers. In the UK OBN was resuming, but surveys were aerially small, mostly targeting field & prospect scale (e.g. Culzean, Alwyn, Dunbar, Kinnoull 4D, Schiehallion, with occasional semi-regional exploration or development surveys (CGG Cornerstone)). Worldwide, the seismic acquisition market has strongly recovered in 2023, with streamer vessel day rates increasing by 35% year-on-year and OBN crews booked through 2023 and much of the way through 2024.

Factors hampering OBN uptake

- Cost multiplier w.r.t streamer (~5x cost of streamer survey) (section 9)
    - Costs have recently risen within OBN market
- Cost strongly dependent upon source & especially node density
- High demand coupled with limited node and crew availability
    - Limited number of crews, distributed widely across the world
    - Increase in number of nodes per crew has slowed down (unlike onshore "1 million node" crew)
    - Half worlds nodes being employed in mega- multi-year Arabian Gulf
    - Potentially long mobilisation distances
    - Crews with intermittent & occasional in-season work,
    - Crews depart UKCS in winter
- Currently limited global node count & crew availability in short-medium term.
    - Costs likely to rise as demand exceeds supply.

Small surveys (OBN or streamer) remain relatively inefficient.

- Require a large aperture halo for even small patch.

Potential levers:

- Adopt hybrid: Streamer wherever possible, and OBN for exceptional difficulty areas.
- Regional OBN multi-client surveys are beginning to appear.
- Early planning & coordination to maximise scarce worldwide crew distribution:
    - Adapt timing to coordinate across CCS and hydrocarbon OBN surveys.
    - Encourage operators to fully utilise an OBN crew season.
    - Rare transition zone crew availability in very near shore areas.
- Reduced Node size & increasing in- vessel inventory.
- Autonomous nodes.

(Refs. 7ce, 7cf & 7cg)

OBN market booming despite cost multiplier and limited supply issues

8 . Seismic Surveying Around Offshore Windfarms

Updated from Phase 1 Report

8.1 Seismic acquisition & Windfarms

North Sea Transition Authority

This section provides an updated view of seismic acquisition in and around windfarms and re-iterates **that towed streamer reservoir seismic co-existence is not considered safe nor practicable in or around a windfarm. In this report, we go further by asserting that node acquisition cannot currently be safely undertaken within the confines of a windfarm (section 1.9).**

In 2017, the UK had the largest number of offshore windfarms (31) and associated turbines (1753) providing 16Gw of capacity and is predicted to rise to 50Gw by 2030 with a mixture of fixed and floating turbines. There is a pipeline of 70Gw of projects. Streamer seismic acquisition is often undertaken around a small number of isolated surface obstructions such as platforms or drilling rigs (section 7.7) and can work with transitory vessels (fishing boats, shipping). In contrast, the tightly constrained array of installed wind turbine surface obstructions is an extremely challenging environment for any vessel and an impossible scenario for towing large and wide array of equipment behind a vessel. Whilst node deployment is theoretically able to work in a constrained environment, within a windfarm it is likely to extremely costly, complex (section 1.9 & 8.6) and only deliver sparse data.

Recommendations are:

1) **Modern parameter seismic acquisition is completed before windfarm development commences.**
- **Node hybrid surveys around the edge of windfarms can prove a useful halo extension (if required).**

2) **Intra-windfarm seismic operations will be complex, costly and currently appear operationally impractical and only deliver sparse datasets. They should not be part considered part of a base plan.**

3) **An inter-disciplinary HAZID workshop is necessary to assess the full range of risks for node deployment surveys close to windfarms.**

3D image showing range of wind turbines and foundations. Catenary cables & multiple anchor points, tension leg turbines OBN equipment fragile/ NOAR not laid over catenaries. AUV, ROV needed.
To date, most turbines have been installed on monopile foundations, moving to deeper waters is likely to see an increase in floating windfarms (catenary cables & multiple anchor points, tension leg turbines), whose anchors bring their own distinct issues in terms of extent of in water equipment and different noise regimes. Floating wind turbines might have up to 8 catenaries.

To emphasise, where co-location is likely to be an issue, it is preferable to have a high-quality CS baseline seismic image acquired before any development work commences.

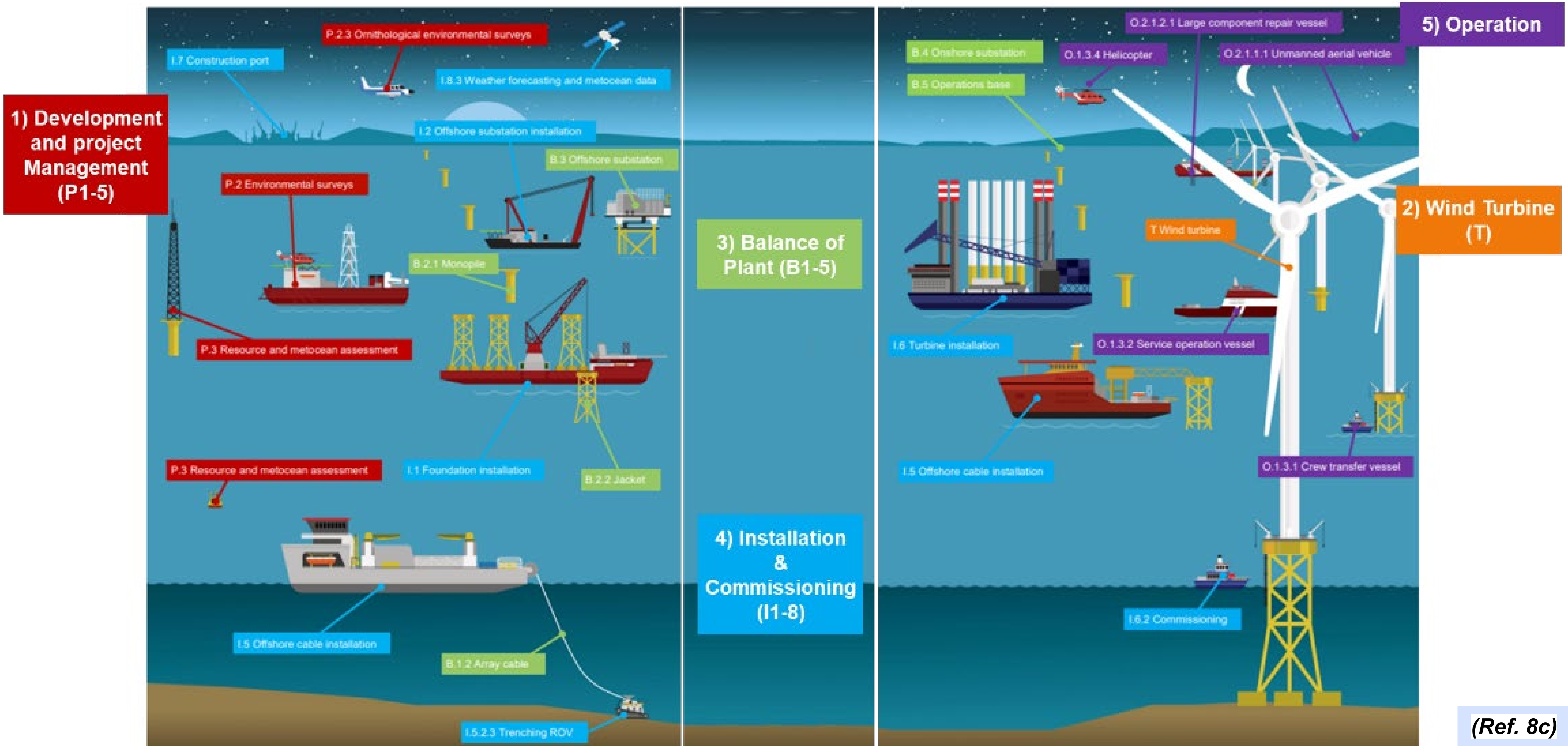
Note: the 2022 Scotwind timing implies that turbine layouts will be defined in the next 2 years and developed 2 years later. Therefore, there is only limited time to influence the design or collect a baseline survey prior to turbine installation potentially sterilises the acreage for seismic imaging.

Section 8.2 introduces a generic guide to windfarm operations, sections 8.3 & 8.4 revisits a series of acquisition options within a windfarm – quickly ruling out long streamer seismic but leaving highly restricted 2.5D or short P-Cable (UHR) seismic as highly challenging options. We have very little industry experience (section 8.5), but operationally turbines bring additional risks, that have seldom been considered during conventional seismic acquisition. These risks are not just from bringing a significant number of large vessels within a tightly controlled infrastructure (collision risks), but also considering the entanglement on the seabed layout and risk of dropped or unrecovered object.

Seismic acquisition close to and within windfarms provide substantial unique challenges and are currently deemed impractical.

8.2 Guide to offshore windfarm

North Sea Transition Authority

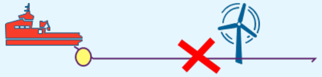


(Ref. 8c)

Operational summary of windfarm

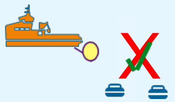
8.3 Seismic acquisition around Windfarms

- **Co-existence using reservoir towed streamer seismic is not considered safe nor practicable.**
  - Schematics show challenges of acquiring streamer seismic (towing long receiver cables) within confines of windfarm.
  - Long cables and their unpredictable lateral movement / "feathering" presents unacceptable collision risk.



- **Very Restricted Towed source only, Very short streamer or multiple ultra-short cables** (P-cable: 5.12) **may** work amongst turbines.
  - Short offset data only suitable for very shallow targets or overburden localised near well bore.
  - HR contractors **unwilling to commit** to minimal HR scope (any more than 1 x 600m cable) between turbines.
  - Complex and risky operation
  - Unlikely to deliver reservoir image
    - "2.5D" monitoring gives very limited image (section 8.4c)
    - Alternative P-Cable still does not provide full spatial data
      - Would need to be assessed for 4D (near offset only/ No AVO, low fold and shallow tow/ higher noise)

- Ocean Bottom nodes (OBN) theoretically **may be deployed amongst** turbines.
  - Very complex operation
  - Coverage Gaps will remain.
  - 4D Differencing Baseline Streamer (e.g. pre turbine) & Monitor OBN (post installation) currently not effective.
    - Some recent indications in 2023 suggests breakthrough starting to come.
  - The operational complexity currently makes intra-windfarm seismic OBN unfeasible (section 1.9)
  - Possible to deploy node around the edge of windfarms, More detailed intra-windfarm risk HAZID assessment needed

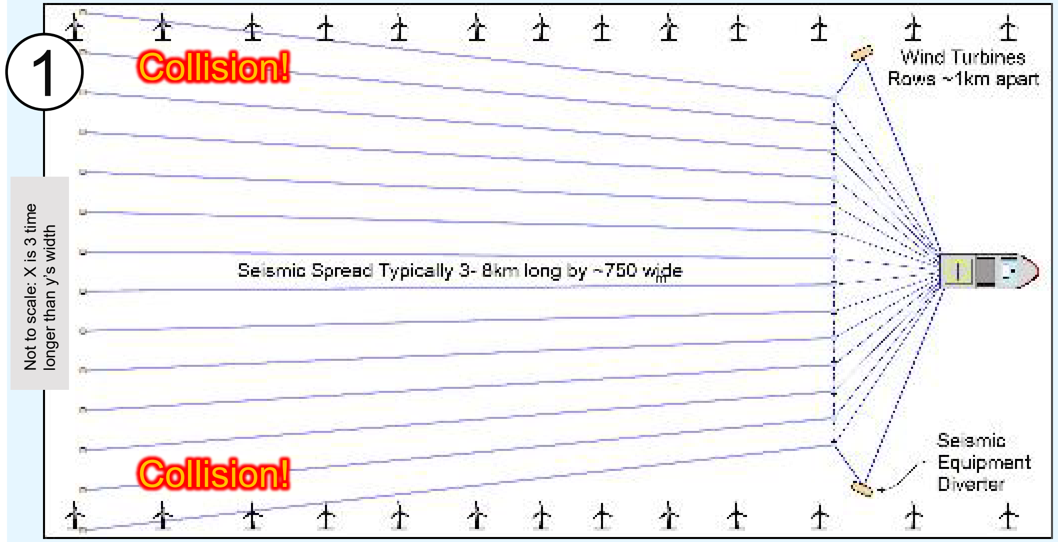


Update from Phase 1 report

Reservoir streamer seismic acquisition cannot be safely undertaken within a windfarm

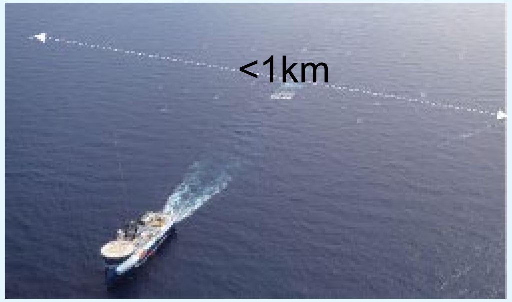
(Modified from Ref. 1a)

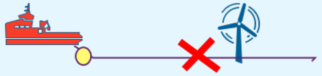
8.4a Streamer seismic options #1

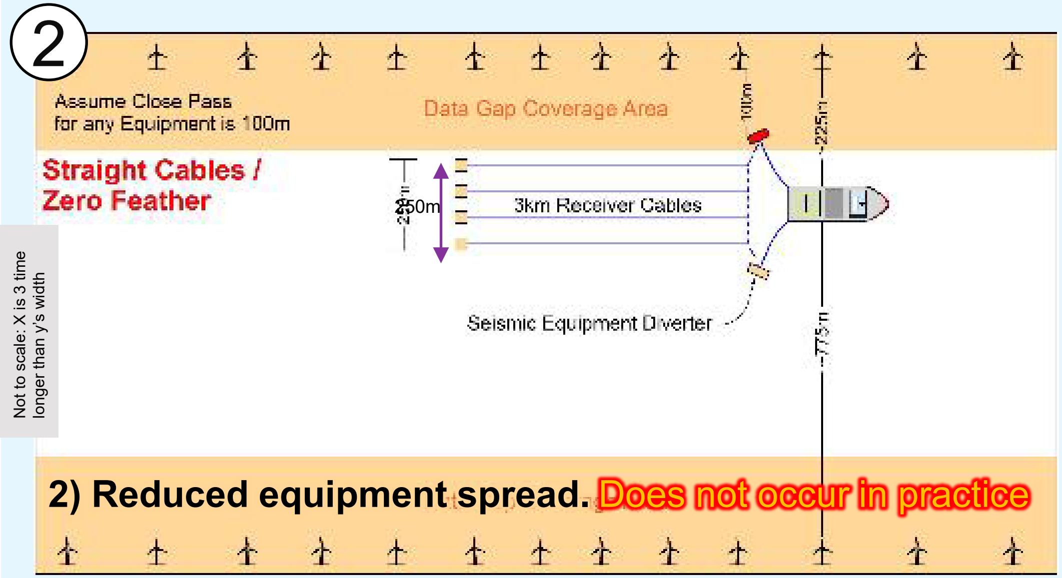


1) Typical Reservoir Streamer spread width along turbine corridor: Impossible

- Fantail spread: Streamers wider at tail → collision risk +
- Feathering (lateral drift) displaces tail 100's m → collision risk +
- No vessel escape route → unacceptable for captain.







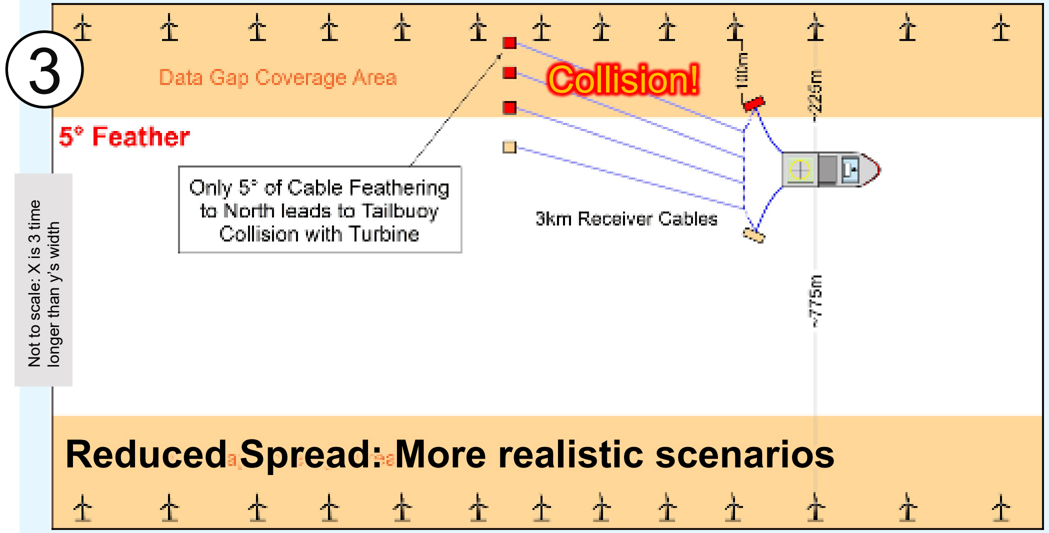
- Transition point to HR contractors
- Theoretically possible, but
- Even with zero feather → Significant 3D coverage gaps
- Furthest point for vessel is only 775m → Very little escape room

(Modified from Ref. 1a)

Any significant multi-streamer seismic is operationally impossible

8.4b Streamer seismic options #2

North Sea Transition Authority



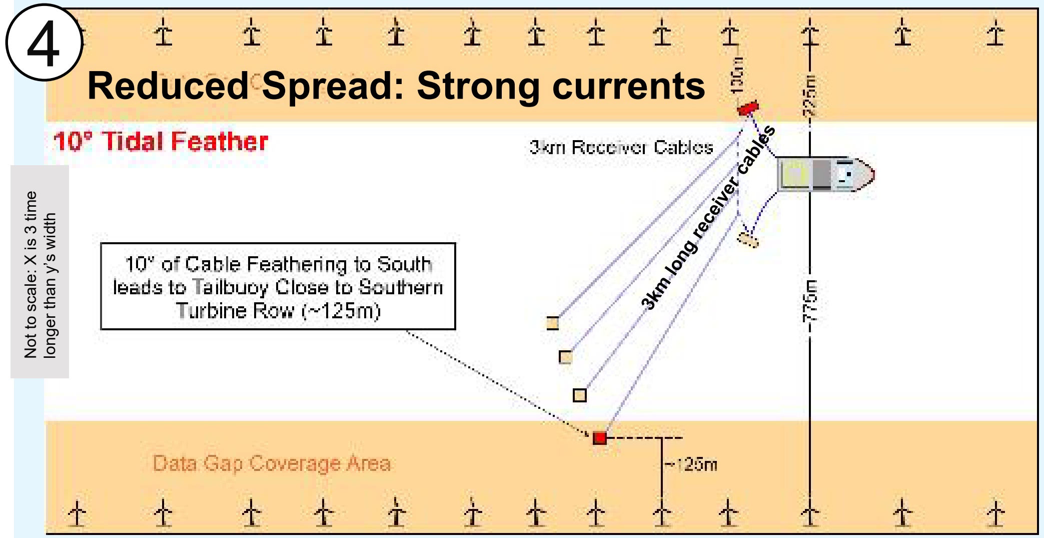
3a) Less strong & tidal currents, leading to low cable feathers

Subject to risk assessment acquisition **may be possible, assuming:**

- Short as feasible streamers
- Acceptable vessel capability & escape routes.
- **Large data gaps remain.**

3b) More typical currents: Impossible

- In high current/tidal areas (e.g. SNS) high feather often occurs
  - >5° feather → collision would occur
- Seismic contractor utilises tides to provide safe streamer drift to "south"
  - This further enlarges the data-gap



4) High or unpredictable currents → moderate/large feather: Impossible

- Very high tidal flow (e.g., 10°) gives very little room to manoeuvre:
- Plan for vessel drift-off to north, but tailbuoy drift-on to the turbines in south
- Data coverage further squeezed to N & S

Note: all these scenarios are simplifications and do not show:

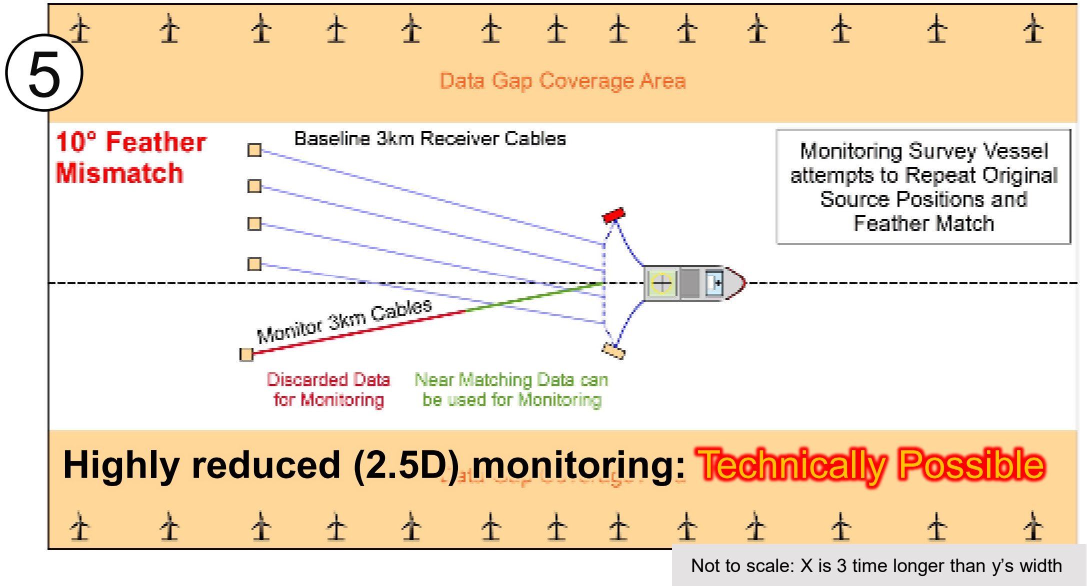
- **Vessel escape routes and**
- **Turbines in more complex arrangements**

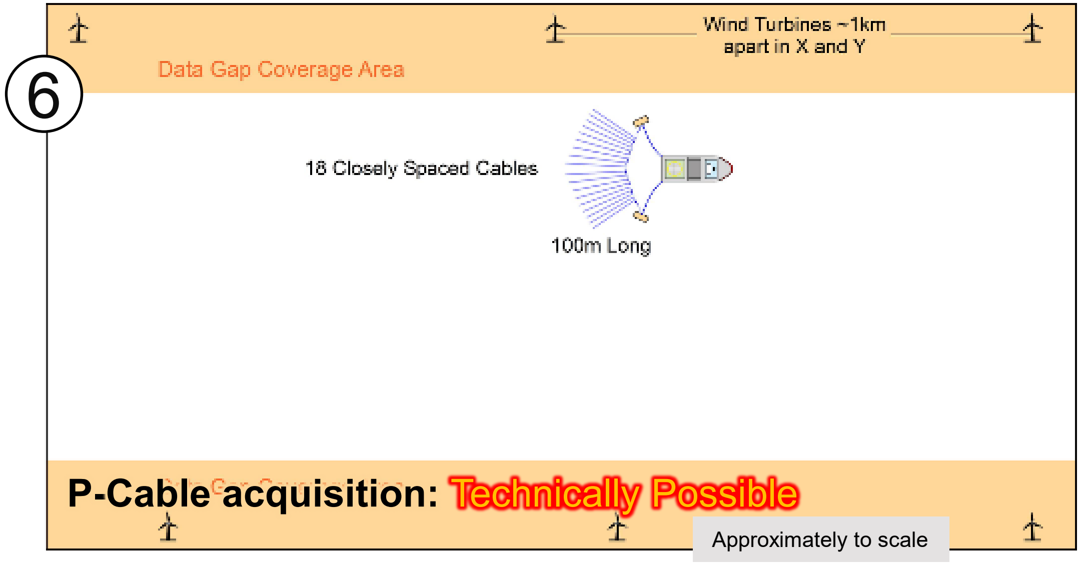
(Modified from Ref. 1a)

Any significant multi-streamer seismic is operationally impossible

8.4c Streamer seismic options #3

North Sea Transition Authority





(Modified from Ref. 1a)

"2.5D" acquisition

1) If a clear water **baseline** streamer survey is acquired, then
2) A restricted 2.5D **monitor** survey may technically be possible with turbines using selected subset of matching data with reduced acquisition by:
    - Monitor survey vessel attempts to replicate baseline acquisition.
    - Green data can be matched to existing baseline
    - Red data discarded: no feather match between baseline and monitor
    - **Result: restricted short offset 2D seismic line**

Positives

- Very small footprint, but ~ same towing width
- More acceptable for Captain/Party Chiefs working amongst windfarms.
- Potentially very high resolution in the overburden.
- Smaller airgun sources so more marine mammal friendly

Negatives

- Smaller power need to be tested for penetration and resolution over target
- Lot of equipment remains in the water at (lessened) collision risk
- Diminished escape routes
- Still data gaps along lines of turbines
- Only near offset data

Short offset surveying may be technically possible in conjunction with carefully designed windfarm

Very small footprint (short single or very short multi cable) is theoretically possible but operationally challenging

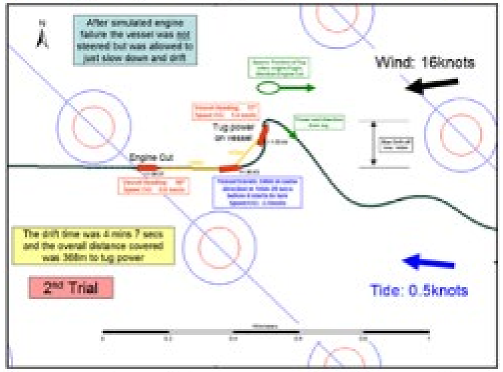
8.5 Very limited intra-windfarm experience

There is only a known intra-windfarm 2D HR survey in the UKCS. The survey required very careful planning & favourable conditions for operations. The extensive planning included modelled scenarios of wind speed/direction and current speed/direction for the safe entry into the windfarm area, abort procedures, and maintaining a tug-boat on close standby; this survey also included tow & drift trials.

The survey required extensive documentation and derivation of an agreed set of procedures, and a proximity agreement between the parties involved. Additionally, wind turbines were shut down during operations (wind turbine & energy isolation).

HR seismic vessel within windfarm

A 2DHR seismic survey was acquired over Knox and Lowry in Q1 2013 included shooting through the Ormonde windfarm – a UK first. Extensive planning and pre-survey modelling were required.



A support vessel tug was required in case the seismic vessel's engines failed inside the windfarm, requiring it to be brought under tow.

The modelling and sea trials defined a weather window with a 400m drift radius is required to bring vessel under control.

The NSTA is grateful to Chris Ward and Spirit Energy providing the details of this survey


Small HE vessel with bubble visible

The picture shows clearly that there was **very little room** to manoeuvre in this survey.

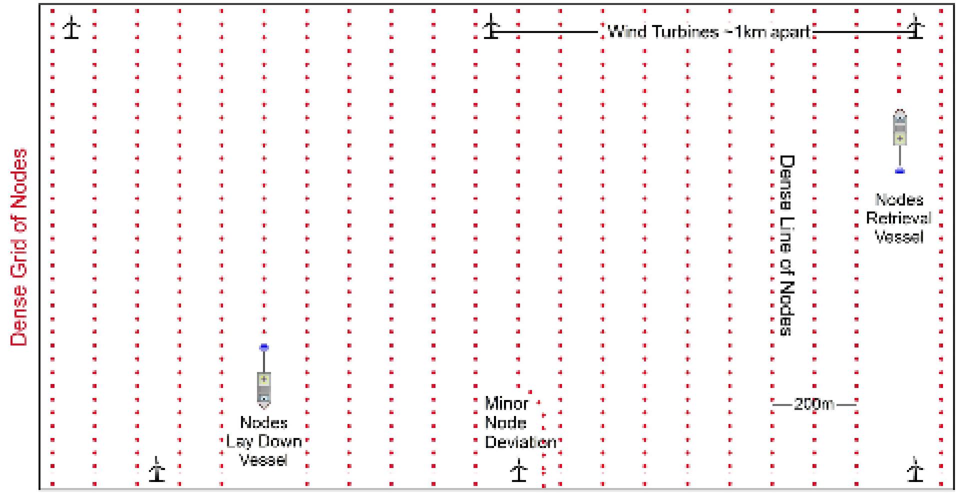
Unclear if local currents (eddies) are affecting the movement of short streamers.

Research into windfarm noise analysis from this data is presented in section 13, part 2.

Carefully planned, restricted intra-windfarm 2D HR seismic survey

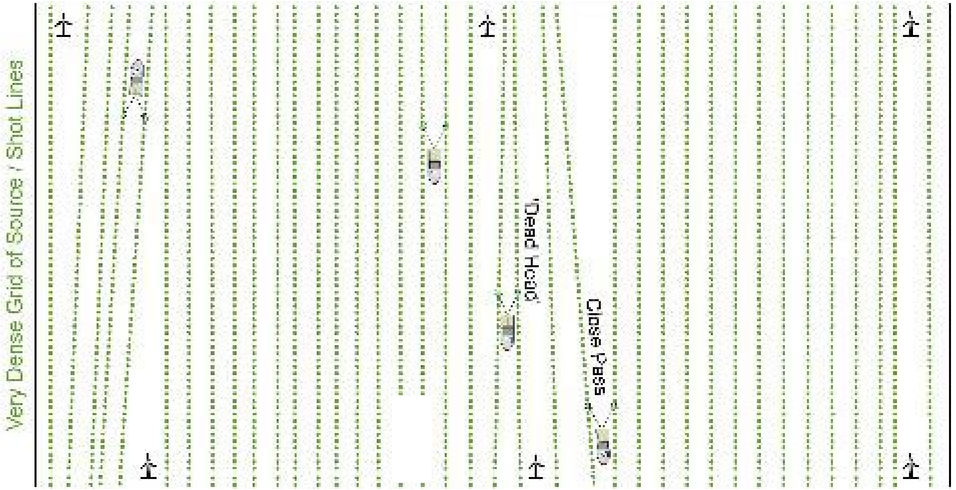
8.6a Theoretical OBN Acquisition within Windfarm

Theoretical Node deployment pattern around windfarm



Node density major cost control

Schematic Source Vessel pattern around windfarm



Without streamers, Vessel can acquire close to obstructions

<u>No industry experience</u>

- Operationally very challenging
- High density /quality broadband baselines to enable future 4D differencing.
- Vessel capabilities entering close turbines.
- SIMOPS (Simultaneous Operations).
- Exclusion zones

OBN Positives (see section 7.1)

Robust to exclusions

- Node vessels lay in very controlled manner / Can easily and safely make minor deviations
- Orderly grid and complete coverage
- Greater 4D repeatability
- More comprehensive seismic acquisition than highly restricted streamer

OBN Negatives (see also section 7.1)

Cost & duration

- Deployment Speed
    - Placing receivers much slower than towing streamers
    - Individual placing/ retrieval by ROV deployment is accurate but very slow
- Multiple vessels (source, lay-down pick-up, guard)
- Coverage gaps @ seabed & shallow overburden (section 7.9)
- Needs High density/ very narrow receiver line spacing to compensate (7.12)
- Gaps much larger if contractors unable/unwilling to sail under turbines (8.6c)
- Dropped objects/ unrecovered nodes must be surveyed and may need to recovered to allow jack-up access to turbines
- Access permission and liabilities.
- Completion of survey within seasonal weather window

OBN access within a windfarm is considered impossible without detailed HAZID assessment

(Modified from Ref. 1a)

Schematic of OBN potential approach within windfarm

8.6b Intra windfarm Seismic Hazard risk

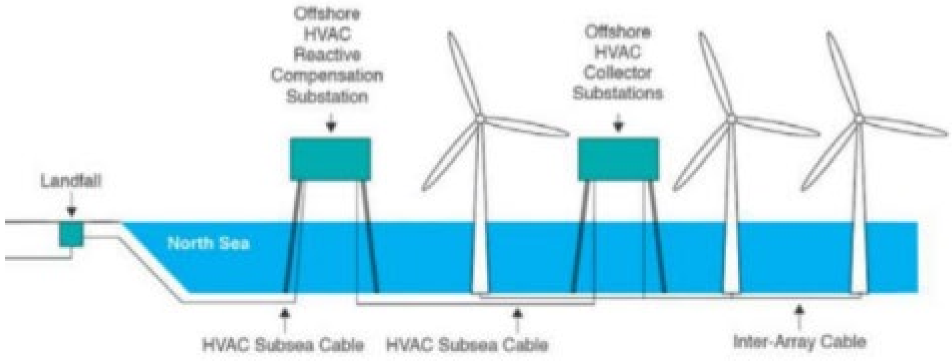
It is well understood, that piling/foundation operations prior to turbine installation during the development phase of windfarms, generate clear no-go areas for seismic acquisition owing to both SIMOPS and very high levels of impulsive noise which can be detected over long distances.

Operational windfarms also provide additional unique operational hazards with multiple array of surface obstructions and the need for vessels passing along turbine corridors. Often there are a higher density of turbines deployed around the edge of the windfarm, where the wind power is strongest. This creates additional access restrictions for a survey vessel to enter the windfarm.

On the seabed, the turbines are all connected by inter array cables (IAC) which may have scour protection or rock armour which may preclude node deployment. These very high power/high voltage cables will have strong induced electromagnetic signatures would preclude the use of traditional electronic nodes although fully fibre recording could be possible. Cables and turbines usually have an exclusion zone around them that is kept free of obstructions (150 m to 200 m for turbines and 50m for IAC).
NOAR (7.5a) – the most common type of node deployment would have a significant risk of entanglement. It is unclear if the cables are partially trenched, in which case the entanglement risk may be manageable.
Moreover, an unrecovered node or other dropped object (e.g. node anchor) would have to be surveyed and almost certainly be removed, as future jack-up access will be required around the turbines. This is tied to ALARP certifications for allowing jackups on site for major service and replacement works. The concern over UXO is understandable, but it may be that surveyed nodes could be considered to be treated differently.

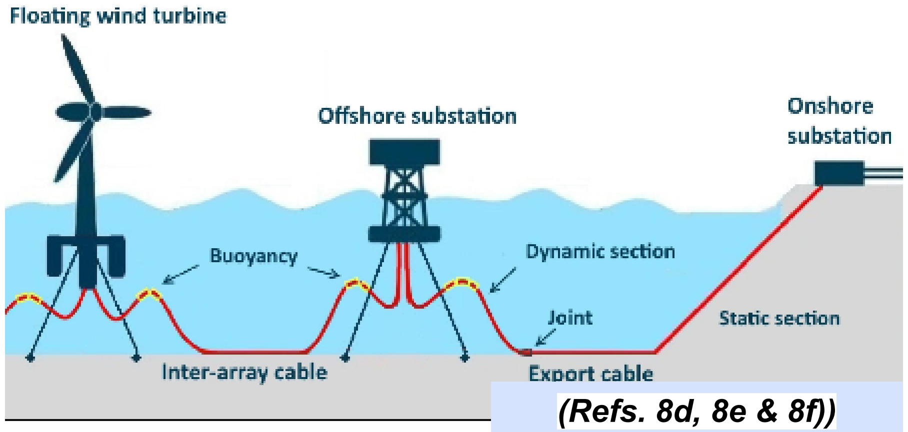
Without completing a HAZID, deploying nodes in these zones would likely be a no-go for a developer and the insurance liability.

Hornsea fixed turbine surface and subsea equipment



Hornsea IAC pre deployment

Notional floating windfarm with floating dynamic sections



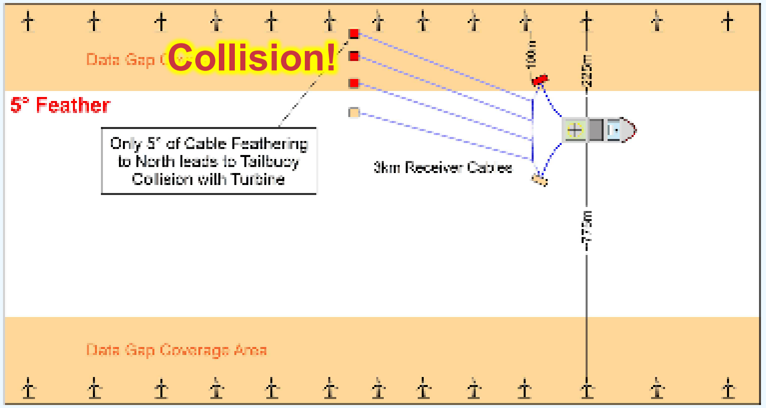
(Refs. 8d, 8e & 8f))

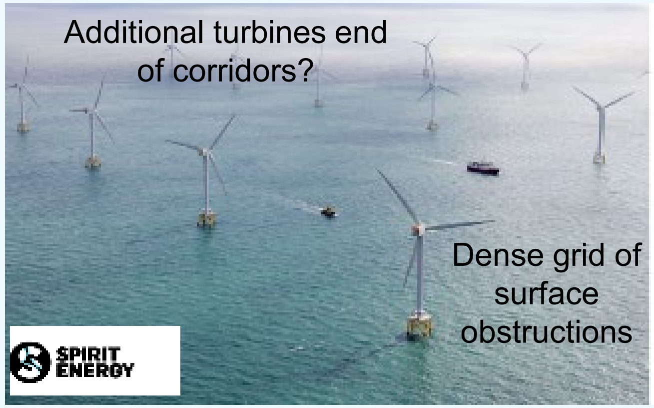
Not a comprehensive risk assessment: Node deployment within a windfarm appears operationally very diffcult

8.6c Intra-windfarm Seismic cannot currently co-exist | North Sea Transition Authority

Streamer Seismic

Unpredictable currents/
Cable feathering
Collision risk
(even for short streamers)





HR (short streamer) seismic vessel within windfarm

Careful pre-planning & operational drills

Risk Loss of propulsion?
No space to drift off
No space to manoeuvre
Standby tug

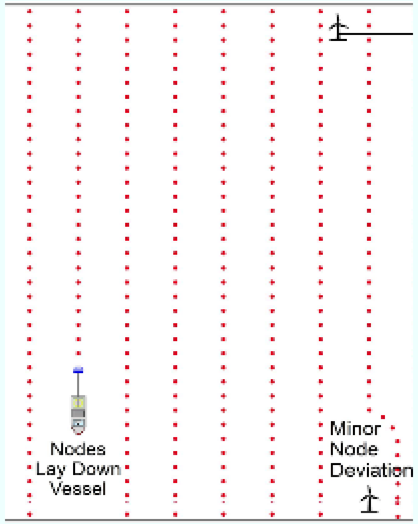
The NSTA is grateful to Chris Ward and Spirit Energy providing the details of this survey

Seabed (node) Seismic
In Theory:

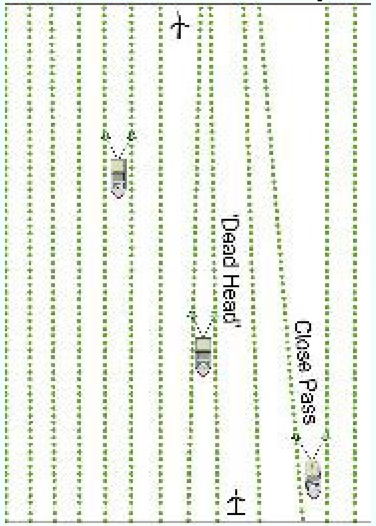
NOAR:
Node on a rope

Or very slow ROV deployment & retrieval

Nodes laydown



Source vessel
Shoots over the top



Seabed (node) Seismic
Practicality:

Turbines shut in during operation?
Loss of revenue

Tall seismic vessels under turbines

Electronics on nodes near high voltage cables
Fibre based nodes?

Fragile nodes

Dropped or unrecovered objects need surveying & removing (Jackup access?)

Collaboration between multiple disparate parties

Seismic crew unfamiliarity

Captain/Party chief & windfarm operator access agreement

Proximity/ exclusion distances

High risk of power Cable entanglement?

See also section 1.9

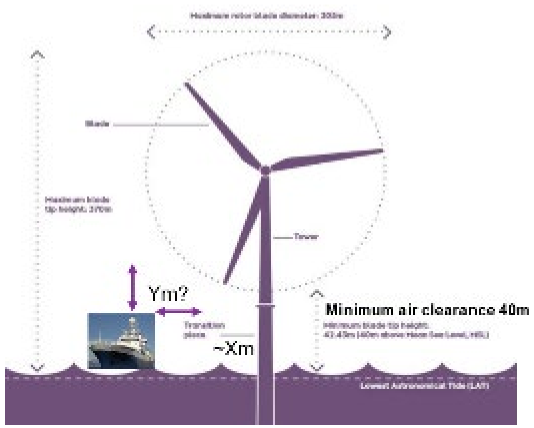
A lot of effort and significant risk (needs to be fully assessed) for a very sparse dataset

Nodes can be deployed towards edge of a windfarm, but intra windfarm deployment untenable without full (HAZID) risk assessment

8.6d Windfarm Proximity Seismic Hazard assessment

The issue of access remains uncertain, as this work does not constitute a full risk assessment. To fully test the scale of the seismically sterile zone near the edge of a windfarm, the next step would be a HAZID assessment to really test the proximity challenge. This is a first pass summary of some of the risks:

Proximity: Acquisition consultees could offer no clear view how close a seismic vessel could get close to a turbine base (X) or the separation below the rotating blade (Y) – recognising this would be prevailing wind direction dependant.
The passing, or not, of seismic vessels under turbine blades is an unanswered question and could lead to large swathes (~305m in this diagram) of no data. **This would be a serious detriment to OBN acquisition around Windfarms.**



A **close approach** distance may compromise:

- A safety distance to any in-sea equipment (turbine related).
- Paravane offset (seismic equipment).
- Half spread width (seismic acquisition).

This gives between 250m (OBN) to 400m (streamer) distance to the turbine.
With a 1km turbine spacing, this is only a very narrow corridor of possible acquisition.

Can turbines be yawed to inline direction?

- Parallel to turbine tows and seismic line direction.
- Would affect 3 rows of turbines at any one time
    - 1) leading edge (node laying),
    - 2) mid seismic spread (shooting)
    - 3) trailing edge (node retrieval)
- Survey would roll on with up to 3 rows potentially shut down at time.

Proposed Cross-disciplinary HAZID assessment: Is OBN acquisition close to edge of windfarm feasible?
The proposal is to gather a number of experts (SME's) to identify the full range of risks and assess the feasibility. What are the additional risks working within/ beneath turbines? Consider intra-windfarm environment access, HSE, noise levels, which need testing:

- Collision impact assessment
- Navigation/acoustics & Radar
- Impact on WF layout (higher density around periphery of windfarm)
- Impact of type turbine base (monopile vs floating)?
- Turbines yawed in-line or shut-down on progressive basis?
- The impact of IAC power cables and ensuing node gaps
- Model acquisition with WF overlay by expert vendor?
    - Even if modelled OK, would Captain/party chief be happy to sail under blades?
- Liabilities, indemnities, proximity agreements need to be better understood.
- Can additional WT noise be successfully processed (section 13)
    - Impact of additional noise on 4D repeatability.

Debate about intra-windfarm access risks and close approaches to and within windfarm: Recommend inter-disciplinary Dry-Run Hazid risk assessment

8.6d Intra windfarm seismic future?

It is clear the current layout and separation of turbines precludes seismic acquisition; especially as current configuration of turbines have not been designed with seismic vessel access in mind.
In part, co-location issues between seismic and windfarms start with the relatively narrow separation of turbine corridors (typically ~1km). If the next generation of even taller (15Mw) turbines are developed they could have a potential 2km spacing, which substantially increases the seismic corridor by a full 1km, helping coverage, but does not substantially mitigate collision risk for streamers or deployment risk for nodes, so would be unlikely to change access to the windfarm area for seismic operations.

If the wind industry was to adopt the single large windcatcher conceptual design, then the seismic co-location problem looks considerably more tractable and largely reverts to a relatively common platform undershoot – mitigated by either

- a source and streamer vessel on either side of the structure or
- Hybrid streamer and node deployment on the edge of the exclusion zone.

These options are fairly commonplace in acquisitions around oil and gas installations.

(Ref. 8g)

9. Towed Streamer vs OBN Comparative Cost Model

9.1 Comparative cost model

Whilst OBN provides opportunity to acquire data in a constrained environment and gives a superior geophysical imaging solution, the cost multiplier is a major factor in limiting its widespread adoption. This section considers two generic example CS areas and looks at current and future predicted costs of OBN compared with streamer data for a baseline and repeated 4D monitor surveys. The results compare the total cost per survey and the area unit costs. It should be noted that cost **assumptions were made at the start of 2022**. As previously noted, they do not take into effect the recent high levels of demand led inflation in the seismic market and especially for OBN (section 7.22).

The main controlling assumptions are 1) the adoption of multiple sources and associated de-blending and the 2) acquisition of a comprehensive baseline and 3) accept less well-defined monitor, with reduced scope (fringe, reduced shots).

On this basis:

- A good development OBN 3D survey is currently likely to cost 4 to 5 times a streamer survey.
  - This is economically impractical for a large CCS closure.
  - Especially if as we currently assume, the OBN configuration needs then to be repeated for each 4D monitor.
- Small surveys (both OBN and streamer) remain inefficient, even for a small patch.
  - Particularly poor for surveys that need a large aperture halo.
- Whilst OBN survey costs have already reduced by 50% over the last decade.
  - There is some limited room for further OBN technology for 4D monitoring efficiencies.
- Much less scope for efficiencies on the streamer side.
  - Moreover, replacing an ageing fleet is likely to be a factor maintaining day rates.

It is a reasonable assumption that node deployment and retrieval will mean than OBN will always be slower (and more costly) than towing multiple streamers through the water.

This highlights:

1) The importance of undertaking streamer seismic whenever possible, with a small targeted hybrid OBN where necessary.
2) Collecting a comprehensive development survey in relatively clear water.
3) Potentially accepting a much more restricted monitoring in future.

Streamer seismic provides most palatable balance of project cost vs. best technical solution

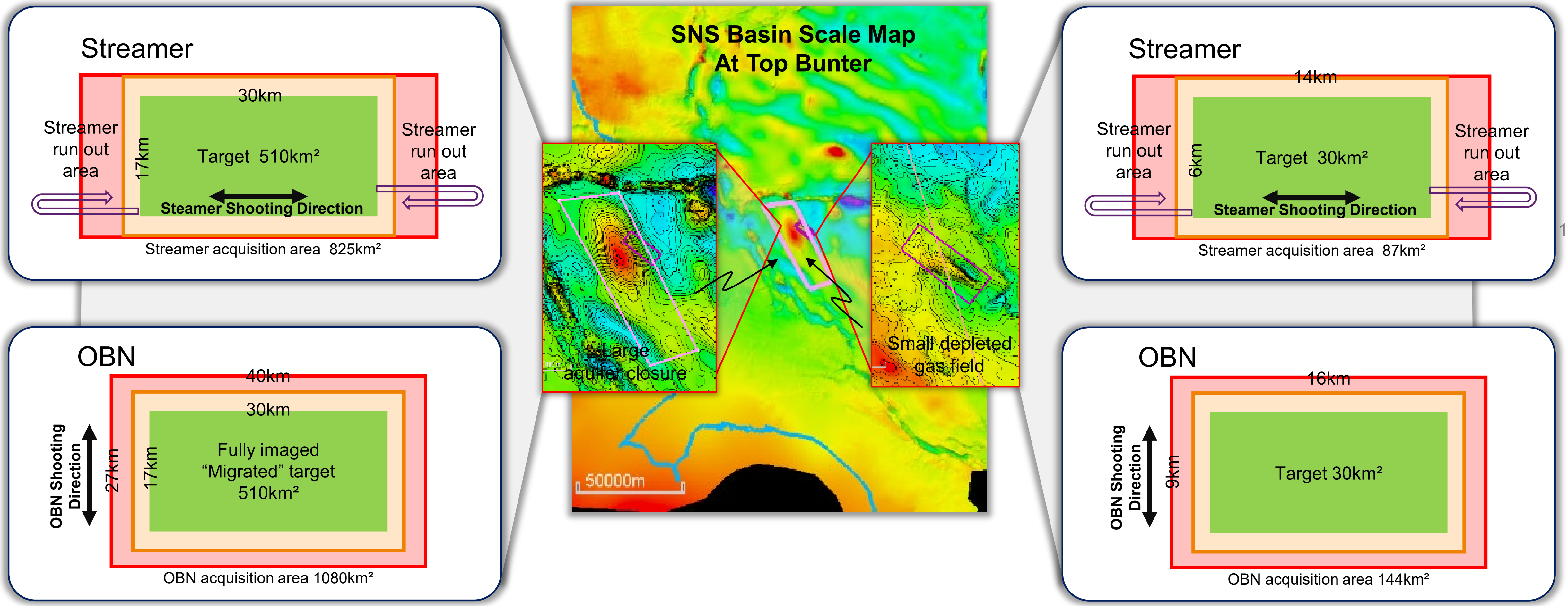
9.2 Seismic Survey Cost Model

North Sea Transition Authority

The large SNS basin has very many opportunities for aquifer and depleted gas field reservoirs. The following assesses the potential future cost model for OBN and streamer seismic, for 2 notional survey end members; large aquifer closure & small depleted gas field. Acquisition area comprises target full fold and actual shot halo, which differ between OBN and streamer surveys:

Large aquifer closure (510km² aquifer closure)

Small depleted gas field (30km²)



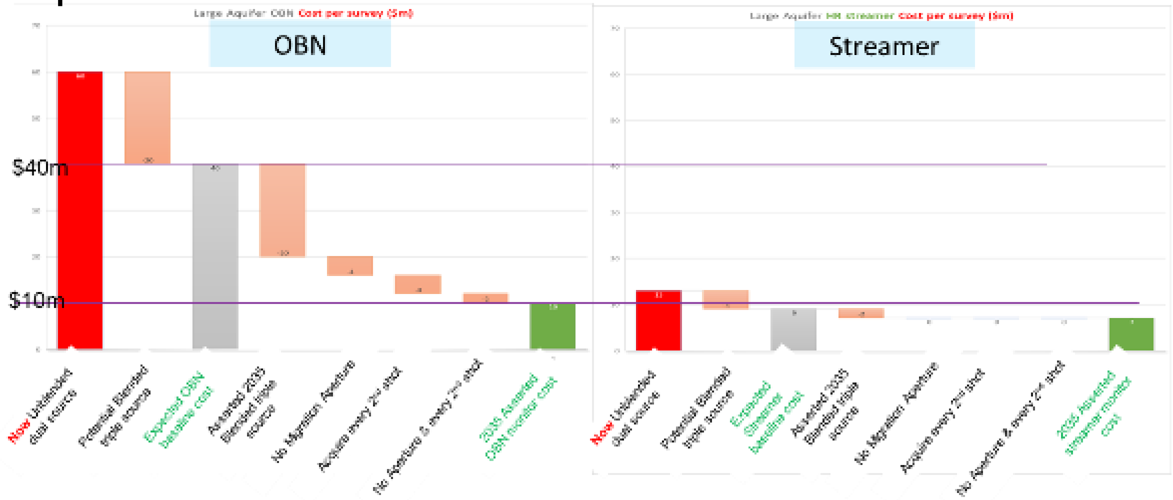
These maps are shown purely to show scale of closures and do not imply any specific CCS activity

Comparison of Streamer vs OBN costs for 2 notional areas

9.3 Survey cost comparison (per survey)

North Sea Transition Authority

Large aquifer

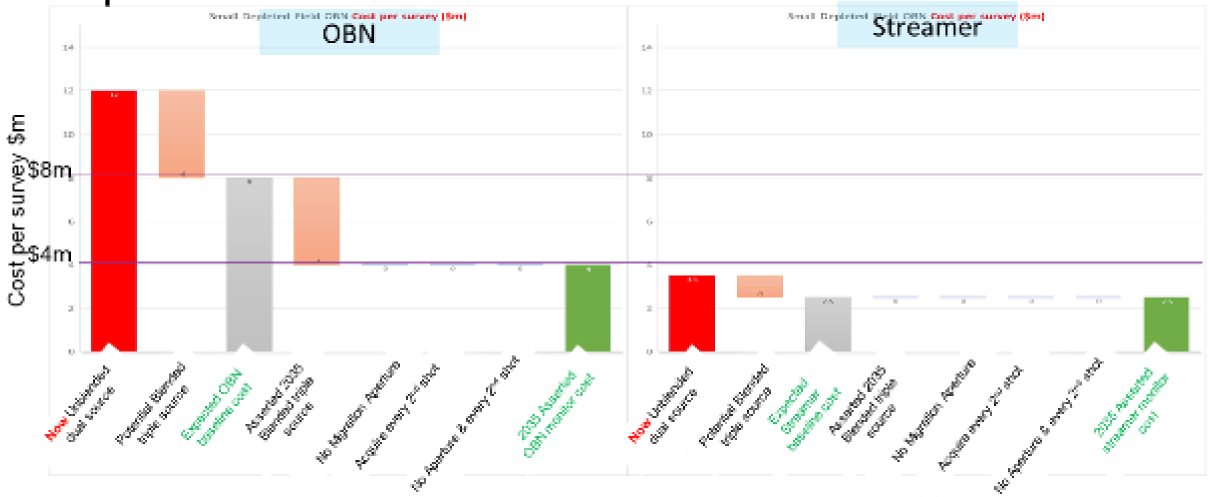


Currently baseline OBN is prohibitively expensive ~$60M
- Large aquifer high specification/ dual source.

Monitoring Options in ~ 2035:
- Triple source baseline OBN reduces cost to ~$40M.
- Technology improvements (e.g., autonomous nodes) further reduce expected cost.
- Reduced monitor scope (migration aperture & dropping shot lines) reduce OBN to $10-$20M/ survey.

