Hornsea Project Four

bp Closing Remarks

Deadline: 7 Date: 10 August 2022
Document Reference: G7.8
Revision: 01

Prepared	Amy Stirling, Pinsent Masons, August 2022
Checked	Francesca de Vita, August 2022
Accepted	Aparna Majmudar, August 2022
Approved	Jamie Baldwin, August 2022

G7.8
Ver. no. A

Revision Summary

Rev	*Date*	*Prepared by*	*Checked by*	*Approved*
01	10/08/2022	Amy Stirling, Pinsent Masons	Francesca de Vita	Jamie Baldwin

Revision Change Log

Rev	*Page*	*Section*	*Description*

Table of Contents

1 OVERVIEW

1.1.1.1 This document provides the Applicant's response to bp's Deadline 6 submission (**REP6-046**) and closing remarks. The Applicant has prepared this response mindful of the significant volume of information already before the Examining Authority in relation to coexistence between Hornsea Four and the NEP project in the "overlap zone", and the multiple submissions already made orally and in writing by the parties during Examination.

1.1.1.2 As such, the Applicant has focused this response on the following points:

a) the decision making "flow-chart" provided by bp at Annex 8;

b) bp's proposed protective provisions provided at Annex 2; and

c) bp's further response to the "Sewell Report" provided at Annex 4.

1.1.1.3 For completeness, the Applicant can also confirm it has updated its proposed protective provisions for bp within Part 8 of Schedule 9 of the draft DCO at Deadline 7 as follows:

a) paragraph 2(b) has been amended for clarity, to specify that the consents required for the NEP Project must be obtained within four months of the coming into force of the Order;

b) paragraph 10(b) has been updated to require that the crossing and proximity agreement between the parties must take account of a minimum distance between each turbine generator of 2,000m in all directions from the centre point of the turbine, in respect of the undertaker's works (i.e. those in the overlap zone).

1.1.1.4 The Applicant's proposed protective provisions provide the only course of action which achieves national policy requirements for co-existence.

1.1.1.5 The Applicant is of course happy to address any further queries the Examining Authority has in relation to co-existence prior to the end of Examination.

2 DECISION MAKING FLOW CHART

2.1.1.1 bp has provided a "Summary Decision Tree for ExA/SoS" at Annex 8 of its response.

2.1.1.2 In that response, bp states that:

a) if the ExA / SoS consider co-location feasible in "the Exclusion Area" (i.e. the overlap zone) then NEP would not develop the Endurance store in the Exclusion Area if wind turbines are also located there; and

b) if there is no provision addressing the risk of "significant compensation" in the Interface Agreement (**IA**) as a result of the Exclusion Area, then NEP would "in all likelihood" not utilise the Endurance Store in the Exclusion Area.

2.1.1.3 The Applicant queries the accuracy of the statements made in the flowchart.

2.1.1.4 bp entered into a Deed of Covenant and Adherence to the IA only last year (10 February 2021) based on terms which:

a) were fully transparent as to the existence and nature of the Applicant's right to develop Hornsea Four in the overlap zone;

b) have the stated aim of seeking "to ensure successful co-existence of wind and carbon storage projects on an overlapping area of seabed";

c) contain a detailed set of provisions relating to compensation for any loss, should co-existence not be possible, with a related dispute mechanism.

2.1.1.5 bp has not submitted any evidence to the Examination to justify its move from a position of "adherence" to the terms of the IA in 2021, to now in mid-2022 alleging it renders its East Coast Cluster (ECC) plan unviable (see e.g. paragraph 2.4 and paragraph 3.10.1 of bp's Deadline 6 submission and bullet 2 in the "Outcomes" box of the decision tree).

2.1.1.6 bp is a commercial entity with a prominent position in the UK energy market. It is difficult to conceive that bp entered into an agreement which rendered its ECC plan unviable only 18 months ago. If the IA was fatal to the ECC plan as bp now alleges, then it would have been open to bp not to participate in the ECC plan rather than accede to the terms of the IA. It did not do so, and instead, it freely covenanted to adhere to the terms of the IA without substantive modification. bp has also continued to develop the ECC cognisant of the terms of the IA.