Streamer mature technology / very efficient for large unobstructed areas.
  - Currently ~ 1/5th cost of OBN
- Monitoring Options: Triple source Baseline & monitors $9M
  - Limited other reductions.

Small depleted field



OBN baseline currently ~ $12M (~$8M triple source)
- Expected to have more opportunities for future efficiency improvements than streamer.
- Technology improvements should also further reduce monitor cost.
- Reducing migration "halo" shots & shot spacing little effect on small survey.

Streamer baseline currently ~ $2.5M (~$2M triple source).
- Fixed costs and dimensions means limited further reductions unlikely.

Large vs small survey and OBN vs streamer cost breakdown

9.4 Summary: cost $K/km² Cost Comparison

North Sea Transition Authority

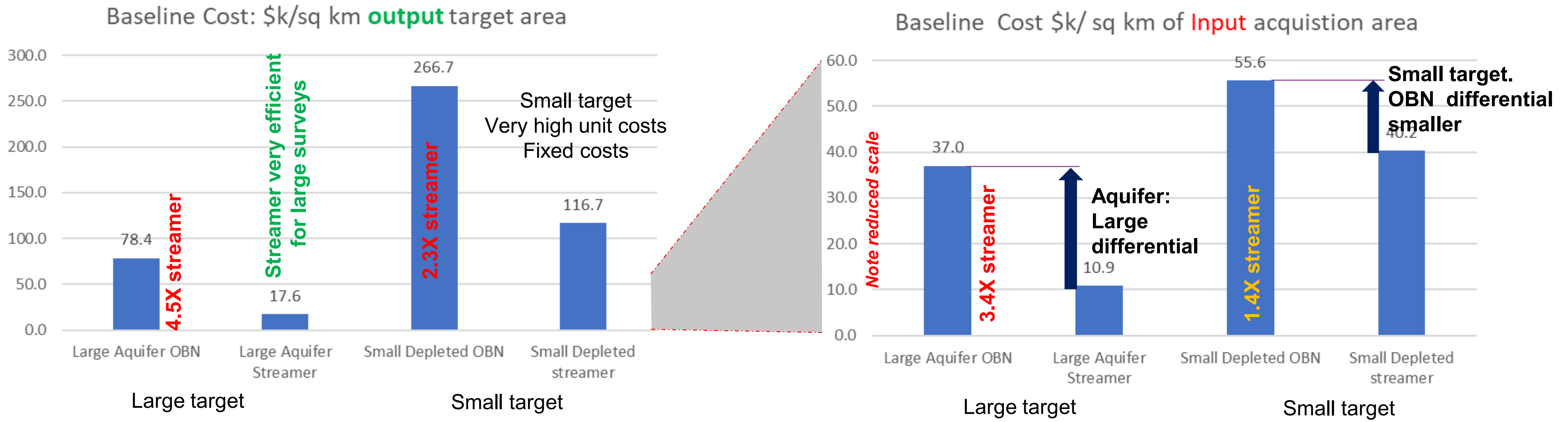
<u>Unit costs</u> are compared for output (target) area, or more importantly are the total costs for the input (acquisition) area:

Streamer seismic is very efficient (~$^1/_4$ OBN price) for large (input) acquisition footprints.
Small target (e.g., depleted gas field) surveys command very high unit costs.

- Fixed mob/demob costs are relatively high proportion of input fringe seismic.
- OBN becomes slightly more competitive for small surveys but remains twice the cost of streamers.

Seismic costs small proportion of total project capex, but very hard to justify the significant additional & repeated OBN cost purely for small imaging improvement for most typical reservoirs.

Target Output area only | **Large input area including halo**



<u>Life of closure Seismic Monitoring costs</u> (assuming baseline 3D & 5 monitors + $1m processing for each)
Large Aquifer: $96-146m (OBN) or $54m (streamer) vs. Whole project costs ~£5bn (1-2% of Capex)
Small Depleted $34m (OBN) or $21m (streamer) vs Whole project costs ~£1bn (2-3% of Capex)

(Prorated upon 9a
(Ref. 9b)

For most "simple" targets, it is hard to justify cost of a baseline OBN, let alone 4D surveys

10. Seismic Processing

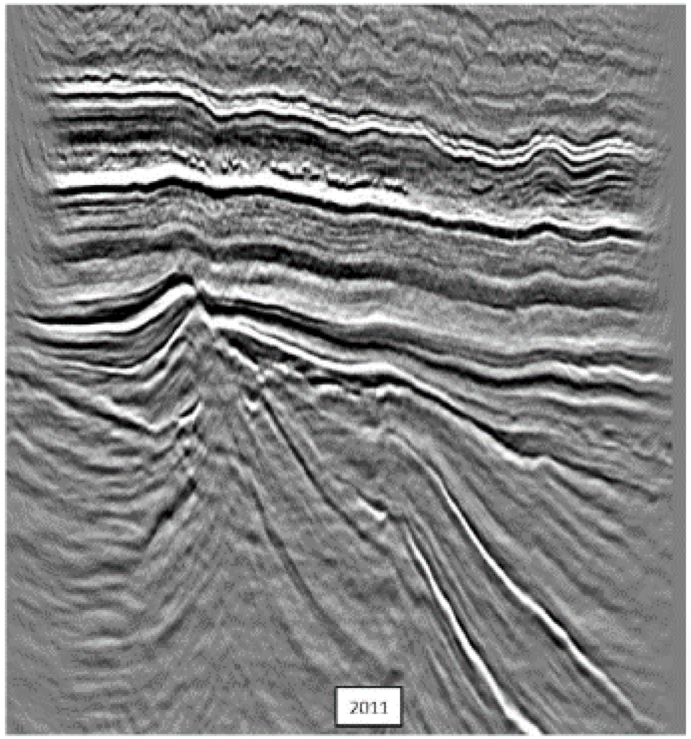
10 Processing Preview

Processing techniques and algorithms are continually being developed and updated, enabled by extensive increases in computing and storage technologies. Reprocessing seismic data from original field tapes, almost always provide substantial enhancements, for a fraction of the cost of a new survey.

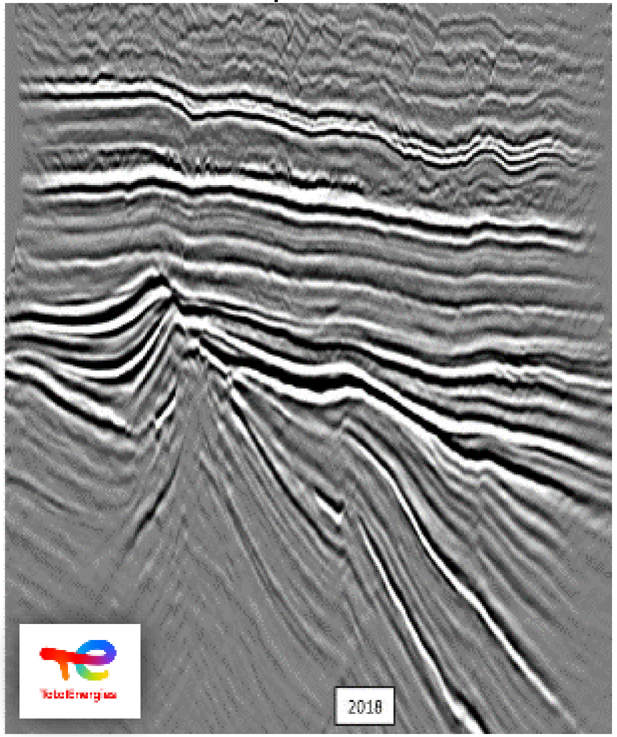
It has long been recognised that processing techniques develop at a rate that legacy processed images are effectively out-of-date after 5 years (as per existing NSTA stewardship guidance – section 3.6a). Even for newly acquired high specification surveys (e.g. dense streamer, OBC/OBN) targeted reprocessing can still deliver substantial improvements in data quality.

The seismic processing (or reprocessing/ re-imaging) continues to be the most cost-effective method of improving seismic image. Typically, this phase represents 2-10% of acquisition cost. Processing flows involve a very large number of highly technical elements, which in themselves often lead to small improvements, but collectively add substantial value.

2011 OBN



2011 OBN reprocessed



Turnaround time continues to be typically of the order of 12 months – largely unchanged for decades, but the computational effort involved has grown substantially.

This section starts by outlining the orders of magnitude increase in computational performance (10.1), then considers the traditional well-established processing (reduce noise, enhancing signal) - termed here as "level 0". Full waveform inversion (FWI) has quickly developed from a technique to improve the velocity field to encompassing much more of the wavefield and the steps are termed levels 1-4 in this report. This is a transformation in the traditional approach.

Seismic Processing Preview: It is a highly cost-effective method and will almost inevitably produce a better image.

10.1 Supercomputers driving processing

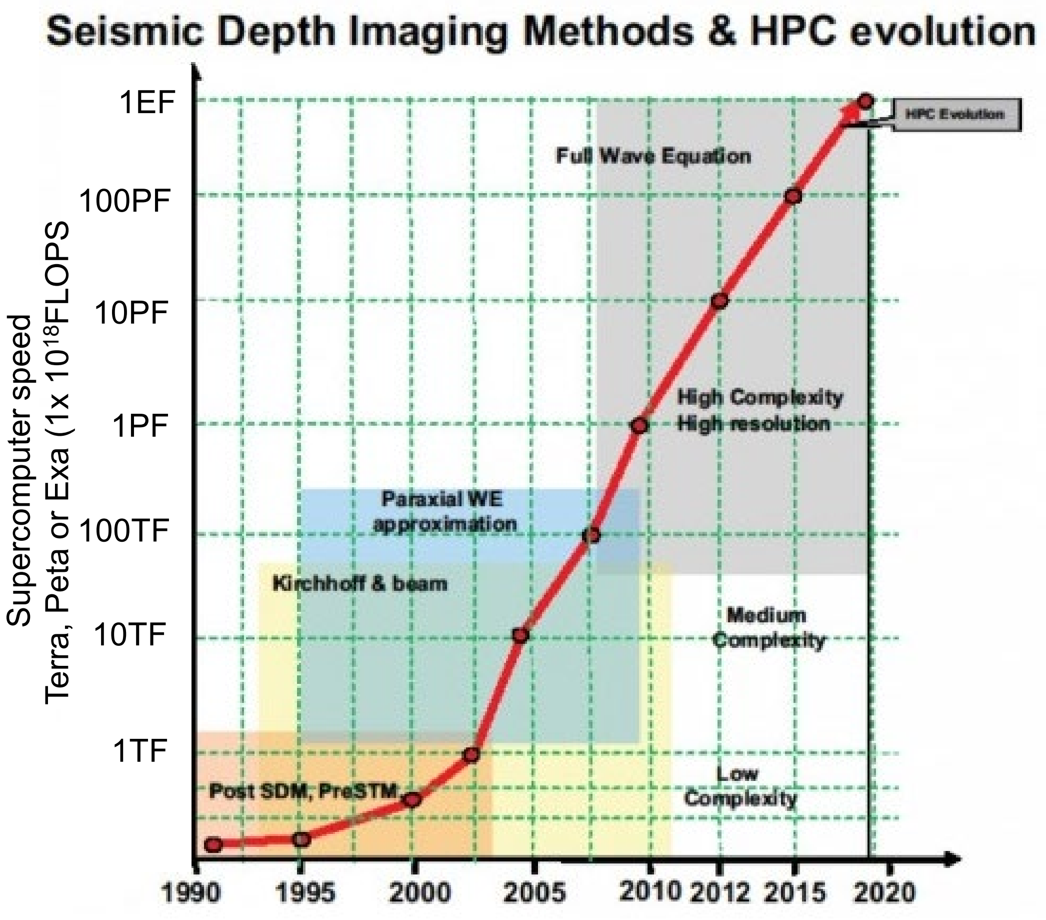
Seismic processing & imaging entails the management of massive data volumes – sometimes petabytes. BP's HPC (High Performance Cluster) has the storage capacity of 90,000 512-gigabyte iPhones, meaning it can hold more than 3,000 times the amount of information in the US Library of Congress and enough computing power to perform 21 quadrillion operations per second.

Seismic data require complex algorithms to be used that require weeks, or even months, to process on thousands to millions of computer nodes running in parallel.

As an example of the evolution, original 1990's North Sea surveys were often compromised, with limited pre-stack processing followed by Post Stack Time Migration, Post Stack Depth Migration (postSDM) or Pre Stack Time Migration (PreSTM). Relatively intensive Pre Stack Depth Migration was only reserved for complex targets (e.g. salt diapirs). The era of the rapid rise of regional North Sea surveys were usually processed using Pre stack depth migrations. Most often Kirchhoff, but locally beam or reverse time migration (RTM) for complex structures.

Specifically for full waveform equation, it initially became computationally affordable with acoustic approximations or with elastic conditions for smaller datasets at relatively low frequencies. Newer dedicated hardware is allowing wave equation solution for elastic media.

Seismic Imaging (migration) vs logarithmic supercomputer growth



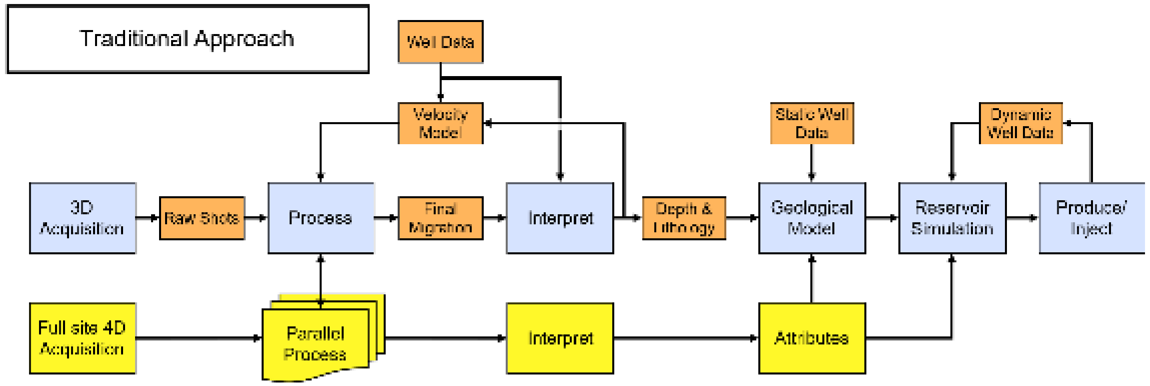
(Ref. 10a, 10b & 10c)

10.2 Transforming Processing: Image or model?

North Sea Transition Authority

Processing is in the middle of a major transformation involving using the whole seismic wavefield, rather than enhancing the good (signal) and suppressing the bad (noise).

The **traditional approach** (termed level 0 for this report) has involved undertaking a series of stages each with increasingly sophisticated algorithms, each designed to enhance the seismic reflection signal and reduce the noise. The main stages 1) pre-processing of the pre-stack data (signal enhancement), 2) velocity model building (sound wave velocity-change-with depth model), 3) migration (re-positioning reflections to their true position), & 4) stacking (summing the pre-stack data together to provide final interpretable image). 4D seismic would take the current and any earlier monitors and match to the baseline at several points in the processing flow.



The term **FWI (Full waveform Imaging)** is a confusing "catch all" for a series of algorithms which are pursuing a radically different is emergent. This involves matching raw seismic to a complex model of the subsurface physical parameters is generated and carefully matched and updated to the whole suite of observed seismic signals (reflections, refractions, body waves – Rayleigh and Scholte). FWI is therefore increasingly achieving two key imaging goals, namely 1) refining the velocity model and 2) deriving a better-quality seismic image, also known as 'FWI imaging'.
FWI is rapidly evolving with increasing sophistication termed "Levels 1 to 4" for this report (section 10.11). In theory, a level 3 FWI model is sufficiently high frequency model to be a structural interpretation product (section 10.19).

<u>This is rapidly leading to fundamental change in the approach. Now interpretation of the model is potentially the final product rather than the typical migrated seismic reflection image</u> (see section 14.3).

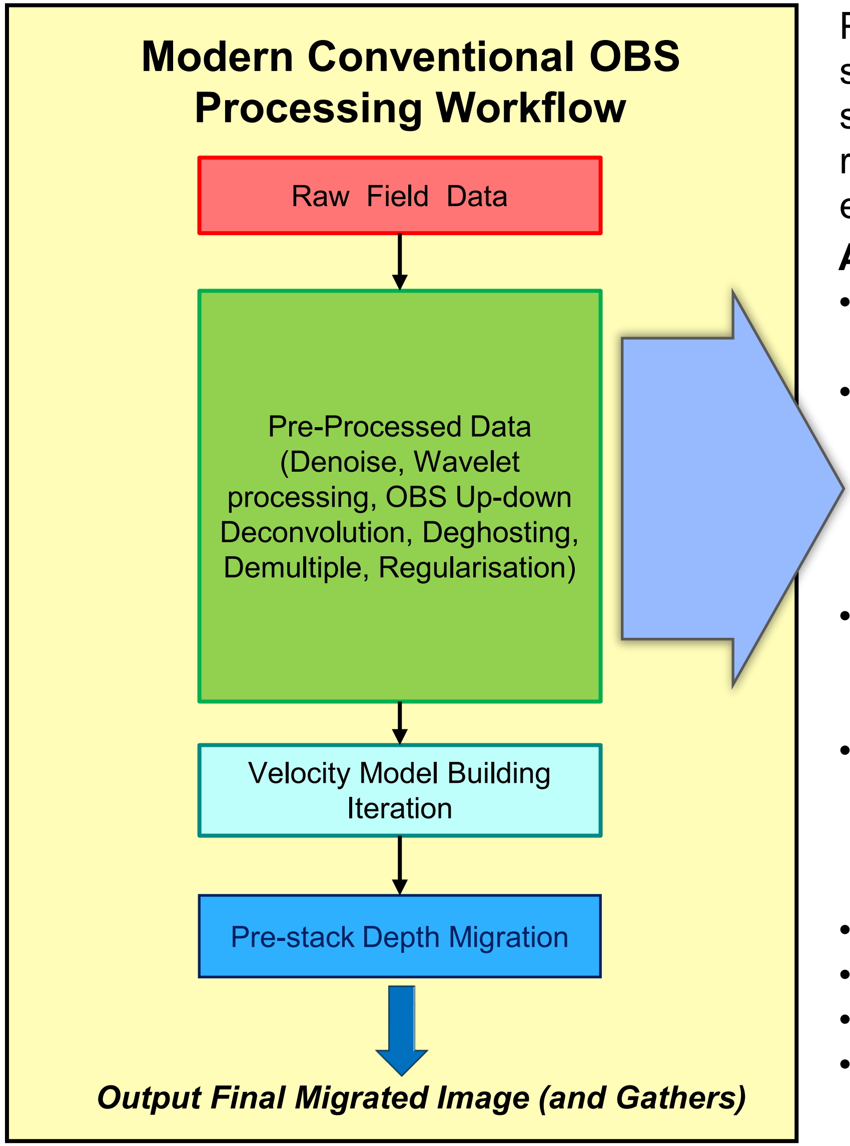
(Ref. 10d)

10a. Seismic Processing: Traditional Approach

Pre FWI: availability “level 0”

10.3 Pre Processing steps

North Sea Transition Authority



Processing has involved taking the original field data through a number of sequential stages each with parameters tested and chosen for a target. Across large regional surveys a single compromise parameter is usually chosen, meaning that future target specific reprocessing would often provide a better outcome, but compromised for a large survey. The end point product would be a migrated image in depth or stretched back to TWT.

Advances in preprocessing sequence

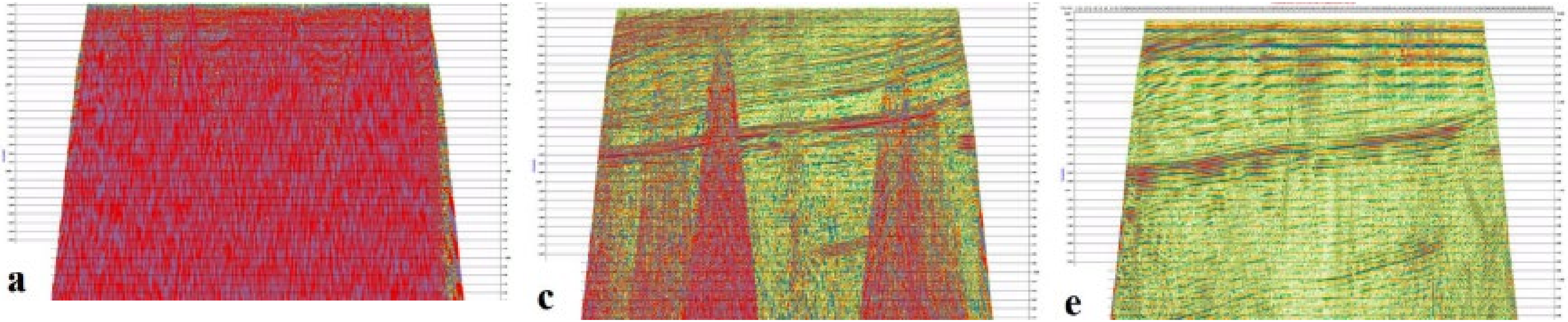
- **Navigation QC**. Apply additional checks to ensure accurate source and receiver positioning.
- **Better Marine Denoise**: Noise comprises swell noise, interference and cable tug. High resolution shallower cables have increased noise, whilst processing techniques can help to improve acquisition productivity, by acquiring in poorer weather. OBC/OBN vertical geophones are particularly susceptible to noise, especially in shallow tidal waters (section 10.4).
- **Zero phasing** produces more reliable interpretation: Modern 3D's apply a near field hydrophone shot-by-shot correction (section 10.5) or by separation of up/ down wavefields (section 5.6c)
- **Demultiple noise removal** (of multiple additional bounces). The toolkit has expanded considerably, especially with ability to provide up/down separation. This is a powerful noise removal technique – often different techniques tested and applied at different stages (sections 10.7 & 10.8)
- **Water column corrections**
- **Receiver motion**
- **Regularisation**
- **Velocity model building** has been transformed from simply "flattening the gathers" to a sophisticated imaging tool in its own right (sections 10.9 & 10.10).

Traditional sequential seismic processing sequence & major advances

10.4 Pre-processing Noise filtering

Seismic data noise from other vessels, tidal/cable noise is often filtered out at an early stage, using multi-channel filtering. This can be carried out in the common shot domain (i.e. all the receiver records compared for each shot) or the data re-sorted into a common receiver domain (for each receiver – all the data from the full range of shots).

Often with OBC/OBN seismic, the vertical geophone component (Z) data is often corrupted by a high level of noise compared to the data recorded by the hydrophone.



Results of the de-noising sequence a) the input Z data, c) after FX in cross-line direction and e) the hydrophone data used as reference for the directional filtering. (Deschizeaux (2013) EAGE).

(Refs. 10e & 10f)

10.5 Pre-Processing: Zero phasing

North Sea Transition Authority

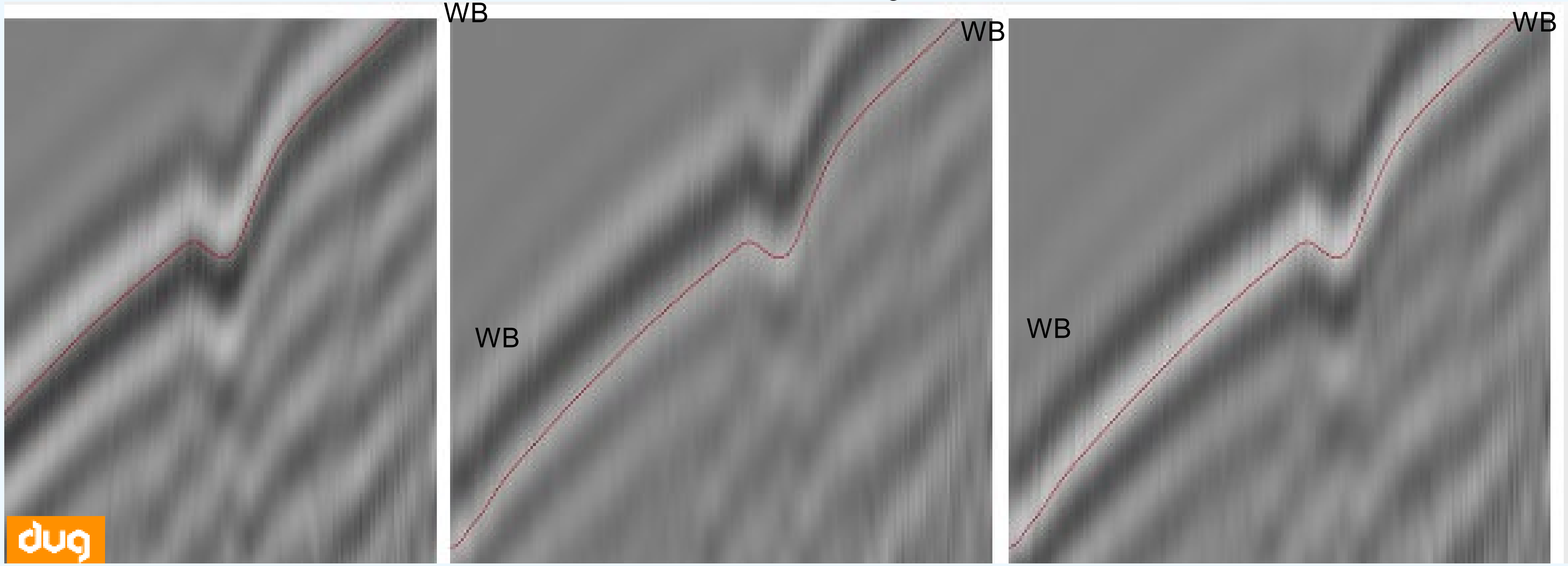
Zero phasing significantly improves the well to seismic tie and can be achieved many ways. Modern seismic is usually delivered zero phased: ideal zero phase response is one in which a clear seismic boundary (e.g. water bottom = seabed (WB) is observed as a strong event, with 2 lower amplitude balanced sidelobes. Legacy data usually employs a single far field signature for the whole surveys, whilst modern acquisition is improved shot-by-shot correction from a near field hydrophone (NFH).

Example of debubble. Low frequency (1-6Hz) stack

Input

Debubbled with far field signature

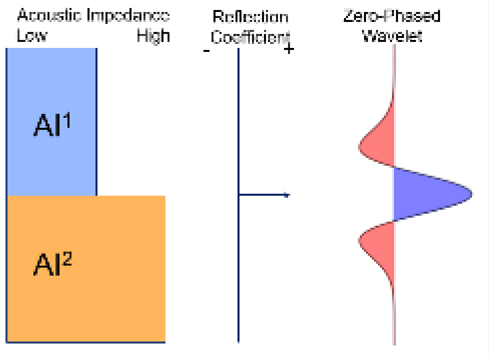
Debubbled with NFH



Water bottom tracks just above a peak

Water bottom tracks along weak trough, but strongest reflector peak above it

Water bottom tracks along strong trough, with balanced sidelobe peaks either side



(Ref. 10g)

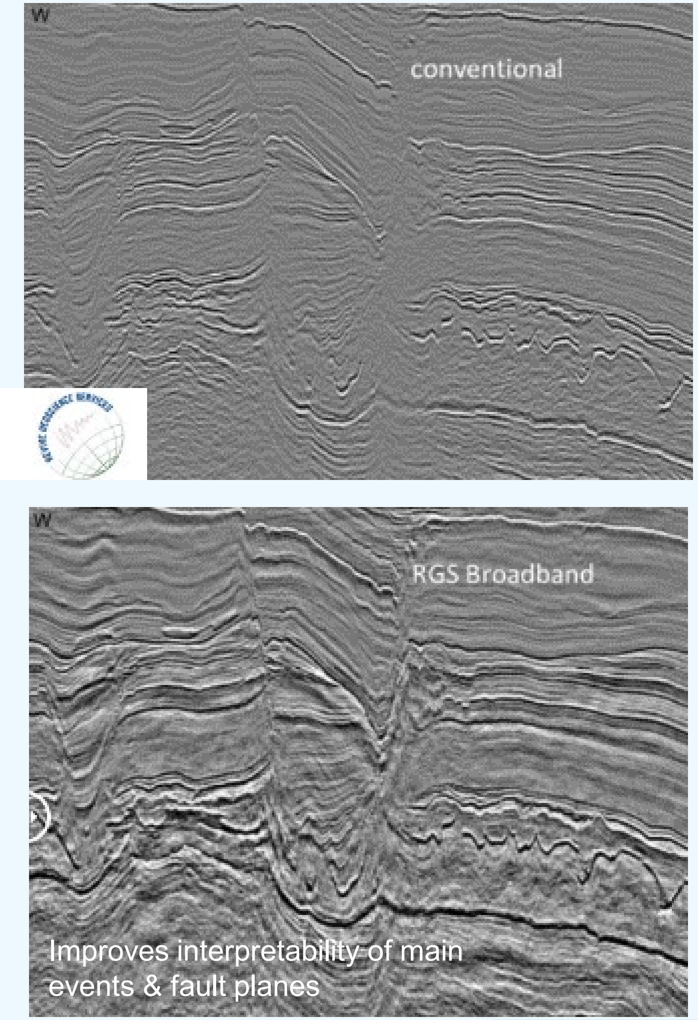
Zero phasing Processing example

10.6 Pre-Processing Deghosting

Modern seismic is usually acquired broadband (section 5.6), but often legacy 2D/3D data can be successfully enhanced with deghosting processing to improve the low frequencies.

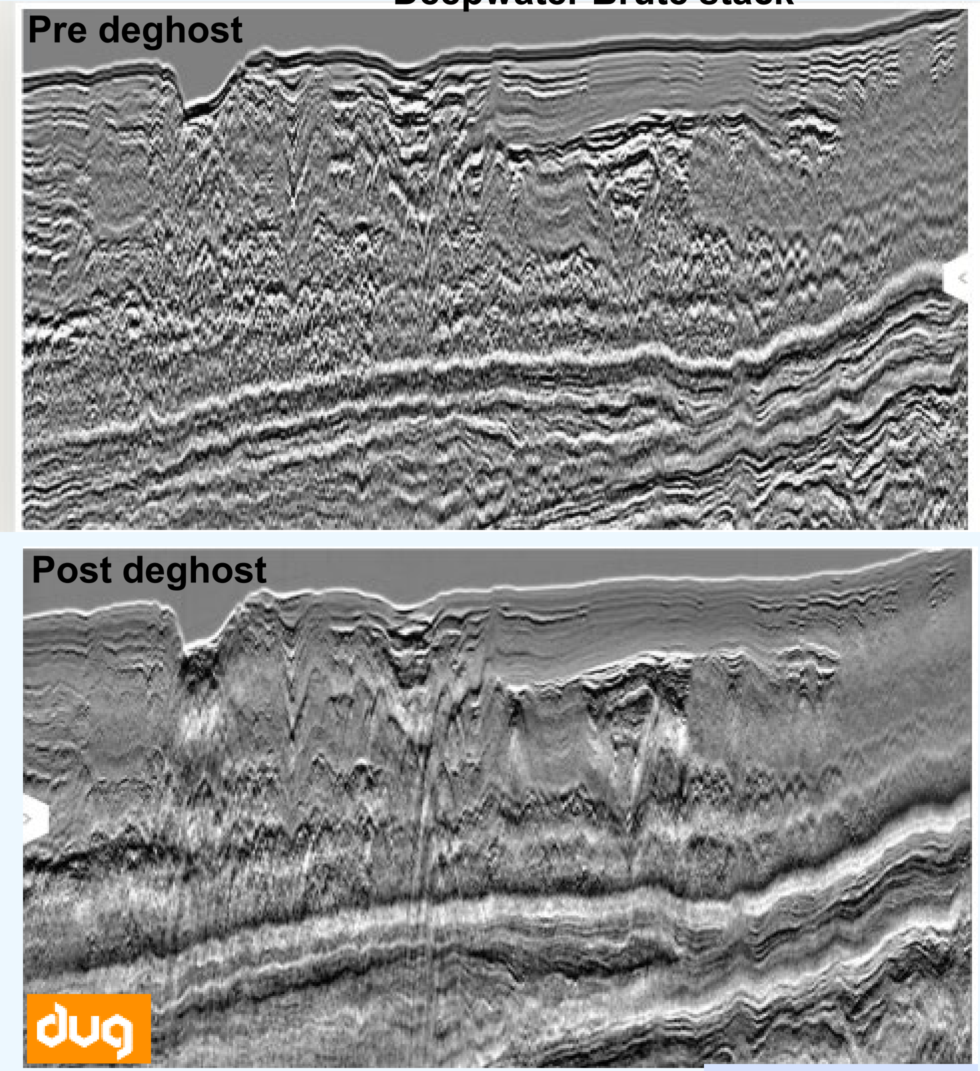
Deghosting is applied on both source and receiver ghosts.

SNS reprocessing



(Ref. 10h)

Deepwater Brute stack



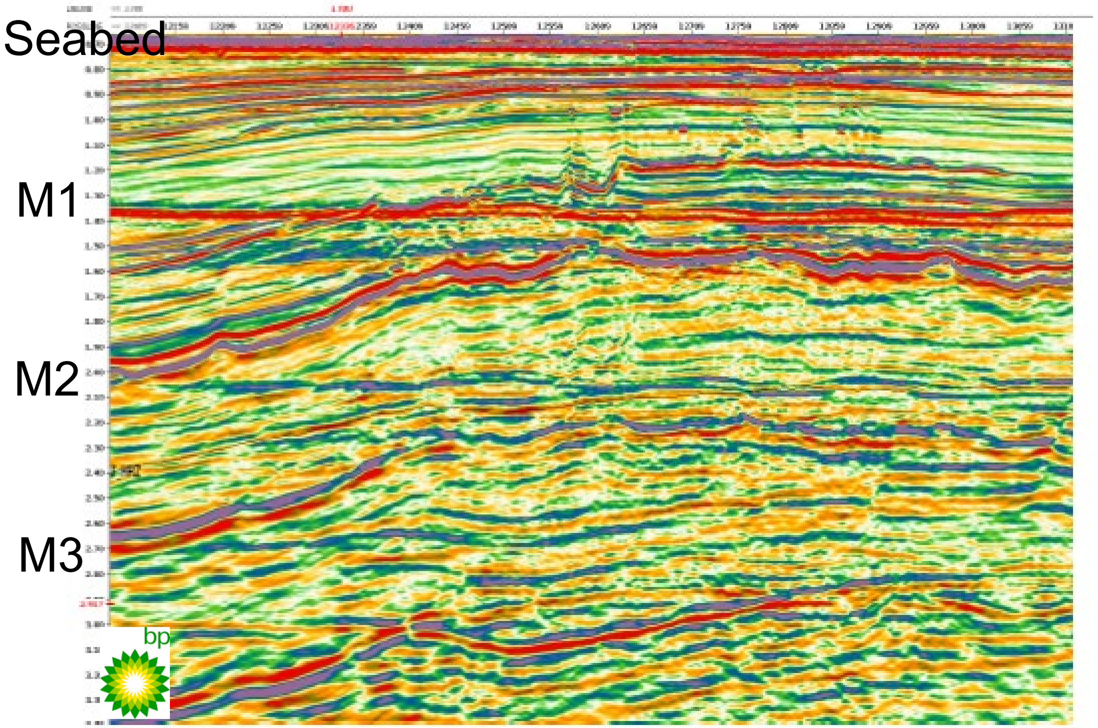
(Ref. 10g)

Deghosting Processing examples

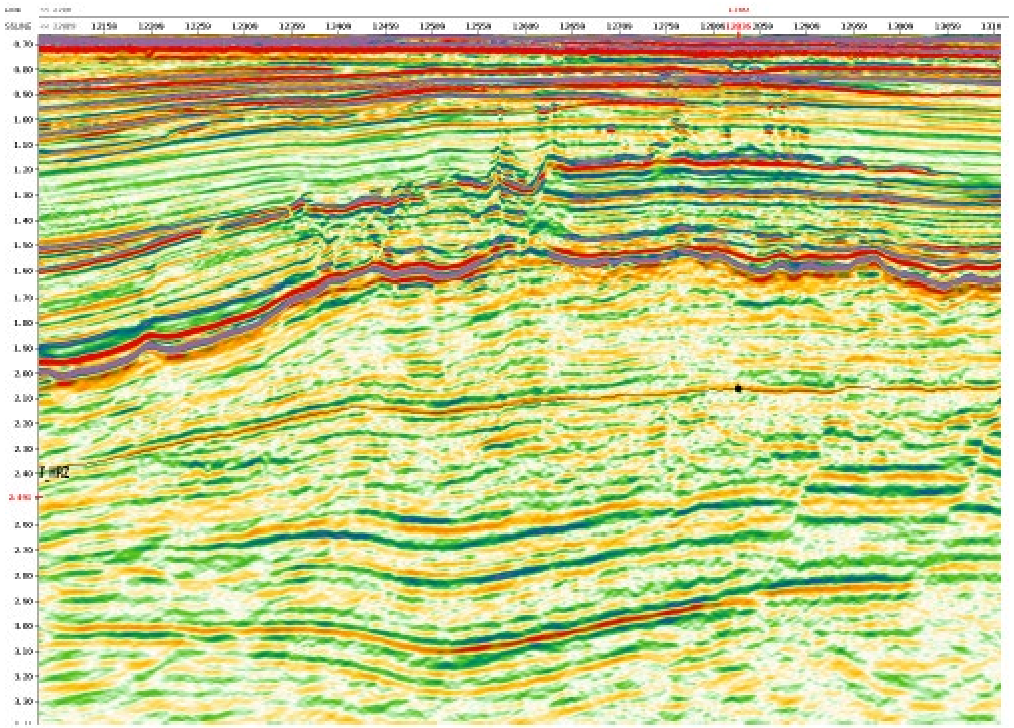
10.7 Pre-Processing Seabed Demultiple

Major processing stage which attempt to removal additional multiple bounces. In this deep water (700ms) West of Shetland example there is a clear sea bottom bounce cutting horizontally across the geology and is pervasive down the section. Adding 700ms TWT periodicity to the seabed creates an opposite polarity M1 and again with M2. M3 is harder to spot put the post- demultiple section is clearer. Shallow water multiples have a higher periodicity and can be much more difficult to spot visually.

Before de-multiple



SRME (Post a stage of demultiple)



(Ref. 10i)

Deepwater Seabed multiples are easy to recognise: SRME is one stage of demultiple

10.8 Pre-Processing Interbed Demultiple

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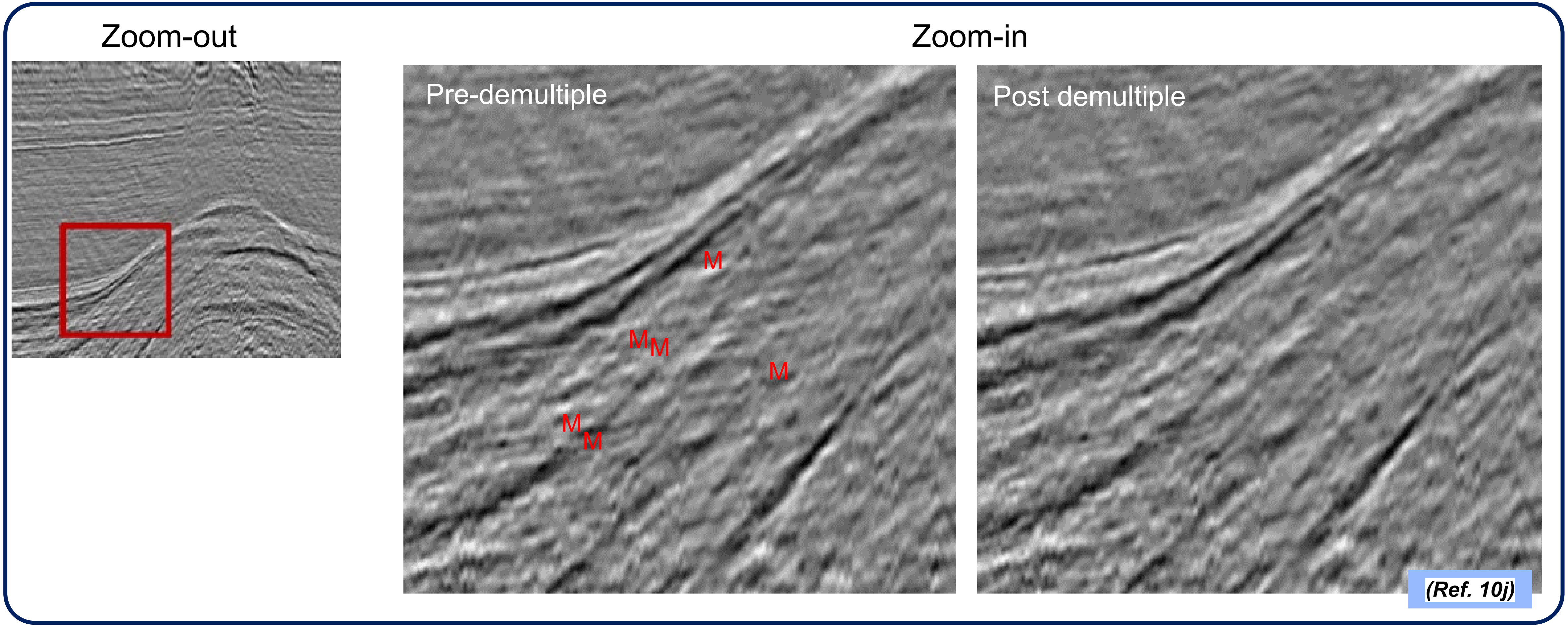
Interbed multiples can be very subtle. In this the horizontal overburden is generating cross cutting high frequency multiples across the dipping deeper section. Leaving such noise in the section would create substantially different interpretations and make attributes highly unreliable. Often testing is an interpretative trial and error.



Interbed demultiple remains a critical stage for shallow water areas like SNS

More frequent Interbed multiples with small velocity discrimination are harder to supress

10.9 Traditional seismic velocity analysis

North Sea Transition Authority

A sonic log represents *direct measurement* of the velocity with which seismic waves travel in the earth as a function of depth. Seismic data, on the other hand, provide an *indirect measurement* of velocity.

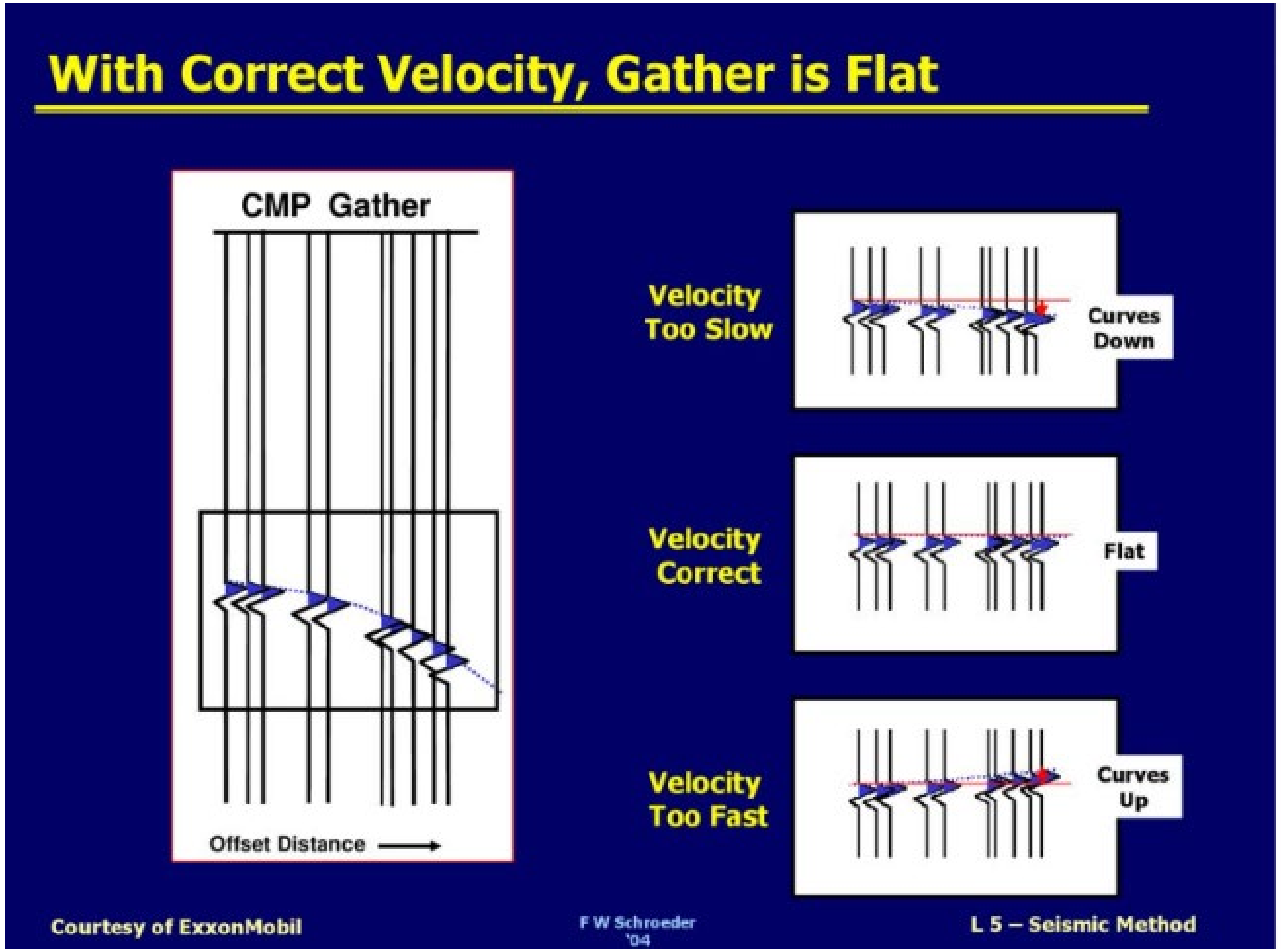
The final stage before stacking (summing) all the traces together is to apply a velocity field which aligns the pre-stack conditioned data.

Traditionally velocity analysis has been undertaken on pre-stack (conditioned) data to estimate the spatial velocity field by “flattening the gather”.

Without any velocity field primary reflections appear at later times, with longer offsets. Applying the correct velocity field flattens the gather.

In this artificial example the gather that drops down has a velocity which is too slow – or more appropriately the correction applied to the gather is too fast.

In reality gathers are seldom this well behaved and will demonstrate “hockey stick” anisotropic effects.



NMO (Normal moveout) correction

Dip discrimination, pre-NMO filtering was applied to the windfarm seismic survey (section 13.2.3)

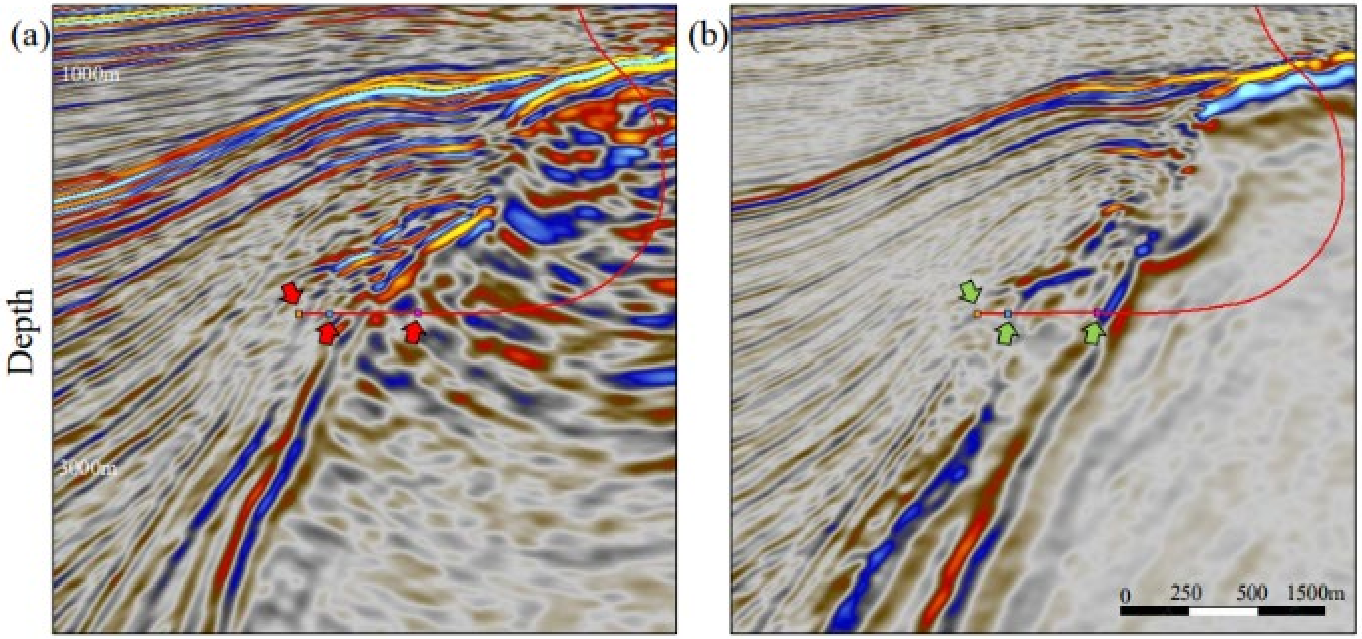
(Refs. 10k, 10l & 10m)

10.10 Migration - need for accurate velocities

North Sea Transition Authority

The goal of seismic migration is to retrieve the true reflectivity of the earth's subsurface structure. Focusing the image back in space to the true reflection point is a long-established process, but the last 10 years have seen a rise in the range of algorithms available. Adjacent to steeply dipping and high velocity salt velocity is critical, especially when targeting spatially very sensitive horizontal wells into very complex and potentially over-turned intervals. This example shows the importance of detailed work getting an accurate velocity.

Impact of velocity model on migrated image and horizontal well tie



Salt diapir flank imaging with (a) legacy and (b) final velocity models overlaid with salt exit and horizon markers. Horizontal mis-ties at the reservoir level are greatly reduced with the updated velocity model.

(Refs 10n and 10o)

Even with OB seismic, accurately imaging salt diapirs to allow accurate seismic ties to horizontal wells imaging takes considerable care and effort focussed on pre-processing sequence, up-down deconvolution, iterative velocity modelling approach to the velocity model build, utilising GWI (Guided wave inversion), FWI (Full waveform inversion), high-density tomography and anisotropic information derived from the PS data.

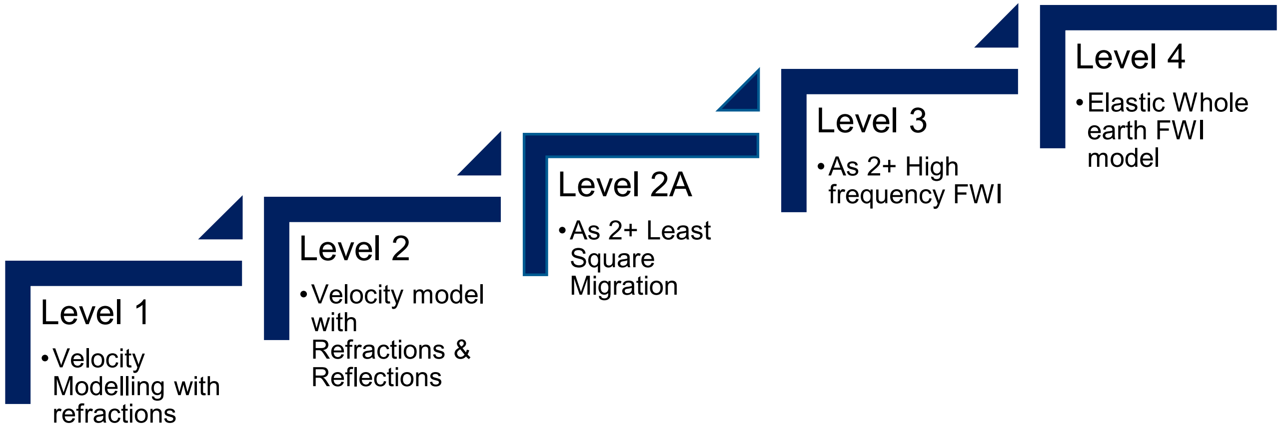
North Sea Transition Authority

10b. Seismic Processing: The Role of FWI

10.11 FWI optionality steps

FWI can be separated into a series of evolutionary steps, which are for the most part enabled by technological advances in computer processing and accessible digital storage. This topic is moving on at a rapid pace, with much active research and processing contractors' developments. Seismic imaging using full wavefield data including primary reflections, transmitted waves and their multiples is now doable, however long offset, wide azimuth ocean bottom datasets are preferred. FWI can be applied to legacy data, with more limited benefits. To try and address some of the confusion in FWI, a series of levels are suggested:

Level 1: FWI first used refractions for enhancing the shallow velocity model, down to the depth of the turning wave. Refractions were previously discarded (muted) from the recorded data. Modern processing/ reprocessing can usually undertake this, but with mixed success on legacy data.
Level 2: Since ~ 2018 FWI was adapted to use both reflections and refractions, to enable velocity modelling to be undertaken deeper in the section (e.g., such as Golden Eagle 3D) followed by a migration algorithm.
Level 2A: A least squares migration could be then adopted to sharpen the image top to bottom and increase its resolution.
Level 3: Currently activity is to push FWI to higher frequencies (60-100hz), so that the resulting velocity model is a significant interpretable deliverable in its own right, rather than just an intermediate step to the conventional reflection image.
Level 4: Research is ongoing to develop fully elastic models, using the range of Earths elastic parameters including shear waves.



However, FWI is a highly nonlinear, iterative process whose success depends on the seamless addition of wavelength features that are missing from the starting velocity model. In order to resolve features that lie below the deepest turning point of the recorded refractions and diving waves, analysis depends upon the low frequency content of pre-critical reflections.

Looking ahead, this approach could be a viewed as a radical departure from the traditional enhance the P-wave seismic feedback loop (section 10.2), as it uses other associated seismic waves, previously only been used for specialist applications (S-Waves), removed from processing (muted-out refractions, surface/ body waves) or treated as noise (multiples, tides, marine traffic, microseismic).
FWI is a very active area of research with over 3000 paper published on the SEG (Society of Exploration geophysics) website. They extend beyond reflection/refraction to include other applications (e.g., VSP, Ground penetrating radar, geohazards) and is an area of growing interest in medical imaging.

10.12 Full waveform imaging velocity model

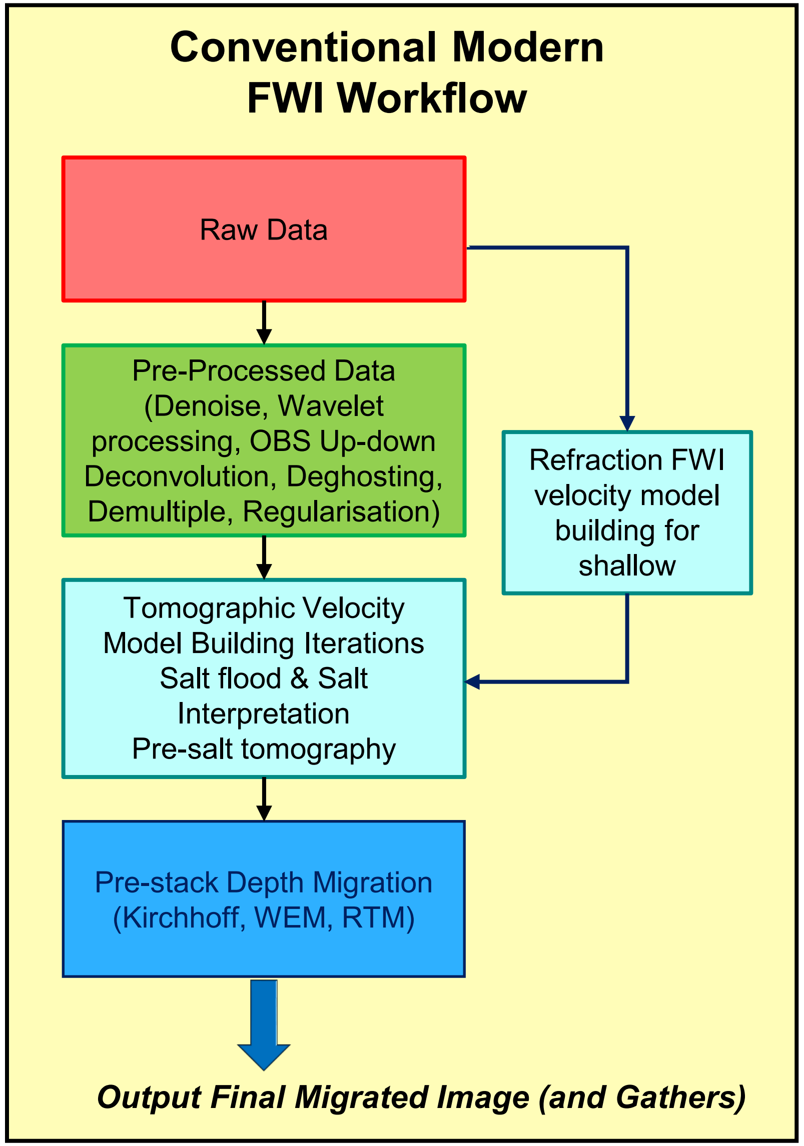
North Sea Transition Authority

Full waveform imaging (FWI) is now routinely used to provide a high-resolution velocity model for complex geology. This automatically & iteratively minimises the difference (misfit) between the acquired data in a seismic survey and synthetic data from a wave simulator with an estimated velocity model of the subsurface.

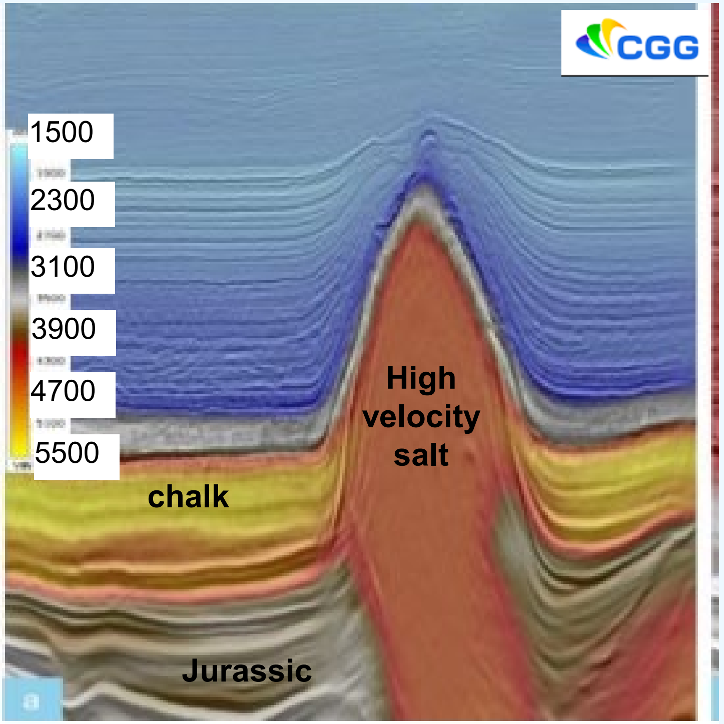
Originally it was developed used to improve the shallow, with many successful examples reported using FWI to update shallow sediments/ quaternary channels in the North Sea, gas pockets, and mud volcanoes.

Such techniques uses refractions and will not work beyond the depth of the diving wave illumination, in the case of the Central and Southern North Sea – this is usually the high velocity chalk layer. To capture these refractions, the best results from FWI imaging come from long offsets and full azimuth recording.

(Refs. 10p, 10q, 10r, 10s,10t, 10u & 10v



Velocity profile over CNS diapir



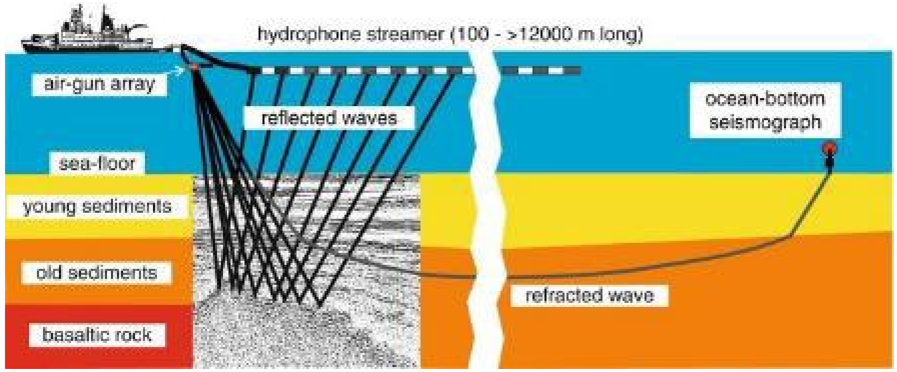
Thick fast Cretaceous chalk Vp ~5000m/s prevents diving wave illumination of slower velocity Lower Cretaceous & Jurassic

Refraction FWI to provide an improved velocity model

10.13 Seismic Imaging - Refraction

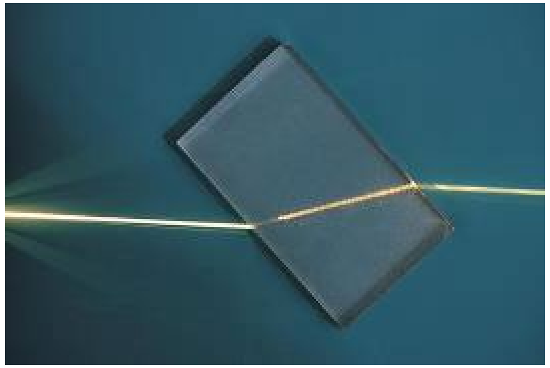
North Sea Transition Authority

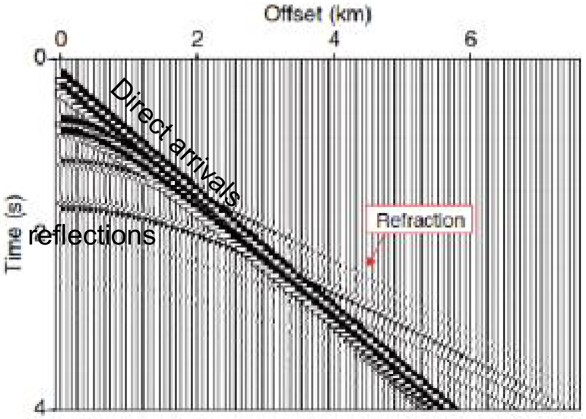
Each rock unit reflects the sound pulse back to the receiver array, but also transmits the signal to deeper levels with some refraction.
Reflections: part reflected back to the surface & part transmitted to deeper layers. They provide a “true Earth” view of discontinuities by reflecting energy near vertically back to the receivers
Direct arrivals: no interaction with subsurface boundary
Refractions: are also P-waves but continuously laterally bending through the layers until it reaches the surface. Refractions occur after the direct arrivals and have historically been deleted in processing from final reflection image (muted out). Full waveform imaging exploits these improve the shallow velocity model, which would previously been be muted out.



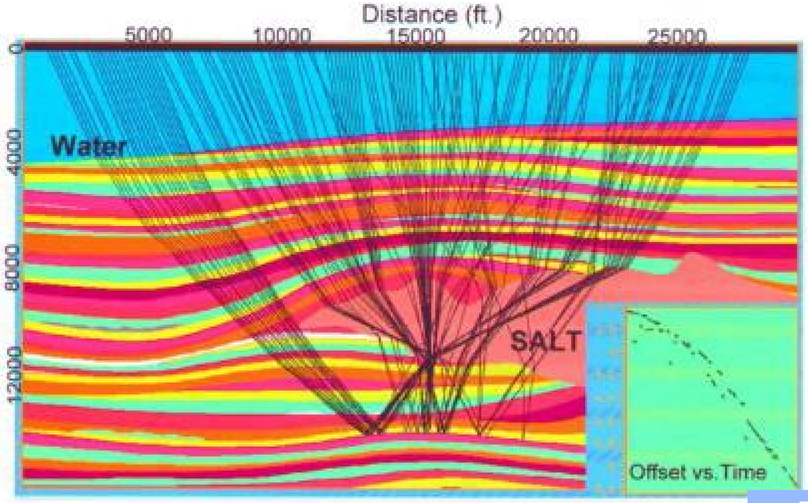
Refraction means that not all the subsurface is equally or evenly imaged. This is a particular problem where there is complex subsurface geometries and rocks with significantly different acoustic properties against each other e.g., SNS contains carbonates and evaporites with large velocity contrasts to shales and sandstones, with structures dominated by complex salt movement histories.

Analogous light refraction and refraction seen on gathers





Refractions rely upon sound waves bending (refracting like prism) and can be observed on reflection seismic records



(Ref. 10w & 10x)

Seismic refraction vs reflection explained

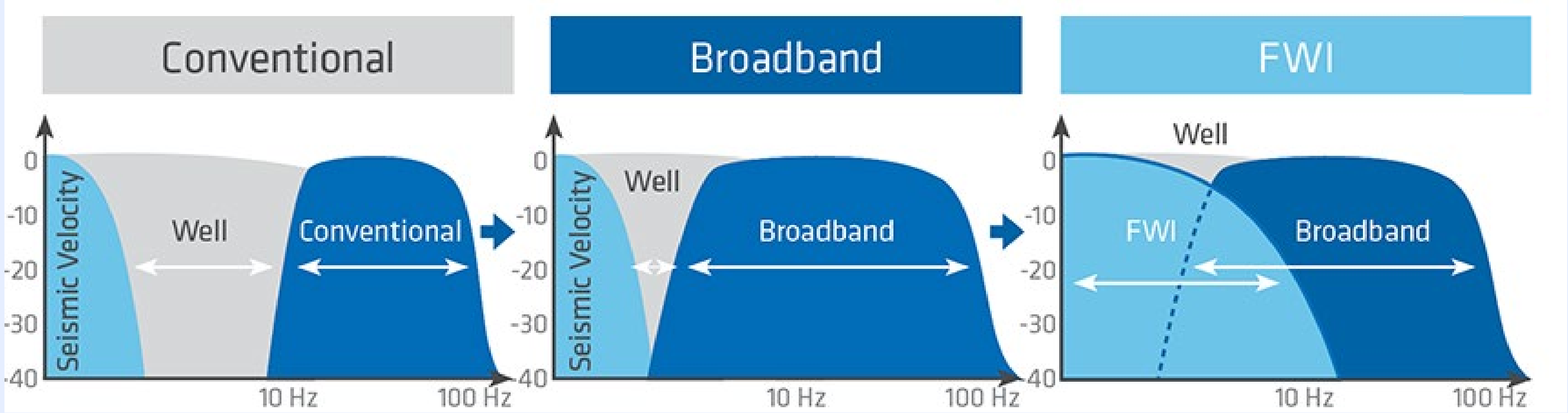
10.14 Role of Full waveform imaging

North Sea Transition Authority

FWI was originally run at the low frequency end of the spectrum to extend the seismic velocities to overlap with the conventional/ or broadband acquisition spectrum. As computing power has expanded, so has the seismic frequency range on which FWI is run. While the greatest benefit for model building is achieved from access to relatively low frequencies, increasing the frequency content in FWI helps in reservoir characterization.

Obtaining full-bandwidth, absolute elastic-attributes for lithology and fluid prediction requires a low-frequency model. The lower frequency component required for the modelling can be generated from velocities, assuming they contain sufficient resolution. This reduces the emphasis on the well and seismic information.

Schematic representation of role of FWI on frequency spectrum



Levels 1 & 2

"Level 3" FWI processing can be undertaken to 100Hz, so the FWI image becomes the product and there is no need to combine with the real data. However, the result may be model driven (section 10.17) and represents pseudo-velocity rather than the velocity*density product of a conventional seismic image.

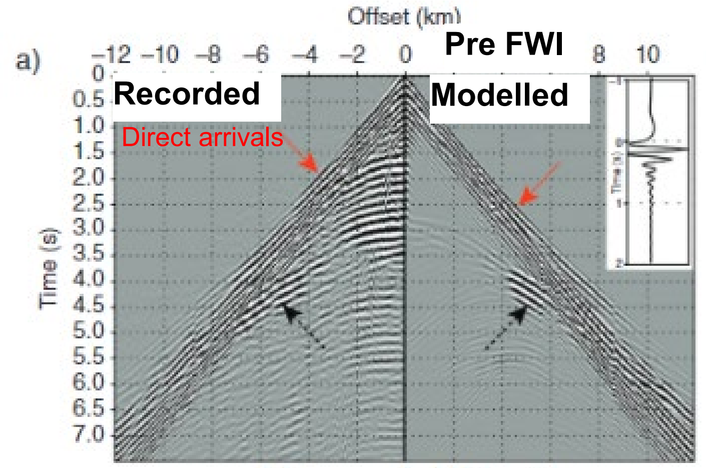
(Ref. 10y

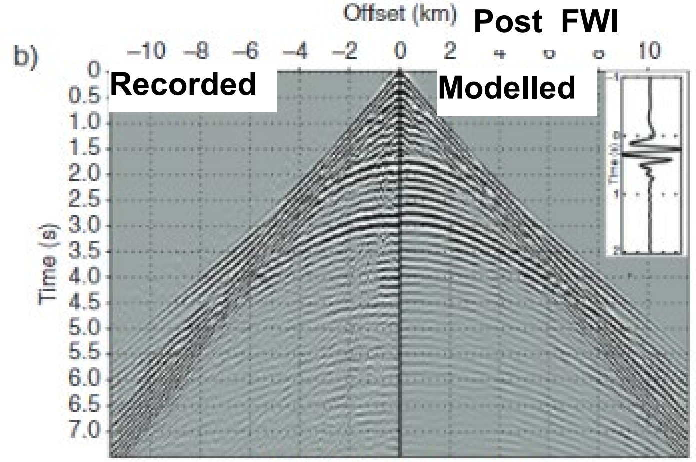
FWI usually used to improve/ infill low frequency part of the spectrum

10.15 Full waveform imaging in practice

North Sea Transition Authority

FWI impact on Mirrored Common offset gather

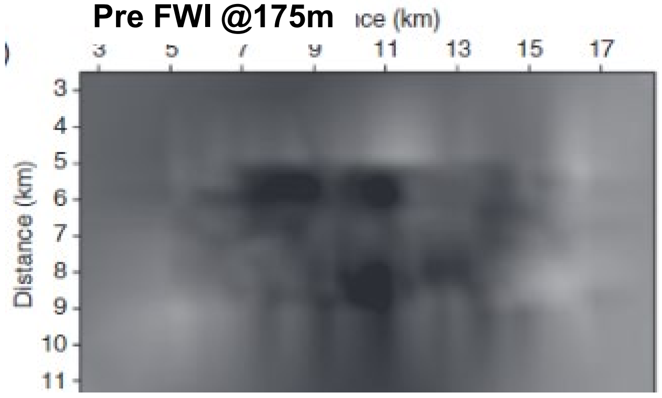




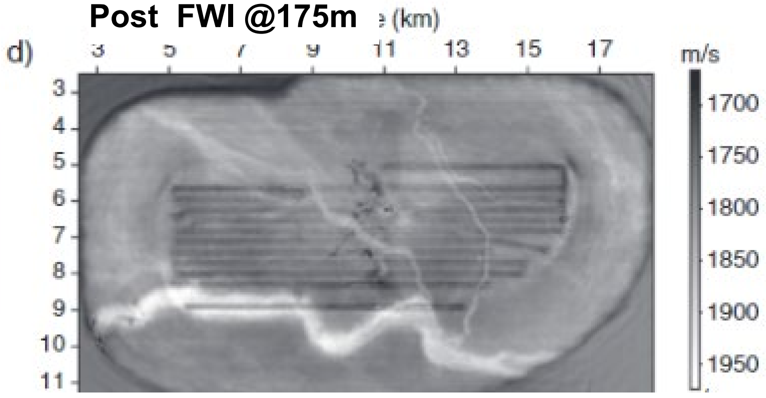
Seismograms for final model

Red = first, direct arrivals
Black = post critical phases
Significantly improved alignment after FWI

Depth slices through velocity model

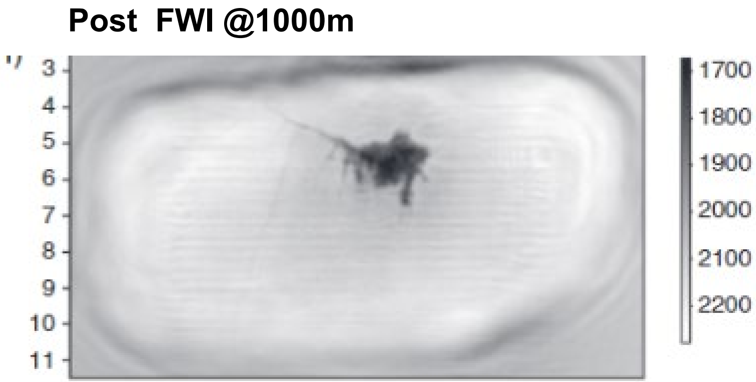


Nothing visible



Paleo river and acquisition imprint clear

Gas cloud blurred



Very precise gas cloud now resolved

(Ref.10t)

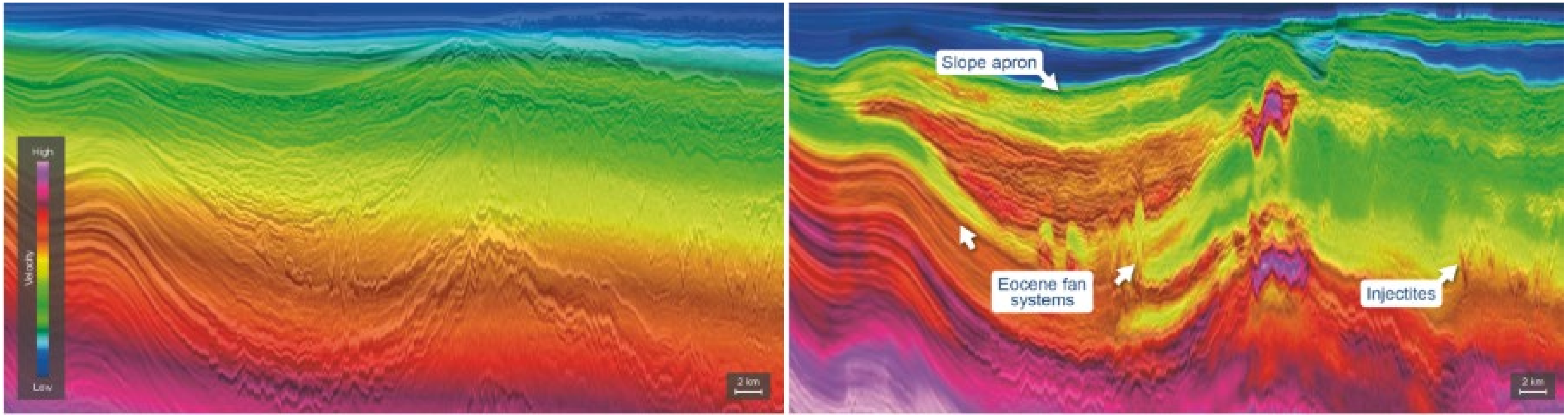
FWI greatly improves spatial resolution

10.16 FWI in the West of Shetland

North Sea Transition Authority

PGS have undertaken a regional reprocessing of legacy 3D seismic surveys using FWI to improve the velocity field

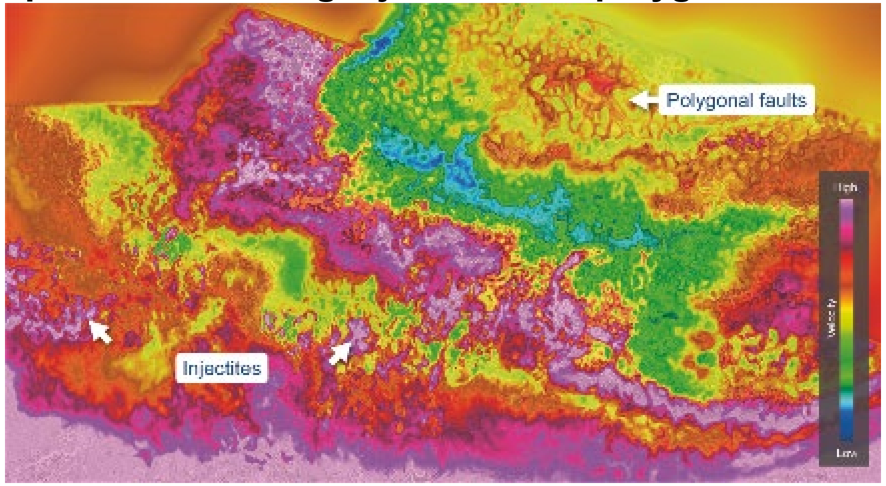
Seismic cross sections coloured by velocity field



In this part of the west of Shetlands, an overburden of upper Tertiary extrusive volcanics benefited from a high-resolution FWI velocity model is beyond conventional tomographic techniques.

Simple input model to FWI shown (left) and the updated FSB (Faroe Shetland Basin) FWI model (right). The resultant model is geologically conformable, resolving the vertical and lateral velocity variation in the image.

Depth slice showing injectites and polygonal faulting

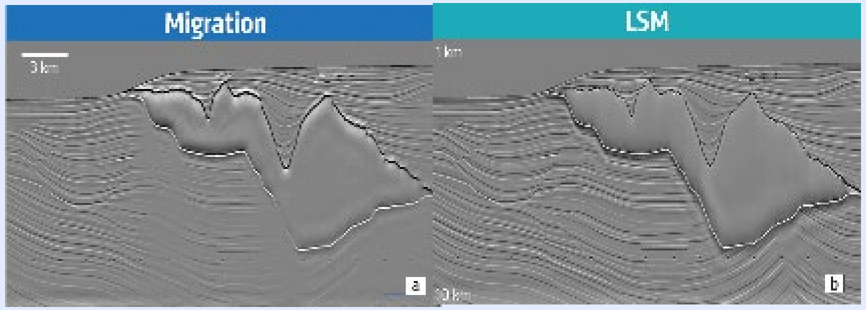


(Refs.10z and 10aa)

10.17 FWI Level 2A (Least squares migration)

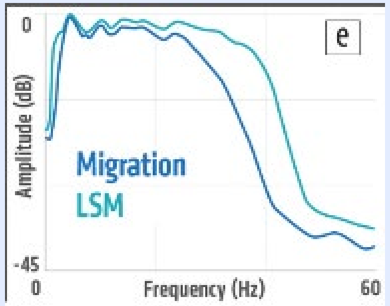
Standard Pre-Stack depth migration (PSDM) is unable to fully recover the reflectivity amplitude fidelity and resolution due to inhomogeneous subsurface illumination and irregular acquisition geometry. This leads to washouts and poor structural definition. Similar to FWI, the addition of Least Squares Migration (LSM) seeks to iteratively minimise the misfit (difference between modelled and observed) data.

Synthetic example of LSM



Standard PSDM gives uneven illumination. LSM balances the amplitudes, reduces shadow zones and improves temporal resolution (bandwidth).

(Refs. 10ab and 10ac)



However, LSM requires highly accurate velocity information. If the velocity model is in significant error, modelled events will not be aligned with the observed data and produce unsatisfactory results.

Level 2A

Least Squares Migration

Input primaries only pre-processed data, velocity model and migrated data

Migrated Reflectivity from conventional sequence → Forward Modelling → Modelled Data → Difference Modelled/ Observed data → Large Difference → Update Migrated Data → (repeat)

Iterative process to minimise the difference between modelled and ***processed*** observed data to obtain an image of the subsurface

Small Difference →

Output Final Migrated Reflectivity Image

Level 2

Modern Conventional Processing Workflow

Raw Data

Pre-Processed Data (Denoise, Wavelet processing, OBS Up-down Deconvolution, Deghosting, Demultiple, Regularisation)

Refraction FWI velocity model building for shallow

Tomographic Velocity Model Building Iterations Salt flood & Salt Interpretation Pre-salt tomography

Pre-stack Depth Migration (Kirchhoff, WEM, RTM)

Output Final Migrated Image (and Gathers)

Both LS Migration& FWI are iterative data driven processes that minimise the difference between modelled & observed data

10.18 Role of least squares migration

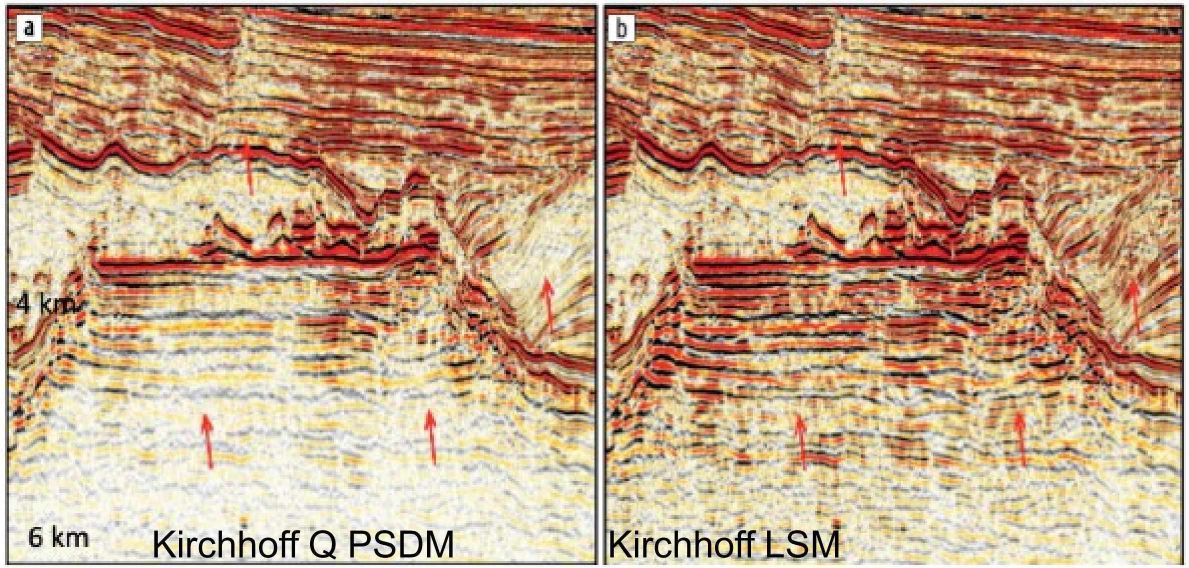
This provides a real example of LS migration in cross section and amplitude maps in an area with a complex overburden.
In this case, the workflow incorporates:

1. FWI velocity model building,
2. Q (absorption) tomography for balancing weak amplitudes where strong absorption exists in the overburden and
3. Least-squares migration (LSM).

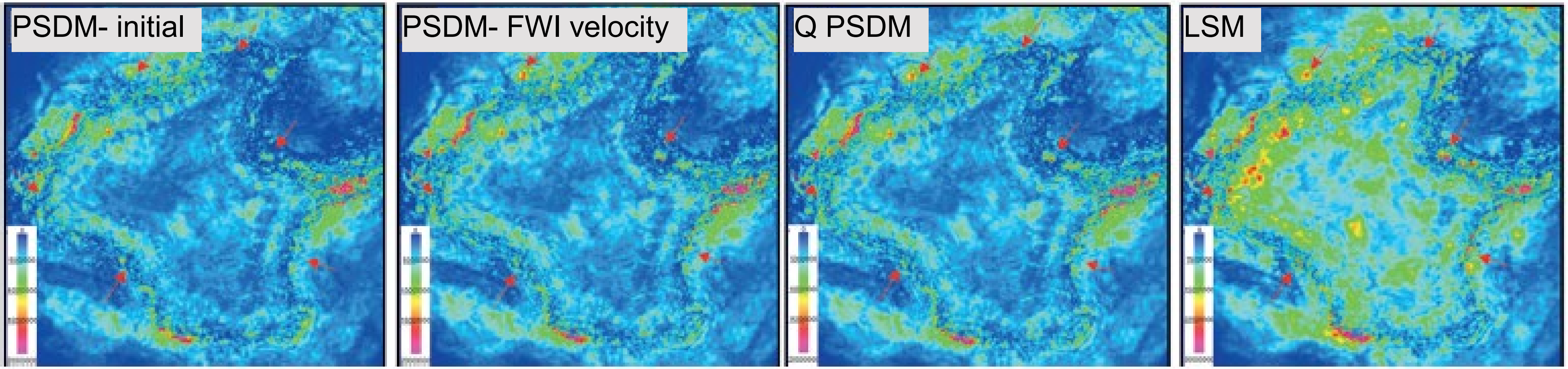
LSM uses processed primaries as input data, but FWI can be extended to include full-wavefield data (section 10.19).

(Ref. 10ad)

LSM improves amplitude fidelity and resolution in both vertical and horizontal directions



Seismic attribute maps show incremental improvement with 3 step approach for general illumination and continuity.

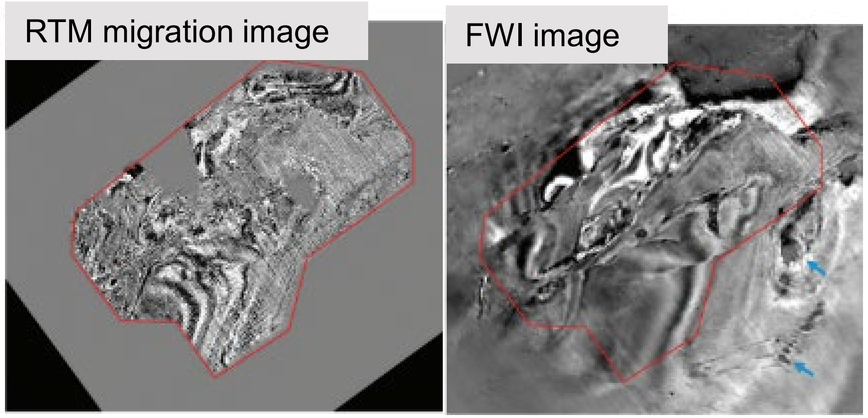


Least square migration improves event continuity in sub-salt environment

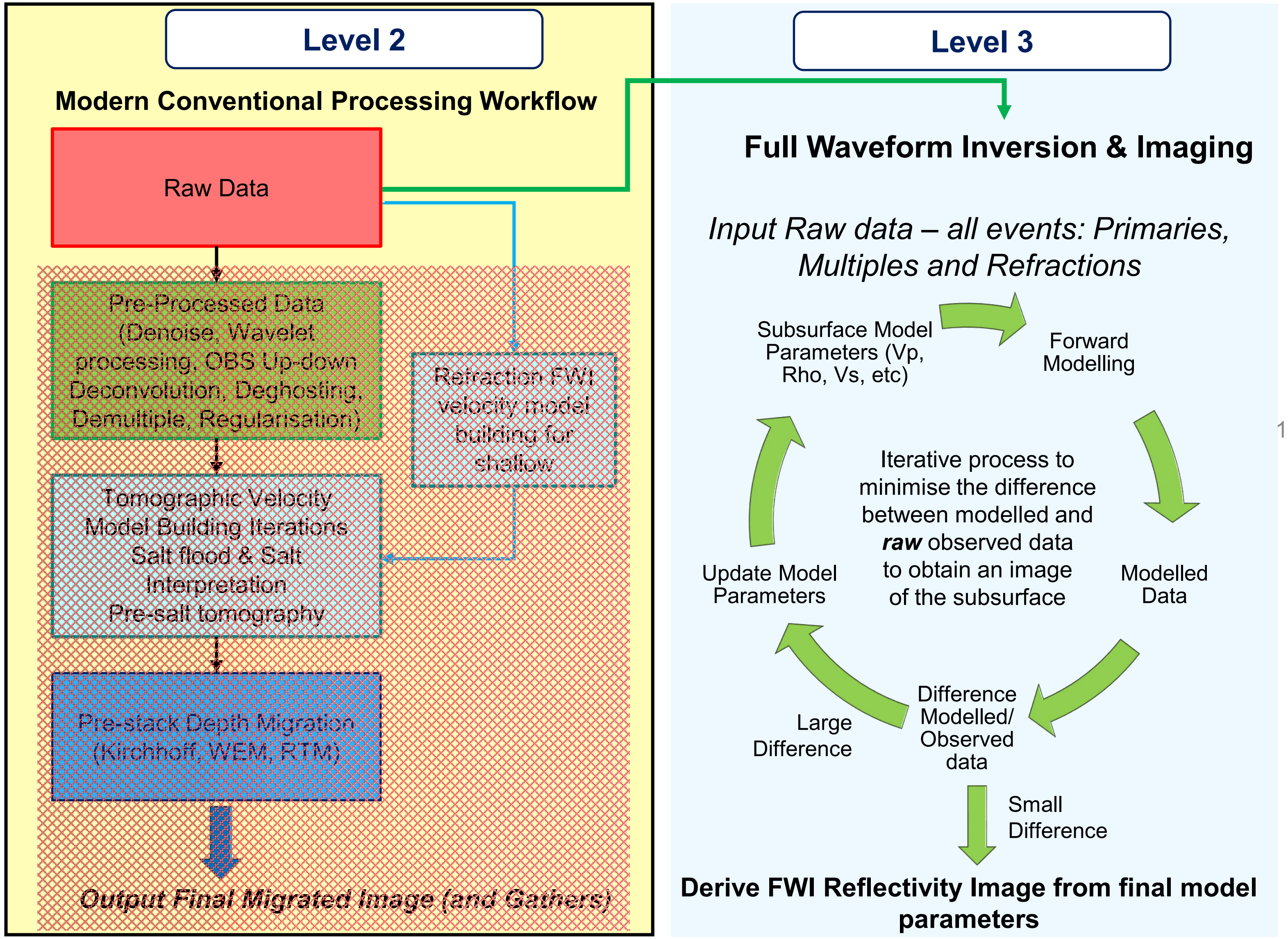
10.19 Full waveform imaging (Level 3)

It is possible now to a step further - modify the FWI workflow to **output the subsurface image or reflectivity directly**, potentially eliminating the need to go through the time-consuming conventional seismic imaging process that involves preprocessing, velocity model building, and migration. Use of the full-wavefield gives additional illumination over LSM.

Shallow water OBN depth slice @200m



FWI fills acquisition holes and extended image from node coverage (red polygon) to shot coverage.



(Ref. 10ae)

Using the full waveform for imaging rather than just velocity model building

10.20 Comparing Level 2, 2A (LSM) & 3

North Sea Transition Authority

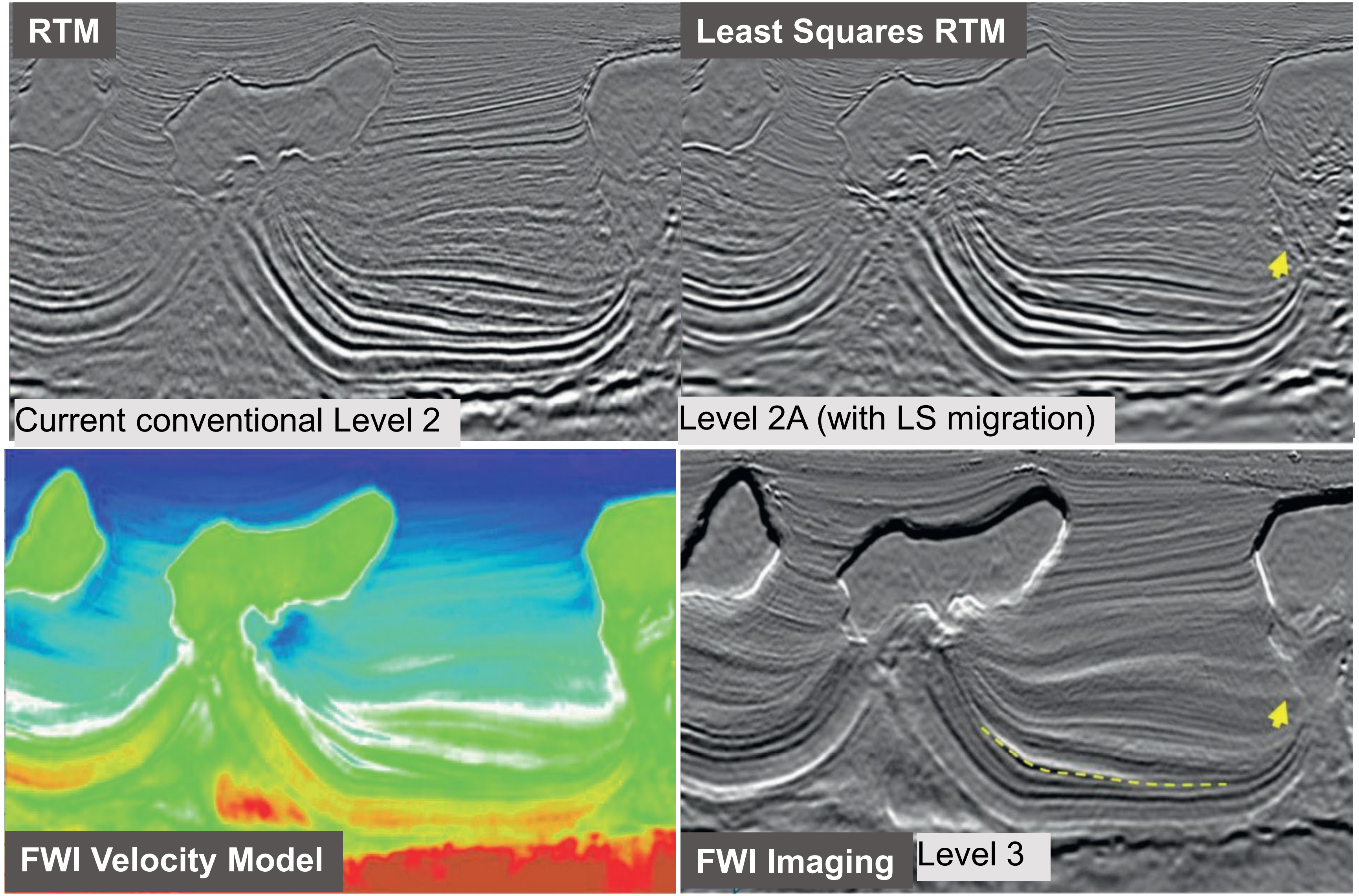
The RTM (reverse time migration) represents the standard complex structure migration algorithm. Least Squares Migration and separately FWI velocity model and Imaging are compared with same velocity model.

Least Squares Migration requires a very good input velocity and uses primary only pre-processed seismic data as per standard migrations.

FWI Imaging uses all recorded raw shot energy (refractions, primary and multiple reflections) to update the velocity model and directly produce a reflectivity image from the model.

There appears to be a noise reduction, improved event and steep dip continuity, bandwidth and resolution.

(Ref. 10af)



The evolution of the FWI/LSM process

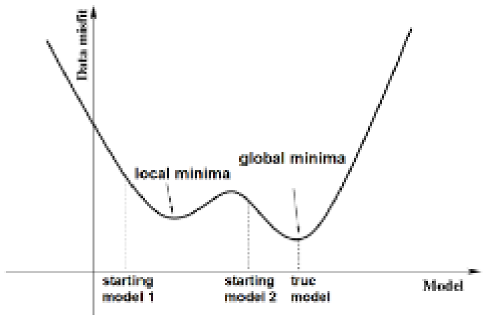
10.21a Limitations of FWI

FWI is not a panacea – it has limitations in which some subsurface environments and acquisition styles which can prove challenging.

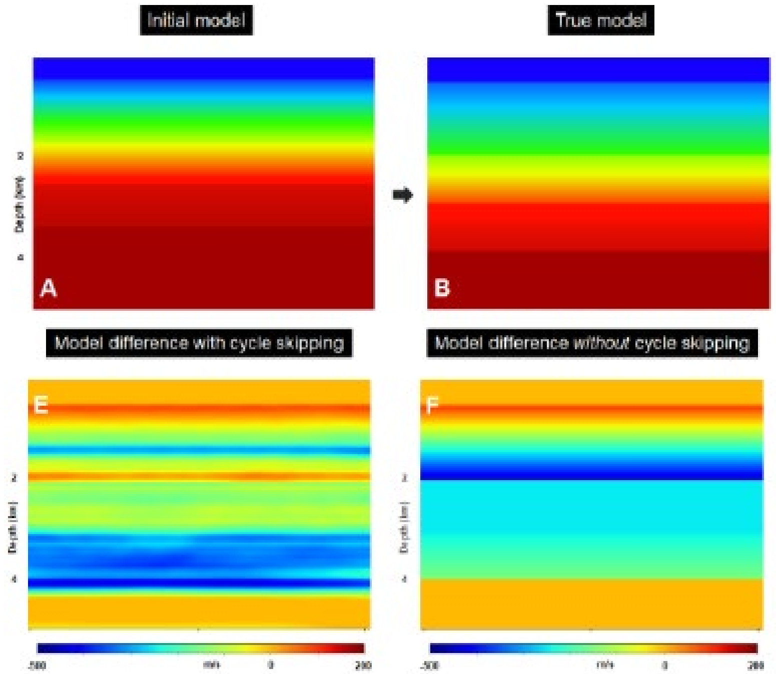
The primary challenge for FWI is to overcome the **cycle-skipping** phenomenon, where the initial velocity model is too inaccurate for the algorithm to find the correct minimum misfit model. A bad model leads to a solution that does not converge or has non-geological features in the final velocity field. Practical solutions include using the lowest possible signal frequencies and the multiscale frequency-stepping approach has become standard. Towed streamer data will generally not provide sufficiently low frequencies (lowest ~5Hz), whilst OBN can provides frequencies below ultra-low 1-4Hz data with high signal to noise (see section 7.8c).

Cycle skipping has to be accounted for within each FWI iteration before the model update can be computed. If the time misalignment between the modelled and observed data is more than half a cycle (wavelength) for any considered frequency, the objective function can easily converge to a local minima, and the iterative process will terminate prematurely.

Schematic representation data misfit



Cycle skipping in simple velocity model



A simple initial velocity model (A) updated without accounting for cycle skipping creates a rapidly varying and erroneous model (E) compared to the true (B).

(Refs. 10ag & 10ah)

10.21b Limitations of FWI and LSM

Water depth: In shallow water, such as the SNS, the sea bottom is often poorly imaged, or may not be imaged at all on legacy data. A short near offset is key – or even employing sources over streamers (section 5.9b)
In deeper water, the water column itself reduces the amount of refracted energy available to be transmitted through the rock layer, creating a weaker response. In general, water depths down to 200-300ms TWT (~150m) are thought to be reasonable for FWI.

Complex & exotic geology (volcanics, salt, SNS chalk which us fast and shallow) have a large contrast compared to the typical sedimentary sequence, large changes in amplitude can cause problems.

Short offsets and NATS: Legacy short offset data, with a narrow range of azimuths, is unable to recover the spatial variation in the wavefield, so will often lead to poorer results, not capturing the full wavefield reflected back (refractions etc.). Running FWI on shorter offset vintage data may be even more of a struggle and requires a better starting model for NATS and shallow water data.

No density information: There will be occasions where the density has the opposite trend to velocity and happen to dominate the impedance. For those areas, the amplitude and phase of the FWI image would be in doubt even if there was an accurate velocity model. Density would be needed to solve this.

Alternatively, this could be described by **2 variables, but one observation.** Seismic data effectively only provides only observation in space, but the signals are controlled by 2 variables (velocity and density) + anisotropy. This means the results are not necessarily unique and an FWI velocity field may provide good resolution and continuity, but the amplitudes may not be reliable if FWI amplitudes are used for imaging (taking gradient of velocity field).

11. 4D & Seismic Repeatability

Update from Phase 1

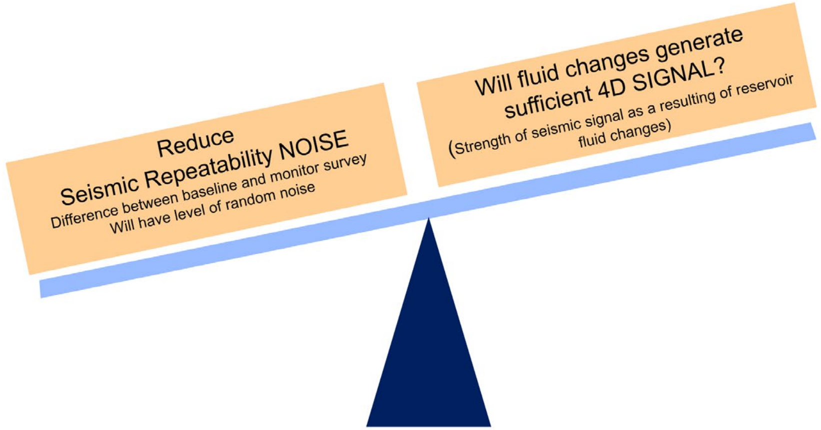
11.1 CO_2 4D seismic within MMV planning

North Sea Transition Authority

Seismic data is expected to be an important component of the broader MMV technology portfolio (MMV1 phase 1), especially with First of a Kind (FOAK) projects. The NSTA expects a CCS complex operator will identify risks & uncertainties that could be mitigated by repeated seismic observations of the rock and fluid response to CO_2 injection.

4D (time lapse 3D) relies upon:
1) A sufficiently large reservoir fluid related **signal** generated by injection (or production) of fluids between the baseline & monitor surveys can be detected.
2) Against from a lower-level **noise** (non- production) differences between the seismic surveys.
3) There are clear plans to use the monitoring data to mitigate specific risk and uncertainties.

4D Signal must be greater than Noise



Seismic repeatability has improved by more sophisticated design (source & receiver steering, OBN and parallel processing). This section focusses on seismic repeatability, whilst section 12 discuss the potential strength of the signal.

It is very likely that many reservoirs will not be amenable to 4D seismic monitoring. This is analogous to the O&G situation, in which it is estimated 50% of N Sea reservoirs which have a sufficiently large response to technically lend themselves to 4D.

Two points are particularly worth emphasising:
1) Whilst it is known that SNS gas fields have had large pressure drops, but only experienced marginally detectable 4D time shifts (section 12.10b), most of the field continued to see production related pressure decline since the typical 1990s 3D survey. It is possible that a small-time shift since the 1990's will cause problems for future attempt to identify subtle 4D differences, especially if they are undertaken with acquisition-light technology (section 7.19). This implies **1990s surveys cannot be considered as baseline surveys for CO_2 injection phase.**

2) It must be emphasised that although 4D is a well understood method mostly used for locating hydrocarbon infill wells, there are a handful of CS stores across the world and the alternative 4D monitoring requirements for such sites means that it is still very much in development phase. **Future proofing for technology changes over the next 60 years is a particular concern.**

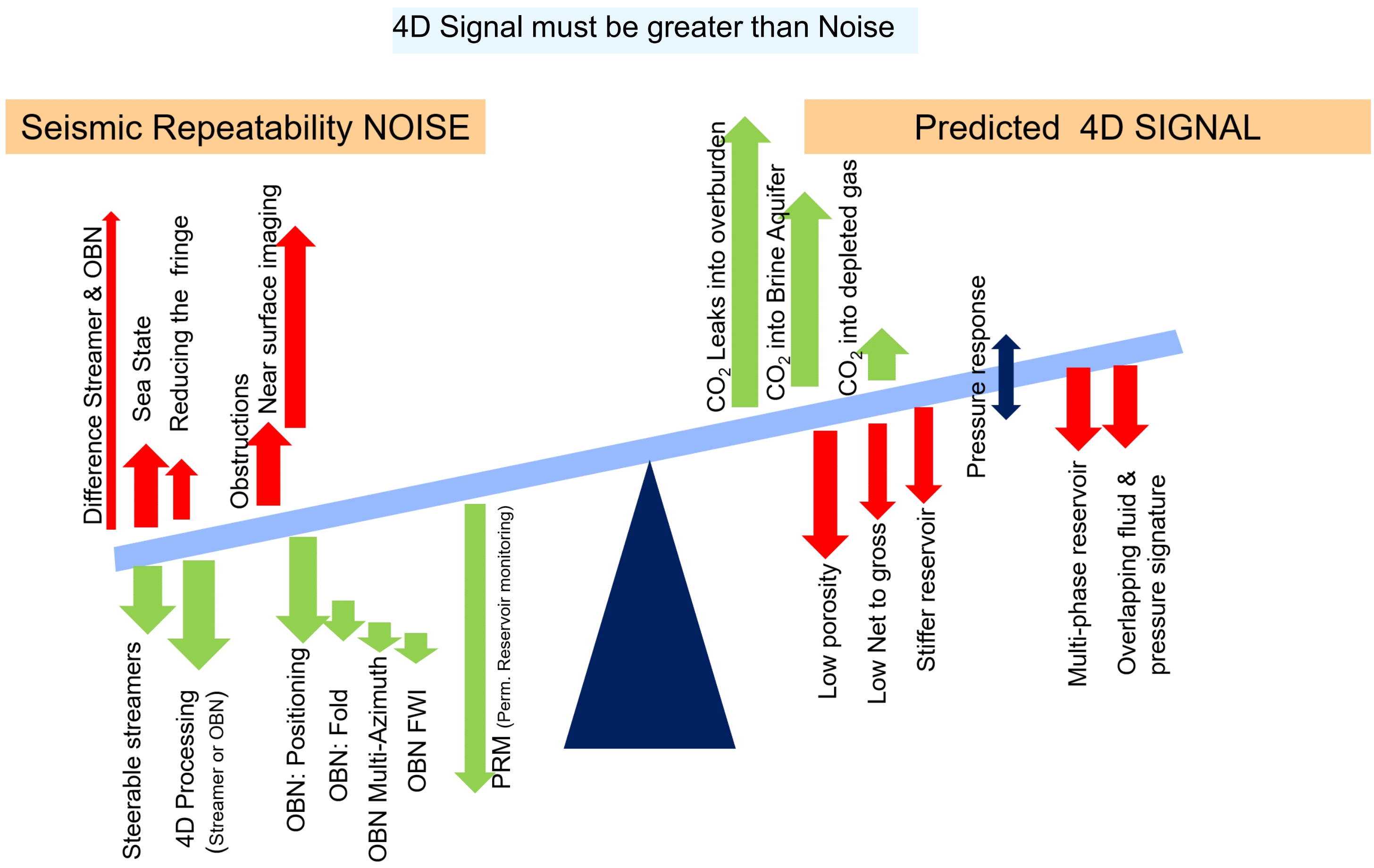
11.2 Factors influencing 4D viability

North Sea Transition Authority

The goal of surface monitoring is to
- Remove all variations in the data that are not related to changes occurring in the reservoir
- Whilst preserving meaningful variations that may be related to production and injection

These unwanted variations can be due to
- Changes in surface or near surface conditions (thermocline, sand waves, channels).
- Variations in source type & size, source and receiver location, wavelet.
- Variable noise conditions at receivers (transiting vessels, distant piling, tidal/swell noise, new constructions, turbine movement).
- Variations in source & receiver locations, orientations, timing and coupling.