2.1.1.7 It is clear that the IA provides a workable solution via facilitating coexistence between the parties, or otherwise providing for compensation. Nevertheless, given bp's submission that the IA is not fit for purpose (see e.g. pdf page 71 of bp's Deadline 3 submission **REP3-047**), it is notable that bp has never expressly sought to renegotiate the terms of the IA with the Applicant, including the terms on which compensation is payable.

2.1.1.8 Finally, as explained in its previous submissions and further elaborated in part 4 below, the Applicant is confident that Hornsea Four and the NEP Project can achieve co-existence in the overlap zone and bp would not be required to abandon its development of the Endurance store in the overlap zone, should wind turbines associated with Hornsea Four be consented in that area.

3 BP'S PROPOSED PROTECTIVE PROVISIONS

3.1.1.1 bp has provided revised protective provisions at Annex 2 of its response.

3.1.1.2 The Applicant fundamentally disagrees with these provisions for the following reasons:

a) rather than working from a premise of seeking to achieve co-existence, the provisions operate as an exclusion of Hornsea Four from the overlap zone at bp's sole discretion for a period of three years ("the Longstop Date" which is in effect a longstop period). There is no incentive on bp to seek to achieve co-existence within this timescale. This is fundamentally contrary to policies supporting co-existence and the national need for both offshore wind and carbon capture and storage;

b) the compensation provisions are unnecessary and unworkable. Firstly, they are unnecessary as the IA already provides a framework for compensation as agreed between the parties only as recently as last year (where no renegotiation was sought). Secondly, the provisions are unworkable the Applicant will not obtain certainty as to whether compensation is payable until the Longstop Date, with payment not being made until some years later;

c) during the lengthy longstop period, the Applicant will be forced to work on the premise that it will not be permitted to develop Hornsea Four in the overlap zone. As Hornsea Four is a single phased project, this means that the Applicant will most likely be unable to accommodate development in the overlap zone within its project programming in the event bp waives its requirement for the exclusion zone before the Longstop Date. Ultimately this could mean that no project is located within the overlap zone, with detrimental results for UK policy for energy security and net zero. As described in the Applicant's previous submissions, this would also result in an increased WTG density in a smaller developable area outside of the overlap zone, which would lead to increases the wake loss impacts of the wind farm and can have a significant effect on the generation performance. In turn, increased wake losses also increase the detrimental impact on the overall business case for the project, particularly should Hornsea Four enter into the highly competitive Contract for Difference Auction Round model where projects are effectively competing against other projects. An inefficiently designed wind farm with high wake losses is very likely to be at a significant disadvantage;

d) the provisions no longer seek to disapply the IA in its entirety but instead seek to remove the liability of bp to the Applicant under that agreement. The Applicant has made detailed legal submissions against the disapplication of the IA in **REP5-076**, which apply equally to bp's revised draft protective provisions, but are not repeated here. The Applicant maintains its position that the disapplication of provisions of the IA would be to deprive the Applicant of its contractual rights in an unprecedented manner, which is not in the public interest, and that there are alternative means freely available to the parties to revisit compensation quantum via renegotiation of commercial terms. The Applicant also maintains that such a provision requires consent from The Crown Estate, which has not been provided, nor is it likely to be given The Crown Estate's submissions to the Examination on this point. The Applicant refers to The Crown Estate's Deadline 6 response (**REP6-066**) and ultimately considers disapplication of terms of the Interface Agreement to be a closed point (see also the Applicant's response at **REP5a-021**).

3.1.1.3 The Applicant's position is that bp's proposed protective provisions are unjustified and not supported by policy.

3.1.1.4 The Applicant also continues to question bp's assertion (which appears in part to drive its PPs and its rejection of the Applicant's), that NEP will take a Final Investment Decision on the NEP Project in June 2022. According to bp's Deadline 1 submission, the NEP Project involves "two offshore pipelines leading from each of Teesside and Humber to the Endurance Store" (see paragraph 2.3 of pdf page 121 of **REP1-057**).

3.1.1.5 The DCO application for the Net Zero Teesside project is currently in Examination, with a decision expected in May 2023 (following which there will be a six-week period for legal challenge). The DCO application for the Humber Low Carbon Pipelines project (part of Zero Carbon Humber) has not yet submitted its DCO application (expected Q3 2022 according to the PINS portal). It would be highly unusual for bp to take FID on the "NEP Project" in June 2023 without key consents in place. This consenting uncertainty would also be coupled with uncertainty regarding the timetable for BEIS progressing the delivery investment model for CCUS.

4 RESPONSE TO BP'S FURTHER COMMENTS ON THE SEWELL REPORT

4.1.1.1 The Applicant has included Mr Sewell's response to bp's comments on his report as an Annex 1 of this response.

4.1.1.2 This is supported by the following additional annexes:

a) Annex 2: Energy Integration Project Phase 3 Spatial Co-Location Project, NSTA, June 2022;

b) Annex 3: CCS MMV & Spatial Co-Location Project, NSTA, 26 July 2022;

c) Annex 4: Measurement, monitoring and verification (MVV) of Carbon Capture Storage (CCS) Projects with Co-Location considerations, NSTA, July 2022.

4.1.1.3 For the avoidance of doubt, Mr Sewell's report and subsequent submissions are supplemental to the evidence in the OREC/NZTC report and do not supersede it, as alleged by bp at paragraph 5.2 of its Deadline 6 submission (**REP6-046**).

4.1.1.4 Finally, as Mr Sewell notes, the issues pertaining to access (rigs, wells and helicopter access requirements) were outside of the scope of his report. Nevertheless, the Applicant has provided a response to these matters in its Deadline 1 submission (**REP1-057**) and is confident that coexistence on these matters is achievable, in line with policy, as it is for oil and gas operators in the vicinity of offshore wind farms, including Hornsea Four.

5 FINAL COMMENTS

5.1.1.1 The Applicant is advancing a position of facilitating coexistence, supported by public policy and a commercial agreement entered into between willing parties since 2013 (and to which bp acceded in 2021).

5.1.1.2 The Applicant acknowledges that policy supports development of offshore wind and CCUS, both of which are critical to the UK achieving its net zero target and mitigating the effects of climate change.

5.1.1.3 The Applicant is clear however that the public interest in the delivery of the full capacity of Hornsea Four has increased since the submission of its DCO application.

5.1.1.4 The need for Hornsea Four has been established in F1.6: Statement of Need (**APP-234**), however given the significant change to the global energy landscape, and the publication of the British Energy Security Strategy, this need has been strengthened, as set out in the Addendum to the Statement of Need which is provided alongside this submission at Deadline 7.

5.1.1.5 Notably, the British Energy Security Strategy establishes a policy to **deliver** 50GW of offshore wind by 2030. To put that into context, the Addendum to the Statement of Need finds that National Grid's TEC Register lists 51GW of offshore wind projects with connection dates before 2029, of which 20GW are connected or committed to delivery. It finds that 97% of those projects must connect, at their current estimated capacity and without delay, in order to meet the BESS aim of 50GW of offshore wind operational and connected by 2030. There is no scope for delay or attrition if energy security and net zero policies are to be delivered.

5.1.1.6 As such, it is imperative that Hornsea Four is delivered in a timely manner, maximising its full capacity to not only meet net zero targets, but to provide much needed security of supply to the GB grid.

5.1.1.7 As acknowledged in the Addendum to the Statement of Need, whilst CCUS retains its important place within the BESS, it has not attracted a more prominent role relating to energy security, given it is an enabler of eliminating carbon emissions from fossil fuel use, rather than providing a power source in itself (unlike Hornsea Four).