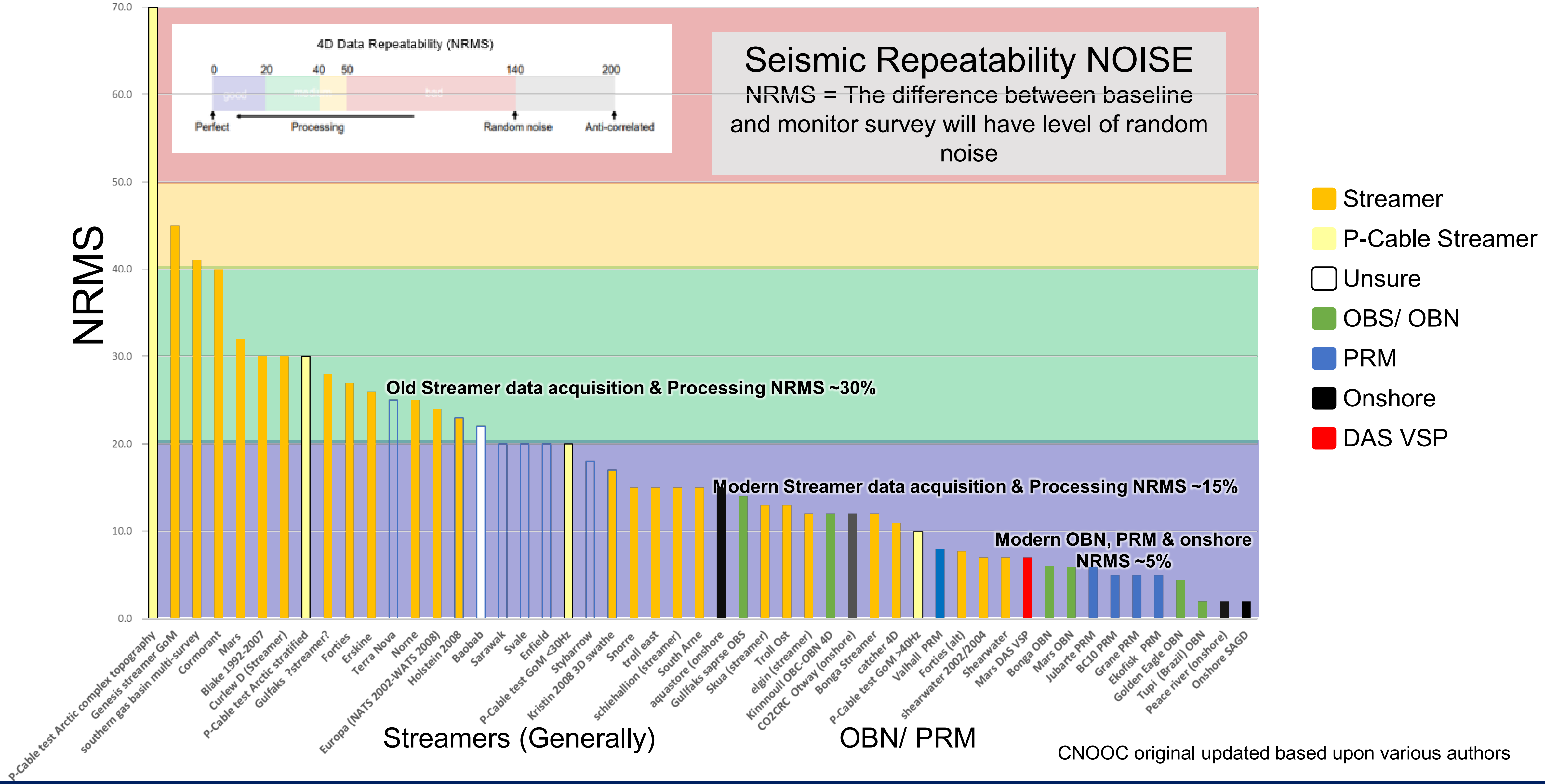
The acquisition impact of closely comparable acquisition and parallel processing to reduce the unwanted variations was demonstrated in MMV Report 1.



Whilst the size of the signal can only be observed, there are many acquisition and processing factors which can control the level of seismic noise. For example, high specification OBN seismic may be able to detect a weak 4D signal, beyond the capability of streamer repeatability.

11.3 Seismic Repeatability & Noise: NRMS

North Sea Transition Authority



CNOOC original updated based upon various authors

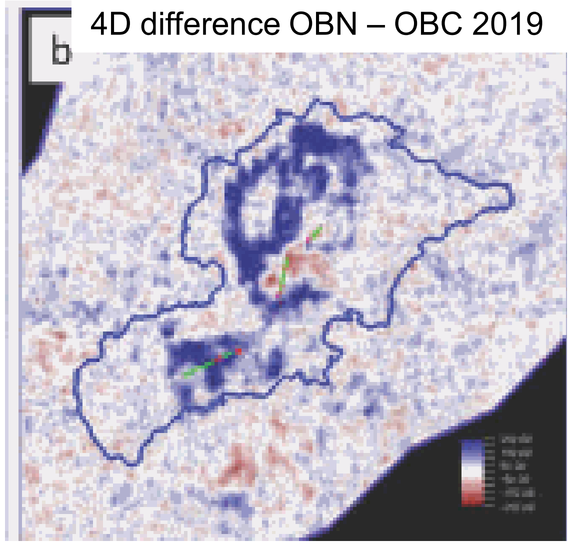
New Streamer acquisition much more repeatable than early 4Ds. OBN & PRM can significantly improve repeatability/suppress the noise level.

11.4a Examples of Seismic Repeatability

Kinnoull OBN 4D against OBC & NATS baseline

The North Sea Kinnoull Field (section 7.16a) has both a pre-production streamer (NATS), OBC and subsequent OBN.

1) The best case OBN to OBC gave an NRMS of 0.18.
2) To understand impact of azimuth, if decimated and processed to “narrow streamer–like” azimuths this had an elevated NRMS of 0.38.
3) If this narrow azimuth OBC was compared to the NATS baseline is was too noisy to interpret with NRMS of 0.58, probably because of the non-repeatable peg-leg multiples.

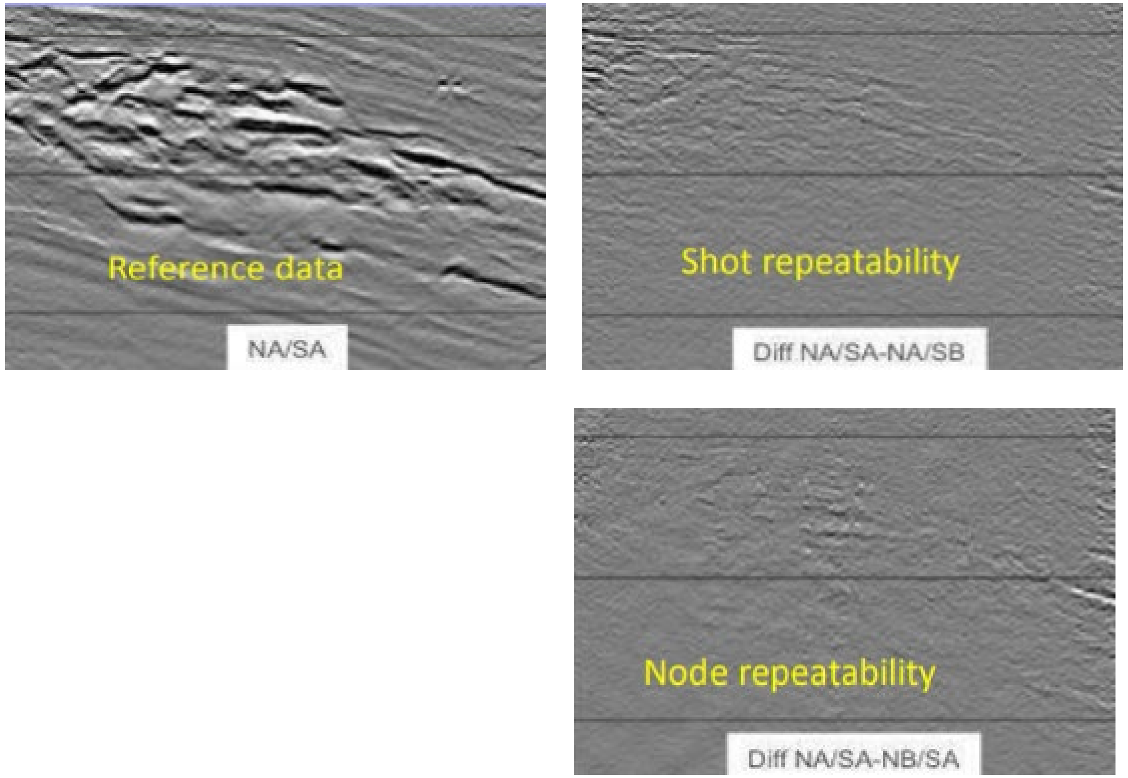


- The production related water sweep shows a hardening of the seismic response up dip from the fields OWC (blue line).
- Switching acquisition between OBC to OBN gives acceptable 4D results.

(Refs. 7bb & 11a)

OBN repeatability

The Dalia project was one of the first node on node 4D surveys and showed a high degree of repeatability, potentially even lower than permanent installations.



(Refs. 11b & 11c)

4D differencing of OBN on NATS not currently possible

11.4b Examples of Seismic Repeatability

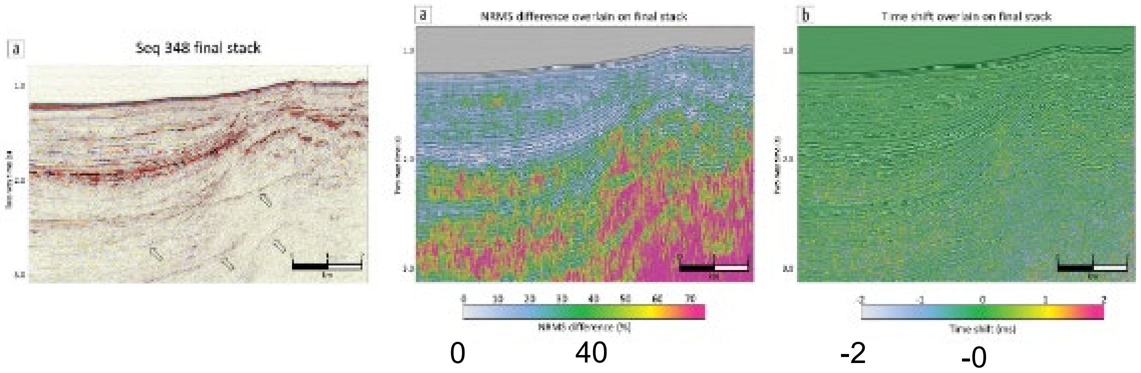
North Sea Transition Authority

P-Cable repeatability test

The short offsets afforded by the P-cables systems (section 5.12) are valuable for imaging shallow section, but with low fold. A repeatability test: a line was re-shot towards the end of a 3D survey. Geometric repetition accuracy was good with source repositioning errors below 10m and bin-based receiver positioning errors below 6.25 m. Seismic data comparisons showed normalized root-mean-square difference values below 10% between 40 and 150 Hz. The technique may be suited for shallow reservoir (<1km below mudline), but is unlikely to be successful where time lapse changes occur on the mid and far offsets.

P- Cable repeatability test

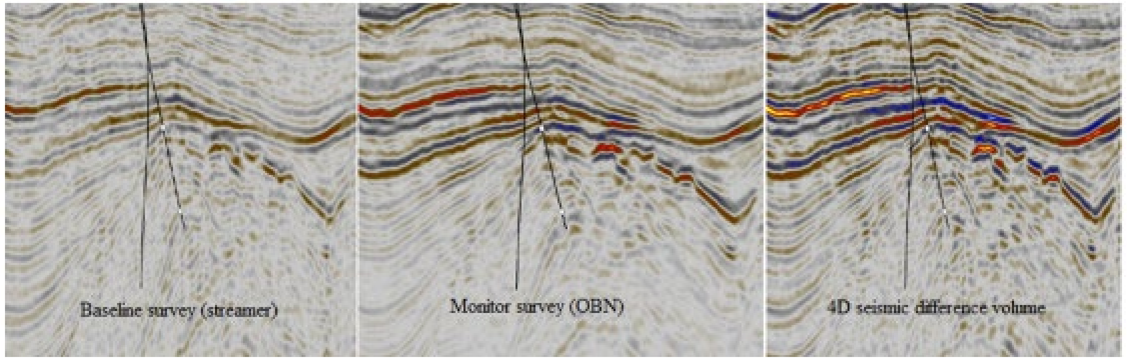
(Ref. 11d



An inline from the final stack with water bottom multiples highlight by arrows (left) and the NRMS differences (middle) and small time shifts (right). The NRMS look acceptable for the shallow section but degrade quickly ~800m below mudline (compare with section 11.3). The time shifts are all small.

OBN imaging and OBN-NATS comparison

Once again, OBN provided improved imaging of Triassic J-Field in the UKCS. However non-parallel processing between baseline streamer and monitor OBN yields 4D difference is very noisy.
Considerable non-production related differences are apparent NRMS 129%.
Unclear how much parallel processing would reduce NRMS.



Commercially and operationally, it would be preferable to be able switch acquisition mode between baseline and monitors (streamer ↔ ocean bottom). In this case, switching from streamer to ocean bottom seismic creates very large discrepancies in seismic ray paths and very high levels of noise.

This is an area of continued research interest in industry and academia and there are some indications of potential breakthroughs.

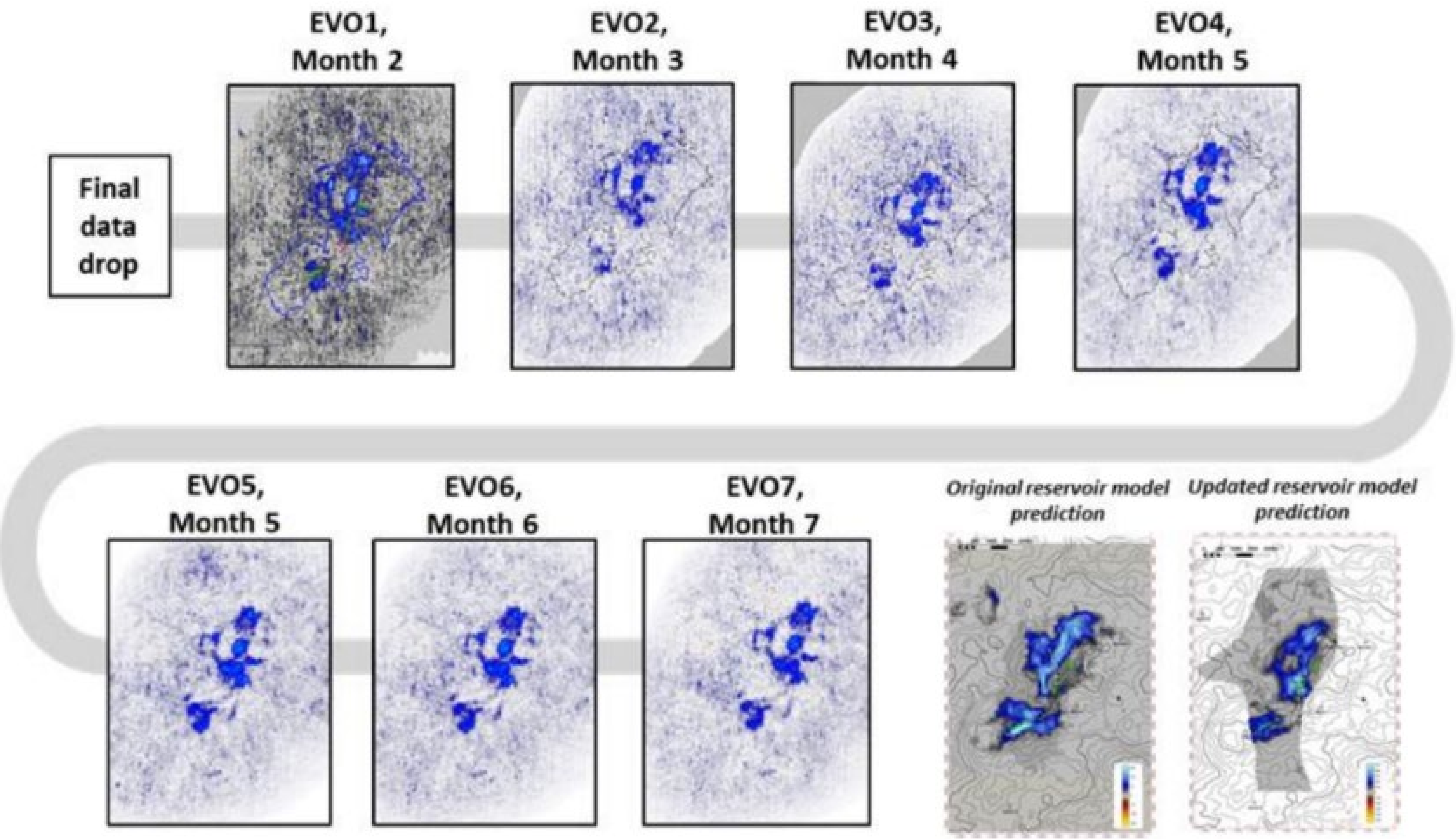
(Ref. 11e

OBN on NATS not currently possible

11.5 Parallel 4D seismic processing

North Sea Transition Authority

Kinnoull 4D difference maps by processing stage



Kinnoull OBC-OBN 4D difference maps
4D signal standout improving by processing step.

(Ref. 11f)

Parallel processing enhances the 4d difference signal from noise

12. CO_2 Detection Project
Rock Physics & Detection Limitations

12 Predicting the 4D CO_2 response

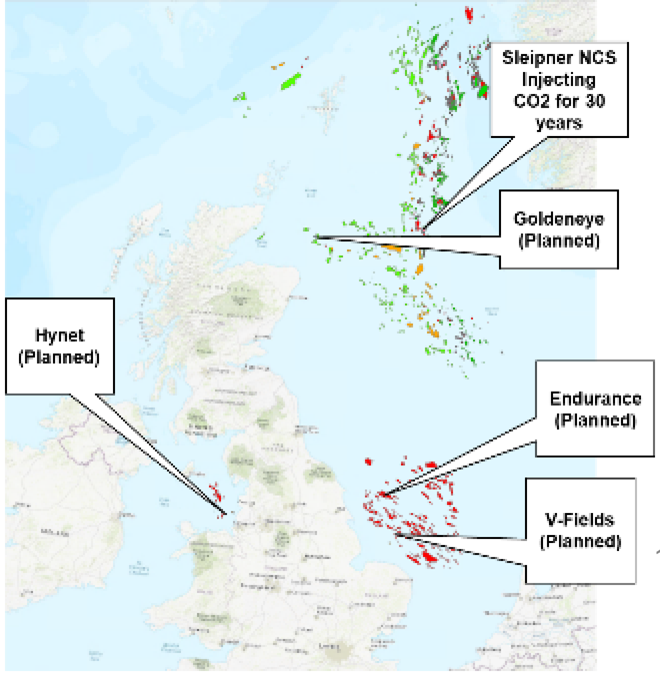
North Sea Transition Authority

Expensive 4D acquisition can only be justified if there is a very good chance that the strength of the time lapse signal will be greater than the seismic noise threshold (Sections 11.1 and 11.2).

Whilst the worldwide experience is very limited, this section considers the predicted time lapse (4D) *amplitude* signal from CO_2 injection.

Rock physics modelling dictates the subsurface setting where CO_2 injection can be monitored by direct seismic imaging. CO_2 injected into the pore-space will displace pre-existing fluids (brine, oil, condensate or gas). The relative acoustic properties of the fluids, the rock matrix and the amount of pore-space will be responsible for creating the seismic response. Rock physics can mathematically be derived for the effects of fluid displacement in the reservoir rock by fluid substitution.

This section mostly taken from a report undertaken by IKON on behalf of the NSTA. This involved refreshing petrophysics and conducting fluid substitution work of existing well log data across a range of targets in the UKCS and the known Sleipner CS site in Norway. ***(Ref. 12a)***

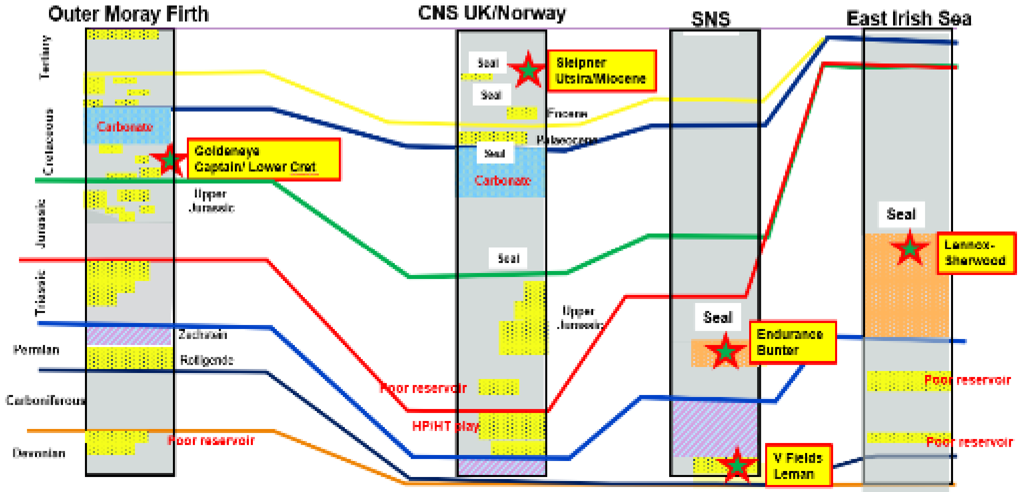


Section 12.1 summarises the range of mostly aquifer targets which could be 4D “friendly”. The work highlights the great difficulty in identifying changes when CO_2 is injected into reservoirs with residual hydrocarbons and the additional role of 4D in monitoring the overburden for CCS.

Section 12.2 demonstrates the range of rock property factors that influence the seismic response & Section 12.3 lists the interpretational 4D issues, especially for a multi-phase reservoir. Sections 12.4 through to 12.8 provides the detailed modelling results for Sleipner, Endurance, Goldeneye, Lennox and the V-Fields. And then section 12.9 compares the rock frame stiffness for these different models.

This study only considered 4D amplitude changes, particularly at the top reservoir. 4D time shifts are usually employed for natural gas reservoir depletion but was not considered as part of this study (section 12.10).

This section concludes by providing other supporting 4D examples (section 12.11).



Study to estimate magnitude of CO_2 response

12.1 4D seismic monitoring summary

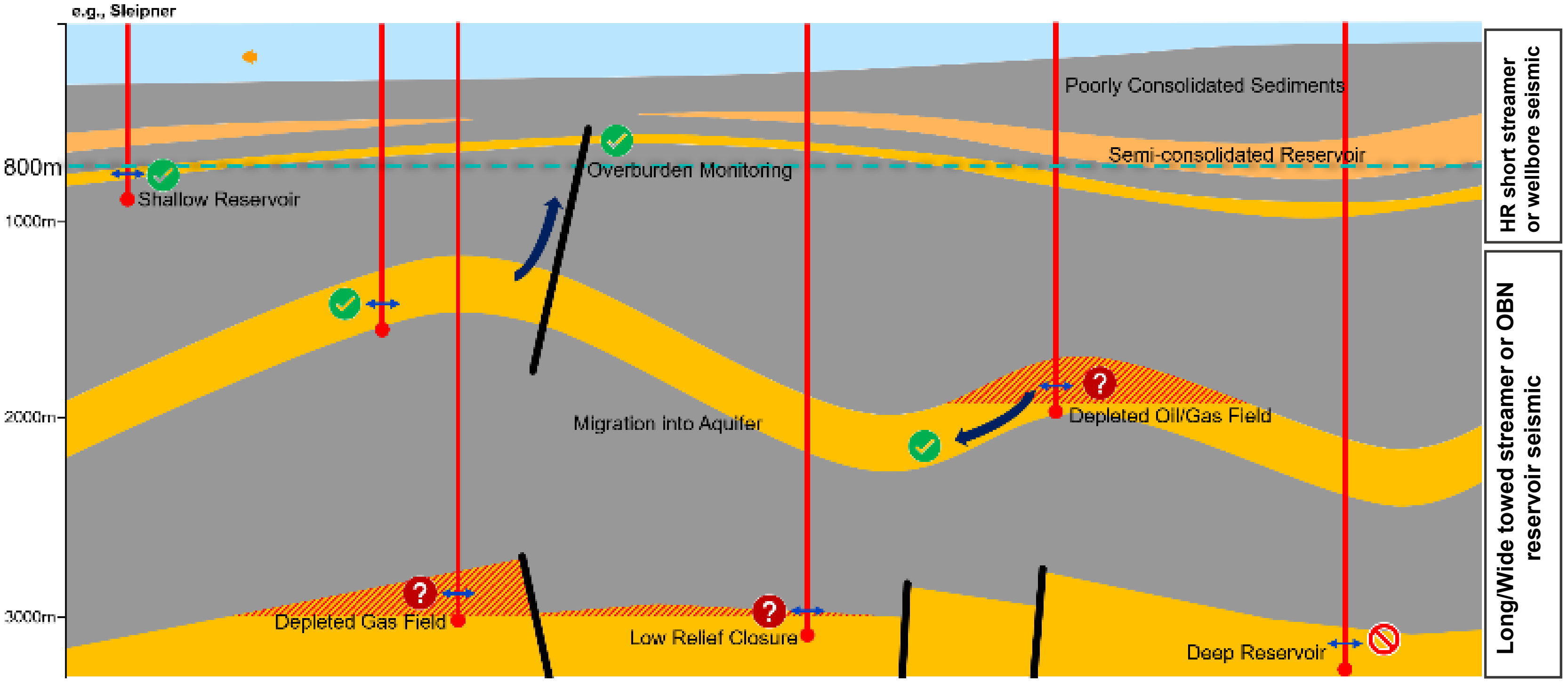
North Sea Transition Authority

Seismic detectability study (section 11 & 12) indicates that a significant 4D seismic signal *should be* anticipated in most situations where the CO_2 is:

- Injected or migrates into an aquifer.
- Leaks/breaches into a shallower overburden aquifer.

The 4D seismic detection threshold is linked to the sand thickness, porosity, reservoir stiffness and level of CO_2 saturation at the time of surveying.

In deeply buried/consolidated reservoirs, a large change in pressure does not produce an appreciable 4D response.



Detection of an amplitude change where CO_2 is injected into a pre-existing depleted natural gas field appears difficult and may require either:

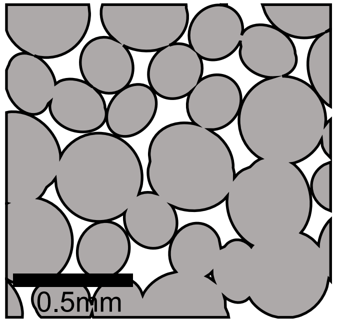
1. Acquisition of higher specification seismic / improved repeatability to reduce the noise floor (e.g. OBN)
   - Albeit the higher cost would be difficult to justify for a smaller signal? ***OR***
2. Await higher CO_2 concentrations / greater separation between surveys
   - Too late to influence further development? ***OR***
3. Assume reservoir seismic monitoring is not part of the complex MMV strategy
   - HR seismic will still be needed for monitoring the overburden.

Multi-fluid phase systems (e.g. brine, natural gas, condensate, oil and CO_2) are likely to provide ambiguous interpretations.

Each CCS site is unique, but Seismic monitoring is likely to be a key tool in most situations

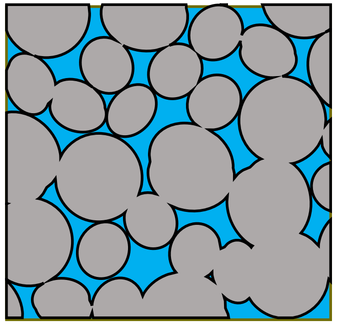
12.2 Rock properties methodology

North Sea Transition Authority



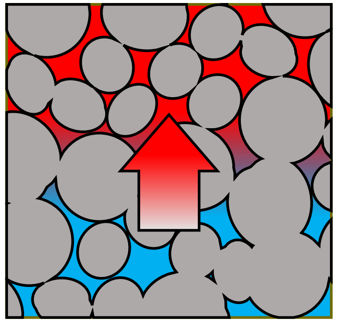
Seismic response fundamentally controlled by the rock physical characteristics:

- Rock Matrix.
- Porosity.



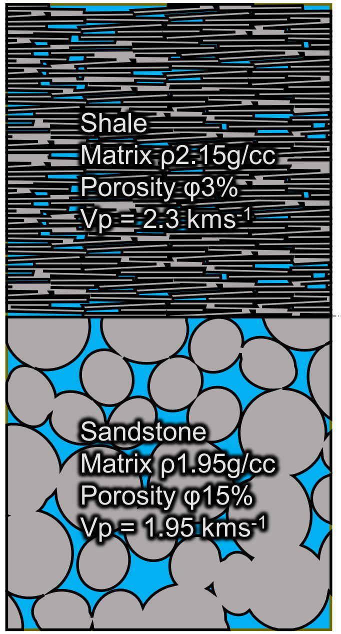
The porosity space will vary with lithology (mineralogical parameters), depth & age of the rock.
The porosity is filled with fluid – water (brine), oil, condensate, gas, or injected fluids such as CO_2.
Each fluid type varies in characteristics:

Water – pressure, temperature, density (salinity).
Hydrocarbons – pressure, temperature, density, GOR/CGR, Sw.
CO_2 – pressure, temperature.



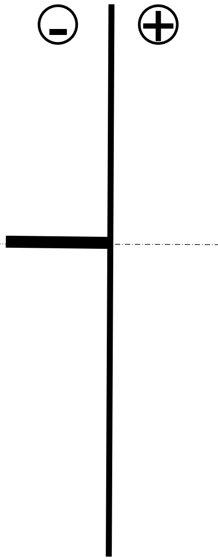
Measuring or deriving these parameters allows conversion between fluid types and modelling of the associated seismic response with Gassmann Fluid Substitution equations:

- Displacement of Oil with Gas or Brine.
- Displacement of Brine or Depleted Oil/Gas with CO_2.



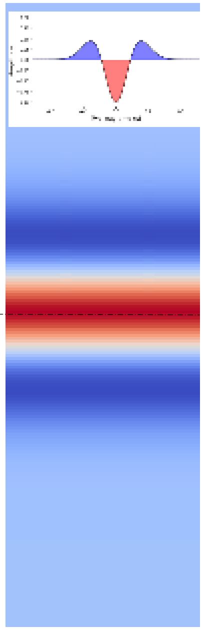
Reflection Coefficient

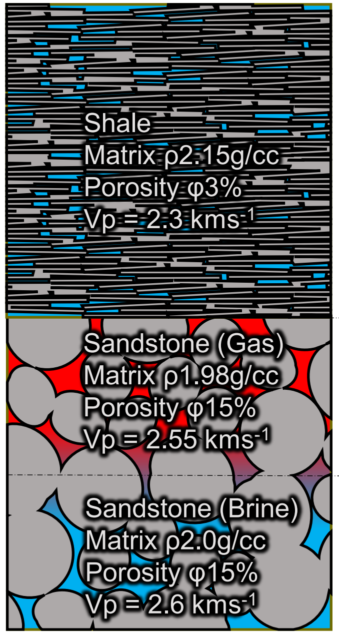
$$= \frac{\rho Vp_2 - \rho Vp_1}{\rho Vp_2 + \rho Vp_1}$$

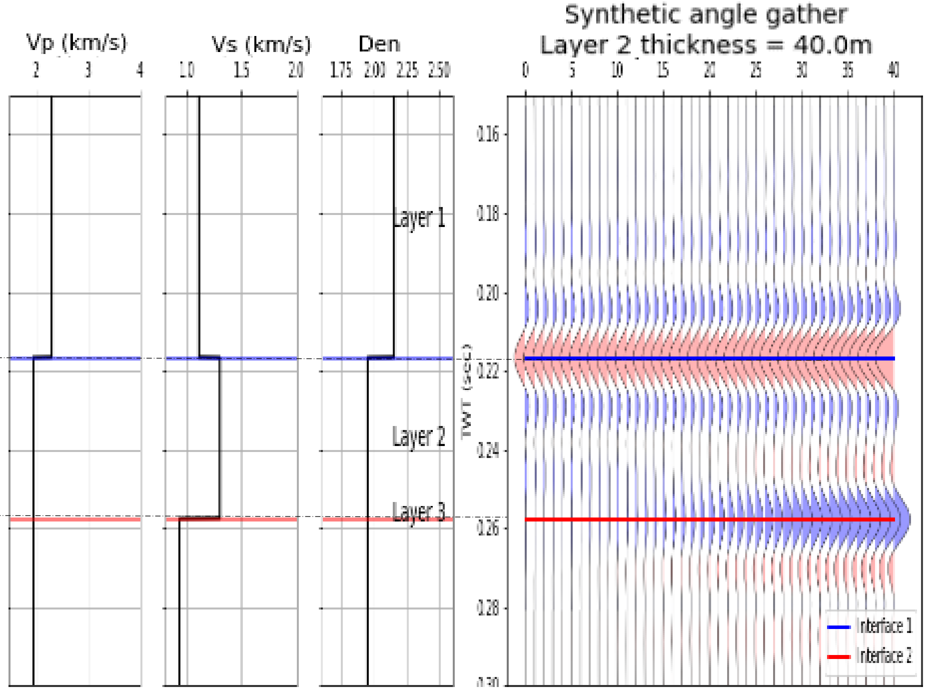


Convolve the RC

RC*wavelet → Seismic Data







Factors influencing seismic response: Frequency bandwidth (wavelet pulse shape) controls the vertical resolution of detection.

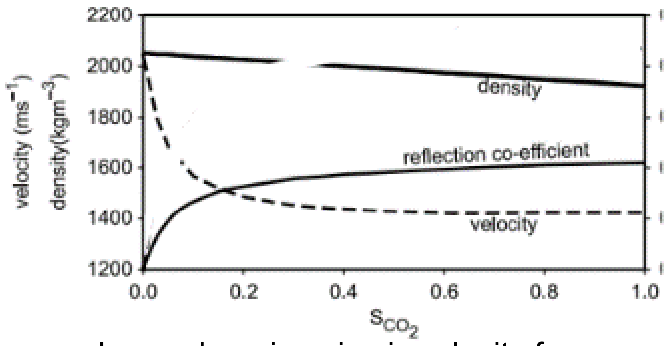
North Sea Transition Authority

Direct Carbon CO_2 detection shares most of the same physical parameters as hydrocarbon detection with a few differences:

Primary controls		Larger signal when….
Net sand within seismic envelope (~ top 30m)	⇨	More reservoir rock
Porosity of reservoir	⇨	More pore space for interstitial fluids
Rock fabric strength	⇨	More unconsolidated / less cemented/ ~ younger rock
Difference in mixed fluid density (RhoB)	⇨	Large contrast between CO_2 saturated and **in-situ** fluid
Difference in mixed fluid sound velocity (Vp)	⇨	Large contrast between CO_2 saturated and **in-situ** fluid
Secondary Controls		
Pressure change	⇨	Large pressure increase from injection
Temperature change		

Observed seismic changes are: 'hardening' (increase in impedance) or 'softening' (decrease in impedance)

Velocity & density of Water-CO2 system



Large drop in seismic velocity for Small initial changes in CO_2 saturation

Compare and Contrast 4D for hydrocarbon vs for CCS

Low quality reservoirs (low porosity and/or low net to gross)- Weak/ invisible 4D

Hydrocarbon 4D experience

Up to 3 initial fluid phases: Brine , Oil & Hydrocarbon gas

- Natural gas breaking out (exsolving) from oil → Softening
- Water injection into oil leg → Hardening
- Aquifer brine sweeping oil reservoir → Hardening
    - But pressure increase causes overlapping softening
- Gas reservoirs little depletion observable on 4D,
    - Rare very large pressure drops in very good reservoir

Expected CS 4D experience

CO_2 injection into:

- Brine reservoir: 2 phases → Softening
- Depleted gas field: < 3phases (Natural Gas, CO2 and ?brine?) → difficult to separate
- Swept oil field < 4 phase (as above + residual oil) → Very difficult to distinguish

Hydrocarbon or CO_2 displaced into water leg → likely softening

The ability for seismic monitoring to manage to detect multiple fluid phases is a great concern.

Effects can cancel each other out and have ambiguous interpretations:

- Pressure increases from CO_2 injection (softening) cancels out prior natural gas depletion (hardening).
- Softening from pressure can be mistaken for a softening due to gas exsolving from solution.
- Separation of 2 soft responses from different influences overlapping (hard/soft) response is at best semi-quantitative.

Secondary long duration effects of CO_2 dissolving the rock fabric are not part of this study.

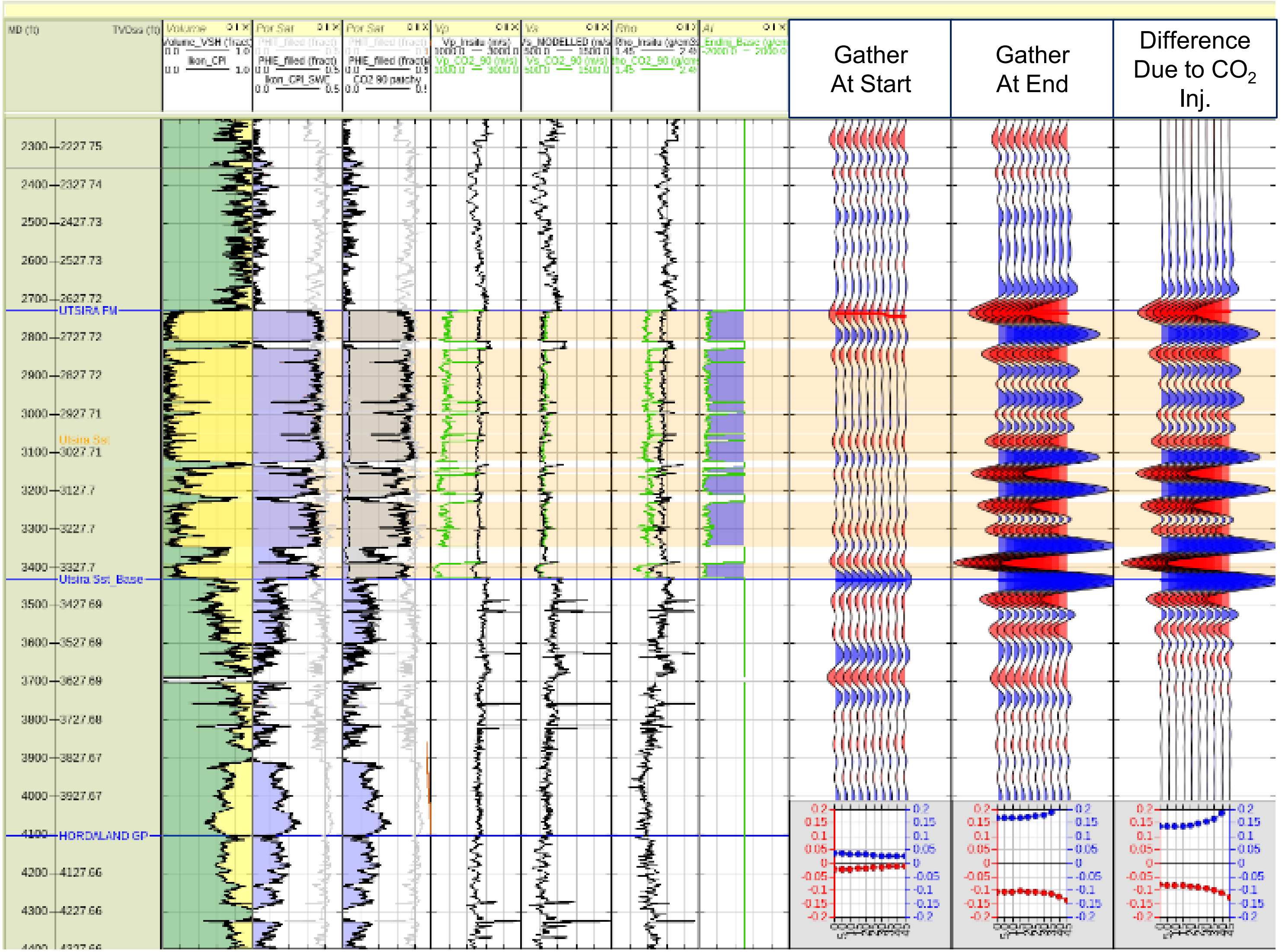
(Ref. 12b)

A 4D signal can be weak and subject to uncertainty in interpretation. CO_2 injection into a reasonable aquifer reservoir seems most assured.

12.4. Sleipner, NCS

Large predicted and observed 4D response

12.4a Sleipner Rock Physics



Licence: P046 Sleipner
Location: CNS, Norway
Operator: Equinor
Reservoir Age: Miocene
Lithology: sandstone, unconsolidated, thick, high NTG, high porosity
Depth: 820m MD
CS Type: Aquifer
Well: N15/9-17

Results: Injection into aquifer- large 4D response expected (& observed, 1 Mtpa since 1996)

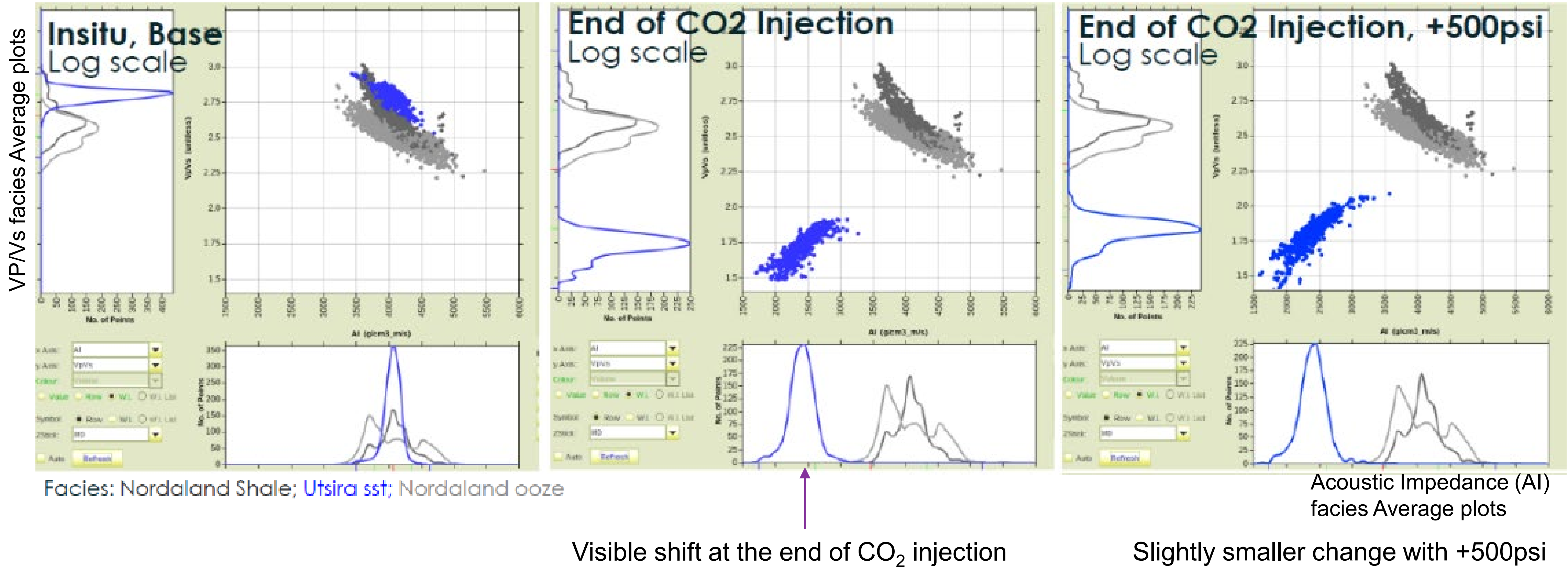
- Reservoir is a poorly consolidated sandstone and large pore spaces.
- 90% CO_2 saturation at the end of injection.
- Clear and definitive seismic response calculated for a CO_2 charge of the reservoir, displacing brine.

Good seismic response to CO_2 injection

Sleipner well log

12.4b Sleipner Summary

AI vs Vp/Vs plots for brine sand and surrounding rock

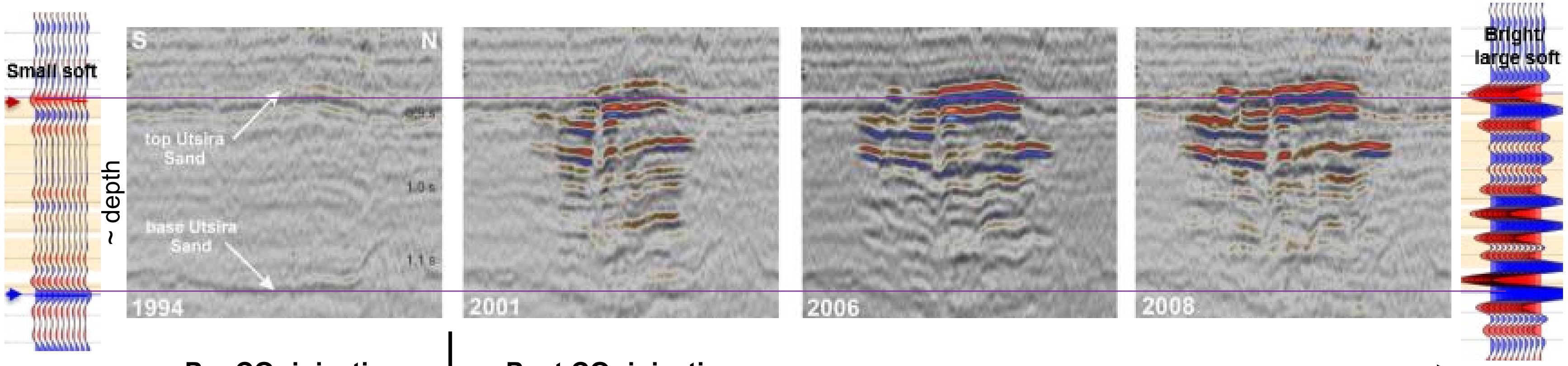


Sleipner predicted to have large change in both AI and Vp/Vs. Pressure has only small impact

12.4c Sleipner Plume Evolution

Sleipner is a well-studied real situation of CO_2 injection on the Norwegian Continental Shelf. The site has been injecting CO_2 for ~30years and has a known significant seismic response.

Real seismic shows weak Top & base seismic response prior to CO2



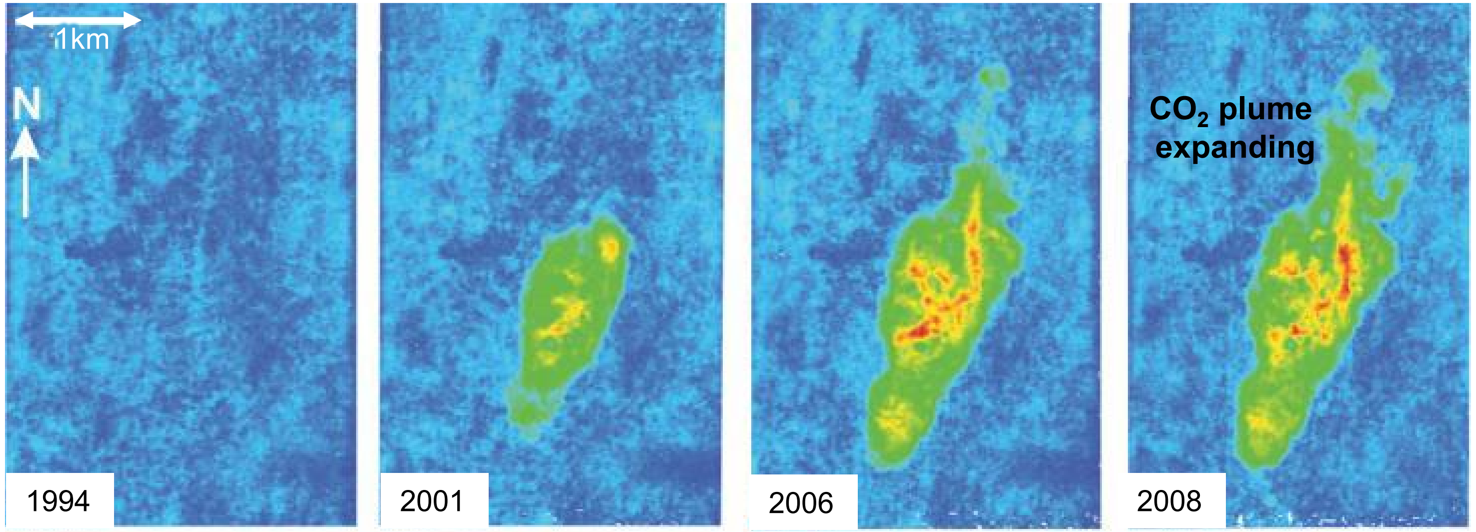
Shallow bright spots ~ Match real seismic

Deeper bright spots Not present implies CO_2 not reaching Base of reservoir

Pre CO_2 injection | **Post CO_2 injection** →

Seismic Maps

Mapping upper event shows CO_2 migrating in clear NNE direction through time

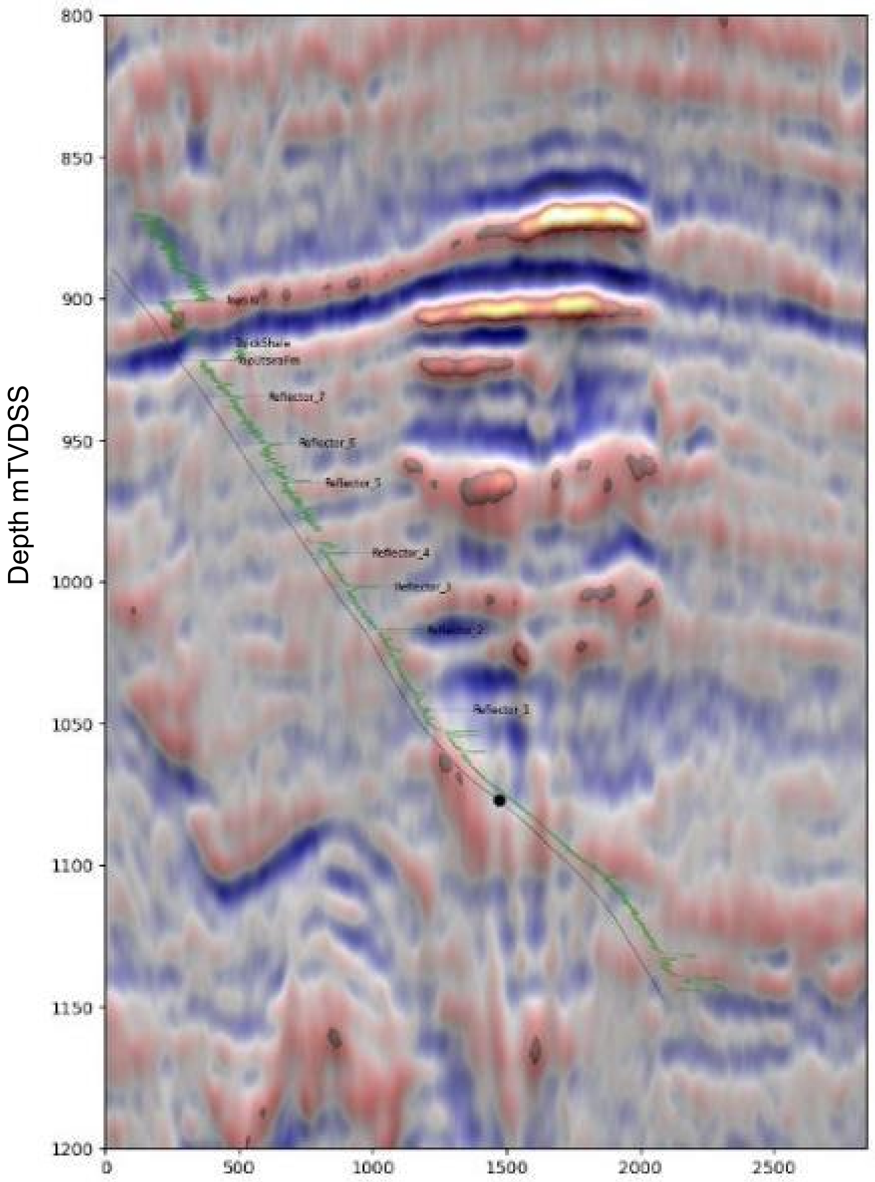


(Ref. 12c)

Proven CO_2 site: Linking prediction modelling to real CO2 sequestration

12.4d Sleipner 4D further seismic analysis

The Sleipner seismic and well data have been publicly released for the benefit of further CO_2 researchers have adopted a "stratigraphic" style of display which enhances the plume within a stratigraphic context. In this case several flat spots can be detected, and a vertical "pipe" observed.