Hornsea 4 - NEP Overlap

Comment on bp response

This document has been prepared by Andrew Sewell of Xodus Group Limited upon the instructions of Pinsent Masons LLP for Orsted UK Limited, to provide commentary on bp's responses to deadline 6

August 07, 2022

ASSIGNMENT L400721-S00
DOCUMENT L-400721-S00-D-REPT-002

XODUS

London

Cheapside House
138 Cheapside . London
EC2V 6BJ . UK

[redacted]

Feedback on bp's further technical response Annex 4 – 06/08/2022

In 2.1.4 bp states that hybrid OBN and towed streamer seismic data would not provide a "*consistent, reliable and repeatable seismic image*". The NSTA co-location slides [1] provide an example of hybrid streamer and OBN survey around an obstructed area in Malaysia (slide 11), and although this does not appear to be for 4D purposes, there is no reason why a hybrid survey would be less repeatable than individual streamer or OBN surveys.

2.6 states "*Given Mr Sewell's agreement with bp's position concerning emerging technologies and the need for NEP's MMV plan for Endurance to use 3D/4D seismic imaging, the evidence before the Examining Authority does not support finding that emerging technologies would allow co-existence to occur in the Exclusion Area or that NEP does not need to use 3D/4D seismic imaging in its MMV plan*"

It is my opinion however (and I believe bp's also based on section 3.1 of Annex 4) that neither OBN nor P-Cable are "emerging technologies" but are proven technology in general, even if not yet for 4D for CO2 monitoring. The NSTA co-location slides [1] and [2] provide ample evidence of this for OBN, including bp's experience at Clair Ridge, slides 19 and 20 in the June 2022 slide pack [1].

2.16 states "*Given Mr Sewell's agreement with bp's position on these issues* [the use of streamers in a wind farm and P-Cable in general], *the evidence before the Examining Authority does not support finding either that a grid formation of 2x2km would allow co-location in the Exclusion Area or that NEP could use short streamers of less than 200m to acquire seismic data in the event wind turbines were present in the Exclusion Area.*"

To clarify the point made in this section, my opinion is limited to saying that P-Cable on its own is not a viable solution for Endurance. However P-Cable in addition to OBN is a viable solution. OBN would be targeting the Bunter reservoir and sealing formations directly overlaying the Bunter, while the P-Cable would be targeting the shallowest formations from seabed to 500m TVDSS.

4.1 describes bp's initial response to my report and that the scope and timeframe of the field trials and modelling I suggested are unrealistic. I think there is a misunderstanding about the nature of the field trials and modelling that I was suggesting. The field trials I was proposing are related to logistics rather than direct data quality and so do not require a full 3D seismic survey to be acquired and processed.

4.7.2 states "*if in theory it might be possible to use OBN to acquire good quality seismic data at Endurance, if there were wind turbines in the Exclusion Area, then no matter how good the quality of the data, there would be "gaps" in the seismic data at the location of the wind turbines. .... This means that no matter how good the seismic data acquired by OBN and P-cables might be, it would not be sufficient for NEP's MMV plan as NEP would not be able to image the complete Endurance store*"

The purpose of the field trials and modelling that I am suggesting is to show whether or not this is the case. The field trials would show how close to a wind turbine nodes and air guns could be used. The modelling would show the impact of this on seismic data quality and ability to monitor the CO2 plume.

In 4.8 to 4.13 I understand that bp are proposing something more extensive than I had in mind. For example I don't think it is necessary to acquire an actual OBN 3D seismic survey as part of this. If an OBN 4D baseline survey is needed it can be done any time prior to CO2 injection starting. With regards to sand waves, my concern was with nodes being moved during a survey. Field trials for the impact of sand waves physically moving nodes around does not require a full seismic acquisition. In general, I think bp is describing a different set of trials and modelling to what I envisaged. bp might think that more is required than I had suggested, but this has not been the subject of any discussions so far.

In particular, 4.8.1 states "*by its nature, forward modelling is at best only indicative of a likely "best-case" scenario of what is theoretically possible;*"

The modelling I am suggesting is not to produce a single base case, but to consider a range of seismic survey designs and exclusions zones to see the relative impact on signal-to-noise ratio and imaging of each of these scenarios, and in comparison to a base case of long streamer acquisition.

In 4.13.3 bp states "*the rig, well and helicopter access requirements identified by bp (which, as explained above in paragraph 2.17 have not been challenged by Mr Sewell ….) mean there could not be co-existence in the Exclusion Area.*"

This is simply because access issues were outside the scope of my report, and not because I have reviewed these issues and agree with bp's conclusions.

bp's comments in 4.20 are conflating the direct impact of wind turbines as source of seismic noise, with the indirect impact on seismic data quality from small exclusion zones around each turbine. The July NSTA co-location slides [2] contain comments on the direct noise issue from work being done by Heriot Watt university (slide 44). The conclusion says "Windfarms …. appear to be a low level acoustic noise source within the seismic survey spectrum" and "less than an [sic] distant earthquake". This indicates to me that it should not be a major factor in seismic data quality. I would still maintain that the level of noise from an inactive turbine is likely to be less than that of an active one, although this is not something that I have investigated. Measuring wind turbine noise is another of the field trials that I suggested, and which could be done is a short time frame, around existing wind turbines.

In 4.30 bp states "…. *there are large sand waves and substantial ripple effects present on the seabed of the Endurance area and that the strong tidal currents in the area mean there is a real risk that nodes placed on the seabed could move during the time a survey was being undertaken, which would degrade the seismic data that was acquired..*"

I agree and this is why I suggest that a small number of nodes could be placed on the seabed for the equivalent of the duration of a seismic survey, and their movements tracked to quantify the problem. This would not need a full 3D seismic survey to be acquired.

The comment in 4.33 somewhat overstates what I intended. I think that OBN costs will reduce relative to streamer, but will stay more expensive in the time frames that matter to this project and therefore not "significantly reduced". This is also the opinion of the authors of the NSTA co-location report [1] and [2]. Additionally, I don't think that any emerging technology will have matured sufficiently to make a difference to MMV requirements for Endurance. As noted above however, it is my opinion however (and I believe bp's also based on section 3.1 of Annex 4) that neither OBN nor P-Cable are "emerging technologies"

The issues raised in 4.42 relate to how exclusion zones around wind turbines may affect OBN data and is the reason why I suggest conducting field trials and modelling which would be able quantify the relative impact of different acquisition techniques and exclusion zones the ability of 4D seismic to monitor the CO2 plume.

Comments on Annex 5: February 2021 (Endurance 4D Seismic Feasibility) slide pack

I had not seen this slide pack before but there is not much in there that is new or different to the other documents that I had seen. The summary table on slide 6 is good. I note that this concludes that a dense OBN on a grid of 200m x 50m is a viable solution for 4D monitoring at Endurance, with the caveats about mobile seabed and exclusion zones around wind turbines. This is a different definition of dense OBN to that contained in the table on slide 11 of bp's October 2021 slide pack, which describes a dense OBN as a grid of 100m x 50m, which is twice the number of nodes as assumed in the February 2021 summary. The question of what constitutes a sufficiently dense OBN grid to enable the necessary MMV at Endurance is what could be answered the modelling I suggested.

It is also worth noting that bp estimated the cost of dense (100m x 50m) OBN as £260M-£315M over the lifetime of Endurance MMV compared to £17m for HR towed streamer, in the October 2021 slide pack. In other words more than fifteen times the cost. The work done by the NSTA co-location forum and shown in the June 2022 slide pack [1], estimates that OBN 4D seismic for CCS would be two to three times the cost of towed streamer over the lifetime of a "large aquifer" storage project in UKCS (slide 8). This highlights that different assumptions about survey design can have a large impact on cost estimates.