(Ref. 12d)

Recent re-interpretation of Sleipner

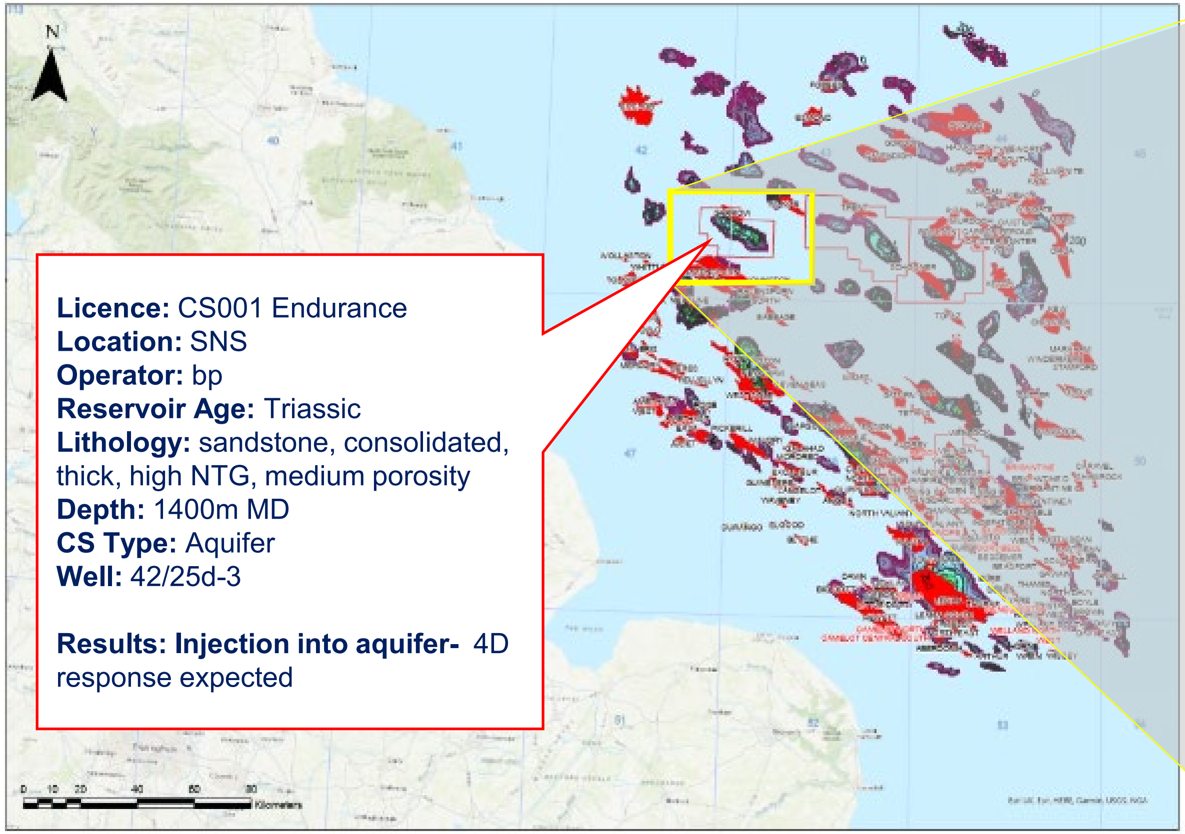
12.5. Endurance, SNS

Medium 4D Response

12.5a Endurance Overview

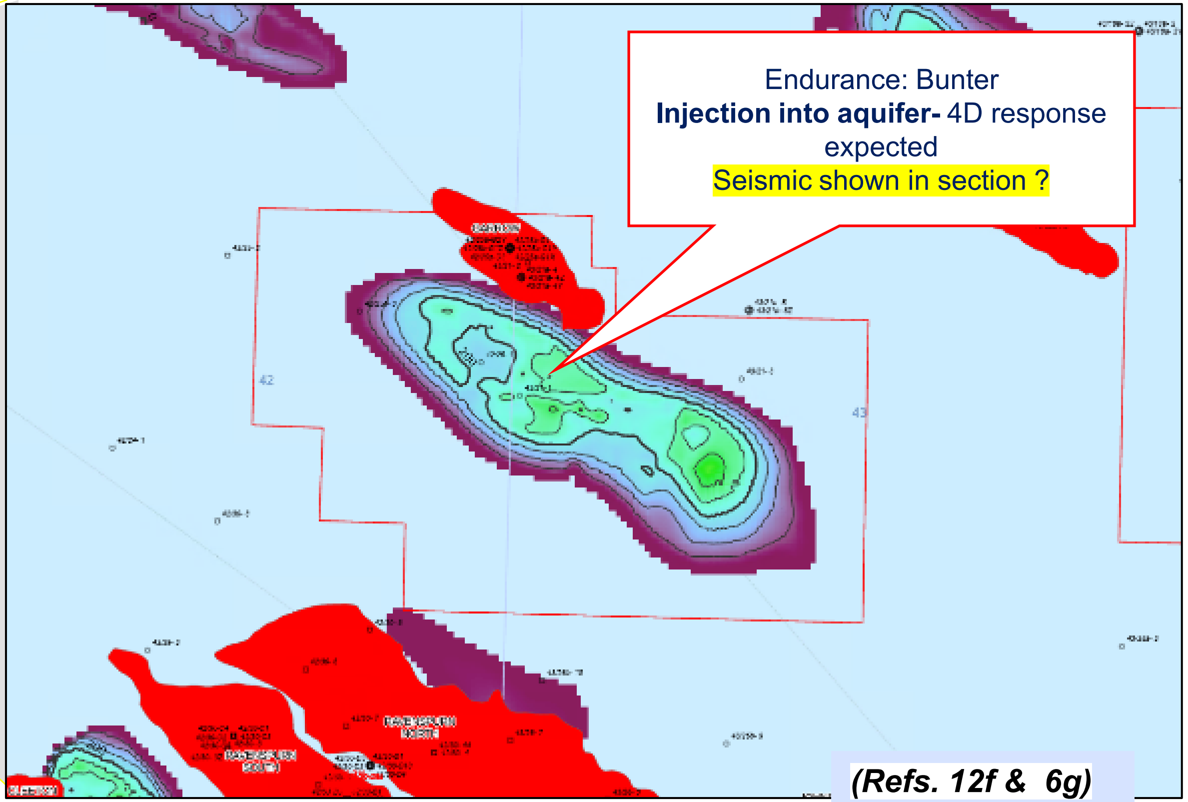
North Sea Transition Authority

Endurance is a 4-way dip closure (periclinal anticline) in the Triassic Bunter Sandstone. Rock physics indicates that a 4D seismic response will be present at the end of store life, and testing of low CO_2 saturation suggests that 20% gas saturation may be detectable, which will help define the frequency of surveying of the store.
The existing seismic was of insufficient quality to resolve fine scale layering and a new 3D HR survey was acquired in 2022 (section 3.5).



Licence: CS001 Endurance
Location: SNS
Operator: bp
Reservoir Age: Triassic
Lithology: sandstone, consolidated, thick, high NTG, medium porosity
Depth: 1400m MD
CS Type: Aquifer
Well: 42/25d-3

Results: Injection into aquifer- 4D response expected

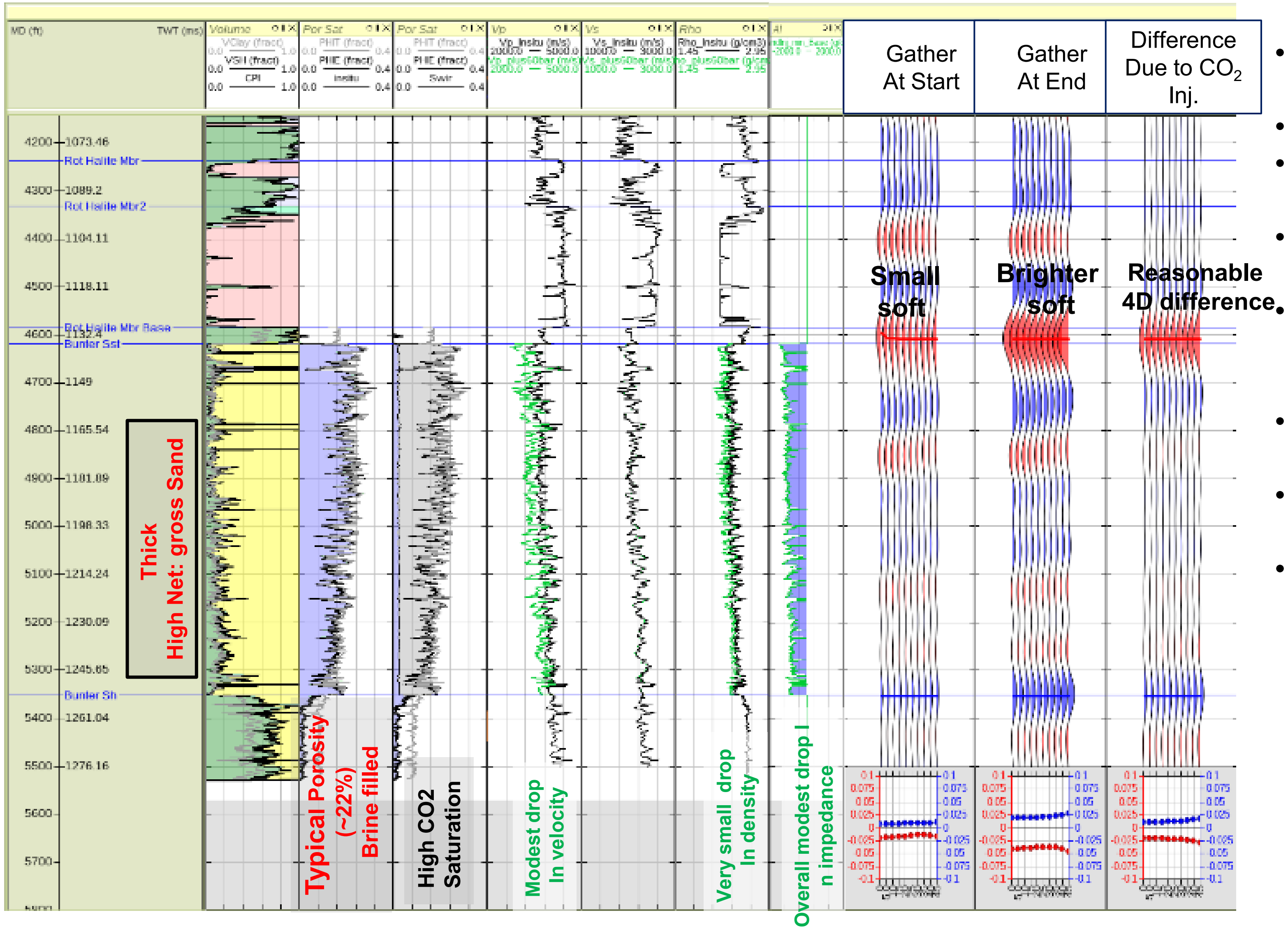


Endurance: Bunter
Injection into aquifer- 4D response expected
Seismic shown in section ?

(Refs. 12f & 6g)

12.5b Endurance Rock Physics

North Sea Transition Authority



- The Triassic Bunter Sandstone is a thick, high Net:Gross consolidated reservoir.
- Higher porosity towards top of reservoir.
- Modest velocity reduction contrast between CO2 fluid injected to insitu brine formation.
- Reasonable saturation change enhancing softening.
- Some pressure increase of 870psi at end of injection, but not significantly influencing amplitude response.
- 5 years after injection there is a negligible effect from pressure changes (30psi increase).
- Smaller effect is interpreted to be the result of heterogenous fluid mixing model.
- Expected to be detectable with conventional seismic.

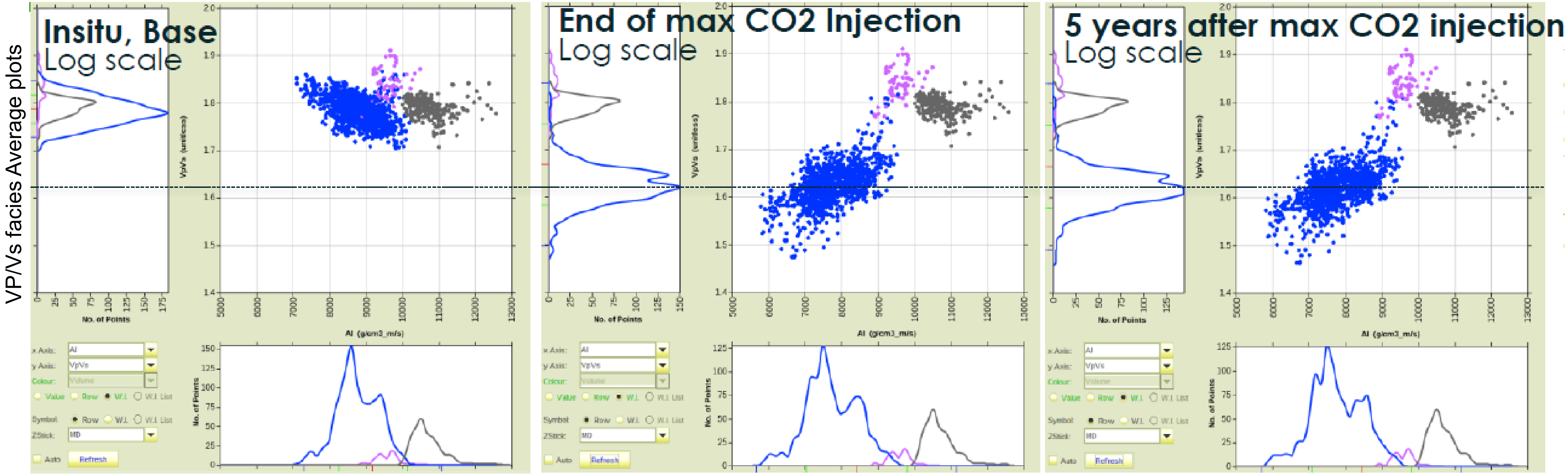
Reasonable seismic response to CO_2 injection at end of store life

Endurance rock physics log

12.5c Endurance Summary

North Sea Transition Authority

AI vs Vp/Vs plots for brine sand and surrounding rock



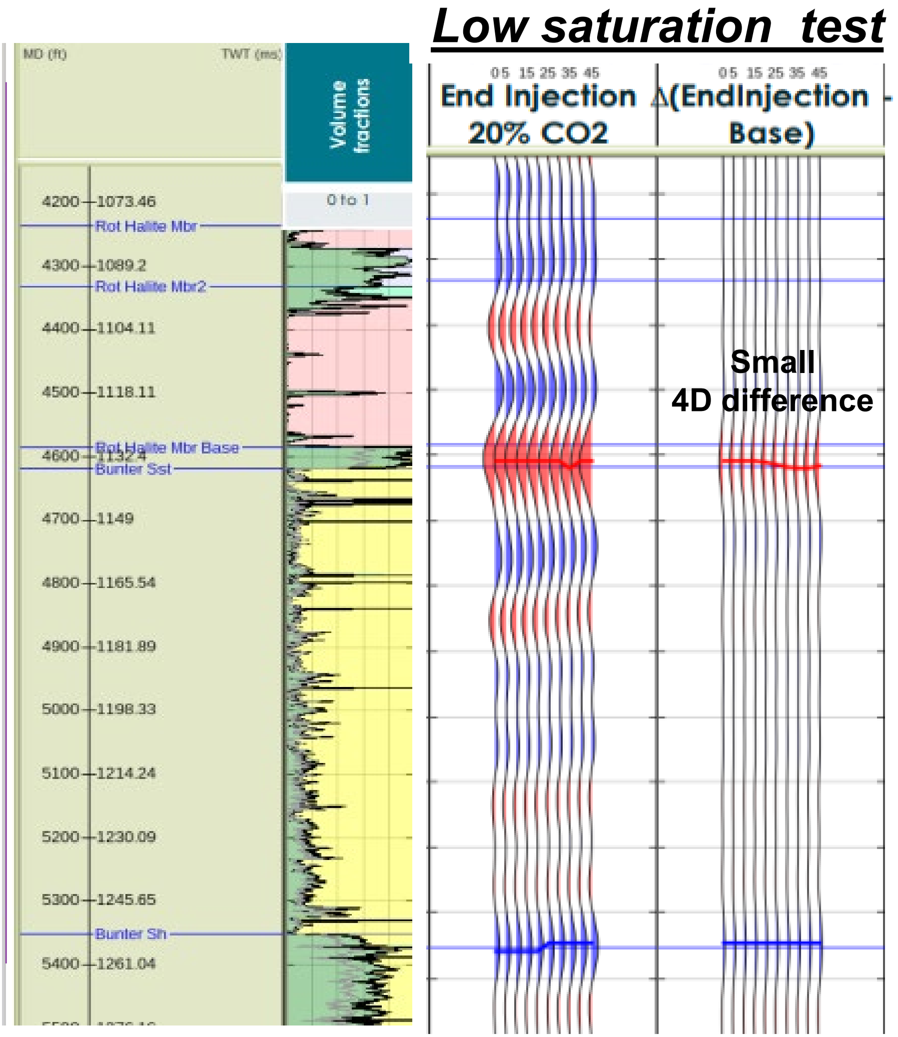
Facies: Overlying Rot Shale; Bunter sst; Underlying Bunter shale

Acoustic Impedance (AI) facies Average plots

- Visible shift in both AI & Vp/Vs domain at the end of CO2 injection (light fluid added).
- Negligible changes at 5 years after injection (due to pressure changes).

Good anticipated 4D response from CO2 injected into brine aquifer

12.5d Endurance Low Saturation test



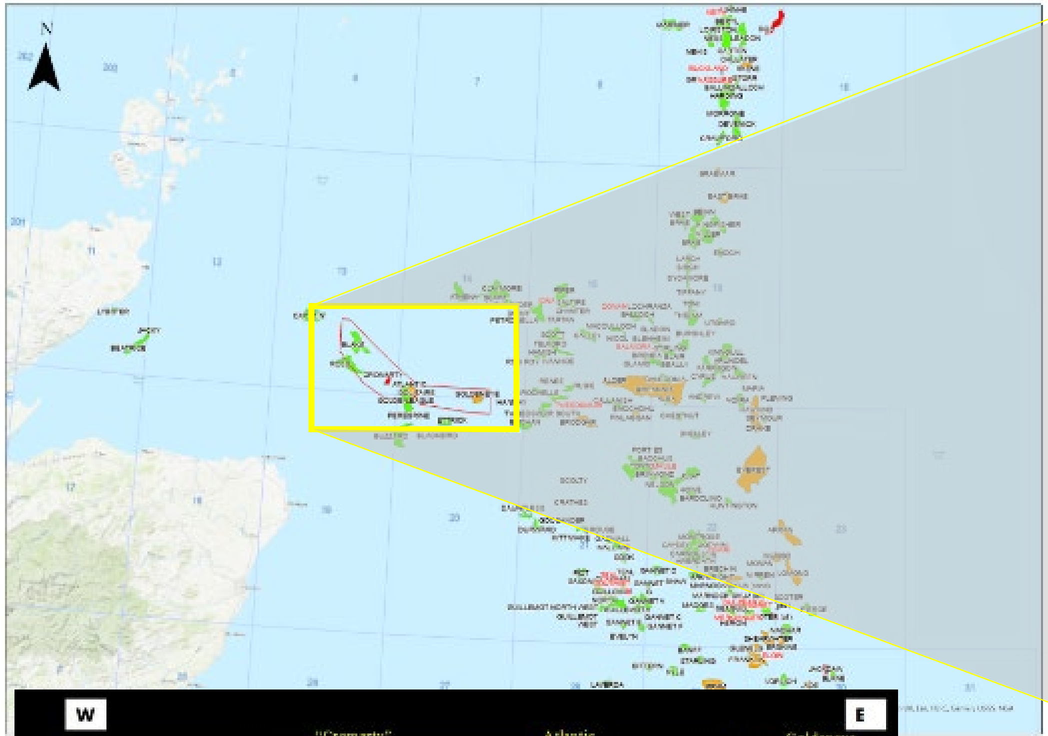
Partial (20%) CO_2 Saturation at limits of detection
Smaller effect because of heterogenous fluid mixing model

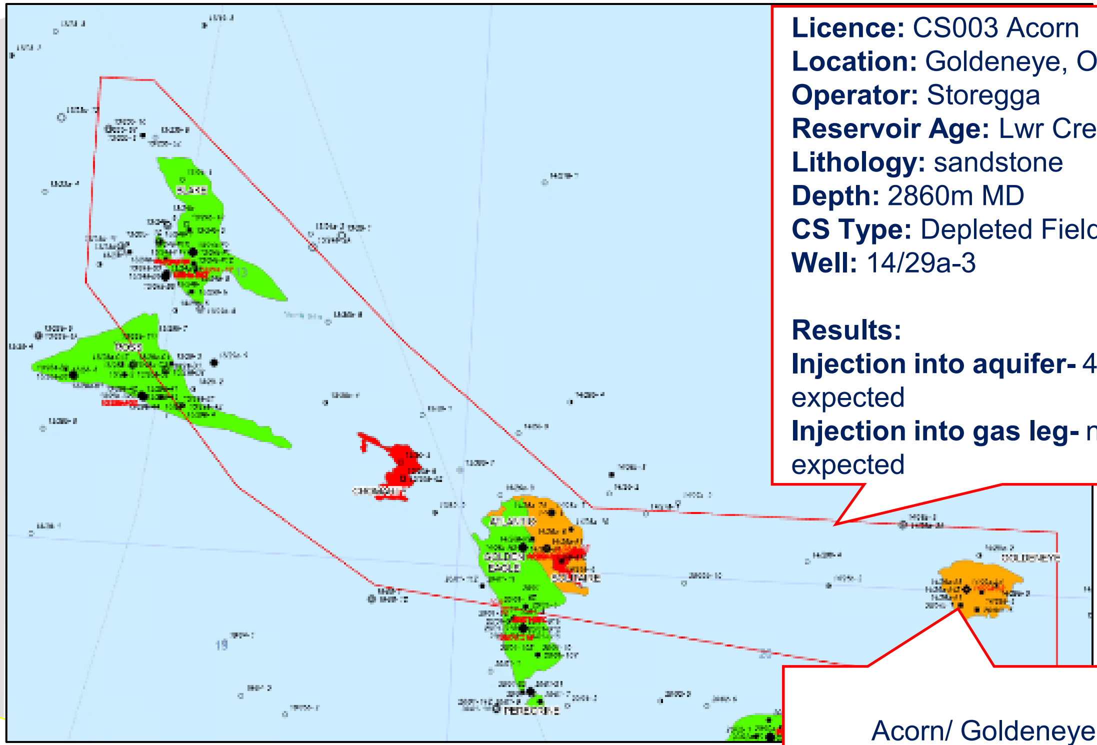
12.6. Goldeneye, Inner Moray Firth

Acorn project: Response only in aquifer

12.6a Goldeneye Overview

North Sea Transition Authority

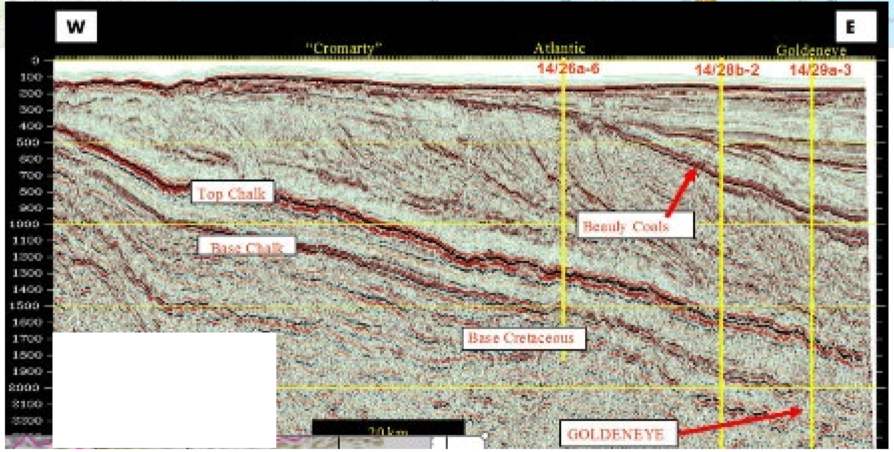


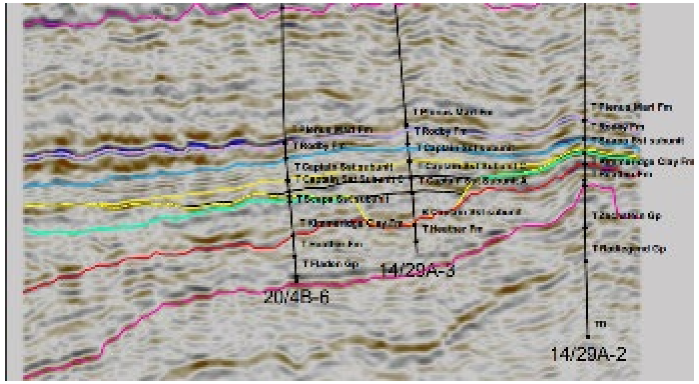


Licence: CS003 Acorn
Location: Goldeneye, Outer Moray Firth
Operator: Storegga
Reservoir Age: Lwr Cretaceous
Lithology: sandstone
Depth: 2860m MD
CS Type: Depleted Field
Well: 14/29a-3

Results:
Injection into aquifer- 4D response expected
Injection into gas leg- no 4D response expected

Acorn/ Goldeneye Captain
Injection into gas leg
Injection/ Migration into aquifer





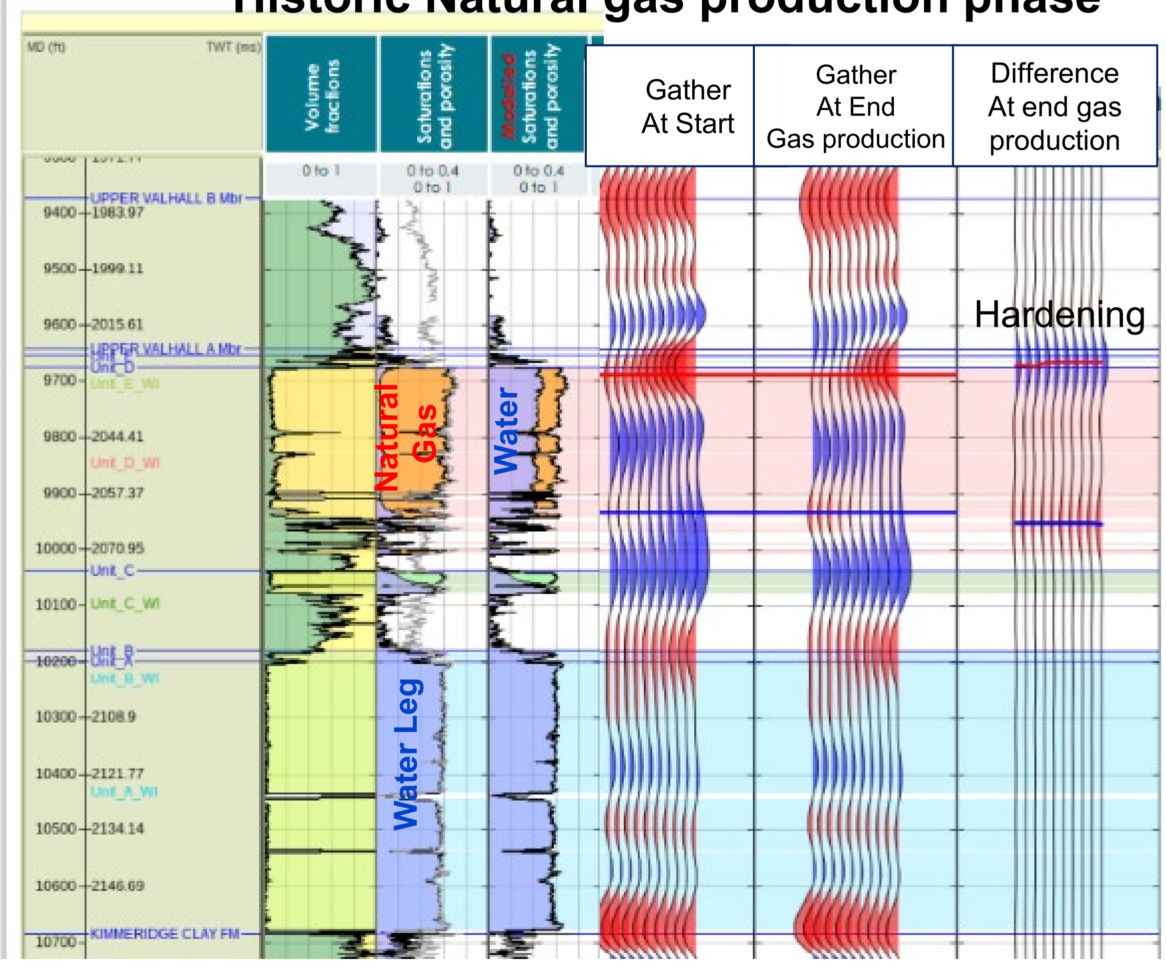
- Goldeneye is a depleted field in the IMF being renamed "Acorn".
- Reservoir is a relatively competent and well-connected Cretaceous sandstone.

(Ref. 12f)

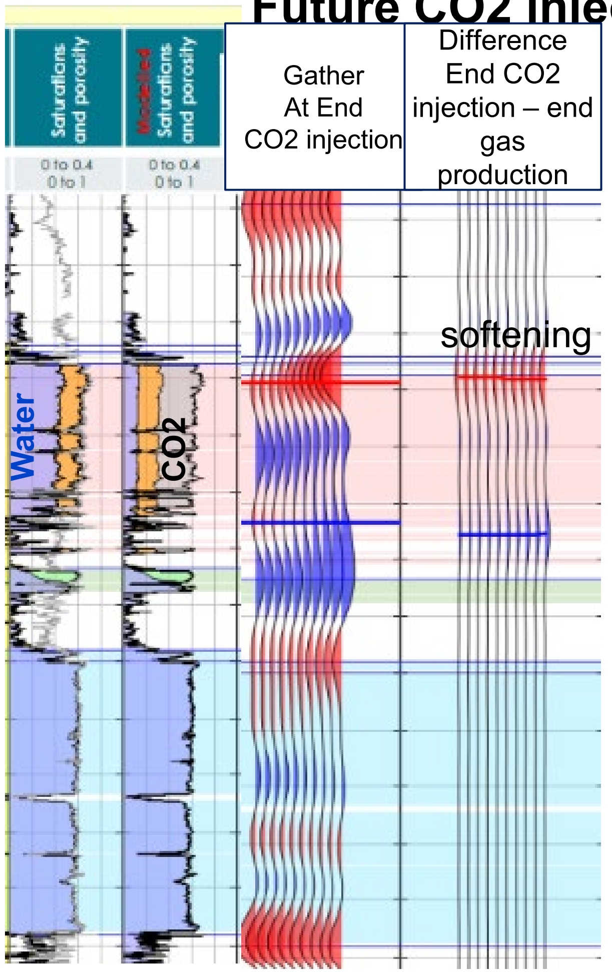
12.6b Goldeneye Rock Physics

North Sea Transition Authority

Historic Natural gas production phase



Future CO2 injection phase



Difficult to detect seismic response to CO_2 injection at end of store life

As a depleted field Gassmann fluid substitution is required to remove residual HC's prior to calculations for effects of CO_2 injection. Post historic gas production the seismic response is expected to have hardened (depletion and some water influx).

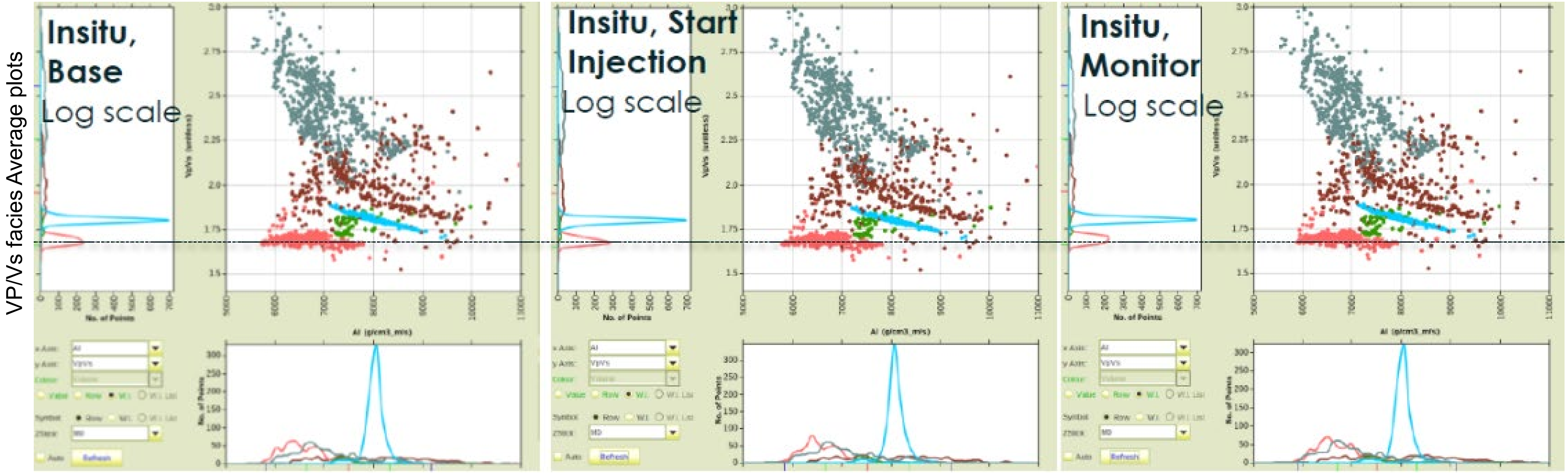
At the end of injection, the reservoir composition will be 50% CO_2, 30% Natural gas, 20% Brine.
Injection drives a pressure response but results in negligible difference in gather 4D residuals.

CO2 into depleted gas undetectable response

12.6c Goldeneye Summary

- No significant difference due to changes in pressure at the start or end of CO_2 injection into original gas and oil leg.

AI vs Vp/Vs plots for brine sand and surrounding rock

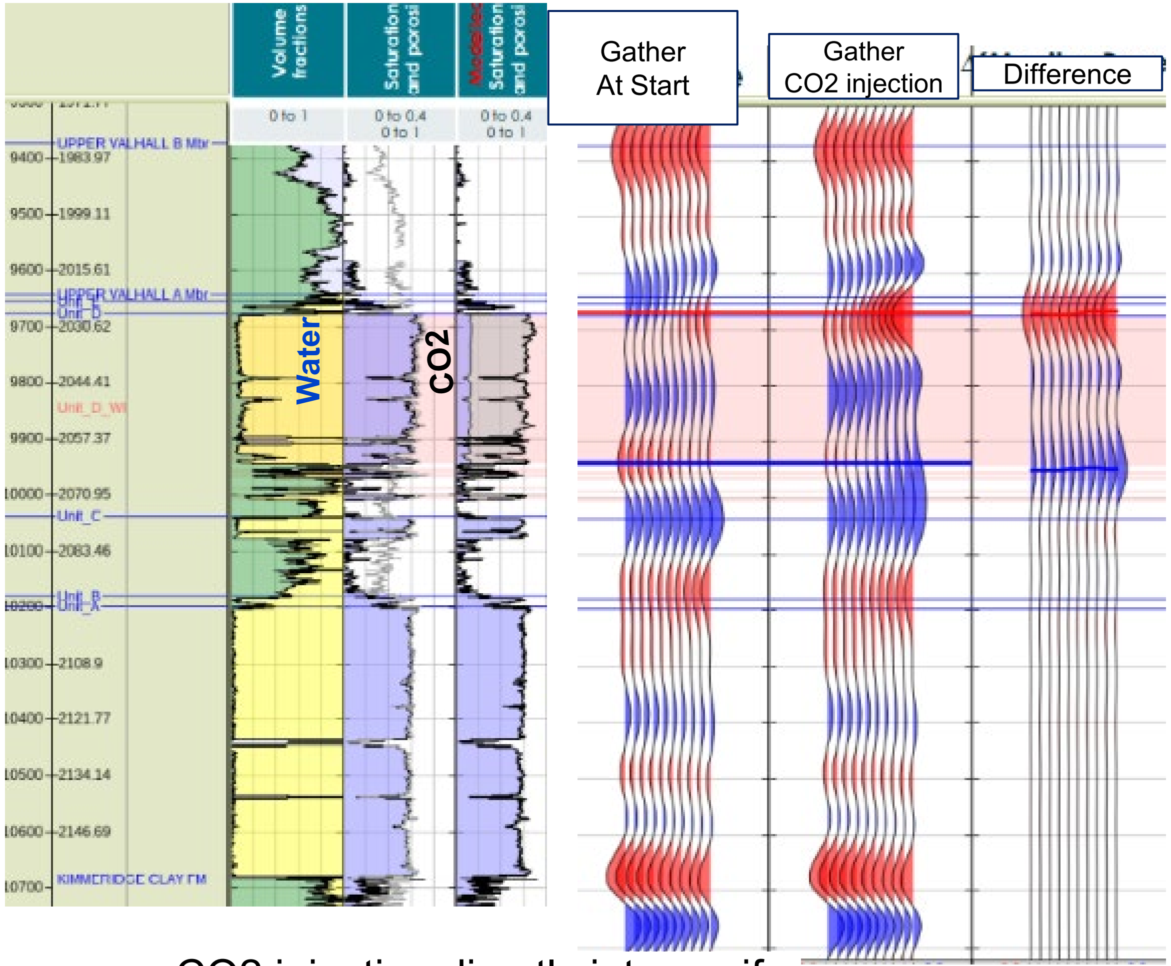


Facies: Unit D sand (GC-> CO2); Unit C sand (oil); Unit A-B sand (brine); Captain Shale; Valhall Shale/marl

Acoustic Impedance (AI) facies Average plots

12.6d Goldeneye CO_2 migrates into aquifer

North Sea Transition Authority



Significant Softening

If CO2 migrates into aquifer, then a significant response is expected.
This is important, as it shows the potential value of 4D even within a depleted oil/gas field.

CO2 injection directly into aquifer

- Noticeable reduction in impedance
- Amplitude softens

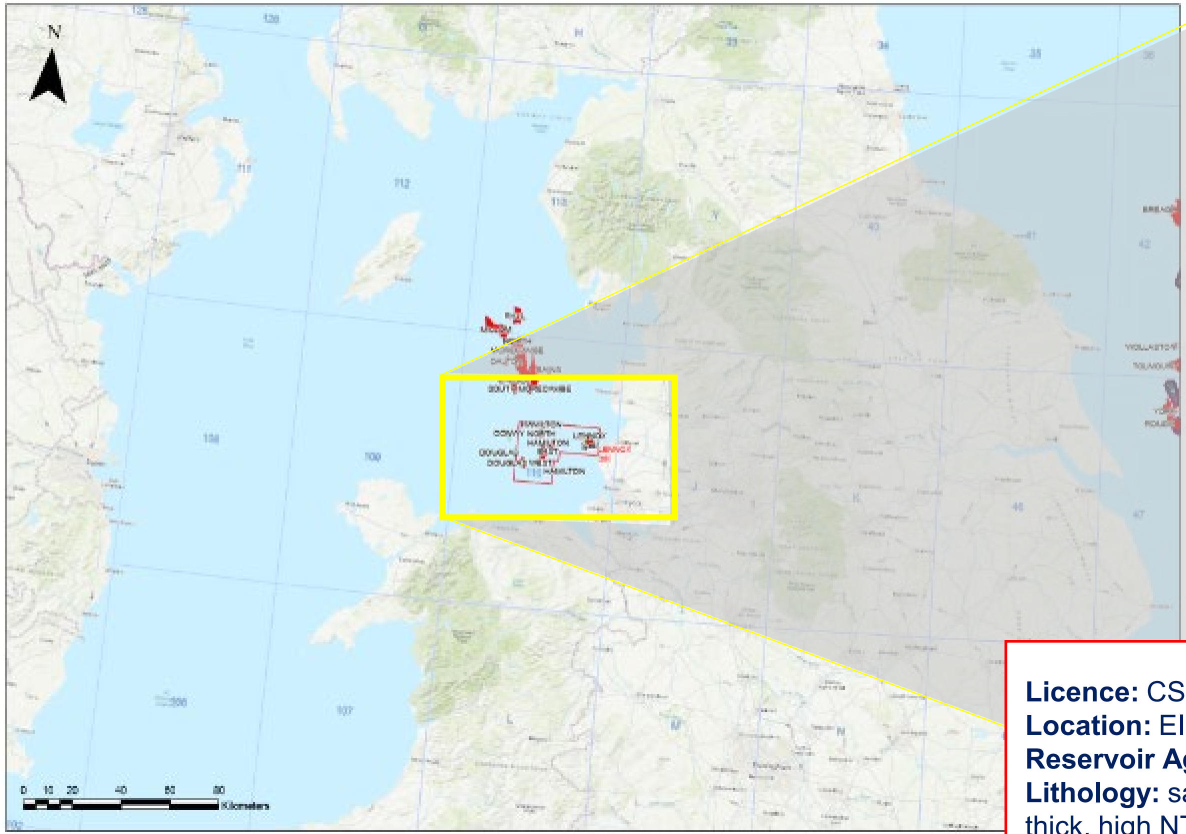
CO2 migration into good aquifer would be detectable

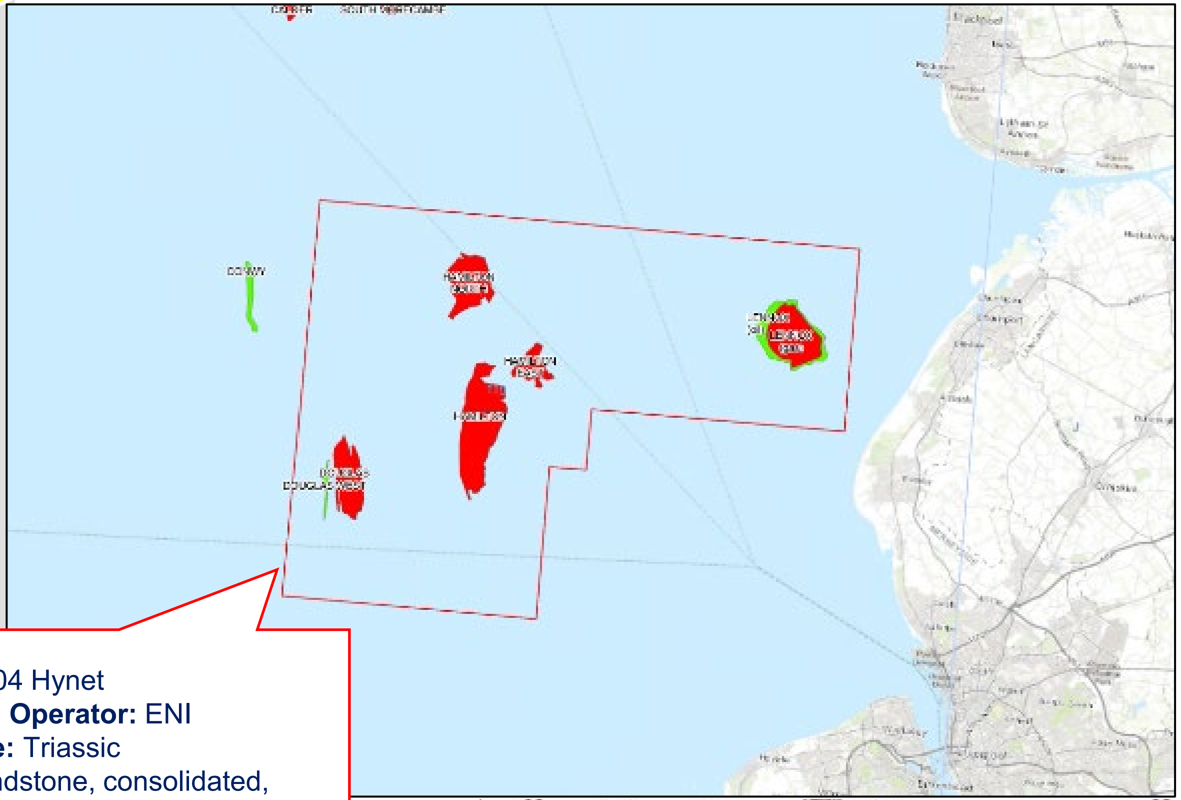
12.7. Lennox, East Irish Sea Basin

HYNET project area

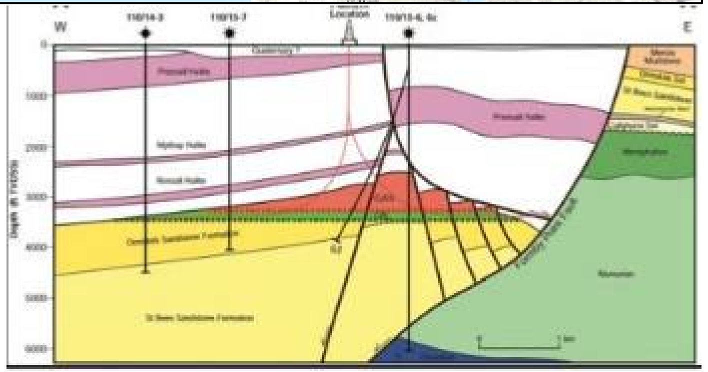
12.7a Lennox/ Hynet Overview

North Sea Transition Authority





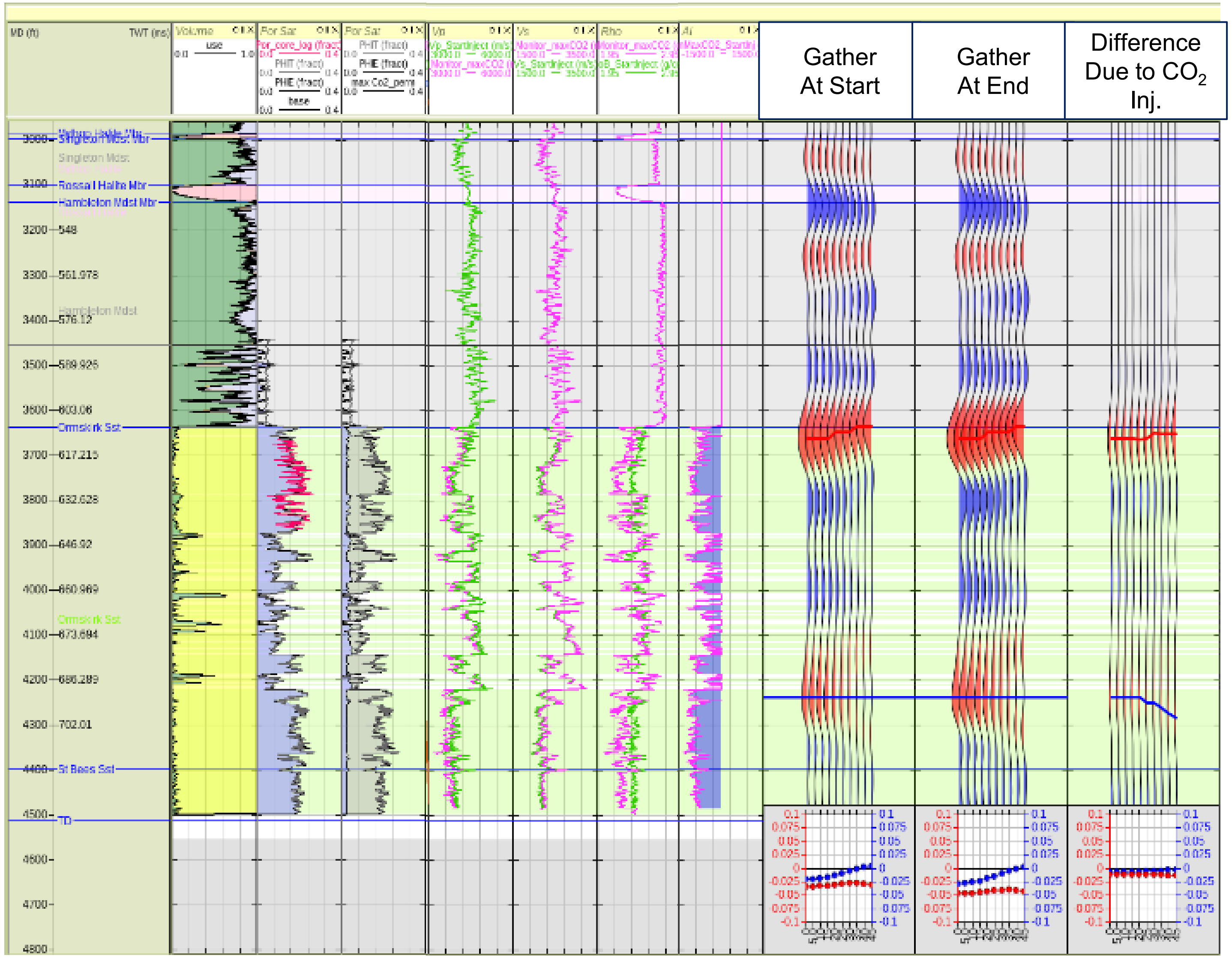
Licence: CS004 Hynet
Location: EIS, **Operator:** ENI
Reservoir Age: Triassic
Lithology: sandstone, consolidated, thick, high NTG, mid-low porosity, very low initial reservoir pressure
Depth: 1110m MD
CS Type: Depleted field **Well:** 110/14-4



(Ref. 12g)

12.7b Lennox Rock Physics

North Sea Transition Authority



- Lennox is a gas field in the Triassic Sherwood Sandstones of the EISB.
- The original gas field underwent a large production related depletion (1436 psi) and associated gas saturation drop of 70%. This was modelled to create hardening at top reservoir.
- Field will be recharged with CO2 as part of the HyNet project.
- Pressure effect on elastic response is negligible
- 1.5 years after injection +479psi increase from start of injection (using Lennox pressures).
- Fluid effect softens the AVO at the top of the reservoir.
- This softening is much less than the original hardening.

Reasonable to poor seismic response to CO_2 injection at end of store life

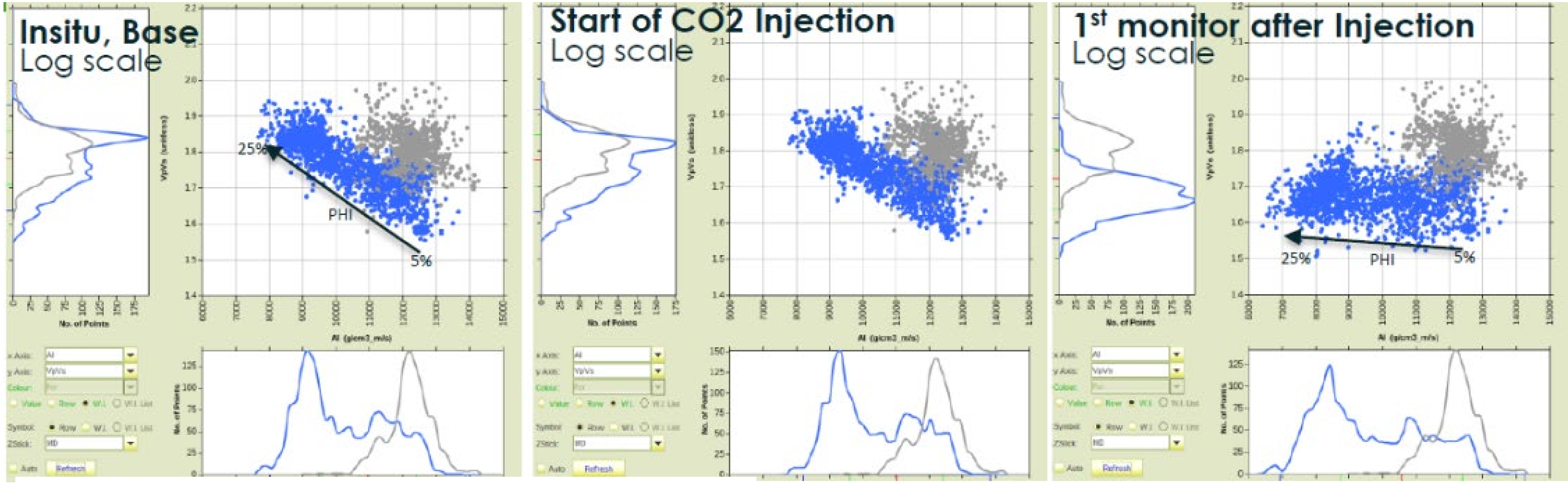
Lennox fluid substitution log

12.7c Lennox Summary

North Sea Transition Authority

AI vs Vp/Vs plots for brine sand and surrounding rock

VP/Vs facies Average plots



Facies: Overlying Hambleton Mudstone; Ormskirk sst;

Acoustic Impedance (AI) facies Average plots

- Negligible changes between in-situ and start of CO_2 injection.
- Visible shift at the end of injection due to high amount of light fluid in formation, especially in Vp/Vs ratio. This is the result of light fluid added to the Ormskirk and drop in vertical effective stress

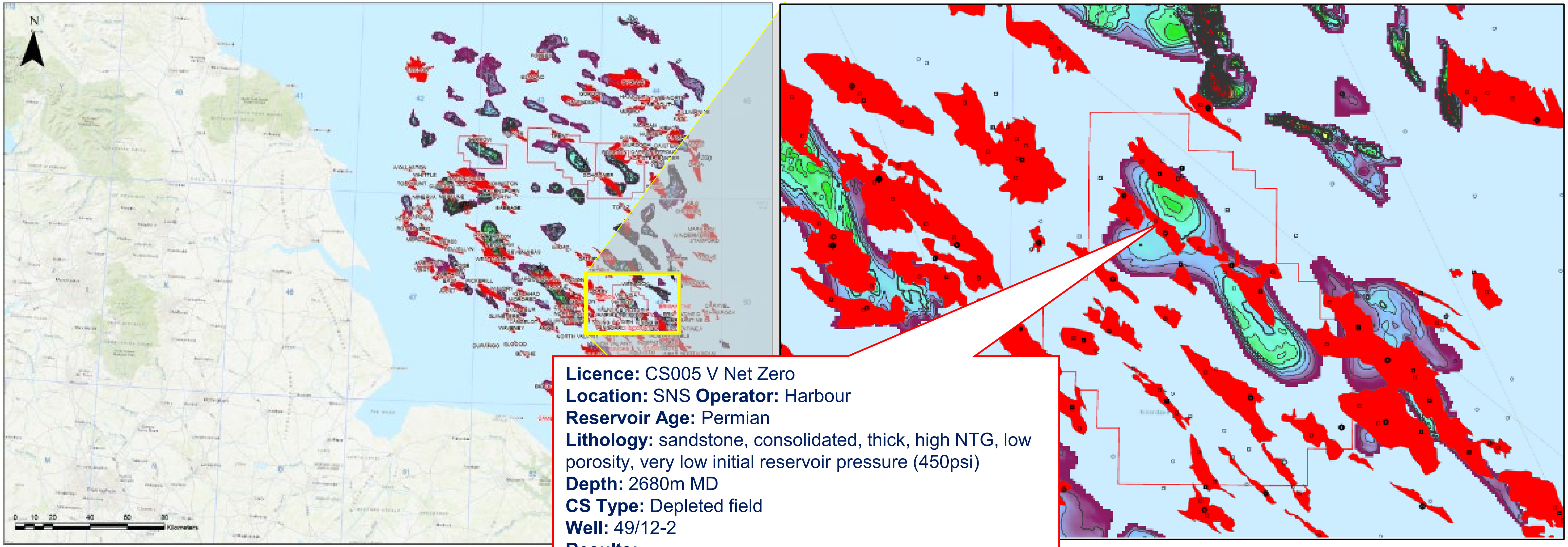
12.8. V-Fields, SNS

Leman depleted reservoir

12.8a V- Fields Overview

North Sea Transition Authority

The V-Fields are sub-salt tilted fault block traps within the Leman reservoirs of the Rotligendes Group. Rock physics indicates that the 4D response will be very difficult to determine. This is in part because of the relatively low porosity reservoir, and because of residual hydrocarbon expected within this depleted gas field.. No detectable *amplitude change* is expected when CO_2 is injected into existing natural gas accumulation. It is possible a small-time shift could be observed on highly repeatable seismic, but this has not been modelled.