References

There are 2 versions of the NSTA co-location slide pack referred to in this document

[1] is "Energy Integration Project Phase 3 Spatial Co Location Project" by Ronnie Parr, June 2022

[2] is "CCS MMV & Spatial Co-Location Project" by Richardson & Parr for the NSTA, July 2022.

North Sea Transition Authority

Energy Integration Project Phase 3
Spatial Co-Location Project

Co-location forum:

Ronnie Parr

June 2022

4D seismic monitoring context

North Sea Transition Authority

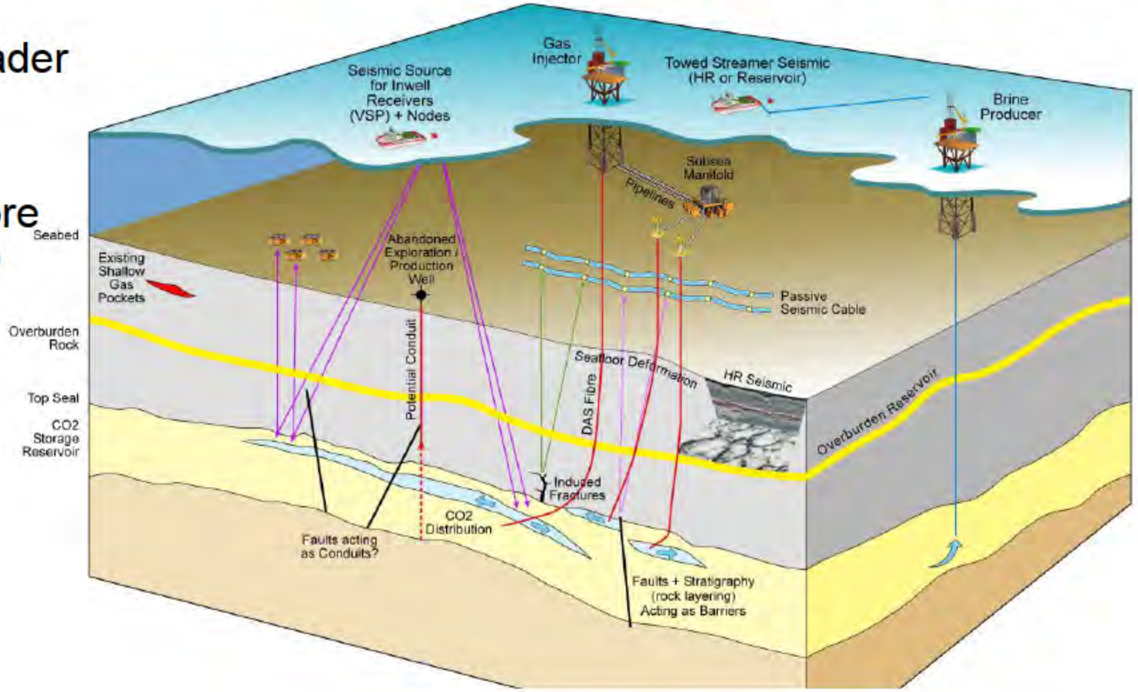
- Seismic is expected to be an important component of the broader MMV (measurement, monitor, verification) technology portfolio.
- Actual MMV approach needs to be customised for specific store (seismic streamer, OBN, gravity, well surveillance, traces, geochemical, benthic,..)
- A CCS complex operator may identify a number of risks & uncertainties that could be mitigated by repeated seismic observations of the rock and fluid response to CO_2 injection.