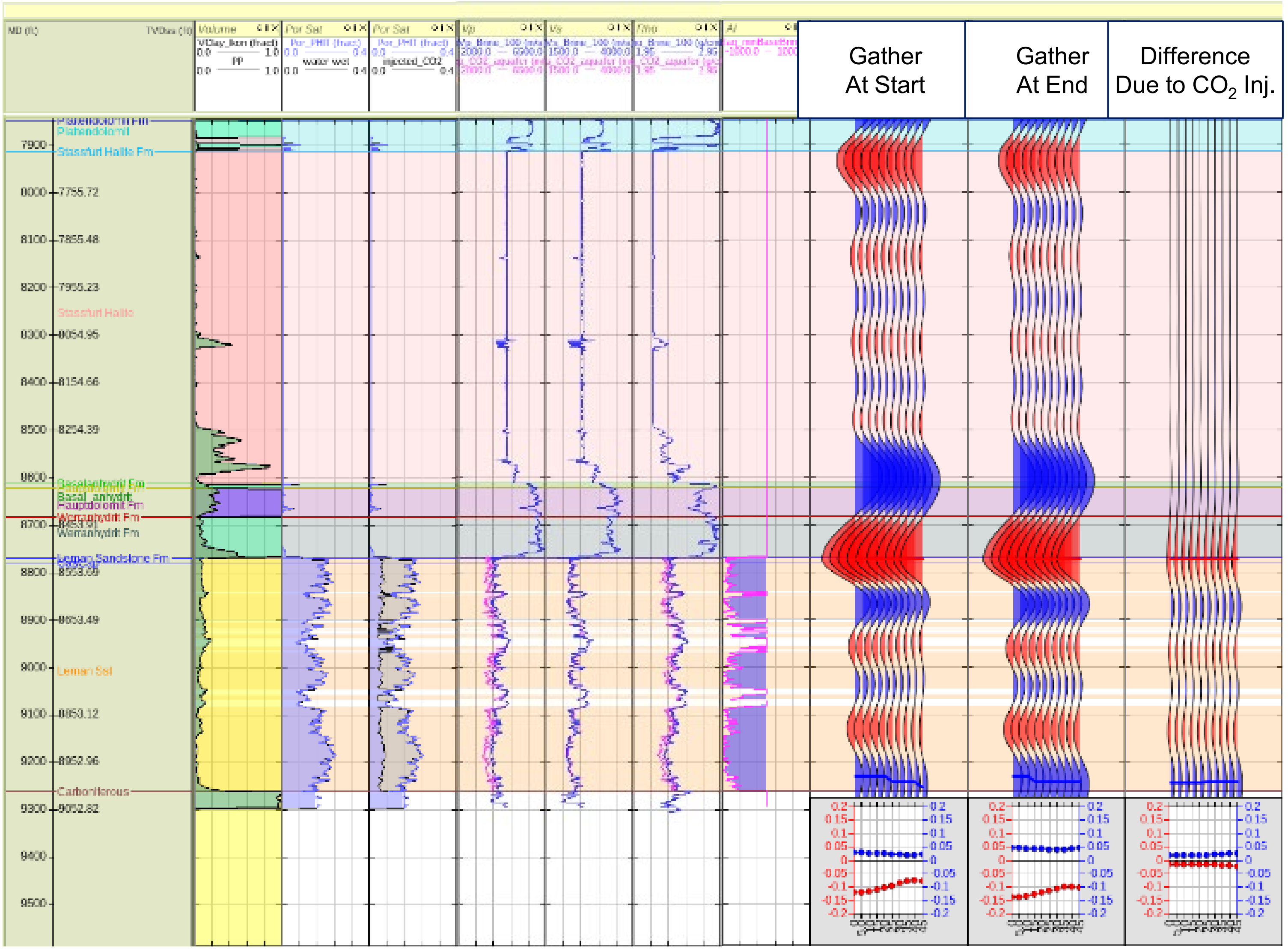


Licence: CS005 V Net Zero
Location: SNS **Operator:** Harbour
Reservoir Age: Permian
Lithology: sandstone, consolidated, thick, high NTG, low porosity, very low initial reservoir pressure (450psi)
Depth: 2680m MD
CS Type: Depleted field
Well: 49/12-2
Results:
Injection into gas leg- No 4D response expected
Injection into aquifer: Very small response

Consolidated reservoirs are probably below 4D seismic detectability

12.8b V-Field Rock Physics

North Sea Transition Authority



- V-Fields are thick, consolidated, Permian Leman aged reservoirs, previously gas filled.
- The average porosity is relatively low.
- Considerable pressure drop from initial to present day, prior to CO2 injection (-450psi).
- No saturation/contact changes suggested, no/little aquifer influx.
- Modelling assumes 30%Swirr & 70% CO2.
- No pressure changes assumed.
- Noticeable reduction in impedance observed, potentially caused by fluid changes.
- At end of injection, pressure now back at pre-production level (c.5500psi), and a fluid contact is expected.
- Modelling indicates velocity decrease and density increase work against each other, so that overall there is no seismically definable change between pre- and post- injection.

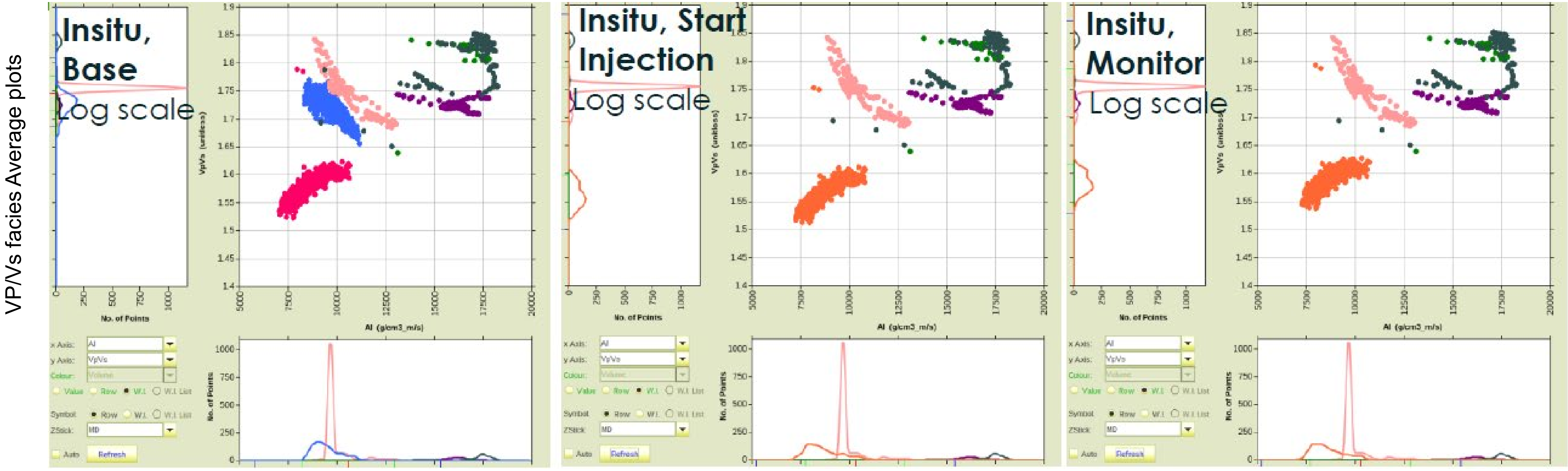
Poor seismic response to CO_2 injection at end of store life

V field fluid substituted logs

12.8c Summary - V-fields

- No visible difference in this domain due to changes in pressure at the start of injection.
- Small Vp/Vs reduction observed at the end of CO2 injection.

AI vs Vp/Vs plots for brine sand and surrounding rock



Facies: Leman sand (brine); Leman sand gas; Werranhydrit, Basalanhydrit, Hauptdolomit, Stassfurt Halite.

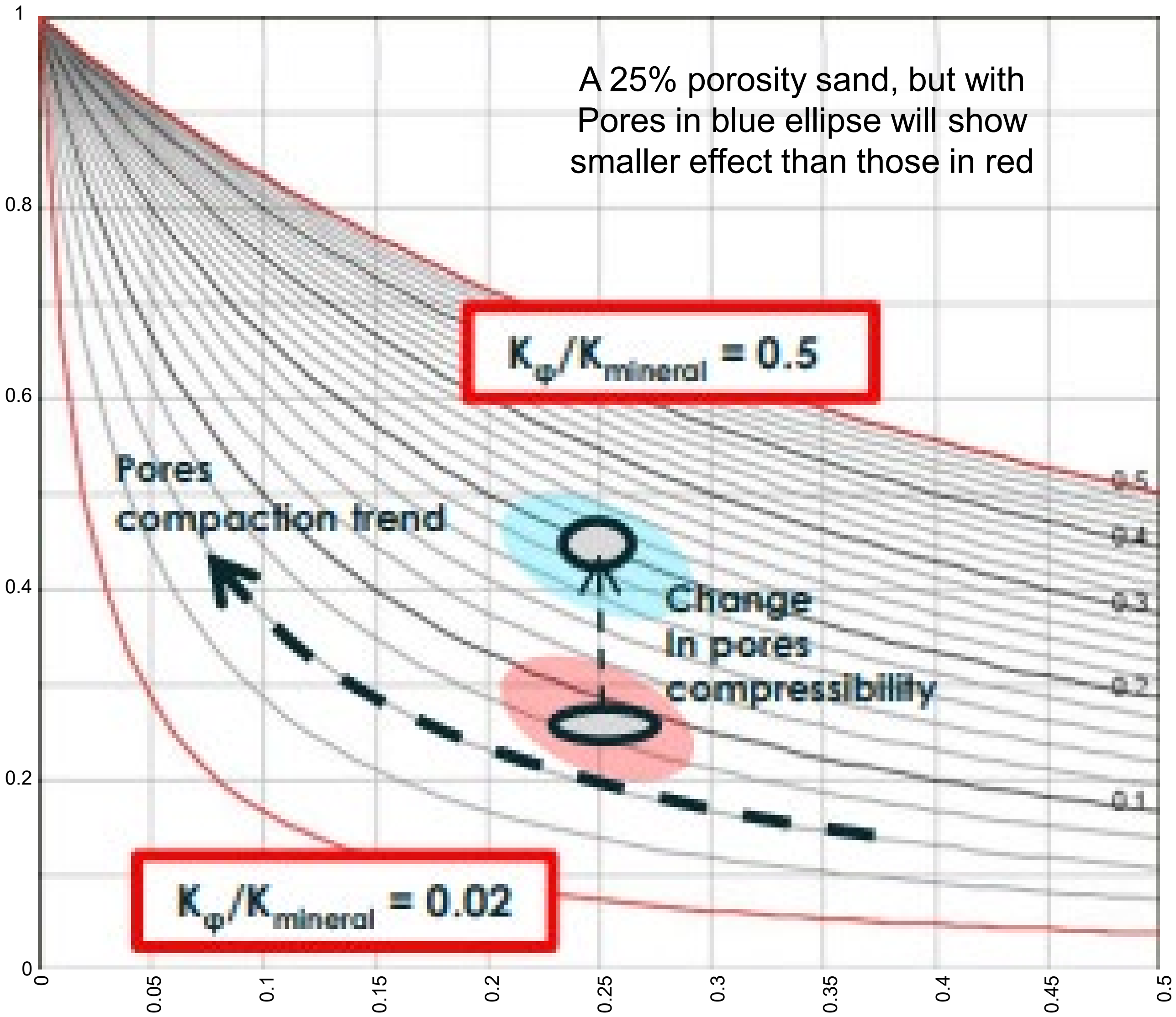
V-Filed rock physics cross plots

12.9a Influence of Dry Rock Frame/Stiffness

North Sea Transition Authority

- A comparison of the rock frame from these 5 areas can be useful. This slide provides an example explanation of the cross-plot.

- The dry rock frame (friable to consolidated & cemented sand) has a major influence on the magnitude of the seismic fluid effect response.
- Greater response for increasing % of pore-space in rock.
- The stiffer the frame ($K_{dry}/K_{mineral}$), the smaller response for equivalent porosity.



Example: Understanding dry rock frame is key to predicting 4D response

12.9b Influence of Dry Rock Frame/Stiffness

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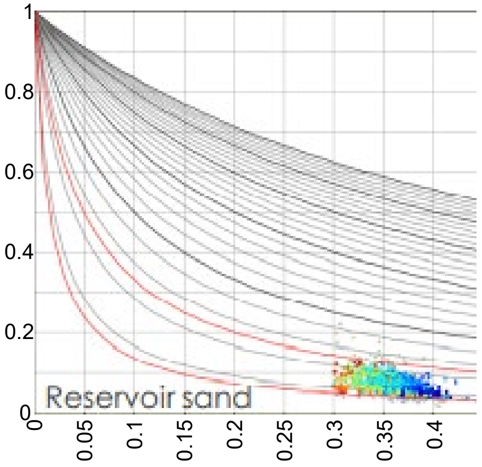
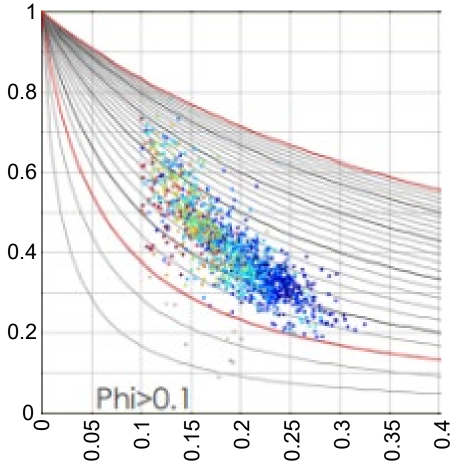
Sleipner – Northern North Sea
Miocene



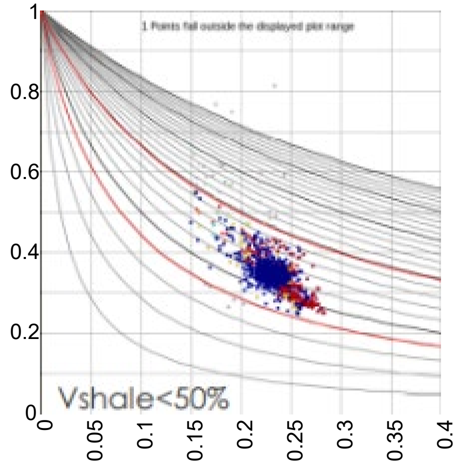
High porosity, friable & very unconsolidated sandstone.

Endurance- Southern North Sea
Triassic



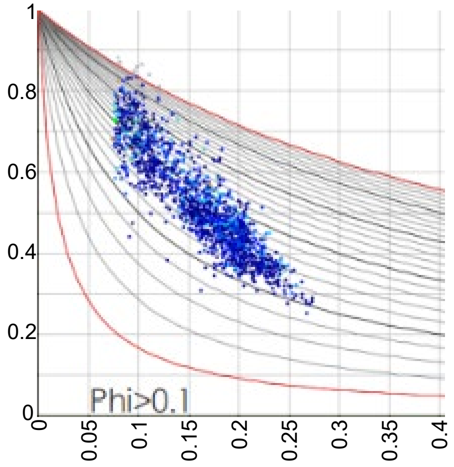
Consolidated.

Goldeneye - Moray Firth
Cretaceous



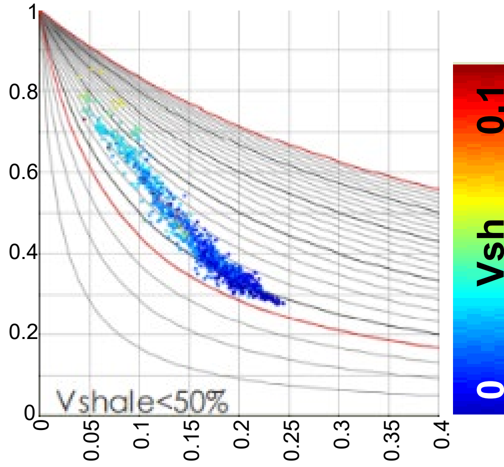
Further porosity reduction with stiffer frame.

Lennox - East Irish Sea
Triassic



Stiffer Triassic than SNS. Greater burial & uplift in EISB.

V Fields - SNS
Permian



Lower Porosity than SNS Triassic.
Greater reservoir depth.

- The dry rock frame (friable to consolidated & cemented sand) has a major influence on the magnitude of the seismic fluid effect response.
- As might be expected, to first order, these show increasing stiffness with increasing age of reservoir.
- However:
  - The Endurance “Bunter” Triassic is less stiff than the approximately equivalent “Sherwood” Triassic of Lennox. Endurance has comparable or more even more favourable trend that the geologically younger Lower Cretaceous of Goldeneye.
  - Whilst the Triassic at Endurance and Lennox sit at comparable current day depths, it is possible that Lennox has been more deeply buried in the past, thus affecting its rock frame stiffness. Whilst this exhumation has been studied in the SNS, there is no comparable publication for the East Irish Sea.

(Ref. 12h)

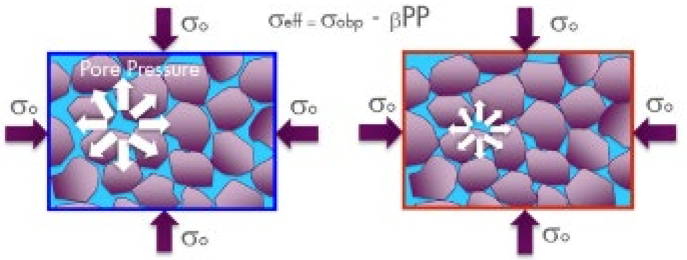
Variation in rock frame stiffness is not entirely age/ current depth related

12.10a Supporting SNS 4D Gas reservoir depletion | North Sea Transition Authority

SNS Hydrocarbon depletion 4D
The modelling conclusion here broadly reflects the view of the difficulty in SNS hydrocarbon 4D seismic monitoring. Heriot Watt University judged this to be the result of the main production effect is a pore pressure reduction and frame stiffening because of gas production in tight sandstone reservoirs that also have no real seismic direct hydrocarbon indicators.

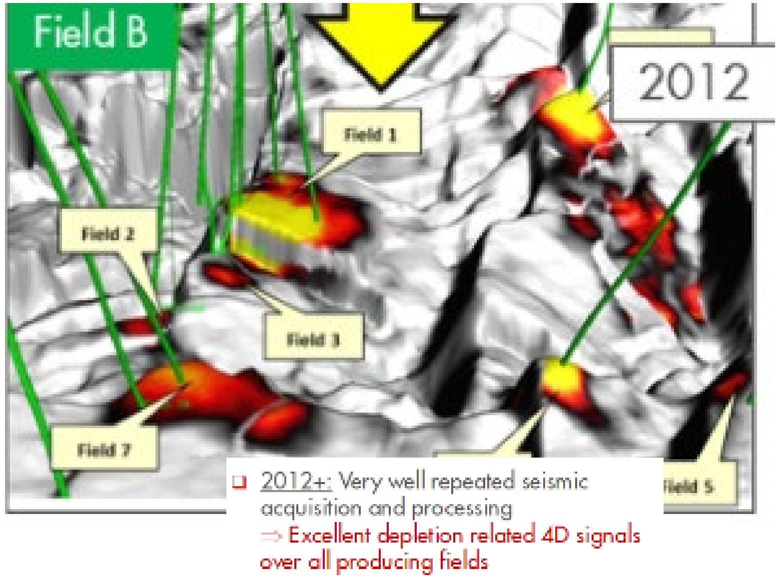
SNS Sean depletion 4D
It is particularly noteworthy that whilst numerous 4D surveys have been conducted on aquifer flood/ water injection fields across the UKCS, there is only one example of a hydrocarbon based 4D survey in the SNS. The 1992 3D survey was used a baseline for the 2002 monitor across Sean field. The expected pressure depletion time shifts were small, and the observed results did not provide confident results.

Dutch SNS Leman 4D
Shell provided a slightly more optimistic view of 4D gas depletion in the Dutch SNS Lema reservoir. They observed the normalised tim shift by the gas column thickness was proportional to the pressure change at the reservoir level.



Gas reservoir depletion -> increases effective stress and stiffens the rock matrix -> Measurable increase in velocity. Physical compaction is insignificant

↓ Pore Pressure by Production of Fluids
⇓
↑ Effective Stress
⇓
↑ P-Wave Velocity



Whilst 4D in SNS depleting reservoirs has not been as successful as water flooded oil reservoirs, the presence of an undetected time shift generated by using historic seismic as a baseline survey, is a cause for concern for future reservoir monitoring during a CO_2 injection phase

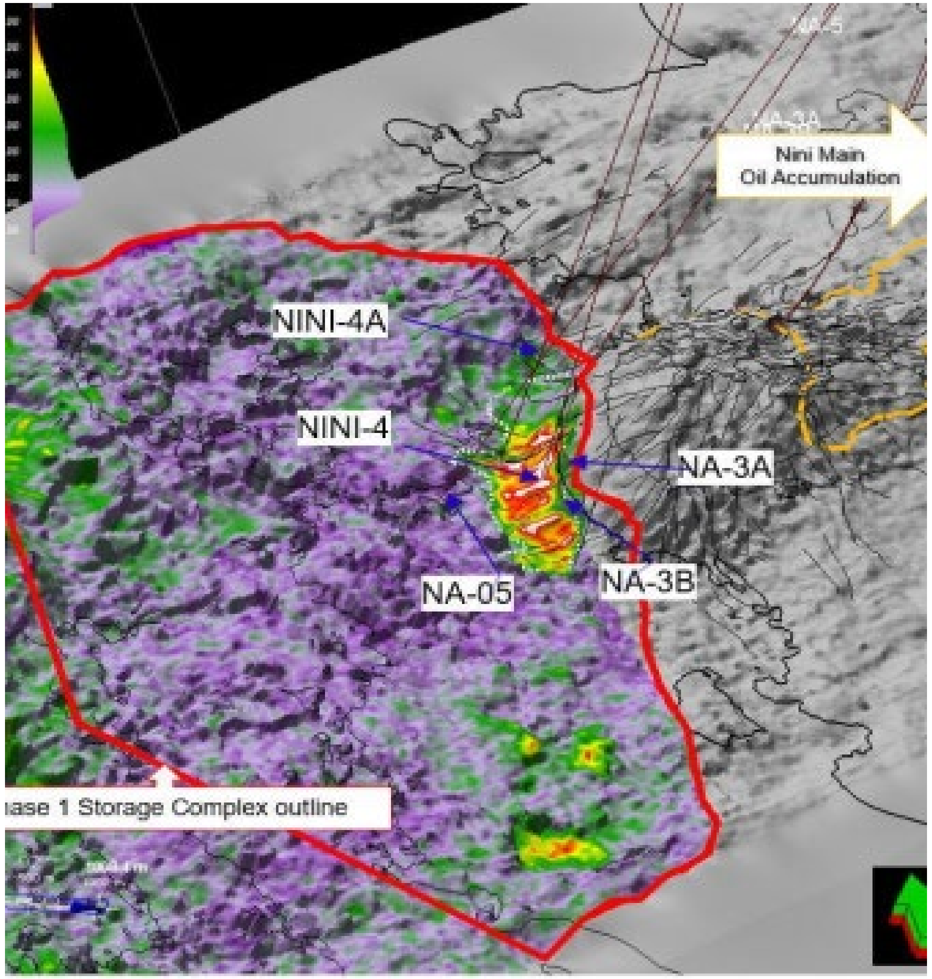
(Ref. 12i, 12j)

PORTHOS CCS project Netherlands
Like the SNS modelling, the Porthos project is also assuming no predicted 4D reservoir signal where CO_2 replaces residual gas within the Triassic Bunter Formation. However, if unexpected behaviour is observed a 4D survey is considered to demonstrate CO_2 containment (for example potential leak paths through the primary seals to shallower sands).

Greensand Project, Denmark
The Greensand project has recently announced injection of trial volumes of CO_2 into the aquifer of the depleted/swept Nini West oil field.
This is in the Palaeocene/Eocene Siri sandstone fairway. The target of the trial is the Frigg (Eocene) sand which has porosity of 20% and permeabilities of 100-300mD.
Pre-injection modelling indicates that 4D could detect injected CO_2 in the reservoir exceeding 4% saturation, whilst the maximum CO_2 saturation at the injection well after the last injection cycle will reach up to 55% and was predicted to radially migrate up-dip, dissolved in formation brine and trapped in the reservoir.
A trial of Spotlight technology (section 7.19) appears to show a related time shift has been observed near the injection site.

The authors of this report note the image on the right appears to show a hydrocarbon related bright spot, implying good Eocene reservoir properties; this has not been verified.

Pre-existing 3D view of Nini West Field (Greensand)



Legacy wells & Bright up dip amplitude anomaly

(Ref. 12k, 12l, 12m & 12n)

13. Part 1: Windfarm Disturbance Literature Review

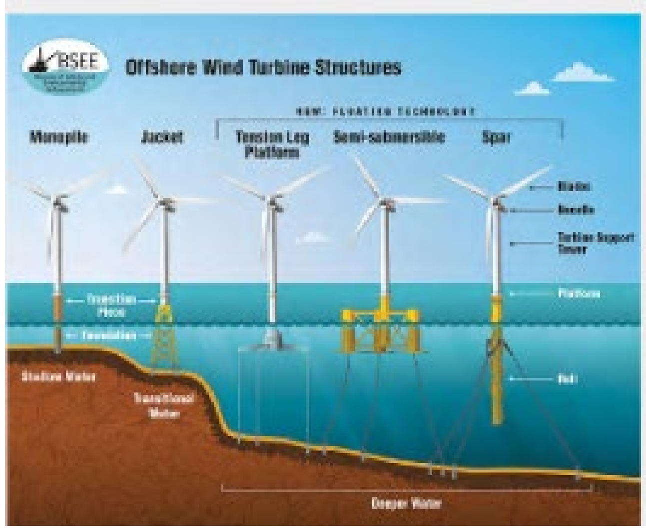
13. Windfarm Noise Overview

Offshore windfarms are operational hazard to any vessel activity, and impossible for those with large spatial footprints like most towed active seismic acquisition (Section 8.3 & 8.4 – repeated from MMV report 1).

This section considers the presence of the wind turbines in generating disturbance within the seismic survey spectrum. This "noise" is because of the action of both wind and waves causing both turbine movement and aero-dynamic motion. Wind turbine disturbance is here primarily considered as a source of low level of noise on seismic reflection data. Whilst there has been limited previous work undertaken for using wind turbines as a <u>seismic source</u>, there is some synergies with research trends across the seismic industry.

The research was conducted in 2 parts: Parts 1 & 2 are largely drawn from worked commissioned by the NSTA and undertaken by Prof Colin Macbeth of the Heriot Watt University, Edinburgh Time lapse project (ETLP) with researchers Maria-Daphne Mangriotis & Phung Nguyen in June 2022 and their 2023 EAGE presentation.

Part 1 provides a literature review of the many variables which generate a continuous source of seismic vibrations generated by wind turbines.
Part 2 provides an opportunistic chance to analyse a rare specific example where active seismic data (with sources firing) has been collected within a windfarm (section 8.5).



(Refs. 13a, 13b & 13c)

In contrast to the long-term low-level wind perturbations generated by turbines reflect changes in wind and wave loading, anchoring style & foundation conditions as well as type of seismic energy transmitted to sea surface vs those transmitted along the mud line. In contrast turbine foundation installation (impact pile driving) is well known to provide creates intense sound that radiates into the environment and propagates through the air, water, and sediment, but is not considered as part of this study.
Part 3 additionally looks examples of parallel research trends for use of ambient noise in seismic research.

Future direction: The literature review and the 2D streamer survey analysis have highlighted the lack of controlled offshore seismic case studies near windfarms. Whilst future seismic acquisition within the windfarm boundaries are considered unfeasible (section 1.9), it is expected that, in the future **<u>active seismic</u>** (OBN) will be acquired around the periphery of the windfarm (sections 1.8 & 8.6d) to allow as fuller extent as possible for the subsurface imaging in potential or active CS monitoring areas.

Potential field trial

The seismic wavefield at seabed is likely to be quite different from the water column, it is suggested that the first experiment is conducted using a small number of **<u>passive</u>** nodes which are deployed close to the edge of a windfarm. Ideally, this is undertaken whilst carefully monitoring windfarm operation activity (e.g., RPM and accelerometer data per turbine with clocks synchronised to seismic shoot). This would provide both much needed "close approach" operational experience (section 8.6), and an opportunity to examine the windfarm generated wavefield and potentially start to consider the windfarm not as part of the noise field, but part of the ambient seismic spectrum for passive monitoring (c.f. section 14.2).

13.1 Introduction to literature review

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Wind turbine seismic disturbance has previously been studied primarily onshore, for the:

1) potential influence on humans and animals and
2) the long-distance decay for safeguarding vibration sensitive equipment (e.g. LIGO: Laser interferometer gravitational wave, seismic networks, CTBTO: comprehensive test ban).

However, the literature is more limited offshore and focussed on assessing impact on marine life & ecosystems. There are few direct observations, so much of this review is based on inference or modelling based upon onshore observations and as far as we are aware, there are no published operational wind turbine noises studies using OBN or towed streamer.

In general, operational turbines generate a low level but continuous and very complex "noise" train of body and surface waves. The structures are designed to avoid turbine fatigue and observations support the presence of discrete frequency peaks in the Power Spectral Density (PSD). These comprise low rotational frequencies, engineered natural resonances & blade pass frequencies. They are usually band limited to 1-10Hz, where they overlap with active seismic reflection bandwidth. Isolated higher frequencies (<20Hz) are possible.
The response itself is a result of complex loading of the turbine a function of wind speed, height, structural dynamic loading, turbine blade aerodynamic movement and transmission through foundation to variable substrate. The magnitude of the disturbance is strongly controlled by decreasing distance from turbine, with generated noise being just being detectable up to a maximum of ~18km away, although in practice the noise is less than a distant earthquake" beyond 125m.

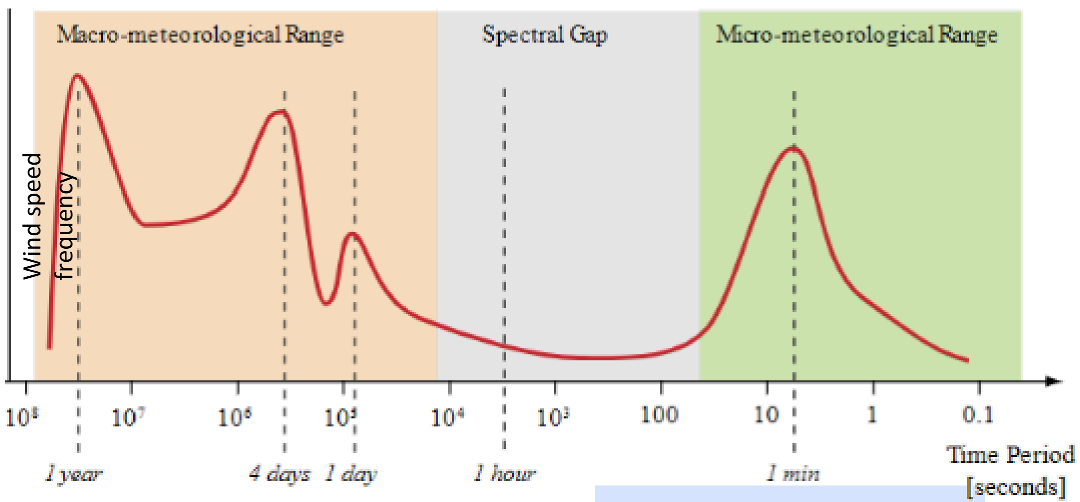
Note particularly, wind-turbines, even when switched off / during shut-down, will still produce significant oscillations at the towers natural oscillating frequency (eigenfrequencies).

This section: outlines the wind (13.2.1) & wave (13.2.2) power spectrum and resulting complex array of turbine loading patterns (13.1.3). This results in the discrete peaks in the frequency spectrum (13.1.4) and their variation with wind speed (13.1.6), distance (13.1.6c) and attempts to discriminate (13.1.7) the eigenfrequencies' from the blade pass frequencies (BPFs). The resulting seismic disturbances waves are mainly surface waves (13.1.8).

(Refs. 13b, 13d, 13e, 13f & 13g)

13.1.1 Wind Power loading & variation

Wind speed Spectrum



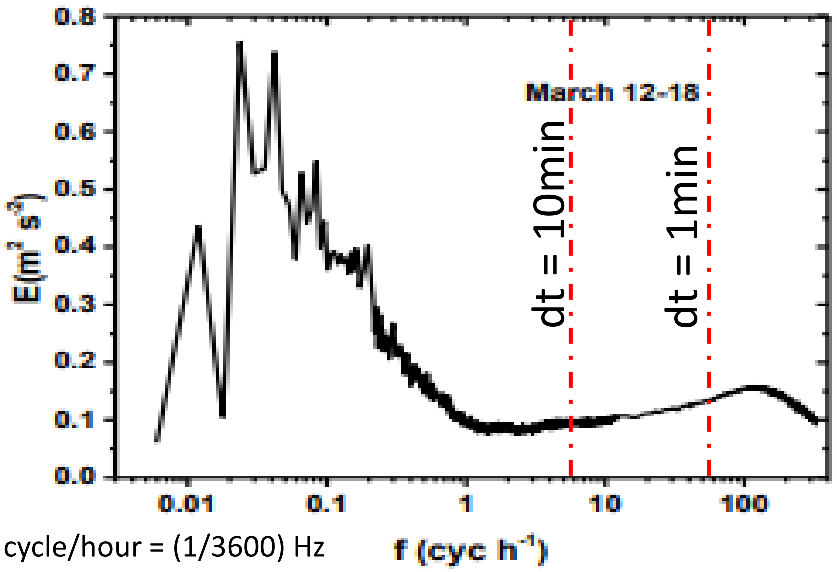
Reproduction of Ref 13h

The wind power has major peaks in spectrum:

- Macro- meteorological end (annual, depressions, diurnal).
- A large spectral energy gap.
- Micro-meteorological (turbulence & high frequency variations) for tower energy calculation.

Seismic is only effectively interested in decay at shortest period (<1s) / highest frequency (>1Hz).

Measured wind speed energy spectra



Ref 13i 1Hz sampling

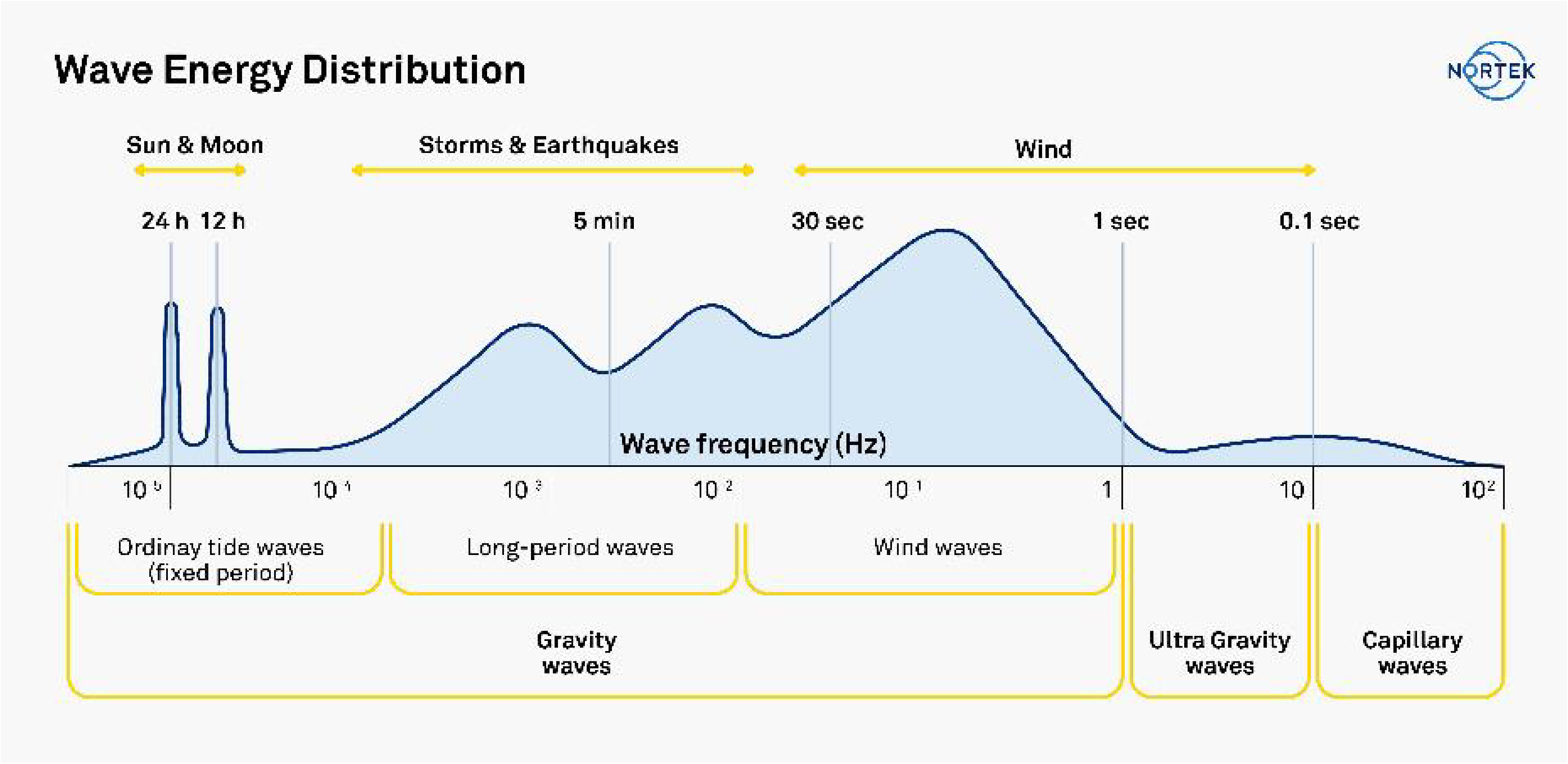
- Wind is typically averaged over long durations
- Study shows power reduction @ seismic frequencies

- Wind predominantly horizontal motion.
- Speeds 0-20m/s - turbines shut in at higher speeds.

(Refs. 13h, 13i , 13j & 13k)

13.1.2 Wave power distribution

- Offshore wind turbines are also affected by wave motion and produces broadband loading with a very low frequency tidal component.
- Likewise, within seismic spectrum (<1sec = >1Hz) the wave energy drops.



(Ref. 13l)

13.1.3 Turbine components and loading

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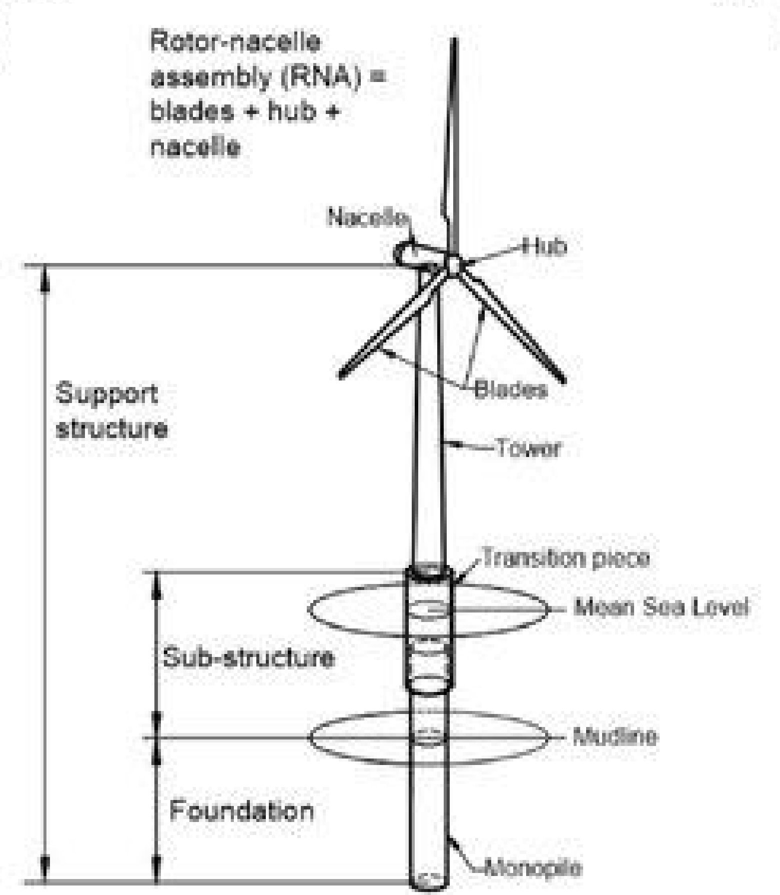
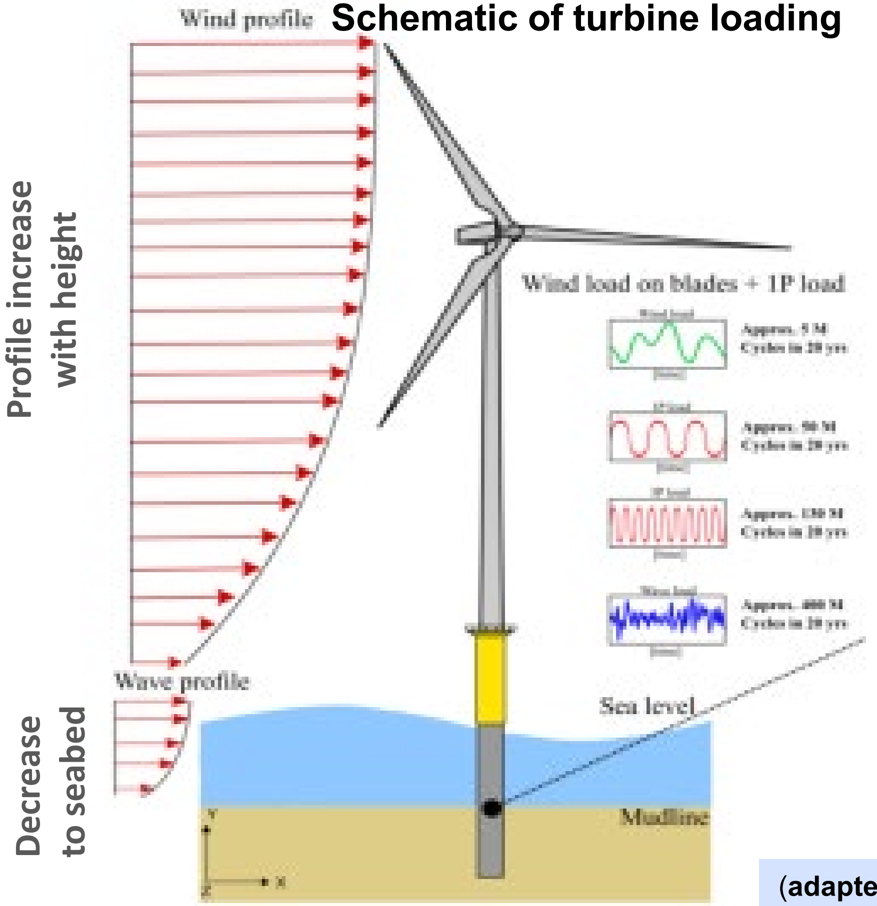


Schematic of turbine loading



(adapted from Ref 13n)

- Turbines are dynamically loaded structures.
- "Shock" wind loading against the structure generates low frequency eigenfrequencies.

- Wind generates a low frequency turbine rotation and a 3x faster blade movement.
- Frequency changes with water depth.
- Water wave produces higher frequencies than rest of loads.
- Additional Shallow water tidal loading.
- Disturbance passing through air and ground.

(Ref. 13m)

13.1.4 Turbine (1P) & blade pass (3P) frequency

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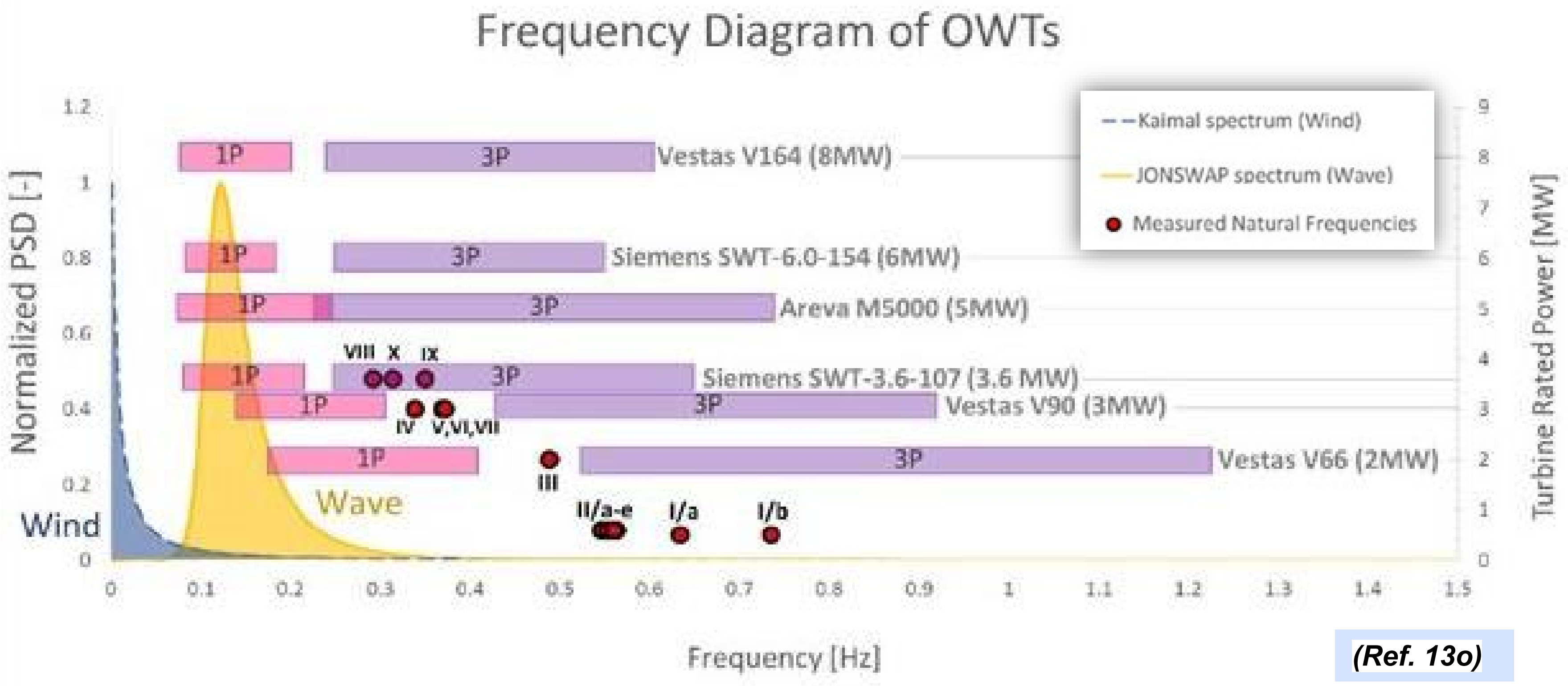
- PSD power spectral density (aka power present in signal) as function of frequency.
- Typical wind and wave spectra, rotational speed (1P) and blade passing (3P) in front of turbine.
- Low rotational frequency and predictable blade passing “thump” function of RPM.
- Heavier turbines closer to wave excitation frequency.
- Critical that turbines designed to avoid fatigue @ natural resonant frequencies.

Water depth influence:

- Shallow water (<30m) wind loading dominant.
- Medium-deep water with stiffer monopile: wave loading equal or higher.
- Extra length of tower in deeper water is more flexible therefore produces lower natural frequency.

Wind and wave spectra for 6 commercial turbines



(Ref. 13o)

Turbine loading generates discrete peaks in frequency spectrum

13.1.5 Complex turbine motion & Eigenfrequencies

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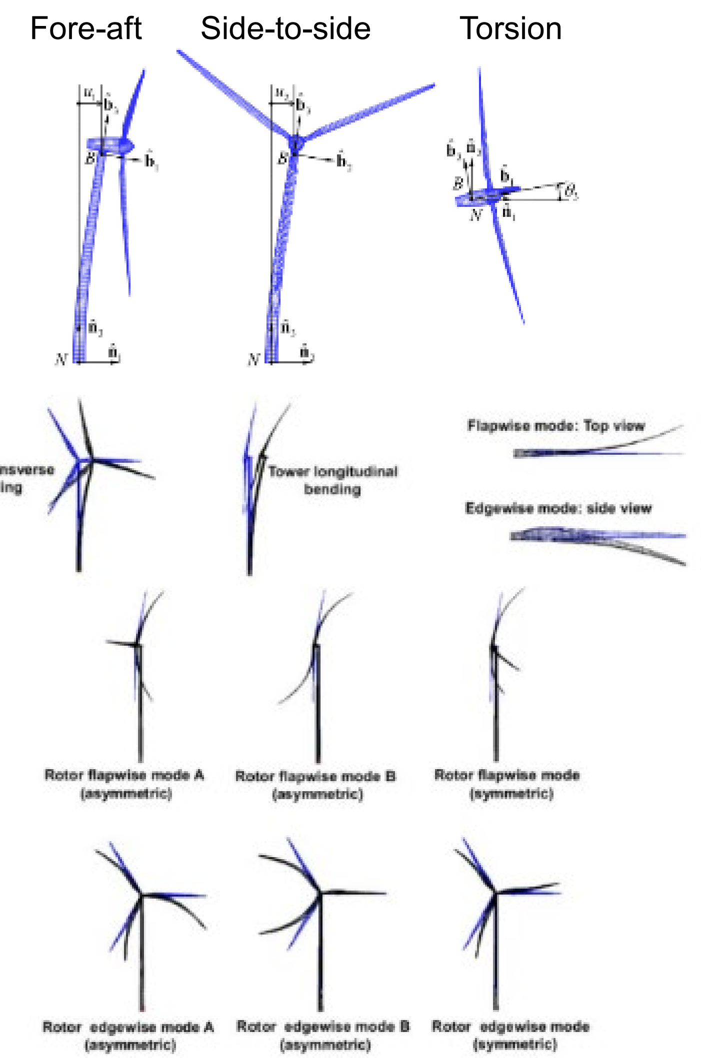
Turbine displacements

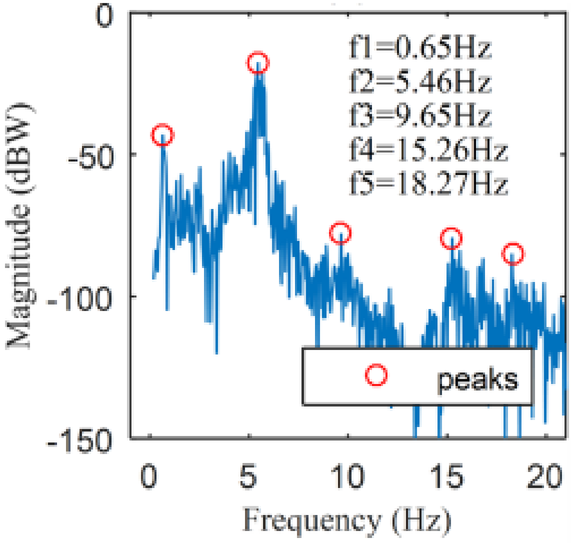


(adapted from Peeters, 2006)

- Fore-aft displacement larger than side to side.
- Horizontal fore-aft direction is 2 orders of magnitude greater than vertical (Mohammadi et al., 2014).
- Other "flapping" motions.
- Resultant Complex input motion to ground: Horizontal dominates.

(Ref. 13p)

Idle state: Wind static & shock against tower <u>without</u> turbine operation



Generates discrete eigenfrequencies

PSD peaks in Tower axial direction.

(Ref. 13q)

During operation more eigenfrequencies arise due to varying turbine mechanism between 0.4 -18.4Hz (Mohammadi et al., 2014). These are combination of mechanical (from nacelle) and aerodynamic (blades).

(Ref. 13f)

Intuitively simple primary horizontal movement, but tower produces complex vibrational behaviour

13.1.6a Time vs frequency domain analysis

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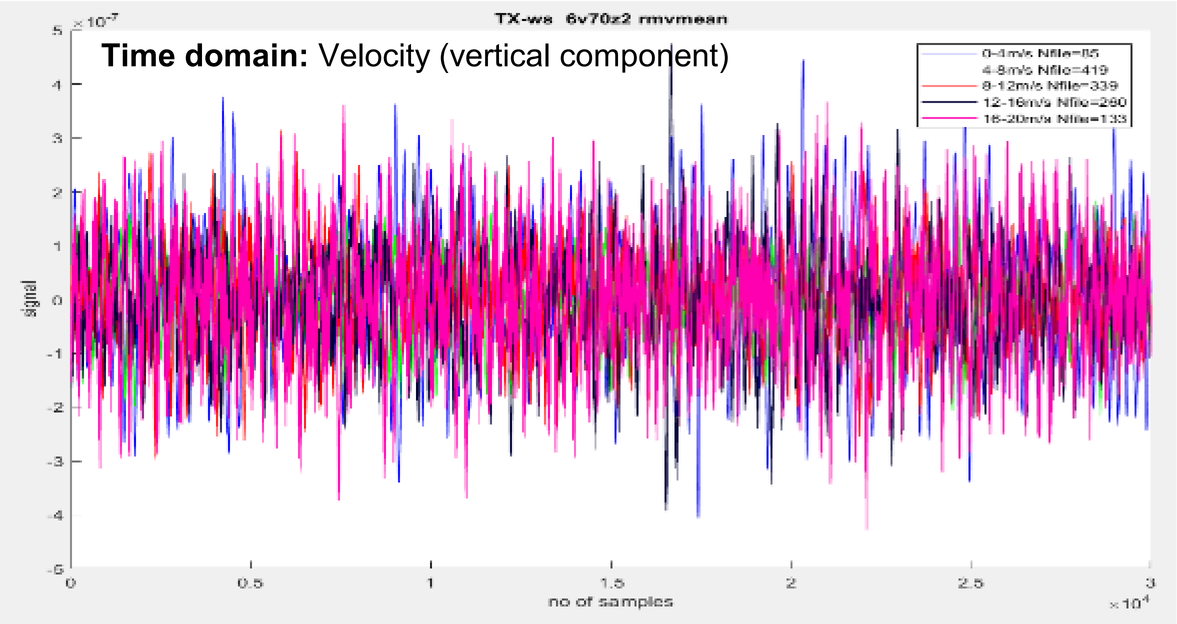
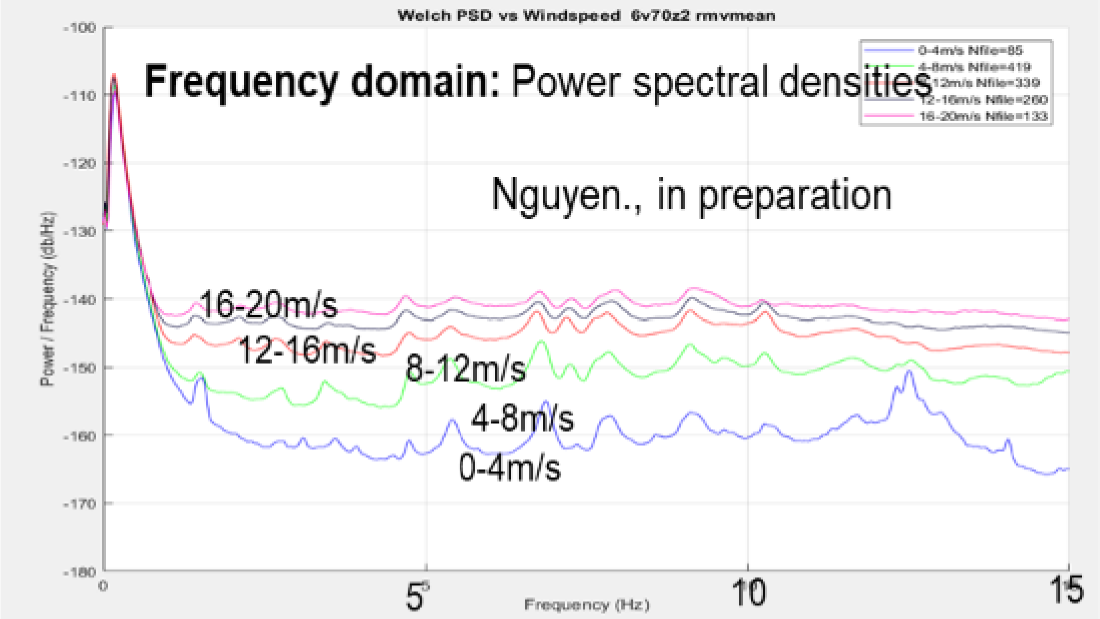
Heriot Watt Noise analysis





- Continuous turbine operation, observed ~ 1km away.
- Cannot separate P, S body waves.
- Variability makes difficult time domain interpretation.

- As expected, there is increasing power with wind speed.
- Turbine start ~2.5m/s, Cut-in ~ 3.5m/s, cut out/ brake 54m/s.
- By design, power limited to 15Hz. ***(Ref. 13e & 13r)***
- Several discrete peaks:
  - Constant across wind speeds: related to tower
  - Others vary and are "gliding": related to blade pass.

(Ref. 13s)

Discrete frequency peaks in PSD: Magnitude related to wind speed

13.1.6b 3 Component Eigenfrequencies

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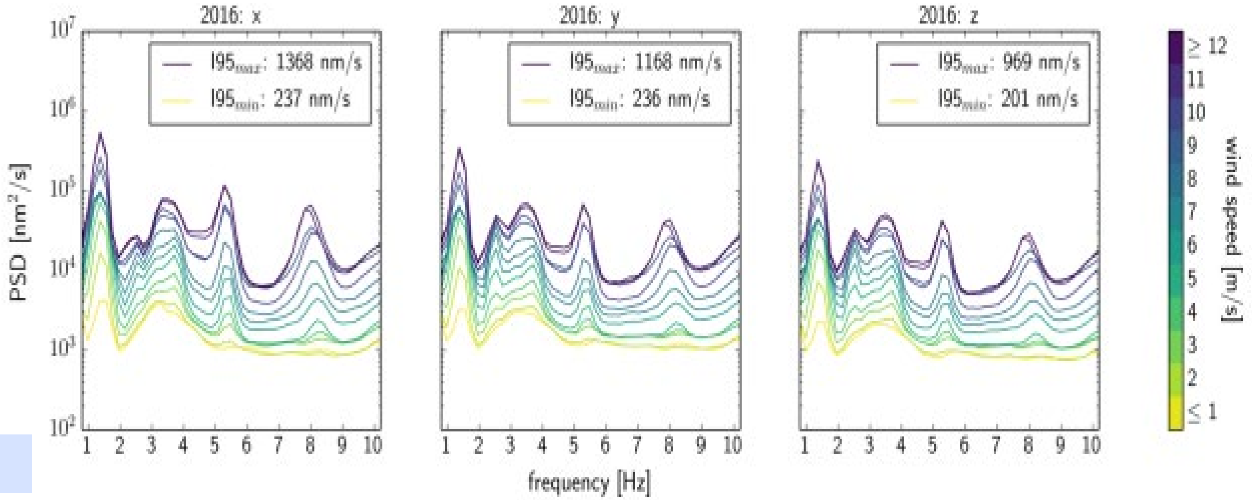
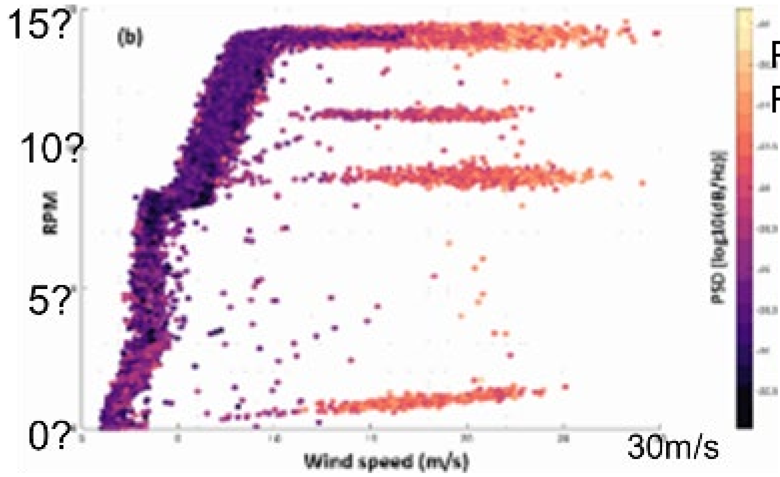
Published PSD variation with wind speed

- Turbines < 5km away.
- Similar/ constant PSD shape for increasing wind speed.
- For all 3 components:
    - Recall dominance **<u>in horizontal</u>** turbine movement.
    - Adapted from Ref 13t.

- Some peaks more prominent at intermediate wind speeds:
    - Some speeds excite certain frequencies?

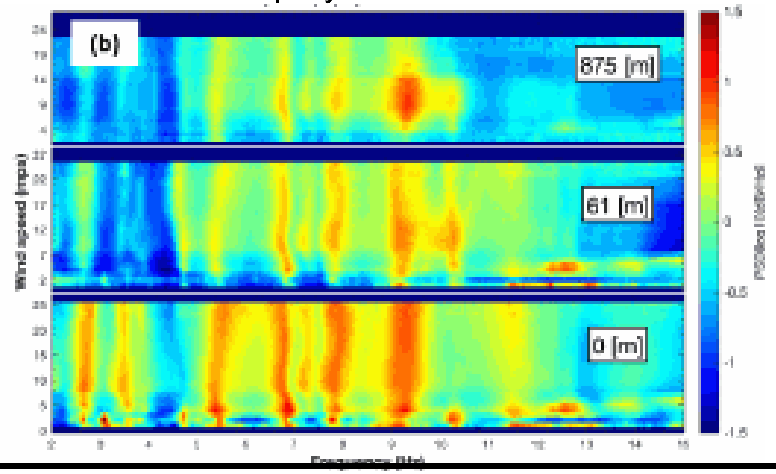
(Ref. 13t & 13u)





PSD increase with windspeed.
RPM not fully at windspeed.

Frequency peaks persist, but PSD decreases rapidly with distance



Discrete frequency peaks in PSD: Magnitude related to wind speed

13.1.6c Turbines PSD with distance

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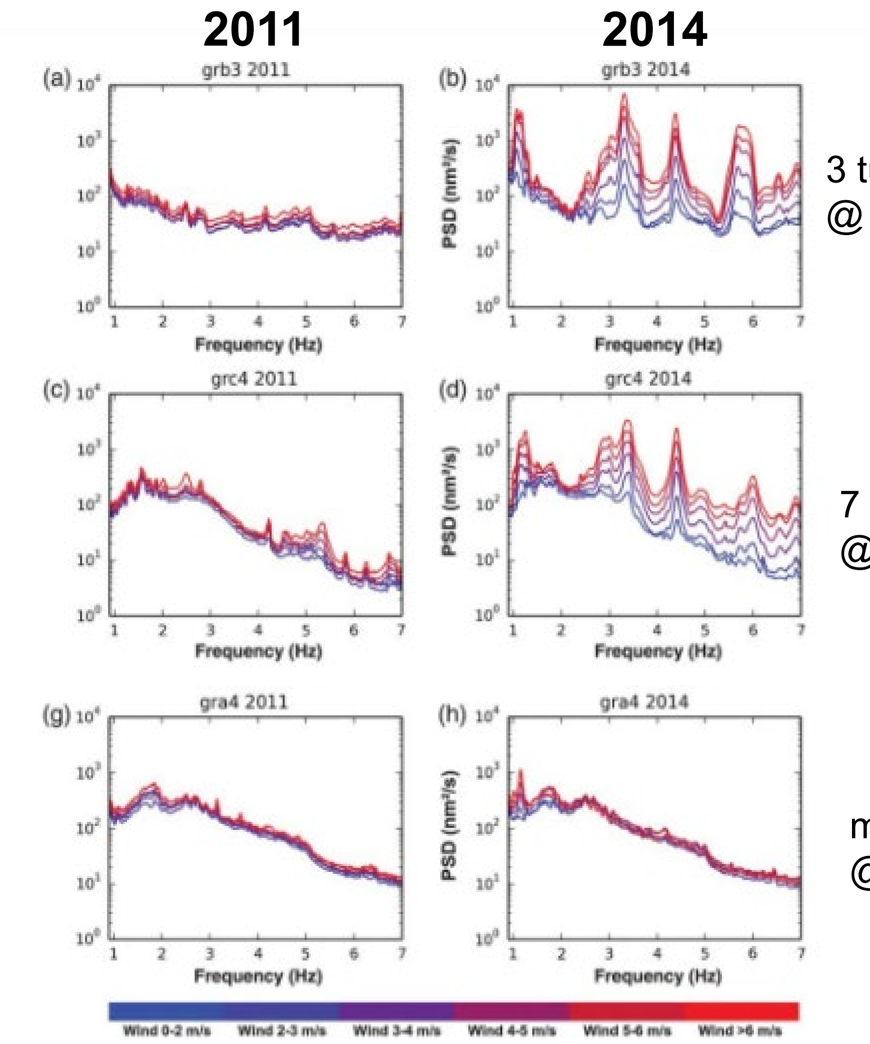

0-2m/s Wind speed colour >6m/s

3 turbines
@ 1.4-2.1km

7 turbines
@ 1.4-3km

many turbines
@ > 15km

4 stations PSD before and after turbine emplacement

2011 pre turbines:

- Background trend: no dependence on wind (overlapping curves).

2014 Post installation:

- Distinct peaks, 1-7Hz strongly wind dependant.

- No disturbance beyond 15km: 2014 matches 2011 trend.
- Other studies: detection distance varies between 2km (ref 13w) to 18km.
- Implies Site and turbine specific disturbances.

(Refs. 13v, 13w & 13x)

Turbine induced vibrations can be separated from background noise

13.1.6d Turbines PSD with depth

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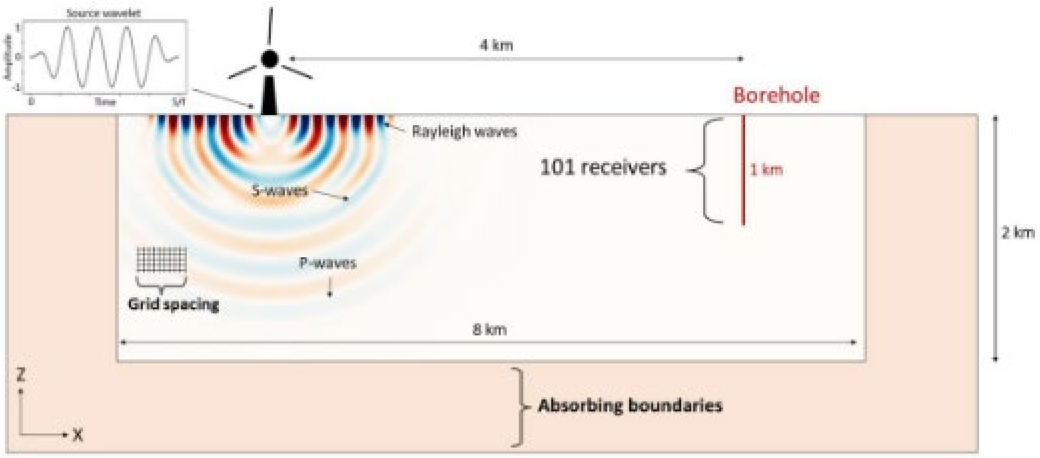
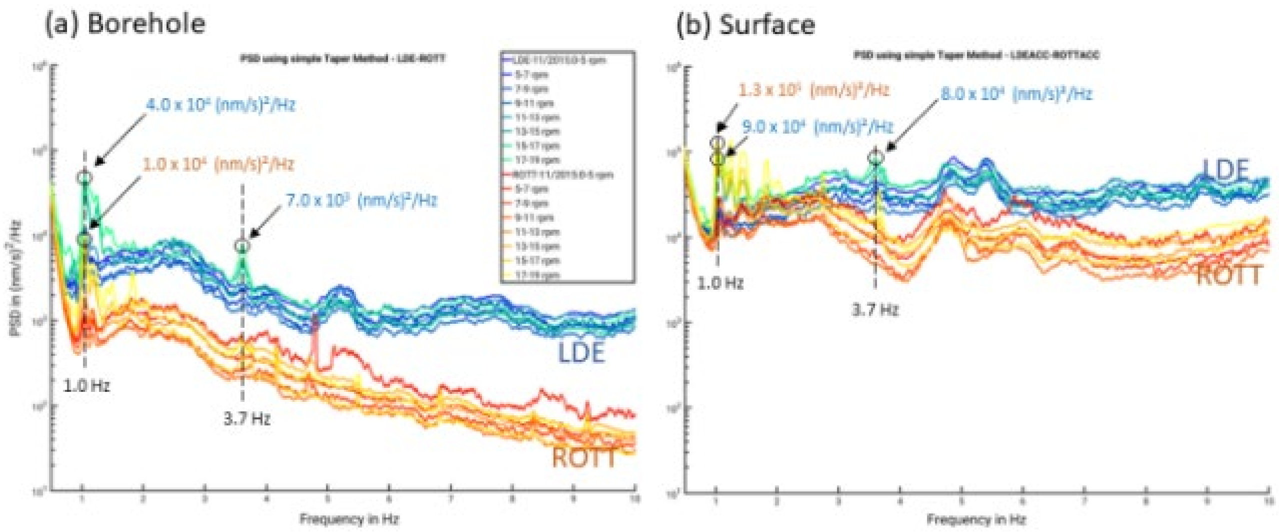
Limberger et al (2023) considered the impact of seismic noise at surface and within 2 boreholes, based on a numerical model and real field observations.

Modelled scenario with turbine generated disturbances



Sinusoidal seismic wave propagation from turbine and in well receivers.

Observed PSD at within 2 boreholes near surface



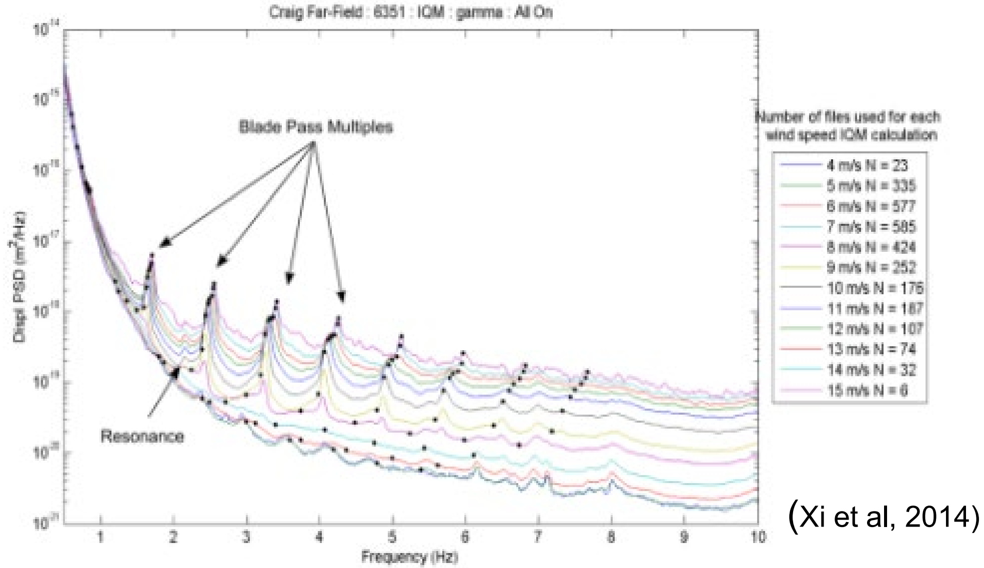
Clear noise reduction @ 2 permanent earthquake monitoring stations (ROTT & LDE)
ROTT greater damping as it is further way (5.5km) compared to LDE (3.8km) from WT.

(Refs. 13z & 13aa)

Turbines are detected at distance, but disturbance decreases with depth

13.1.7 Eigenfrequencies or Blade pass (BPF)

Separating Eigenfrequencies from blade pass frequencies

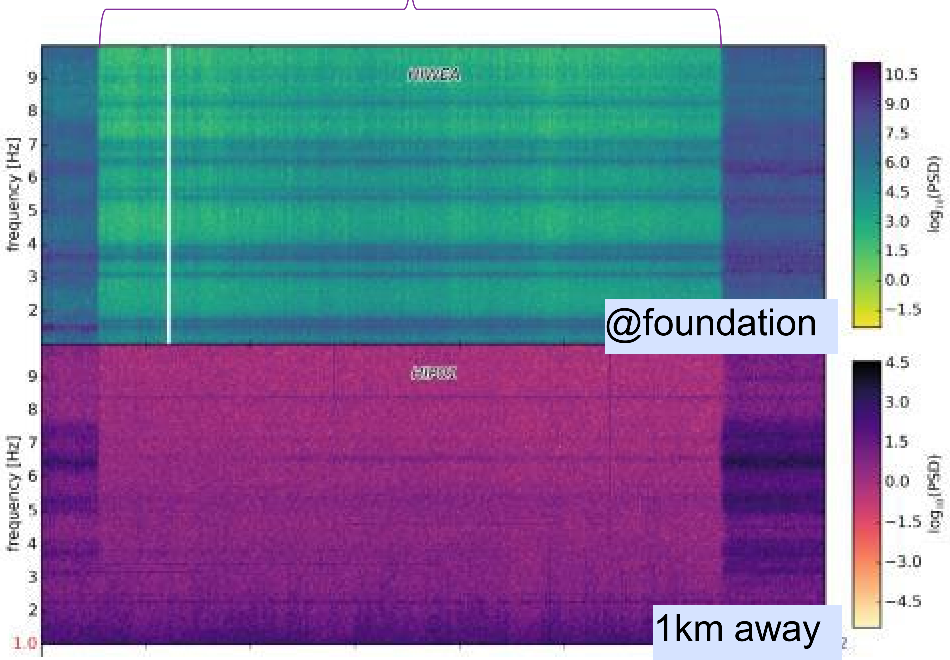


(Xi et al, 2014)

- PSD increase with wind speed.
- Simplistic interpretation:
  - Frequency constant with speed -> eigenfrequency?
  - Frequency changing (gliding) with speed -> blade pass frequency (BPF).
- However, natural frequencies can vary with wind speed RPM is not same as wind speed (e.g. due to operational restrictions).
  - No clear eigenfrequencies vs BPF dominant trend in literature. *(Ref. 13ab)*

PSD from 2 station across turbine shutdown

SHUT-DOWN (OFF) *(Ref. 13s)*



- At foundation, during
  - production: Eigenfrequencies & BPF’s + harmonics.
  - shutdown: Only Eigenfrequencies + Harmonics.
- 1km away:
  - Production: natural frequencies + harmonics: No BPFs.
  - Shutdown: some fainter frequencies still present.

Balance of Eigenfrequencies vs BPF turbine and site dependant

13.1.8 Wave propagation and distance

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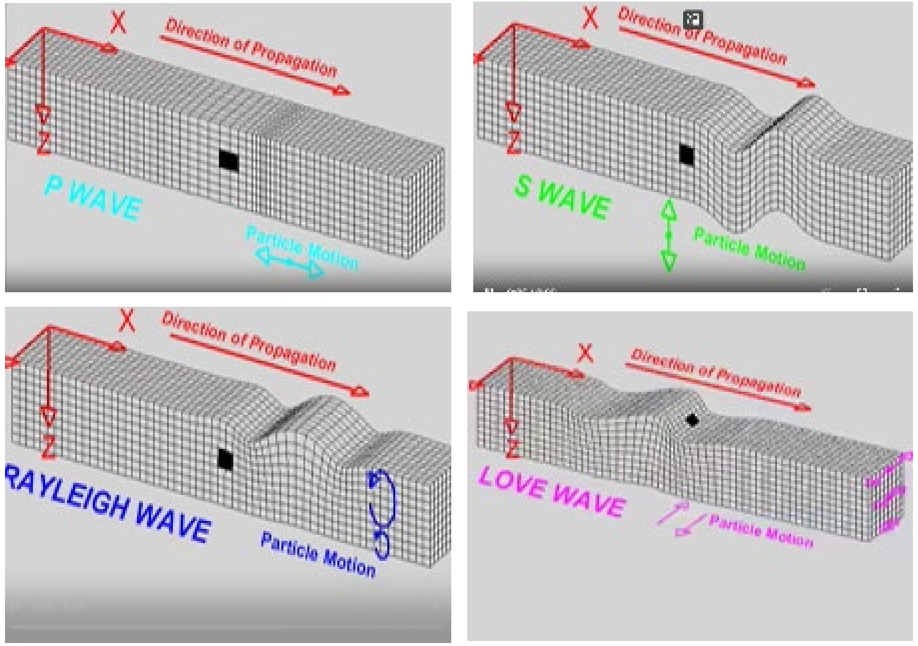
Whilst most of this report has been discussing seismic reflection is mainly concerned with body waves – principally P (primary, compressional) or the secondary S (shear) waves. Turbine disturbance is mostly related surface waves which are guided by free surface of the Earth, following along after P- and S-waves. Surface wave observations show Rayleigh waves with elliptical movement dominate when down wind of a turbine and the side-to-side Love waves when cross wind.

Polarisation analysis by Westwood and Styles (2017) has separated these different waves.

Scholte waves (traveling along the interface of a water layer and the sub-bottom sediments) have a motion similar to Rayleigh but are slightly slower due to overlying water.

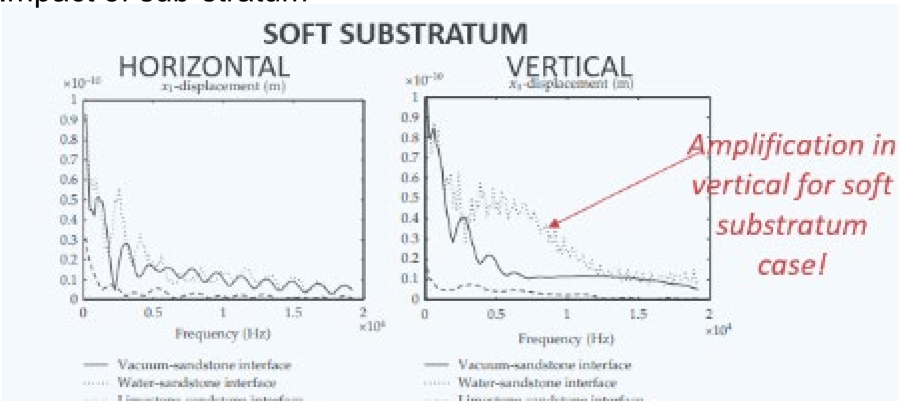
(Ref. 13c & 13r)

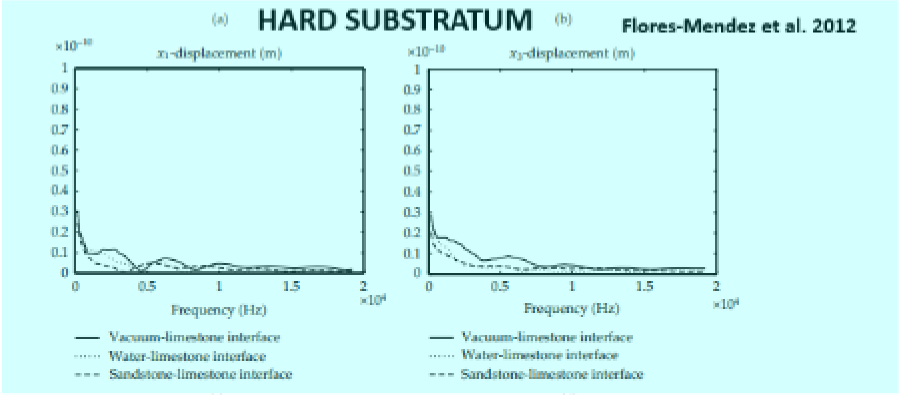
Seismic Wave Propagation Illustrations



Although not measured, the vertical component of surface waves from turbines *may* be amplified/ more energetic offshore, but only where there is a soft substratum.

Impact of sub-stratum





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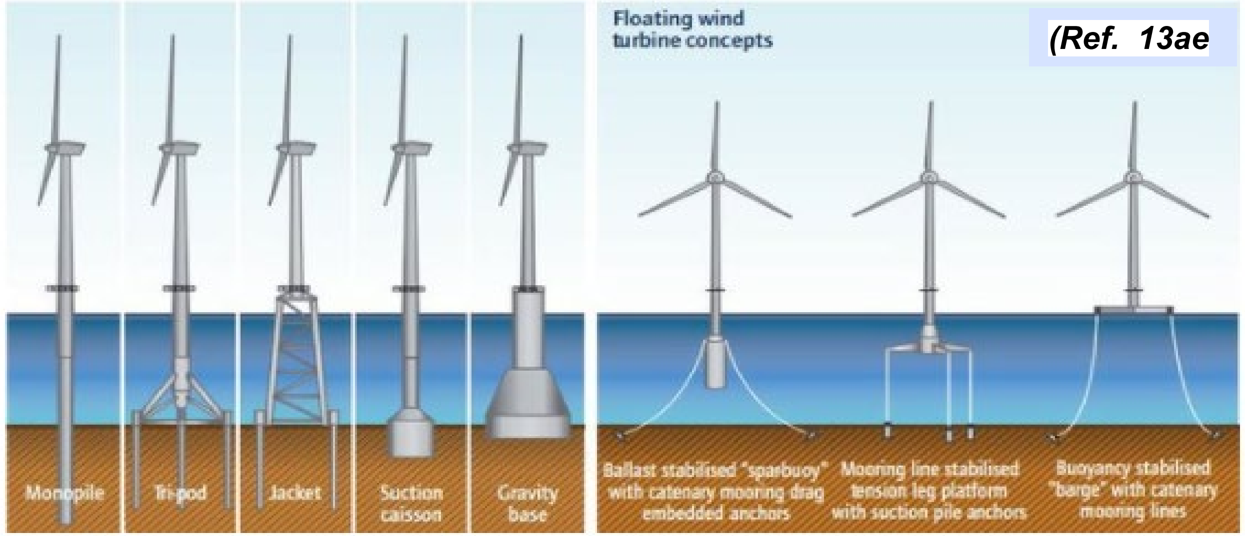
Resulting wave propagation

13.1.9 Other Offshore considerations

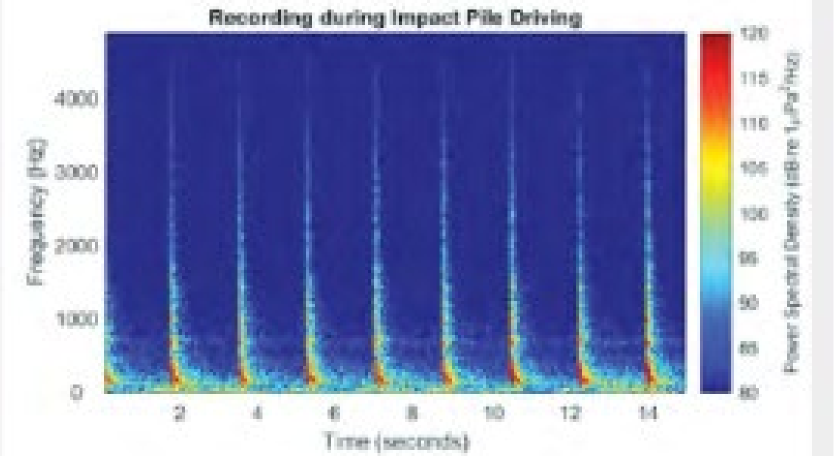
General expectations:
- Much more noise from construction (piling) than turbine operation.
- Distance from turbines is dominant factor: wind speed and vibrations smaller.
- Source level are 10-20Db less than ship noise in same frequency band.
- Transmission dependent upon foundations (Bhattacharya et al. 2021).
- Fixed systems transmit S-waves.
- Noise in water column likely to be very different from the solid seabed.

Floating turbines are mechanically more isolated and do not transmit as well
- Low mass of cable and damping in water.
- Tension leg platforms create greatest water column disturbance of the ‘floaters’.
    - No information on noise levels from floaters/ no comparative reporting.

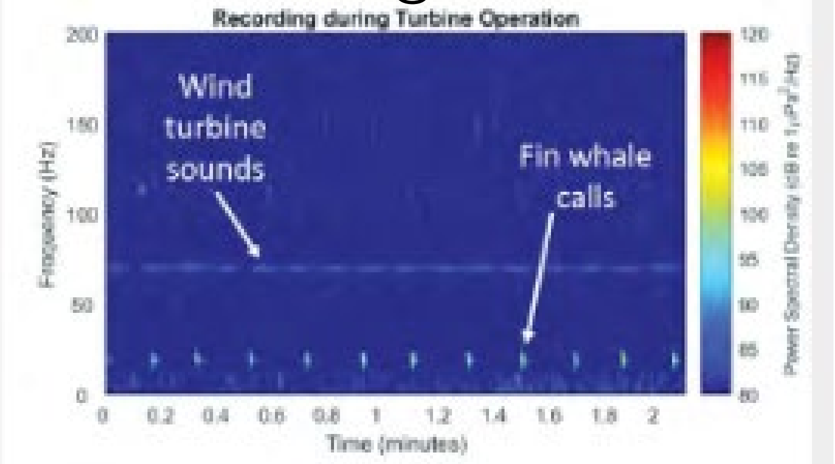


(Ref. 13ae

Pile driving for WF development @ 7.5km range



Turbine @ 50m



(adapted from Amaral et al., 2020)

(Ref. 13ad

13. Part 2: Windfarm Disturbance Seismic Survey Analysis

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13.1 Introduction to Seismic Study

Seismic acquisition close to/within a windfarm is extremely rare and as far as we are aware, no dedicated passive seismic acquisition (i.e. receivers without seismic sources) has been undertaken. This study represents an opportunity to separate the large influence of an active seismic source from the much weaker sources of noise disturbance, which may potentially include turbine generated disturbance. This is extremely challenging, and it is acknowledged that this is an opportunity only, rather than an undertaking of a new controlled and comprehensively study.

We would like to gratefully acknowledge Spirit for agreeing to supply these 2D HR seismic data (section 8.5) to analyse the noise patterns. This section largely drawn from worked commissioned by the NSTA and undertaken by Prof Colin Macbeth of the Heriot Watt University, Edinburgh Time lapse project (ETLP) with researchers Maria-Daphne Mangriotis & Phung Nguyen in Jun 2022. The following provides a summary of their reports.

It is concluded that:

- The level of windfarm noise is very low compared to other sources of active seismic signal or its generated noise (multiple).
- There are **tenuous indications** of enhanced PSD's at low frequencies (~5Hz) in the low to mid offset streamers **around the windfarm**.
- It is unclear if these is turbine generated noise or reflections off the infrastructure, or some other explanation (e.g. swell noise).
- The historic nature of the seismic recording means that there was no data on windfarm operations. It may have been possible to isolate the noise further, if operational data had been recorded, e.g. for 12 hours.

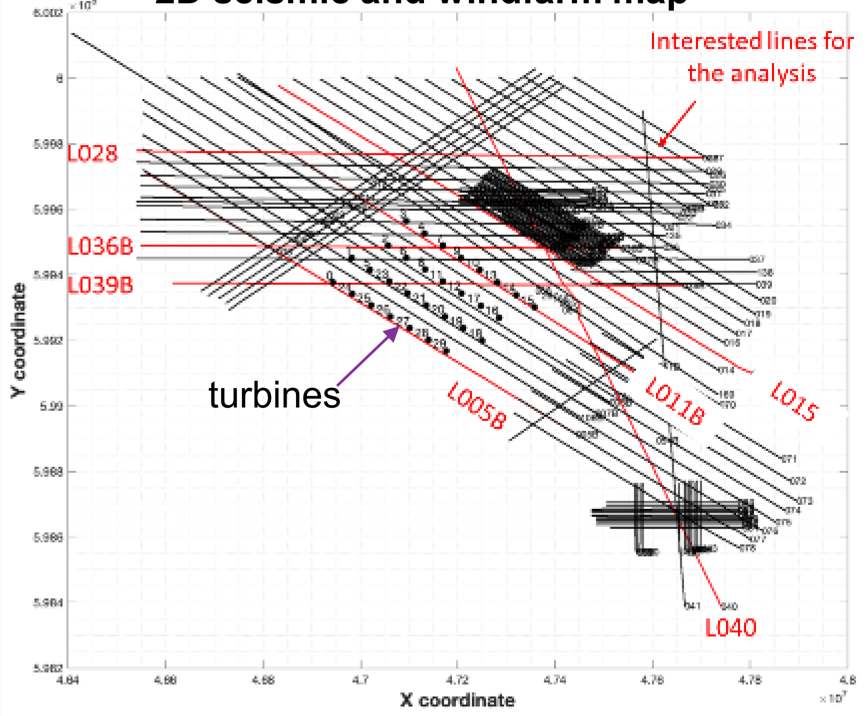
Method:

Pre- and post-stack seismic data was supplied for a series of lines running E-W and NE-SW around and within the Ormonde Windfarm in the East Irish Sea.

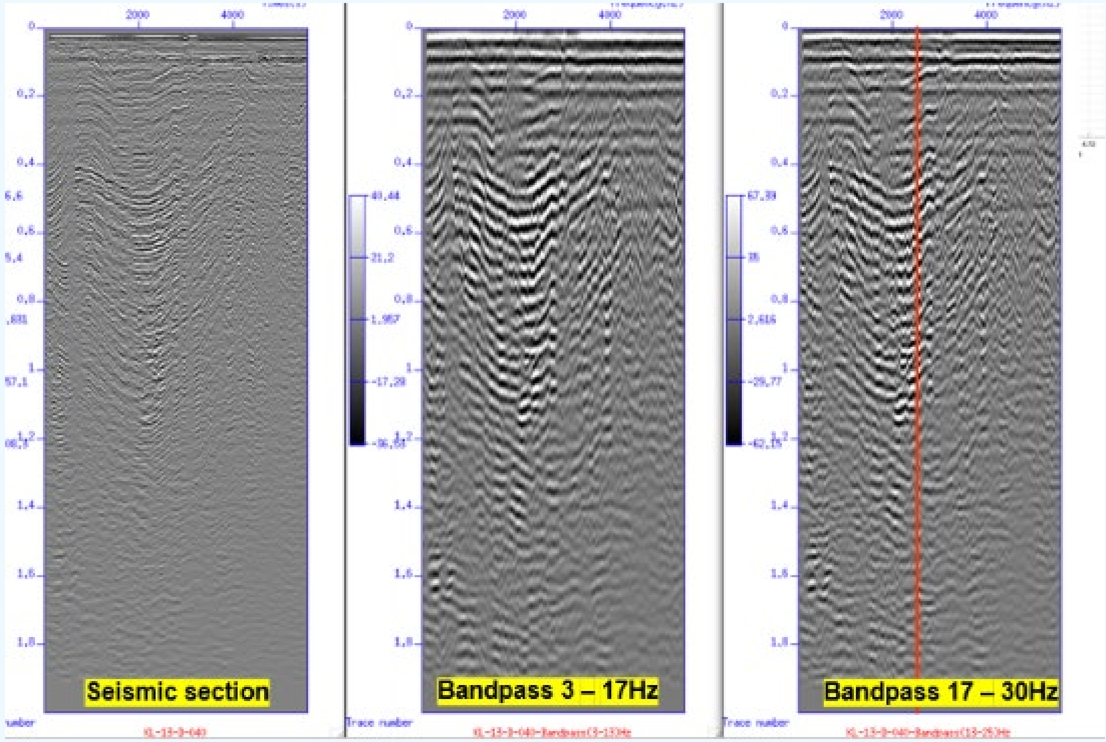
The presence of an active HR seismic source means that typical geological reflectivity and associated multiple trains inevitably **dominate** the frequency spectrums. This is apparent in both post stack analysis of band-pass filtered data and Power Spectral Density (PSD) plots (13.2.1). To isolate the windfarm noise, FK filtering on pre stack, pre-NMO (section 10.9) data was employed remove the dipping events which are more likely to have geological & multiples (13.2.2). This was an attempt to reveal the very small noise trains from other sources: cable tug through the water, vessels, infrastructure sideswipe – and potentially the desired target of any remanent turbine generated noise. The PSD was used to identify low frequency peaks in the spectrum and the amplitude was plotted on a map to identify any potential trends (13.2.3) and a few representative gathers shown (13.2.4), before concluding (13.2.5).

13.2 Introduction to Seismic Study

2D seismic and windfarm map



Final 2D migration and filtered



Post stack data dominated by geology and multiples.

Very shallow water seabed multiples dominate first 400ms
Geology and associated multiples below this.

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2D HR seismic survey comprised series of lines running E-W and NE-SW around and within a 30-turbine windfarm.

- 1ms sampling, frequency range of interest 2-30Hz.

Post stack and raw pre stack (shot) data was supplied.

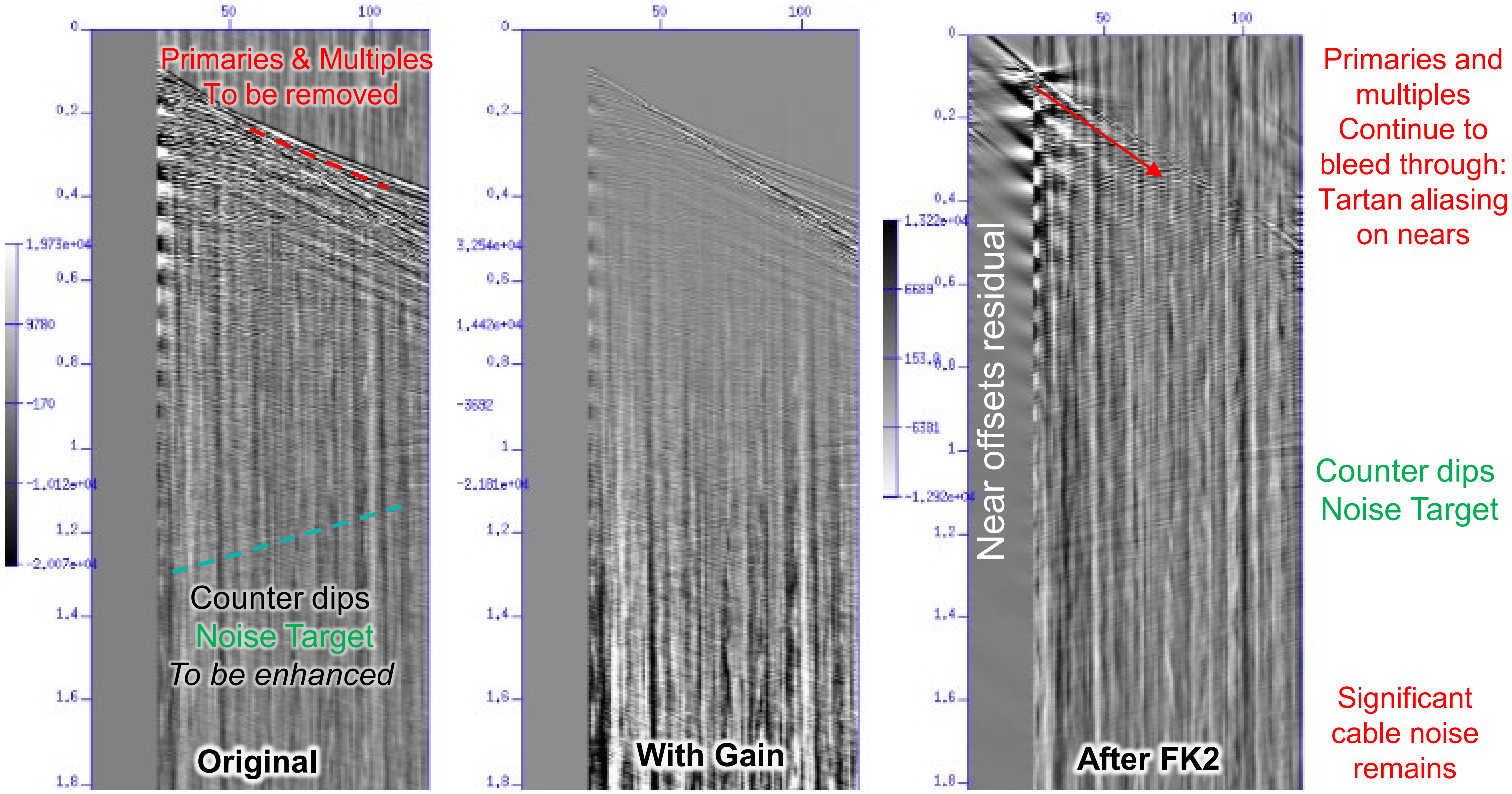
- Selected post stack lines were selected for initial post stack screening.
  - PSD Analysis identified consistent peak in frequency spectrum around 22Hz and 2nd peak in range 10-15-17Hz.
  - Band pass filtering suggested this was most likely dominated by primaries and multiples.
  - Post stack could not separate weak windfarm disturbance/ Post stack data is not useable for separating noise trains.
- Pre stack analysis conducted in Frequency-wavenumber (FK) domain was attempted to remove large geological signature.

13.2.2 Pre stack filtering design

North Sea Transition Authority

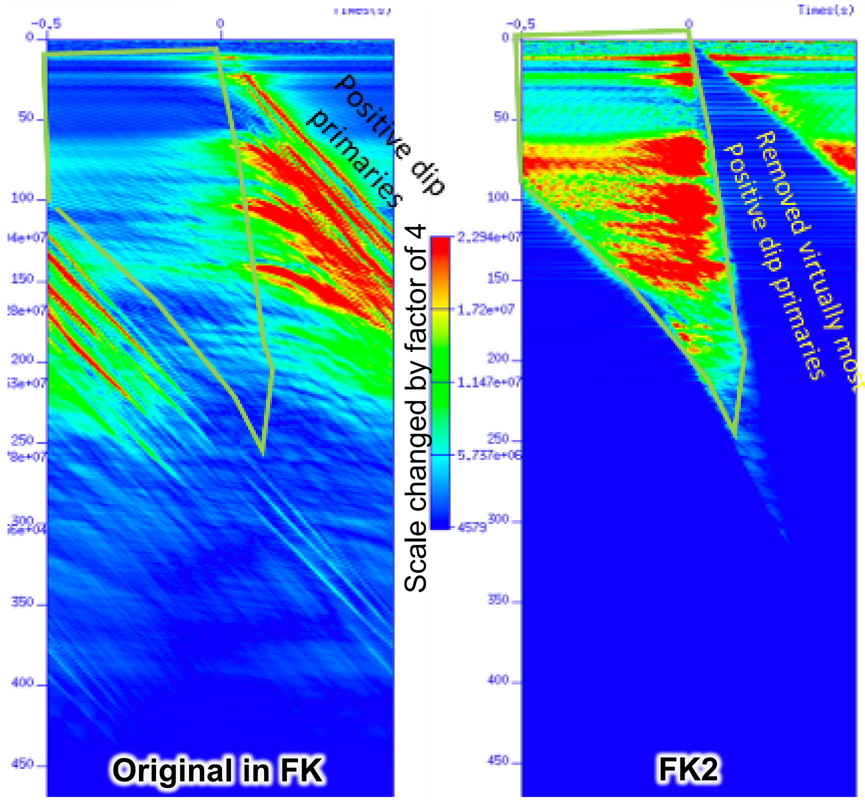
Pre stack data analysed to help separate geology & multiples for potential counter-dipping noise trains of interest.

Offset –Time gathers: Effect of FK filtering



Prior to NMO correction Primaries and multiples dominate with positive dip. Weak contrary dips are the noise target to be enhanced.	Gained original, enhance Low frequency vertical stripes swell / cable tug noise.	Target dips still weak compared to background & decreasing with offset.

Filtering design in FK domain

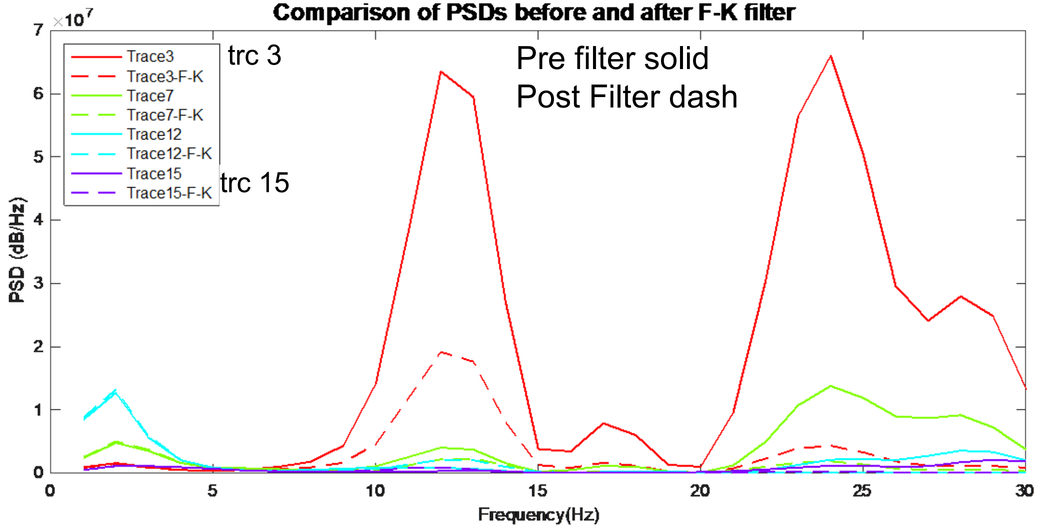


Primaries and multiples dominate with clear positive dip. Isolate sub-area where noise might exist.	Most primary and multiple energy removed.

FK filtering leaves target dips at limit of detection and weak residual primaries/ multiples

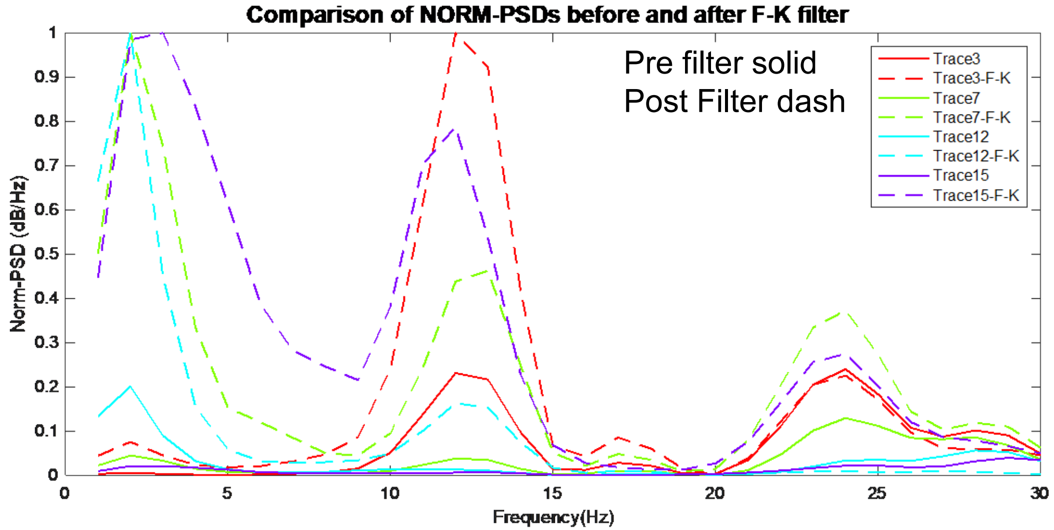
13.2.3a Pre stack filtering on PSD

Comparison of PSDs before (solid) and after (dashed) FK filter
No Normalisation



- PSD peaks at 3Hz (minor), 12Hz and 23Hz.
- Particularly observed on high amplitude near offsets (trace 3).
- Most likely geology and multiples.

Comparison of PSDs before (solid) and after (dashed) FK filter
Normalised



- Normalisation equalised offset spectra; near trace 3 no longer dominating.
- Post FK filtering, PSD peak @
- ~3Hz emergent especially on traces 7-15: Potential target
- 12Hz clearer: on all traces: Geology, multiple or potential target
- 23Hz weaker than other peaks, but ~ unchanged across traces: residual geology & multiple.

3 peaks in PSD generally observed

FK filtering relatively enhanced lower frequencies of possible target

13.2.3b Impact of FK Filtering on PSD maps

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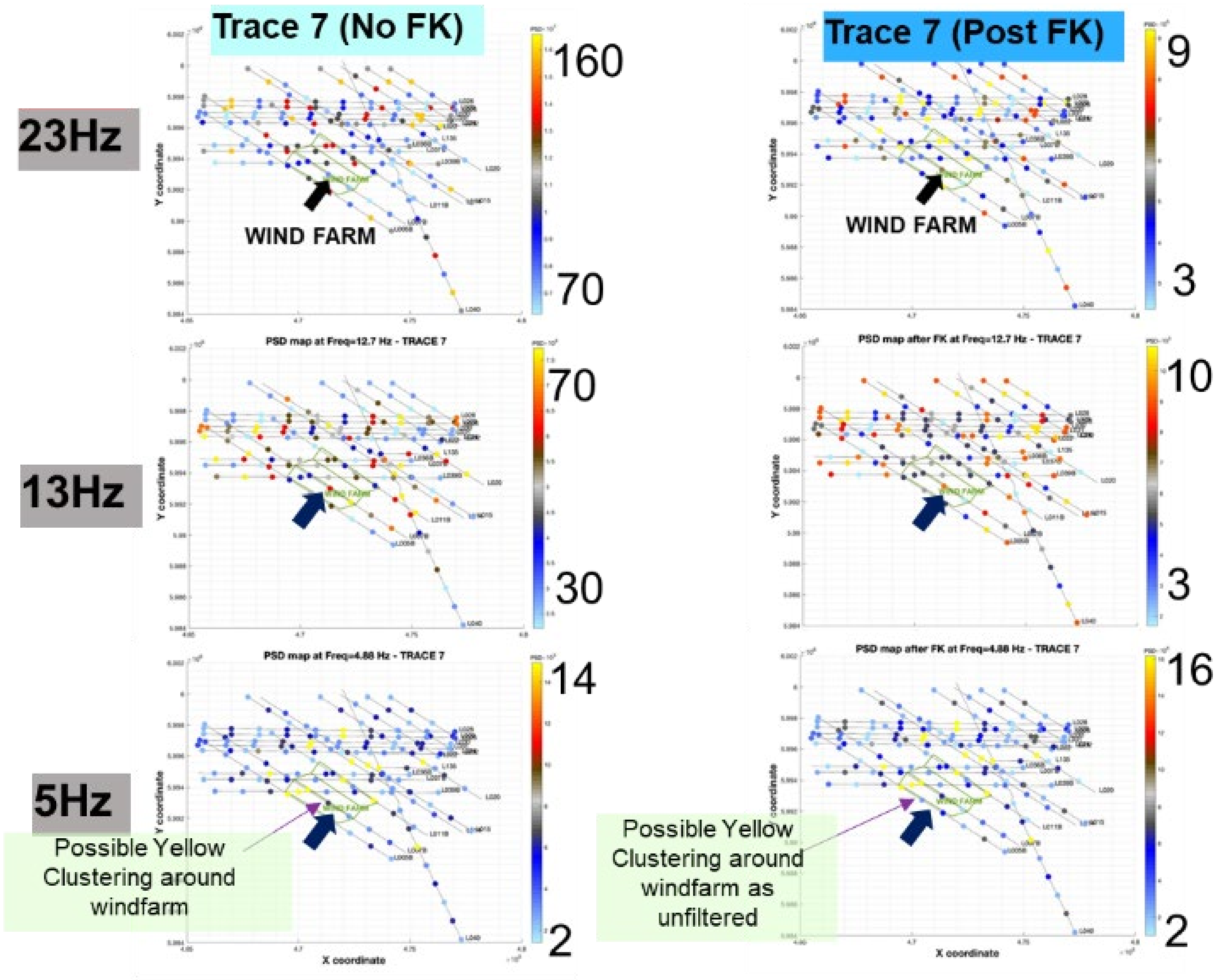

Approach:

1) For the 3 peaks in the PSD, extract amplitude of maximum PSD across a series of shot locations and offset traces.
2) Review Spatial distribution of the PSD to assess if the windfarm is having any impact.

Observations:

1) Higher frequency (23Hz)

Post FK filtering: Big drop in dynamic range & slightly less scattered

- No obvious clustering around windfarm

- Consistent with residual geological primaries and multiples

2) Lower frequencies (5Hz)

Post FK filtering: Minor changes to 5Hz scatter and dynamic range

- Possible clustering within and N of windfarm (Higher proportion of yellow points compared to blue background).

- Consistent with possible noise clustering around WF.
- Alternative explanations:
  - Seismic sideswipe from active source off monopiles.
  - Low frequency cable tug.
  - Tidal noise.
  - Residual geology.

Filtering not changing results on target low frequencies

13.2.3c Offset (trace) variation: PSD at 5Hz

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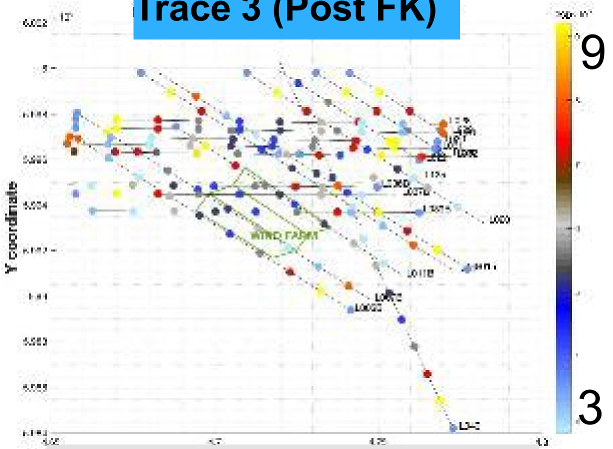
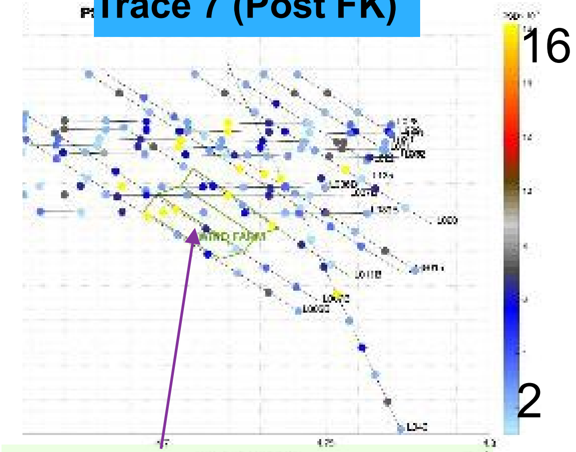
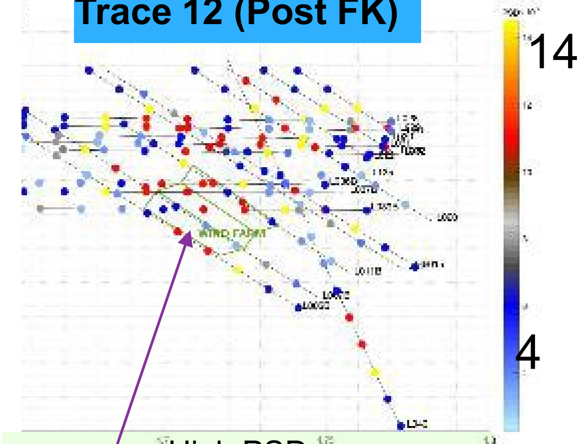


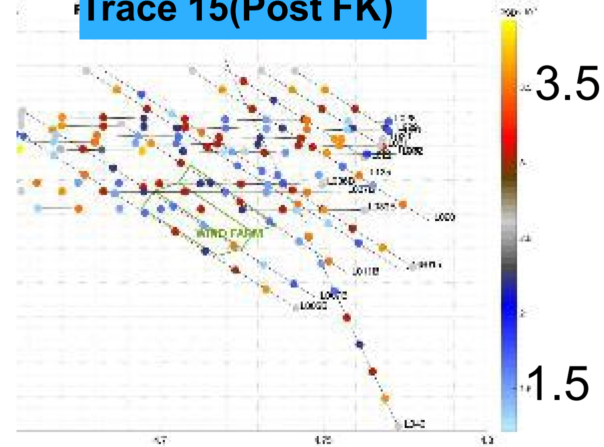
Random pattern
Visually noisy near trace



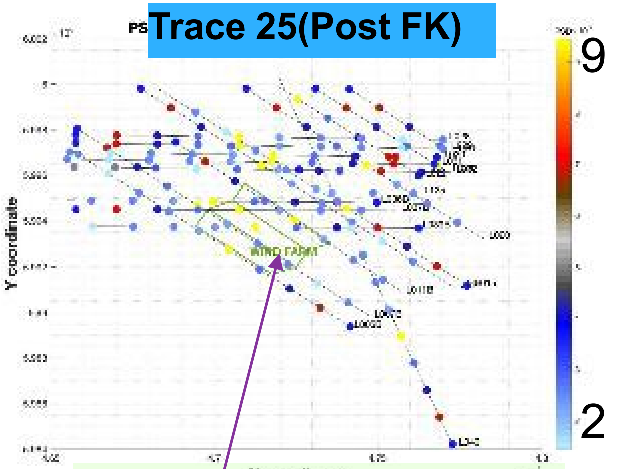
High PSD
More organised Yellow
Pattern around windfarm



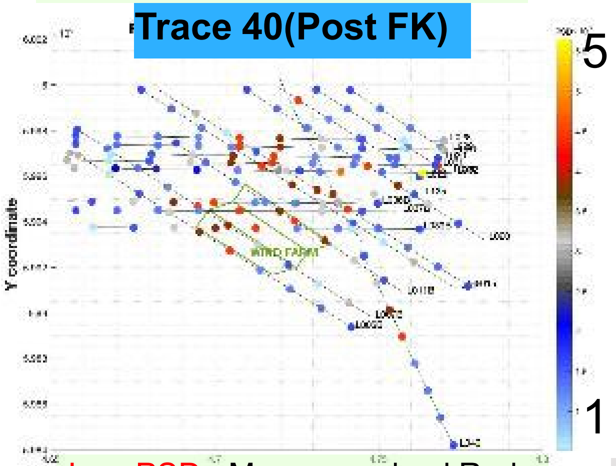
High PSD
More organised Red/Yellow
Pattern around & N of windfarm



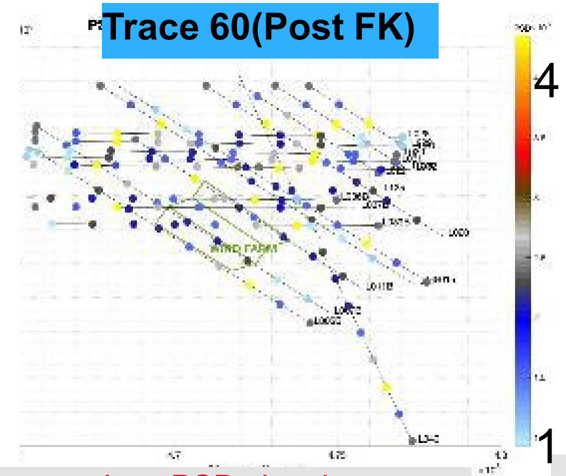
Low PSD/ Random pattern



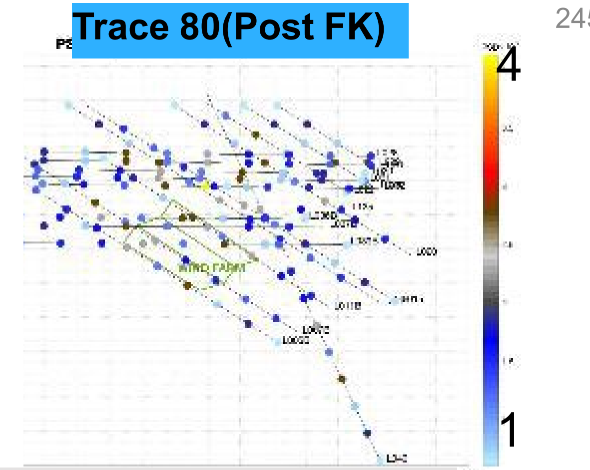
Some yellow clustering around
windfarm/ Reds to NE



Low PSD , More organised Red
Pattern around & N of windfarm



Low PSD signal



Low PSD signal

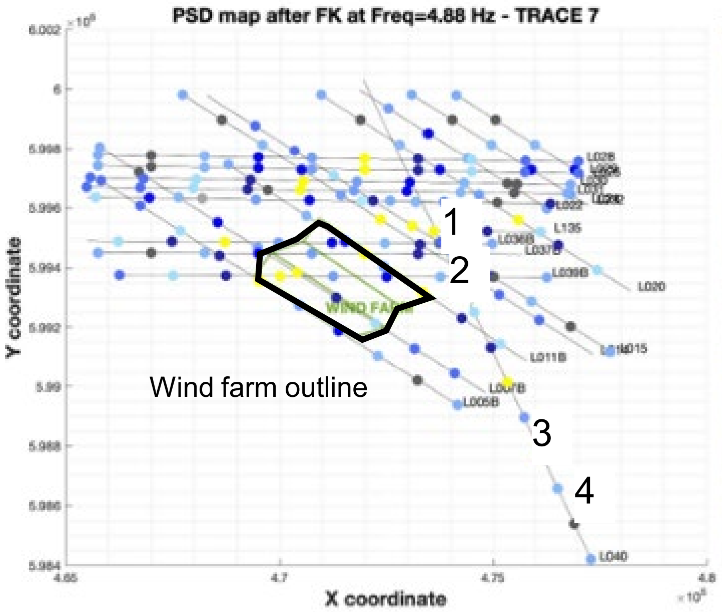
Observations: Low-mid offsets visually give best target signal to noise.
Conclusions: 1) Near offsets residual primary/multiple contaminated and 2) Far offsets low signal to noise.

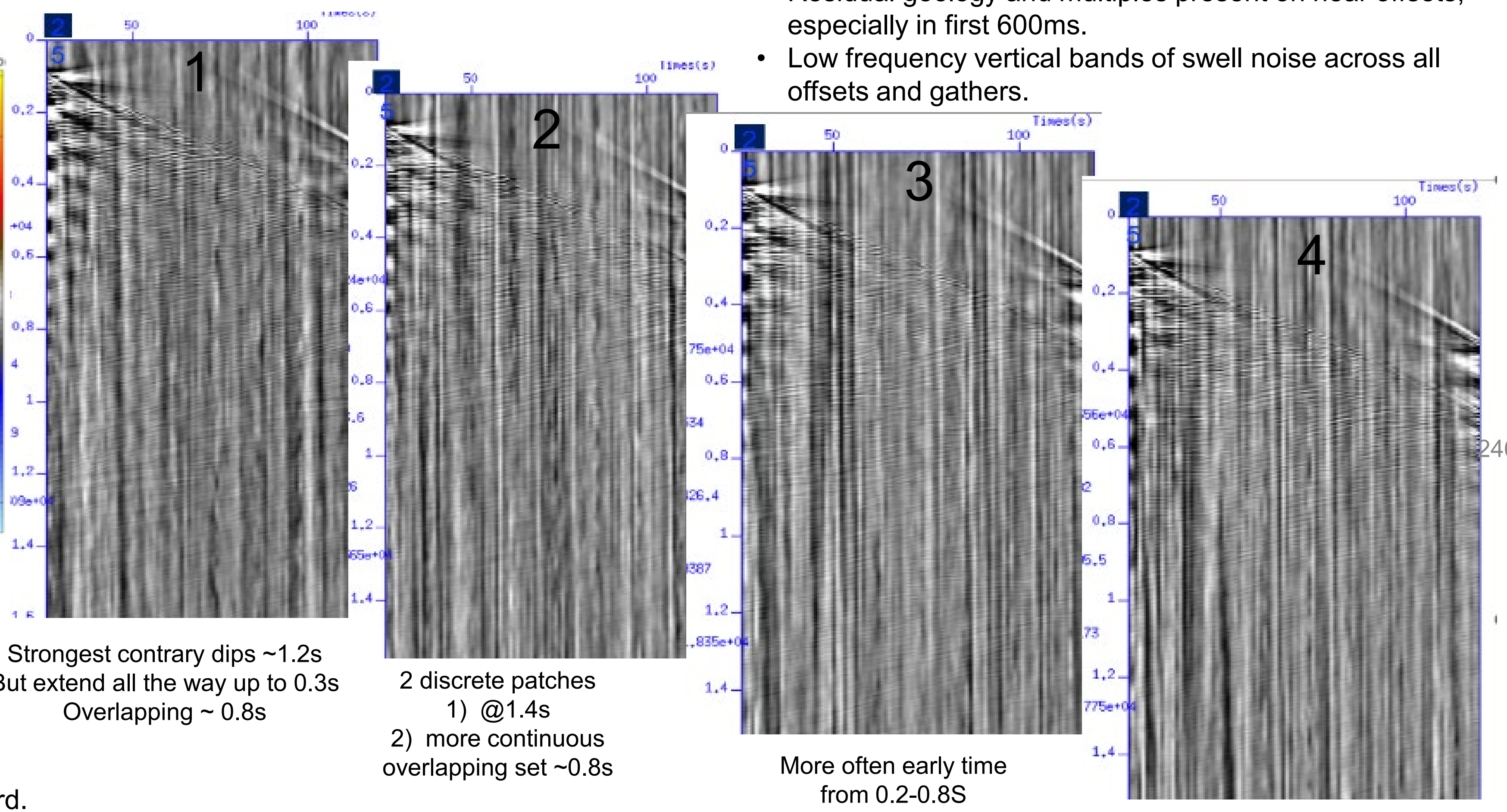
Some indications of PSD clustering in low-mid offsets in and North of windfarm

13.2.4 Example Post FK gathers

North Sea Transition Authority

- Residual geology and multiples present on near offsets, especially in first 600ms.
- Low frequency vertical bands of swell noise across all offsets and gathers.





Strongest contrary dips ~1.2s
But extend all the way up to 0.3s
Overlapping ~ 0.8s

2 discrete patches
1) @1.4s
2) more continuous overlapping set ~0.8s

More often early time
from 0.2-0.8S
But weak response ~ 1.4s

Early time
from 0.2-0.6S
No discernible late time

Observe weak contrary "noise" dips

- Gathers nearest WF show noise across the record.
- More distant ones show noise principally in earlier times.
- Steep angle could give an apparent velocity too great for Scholte waves?
    - If noise source is at an angle to receiver line – the arrivals apparent velocity could increase.

Example pre-stack gathers after FK filtering leaving the residual noise – potentially of windfarm origin

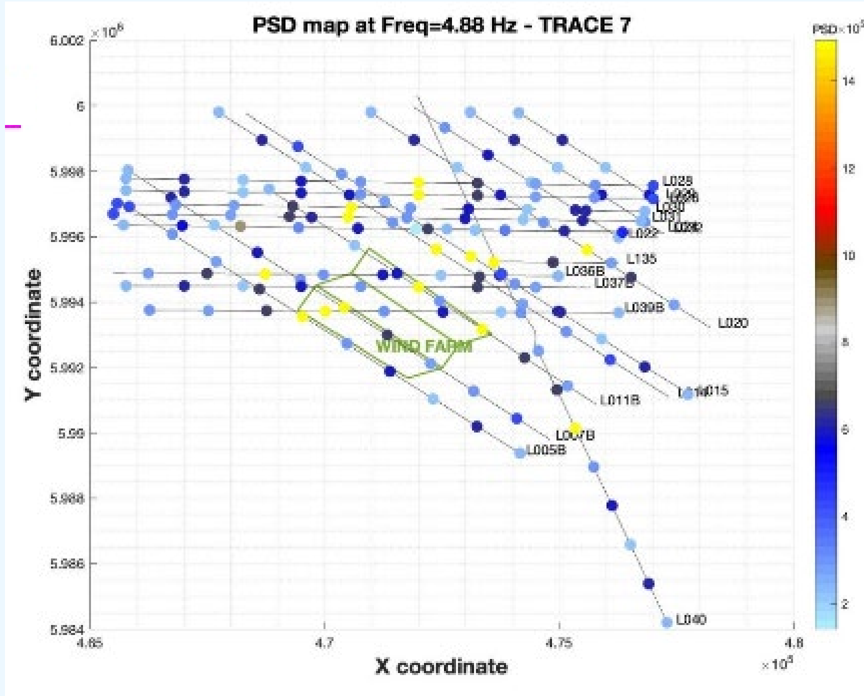
13.2.5 Windfarm noise Review

- Part 1) Onshore focussed Literature review.
  - No published offshore experience. Large Gap in knowledge.
  - Turbine generated noise is low within the seismic bandwidth (>1Hz).
  - “Less than a distant earthquake” beyond 125m.
  - Few discrete peaks exists in the 1-10Hz range.
  - Identified by observational and engineering design.
  - Newer, larger blade turbines have lower frequencies.
  - Turbine motion is very complex interaction of many different factors
    - Wind loading/speed, distance & size of turbine & subsurface properties.
- Part 2) UKCS One intra-windfarm, single short streamer survey:
  - Opportunistic study with available data.
  - Possible suggestion of higher levels on non-induced activity in windfarm.
  - Very low level compared to seismic shot generated.
  - Spatially Highly variable / Very specific to one part of cable and one frequency.
  - Inconclusive as 1) very small response compared to active source, 2) poor seismic positioning, 3) lack of directional control & 4) cannot calibrate to turbine activity at time.
  - Separating High and low frequency Beamforming/spatial filtering to optimise direction signal reception might assist.

Conclusions:

1) Windfarms are a clear operational hazard to active streamer seismic acquisition.
2) They *appear to* generate a low-level acoustic noise source within the seismic streamer spectrum, but different wave propagation means this could appear very different/larger on seabed seismic.
3) To fully assess the level of seismic noise, a controlled seabed seismic experiment is required - with a small array of passive nodes positioned near the edge of a windfarm, correlated with operational data and turbine accelerometers.
4) Using turbines as a low frequency ambient seismic source is an interesting avenue for future research, after suitable dataset is collected.

Map of increased non-shot generated disturbance around windfarm



Slight increase in distribution of PSD magnitude discrete shot points around windfarm
Low frequencies and near/mid offset

Other considerations: It is assumed that the majority of the WT disturbance would be to generate a Rayleigh wave, however there has been no attempt to assess the distance required to build a Rayleigh wave. Bathymetry is known to have an affect on Scholte waves. Towed streamer data may be less influenced by Scholte waves, and these waves are likely to have greater impact on the OBN closer to the firm stratum. In a soft sediment marine environment, the effect could be amplified.

13. Part 3: Potential Use of Ambient Noise for Seismic Imaging

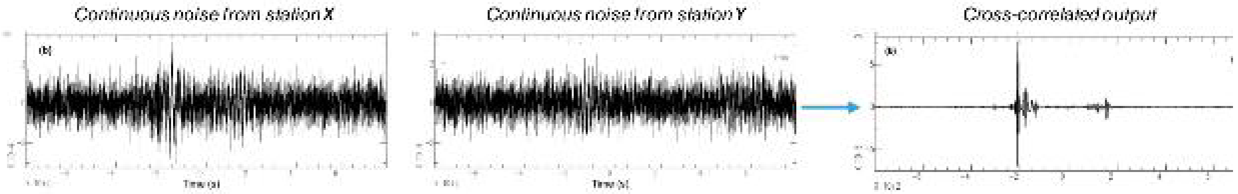
13.3 Ambient seismic

Seismic ambient noise are seismic waves generated by human and environmental activity. This passive microseismic activity is dominated by surface waves which propagate in every direction and occur randomly but carry information about the medium they traverse through.

Ambient-noise seismology is a relatively new passive geophysical technique, based on the interferometry & the cross-correlation of ambient vibrations recorded at two different seismometers over a long period of time. The low resolution of the surface wave at depth means this type of wave is not thought suitable for exploration purposes, but it is presented here as a potential future overburden passive monitoring technology.

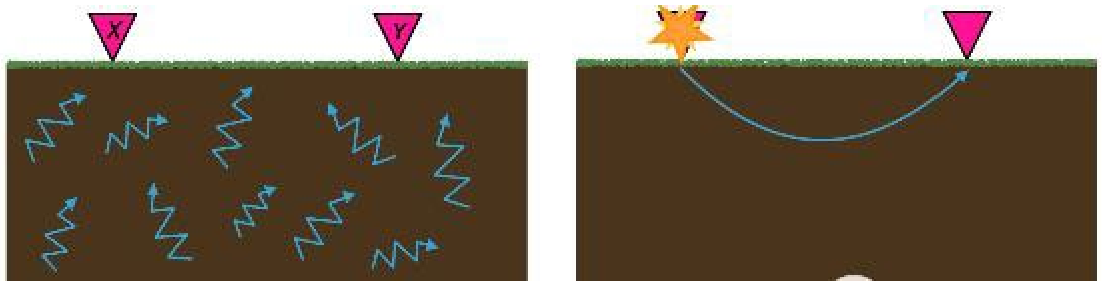
The method uses a cross-correlation of the ambient wavefield at two different seismometers over sufficiently long periods of time. This can be used to approximate the Green's function between the two sensors or a new seismic response by cross correlation at different receiver positions. The receivers can retrieve a signal that would be observed at one receiver if another acted as a source of seismic waves.
In one case measuring small changes in the velocity of seismic waves moving through the earth, we detected changes occurring in the upper ~100 m over several months. Such interferometry is being tested on a range of applications including glacial melt, subsurface void identification using waves generated by motor vehicles.

This section considers the ambient marine low frequency disturbance level and the way it can be used to detect hydrocarbon reservoirs (section 13.3.1) and seep detection (section 13.3.2).



- If this noise is random, the only common "signal" is a function of the impulse response between the two stations

- Each receiver can be turned into a virtual seismic source
- Surface waves are created and S-wave velocities derived from them



(Refs. 13af, 13ag, 13ah, 13ai &13aj)

13.3.1 Tenzor Low Frequency Detection

North Sea Transition Authority

Tenzor acquired a rectangular array of passive seismic OBS data, across a small North Sea oil field with significant direct hydrocarbon indicator and well constrained OWC. This is an area relatively clear of infrastructure and the observed passive background microseismic field is considerably less in this marine environment that onshore. Scholte waves were detected in the frequency range (0.6-1.9Hz).

Offshore and onshore ambient noise field

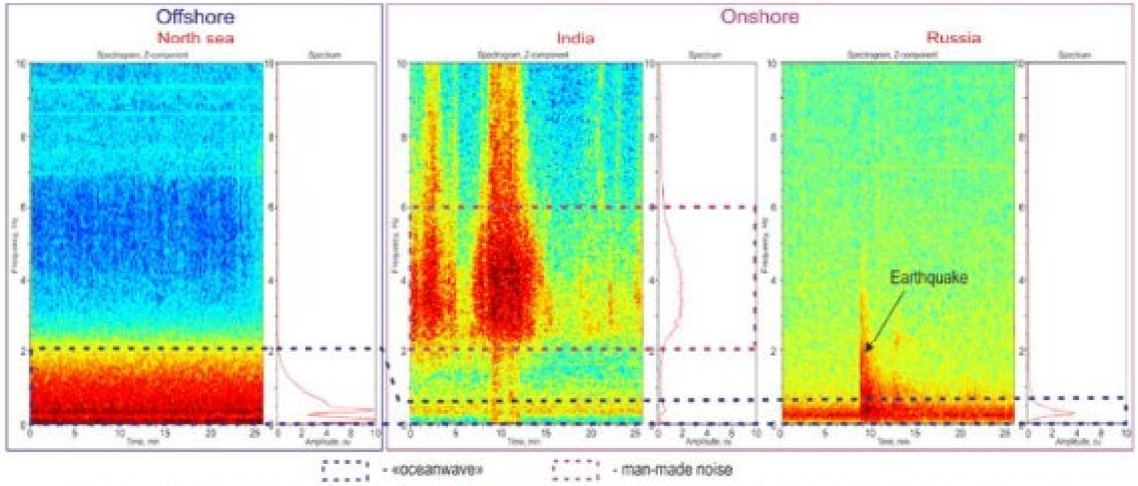
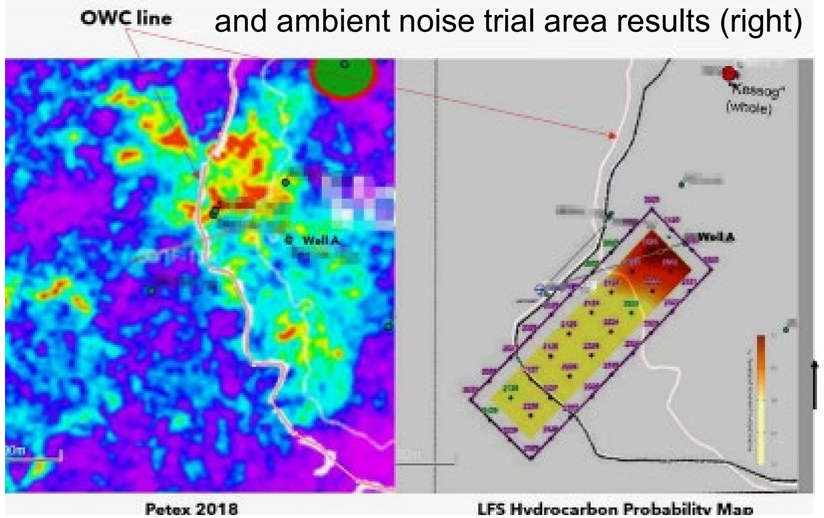
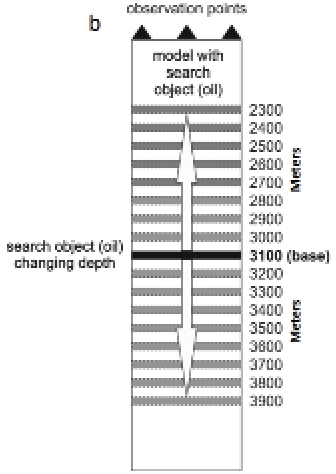


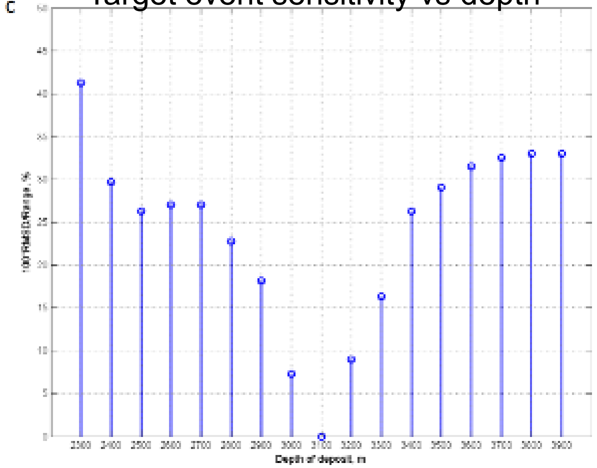
Figure 2: An example of an offshore and onshore passive seismic signal

Comparison of seismic amplitude/ OWC map and ambient noise trial area results (right)





Target event sensitivity vs depth



Modelling hydrocarbon scenarios indicates the oil water contact can be spatially detected by this technique. A further study then showed the degree of depth sensitivity between the modelled and observed OWC.

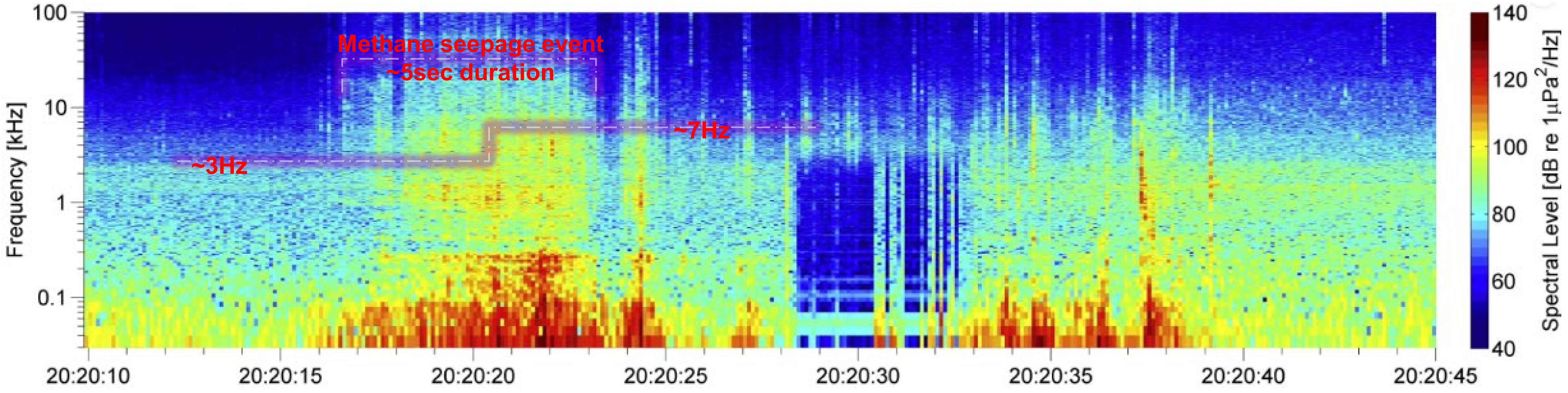
(Ref. 13ak)

13.3.2 Acoustic Seep Detection

North Sea Transition Authority

A combination of very high frequency and low frequency seismic monitoring was undertaken close to a known methane seepage location in UK Central North Sea. This shows a similar baseline noise level interrupted by an interpreted discrete eruption & initiation of methane bubbles at 20:20:16, with broad-band noise returning to a steady state, but at far higher levels afterwards.

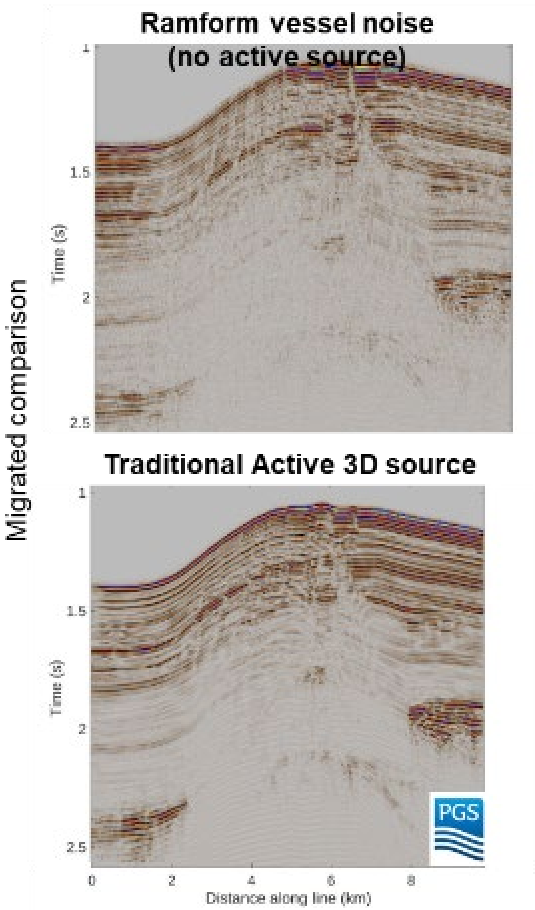
Time variant, low frequency acoustic changes as a result of methane escape

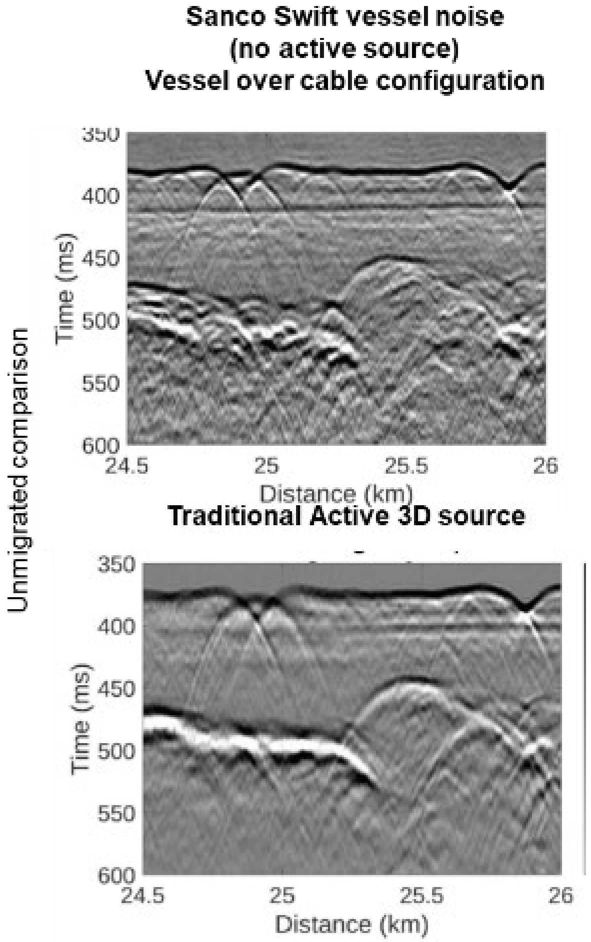


(Ref. 13al)

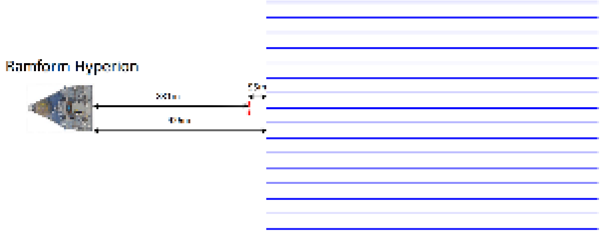
13.3.3 Vessel propellor noise seismic

There are areas around the world where the use of active marine seismic sources is not permitted throughout the year, or only permitted during short time periods, so using the acoustic signals generated by a vessel, without any active seismic sources is being considered. Most vessels are designed to generate as little noise and vibrations in the hull as possible in order to detect the best possible seismic signal. However, the vessel itself can generate broadband signals and these signals are generated continuously while the vessel is moving, allowing for extremely dense source-side sampling along the vessel path. Low resolution seismic images have been obtained from just using vessel noise i.e. comparing with and without active seismic source data.





A deep water/ long offset 16 cable 3D streamer survey was acquired with and without active sources (i.e. just using vessel noise) and produces a passable low fidelity image of the gross structure of the top 300ms. This is frequency band limited up to 30Hz because of the long horizontal distances between vessel and receivers.



A second trial using a second vessel (Sanco Swift) used for its noise and with actives source located above the Ramform cables was acquired in shallower water and again provides a passable gross image of the near seabed, possibly with higher frequency definition around 500ms.

This suggests that low environmental impact monitoring without seismic sources may be possible for the overburden monitoring. This would still require a substantial streamer or OBN receiver array and the expectation of a large signature in the overburden.

(Ref. 13am, 13an & 13ao)

Vessel noise derived seismic for potential monitoring.

13.3.4 Time Lapse ambient noise: Valhall & Ekofisk

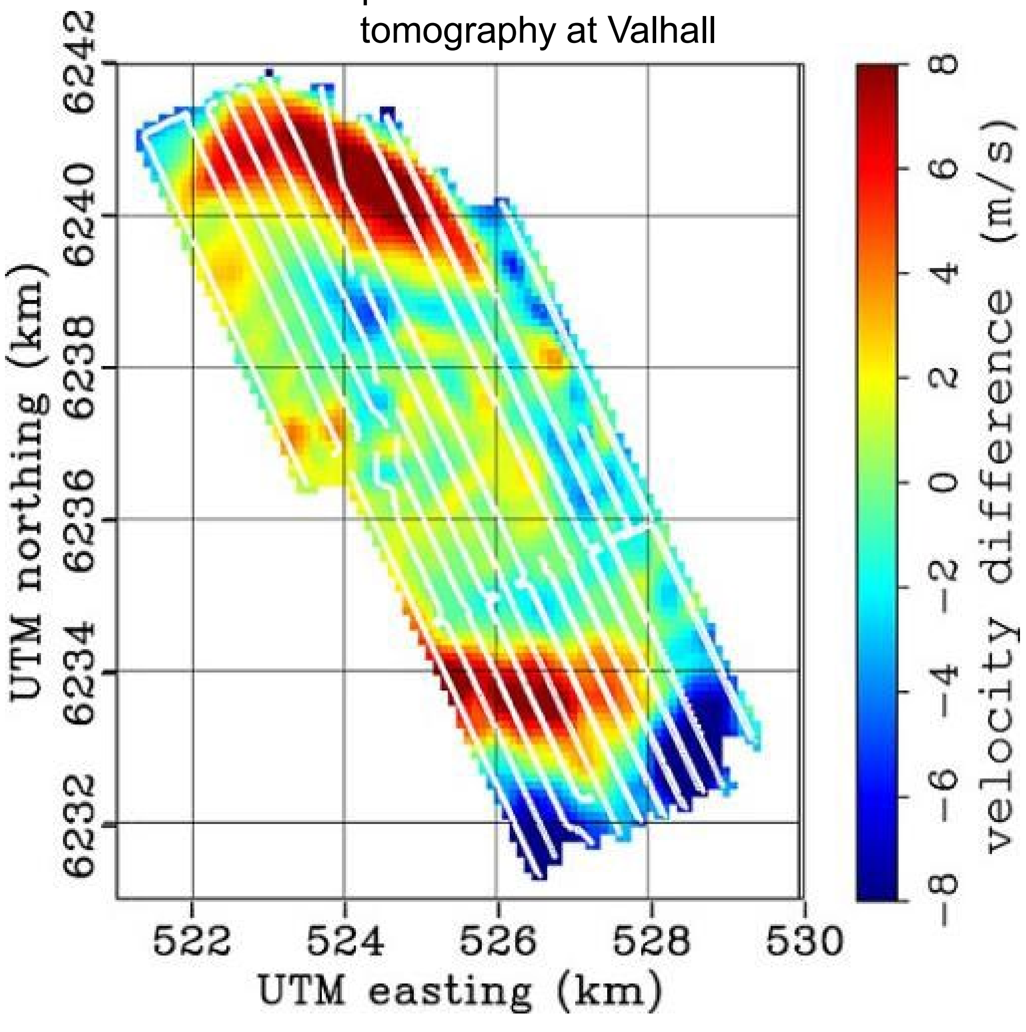
North Sea Transition Authority

Within a dense permanent reservoir monitoring (PRM) seismic array (section 7.21) , deterministic signals can be extracted from cross correlations (CCs) of seismic noise between all pairs of sensors. This results in very dense and well-distributed path coverage. It can be applied to both noise-based surface wave tomographic methods, whilst the permanency and repeatability of the seismic noise and allows continuous monitoring methods.

Studies conducted on the Valhall PRM involved calculating velocity time-lapse differences from ambient-seismic noise by comparing the Scholte-wave group-velocity. The results shows similarities with a time-lapse phase-velocity map obtained from controlled seismic data. Specifically, the a northern and a southern group velocity increase due to compaction and subsidence as a result of reservoir production.

On Ekofisk PRM pressure sensors between 0.4-1.4Hz consisted predominantly of Scholte-wave microseismic energy.
A high-velocity anomaly was identified at the centre of Ekofisk's production-induced subsidence bowl, surrounded by lower velocities. This pattern seemed to result from production-induced seafloor subsidence that altered the near-surface shear strengths. A dispersion analysis showed that the Scholte-wave virtual seismic source exhibited an approximate penetration depth to 600m below the seafloor. These results are significant because they demonstrated that recordings made at the ocean-bottom cable array at Ekofisk Field in the absence of seismic shooting can be used to image and monitor the near surface.

Time-lapse seismic noise correlation tomography at Valhall



Geophysical Research Letters, Volume: 41, Issue: 17, Pages: 6116-6122

(Ref. 13ap, 13aq, 13ar & 13as)

14. Geophysical Technology Direction

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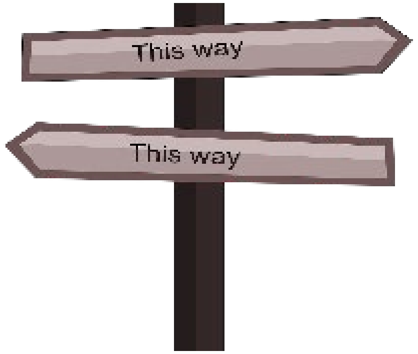
14.1 Geophysical technology direction?

North Sea Transition Authority

There is a range of seismic acquisition and processing options available, with all options having an associated cost (both financial and effort required for completion).

Much of the current UKCS CS & O&G areas are already covered with legacy 3D and there are many excellent examples of very good and cost effective modern FWI reprocessing of the raw data. Whilst this provides assurance up to CS site characterisation (appraisal) stage, often the restricted acquisition parameters and effects of subsequent O&G production/injection mean that it **could not** be considered as a baseline for monitoring of new field/complex development, let alone 50+ year store management.



The NSTA recommends:

- Good quality pre-development 3D survey with broadband frequencies and long offsets parameters appropriate structural imaging of the CS complex (overburden and down to target depth); this also serves as the seismic baseline for future 4D monitoring.
- High resolution seismic for high-risk features (wells, shallow faults) in the overburden.
- Streamer seismic remains the most cost-effective mainstay, but a targeted hybrid with OBN will be necessary for either a comprehensive velocity field by deploying sparse nodes or localised dense node patches around critical infrastructure.
- The NSTA has no technical preference for proprietary vs multi-company acquisition.

Future Implications

The increasing difficulty of access, operational cost & environmental impact of large-scale geophysical data acquisition implies:

1) If not already available, early acquisition of a modern 3D image. A basin scale re-development strongly suggests that opportunities to work together should be used whenever possible.
2) Greater emphasis on the definition & sophistication of the pre-development geophysical description of the CS complex.
3) Support the development of smaller footprint active or passive technologies within the context of updating the geophysical model.
4) Long term spatial and temporal planning; marine infrastructure designed alongside appropriately scoped geophysical surveys which are phased within co-development timetables.
5) Countries bordering the UKCS are facing the same co-location issues (legacy O&G, offshore wind and early CS activities), so improve cross border planning would enable efficiencies and reduced overall environmental impact of MMV activities.

This section attempts to peer into the “crystal ball” - providing some ideas on how technology could develop.
Section 14.2 looks at a single monitoring CS scenario taken from across the range of options available. 14.3 looks from how the traditional workflow approach could be transformed by focussing early effort on building a comprehensive geophysical model whilst the promise of low and alternative monitoring in the future. Finally, 14.4 indicates those seismic related areas supported by the NZTC technology centre.

14.2 One Possible CS Scenario

Each complex is different and has unique MMV requirements. One *possible* scenario, drawn from the wide spectrum of monitoring options available is outlined:

	CS Site Access & Characterisation (appraisal)	Pre-injection/ Development Baseline	Initial Injection Build-up	Injection Plateau	Closure/Post-Closure
Monitoring area	Reprocess legacy 3D to improve overburden description and provide more accurate complex and store imaging.	Full Monitoring area: Acquire/utilise modern high-quality 3D baseline towards the end of any pre-existing hydrocarbon production phase (Note 1).		Repeatable 4D seismic survey for aquifer stores or if fluids (CO_2 or hydrocarbons) have been displaced into the aquifer. Switching to lower impact technologies (Note 2).	Closure 4D based on track record? Continue to passively monitor for trigger events.
Targeted Risk		Acquire High resolution baseline site survey around key current or legacy infrastructure or higher risk near surface geology.	If triggered by unusual injector behaviour or DAS, repeat site survey.	**If required:** Repeat site survey around injection wells or higher risk near surface geology.	
Injector Scale (CO_2)		Install wellbore DAS (Distributed Acoustic Sensors) in deviated wells and acquire local baseline 3D image.	Repeat wellbore DAS to determine near wellbore CO_2 distribution and provide wellbore seal re-assurance.	DAS redundant?	

Note 1) predominantly streamer but consider benefit of incorporating a) sparse nodes to provide a comprehensive velocity field for deeper targets b) optional localised HD node patches around surface infrastructure for hybrid imaging.

Note 2: Develop lower impact, highly targeted, acquisition monitoring technologies focussed on detecting perturbations from the model. Comprising a) Trigger seismic: Passive listening for subtle reservoir changes (microseismic), b) Active seismic: deploying smaller active sources or utilise the ambient noise field (passive seismic), c) Autonomous surface or underwater vessels to improve accessibility and reduce cost/ impact of large-scale vessel, d) Long duration node deployment for localised highly repeatable seismic on demand.

A potential seismic implementation scenario – with greater emphasis on pre and early injection phase activity

14.3 A Geophysical Model Revolution?

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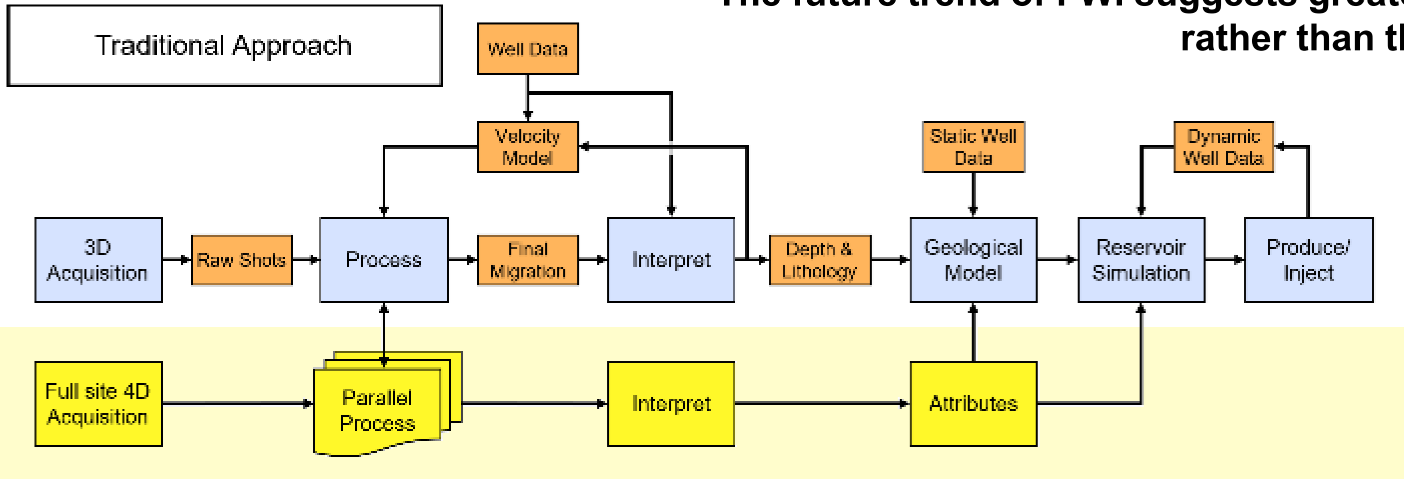
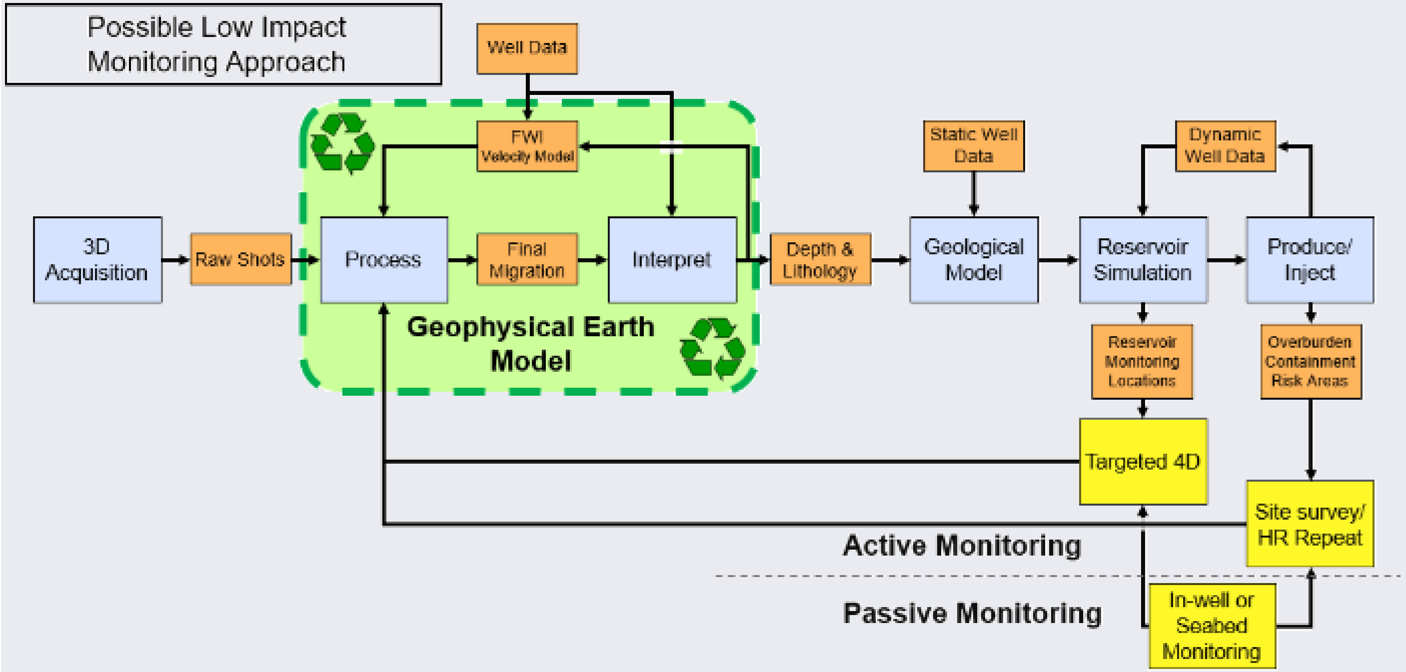
The future trend of FWI suggests greater attention to developing a geophysical Earth model, rather than the traditional feedback loop



Long established approach to acquisition and processing has remained largely unchanged for decades. This is a fixed, sequential model, and difficult to make major changes to the workflow(s).

For CS aquifers storage with an expected 4D signature, the first full scale monitoring survey with a known technology is important to fully test the model.



Possible lower monitoring activity scenario
There are signs of a revolutionary new approach reliant upon greater emphasis on defining a Geophysical Earth Model incorporating comprehensive seismic imaging from the start of the workflow.
In theory, this workflow could be developed to incorporate a range of geophysical data types (continuous passive seismic and focussed active seismic data), but possibly including other datasets (gravity data). The workflow is defined by iteration, assisted by technological advances in computer processing and accessible digital storage.

Front end loading the pre-injection baseline and 1st monitor could lead to lower impact monitoring throughout plateau and closure

14.3 Ongoing Technology Projects

The Net Zero Technology Centre (NZTC) is actively pursuing a number of cross industry technology avenues some of which have synergies with the approaches described here and may be applicable to future seismic developments.

(Ref. 14a)

- New sensors: fibre optics deployed horizontally at surface.

A low cost, permanent, adaptive monitoring system to monitor CO_2 plume development using surface deployed distributed acoustic sensing (S-DAS). This idea offers a radical approach to monitoring CCS sites with a move away from 4D seismic monitoring which focuses on full field monitoring to a plume centric and 'health monitoring' system (SLB).

  - Co-location monitoring solutions (CCS and wind).
  - Importance of acquiring an appropriate 4D seismic measurement to update a subsurface model.
  - Vision of evergreening a 'performance subsurface model' leading to triggered monitoring.
  - Extending this to use passive ambient noise as a 'seismic source'.
  - Funding via grant to address challenges raised by previous NSTA reports.

- SAPIENT (Seismic Auto Processing and Inversion to Explore New Targets). From raw field data, SAPIENT offers the potential to fully automate seismic data processing in an end-to-end data driven process. Testing on Magnus data.

- Autonomous nodes.

(Refs, 14b, 14c & 14d)

Introducing the Net Zero Technology Centre

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