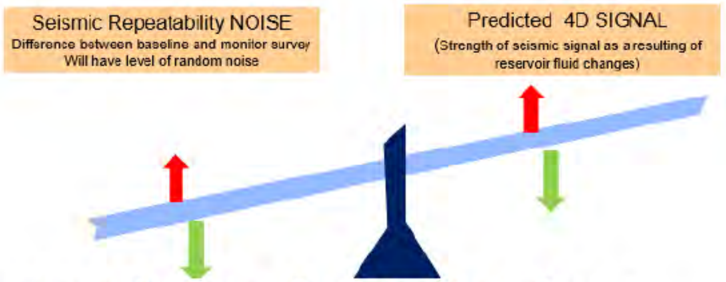
Important considerations:

1) Magnitude of reservoir **signal** generated by production/injection between the baseline & monitor surveys *(this NSTA study)*

2) Sufficiently low level **noise** (non- production) differences between the seismic surveys *(NSTA study in prep)*

3) There are clear plans to use the monitoring data to mitigate specific risk and uncertainties *(NSTA MMV study 2022 in press)*





OBN (Ocean Bottom Node) seismic is a geophysically superior reservoir imaging technology especially for complex imaging targets or within a constrained/ co-location environment. However the cost of each OBN 4D survey (baseline & every monitor) is 2 to 5 times more expensive than it streamer equivalent. This remains a major drawback and cannot justify the cost in most CCS situations.

Project Status

North Sea Transition Authority

- **MMV (Monitoring Measurement Verification):-** NSTA report — Publication summer 2022
- **OBN project (Graham Lilley/ Ronnie Parr)** — Publication ~ end 2022 ★
  - Seismic acquisition review complete
    - Status of Nodes technology & near obstruction acquisition
    - OBN vs Streamer Cost Comparison
  - Processing, Case studies & Assimilation underway
    - Baseline & Monitor Parallel Processing (Streamer or OBN) can improve reliability
    - Many successful hydrocarbon (Streamer & some OBN) 4D case studies
    - Very few CO_2 studies
- **Seismic Signal/ CO_2 Detection Project (IKON & Ronnie Parr)/** — Publication ~ end 2022 ★
  - 5 Wells: Petrophysics & Fluid (Brine, Methane and CO_2) Substitution complete
    - IKON finishing individual well documentation & presentation at EAGE Madrid June 2022
    - Completed Reviews with individual operators
    - Results ~ in line with expectations
- **Windfarm noise (Heriot Watt/ Colin Macbeth)** — Report expected mid June for review
  - Literature review underway
  - 2D seismic shot data analysis: Delayed due to data reading

Acknowledgements

OBN study

AGS, AkerBP, BlueOcean Seismic Services, CNPC BGP, bp, CGG, CNOOC, ION, Energeo Alliance, equinor, magseis fairfield, Ørsted, PGS, PXGEO, Schlumberger, Shearwater, Signum Geophysical Ltd, TGS, TotalEnergies

IKON detectability study

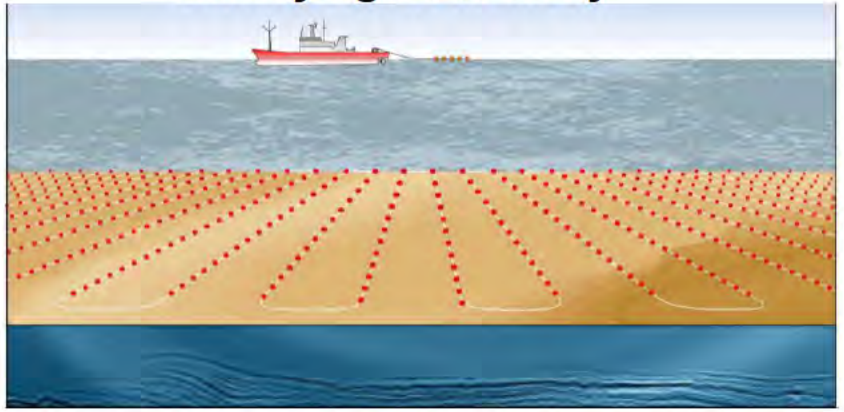
bp, eni, equinor, Harbour Energy, Ikon Science, Shell, Storegga

OBN (Ocean Bottom Node) Seismic Project

OBN acquisition methodology

North Sea Transition Authority

Surveying node array

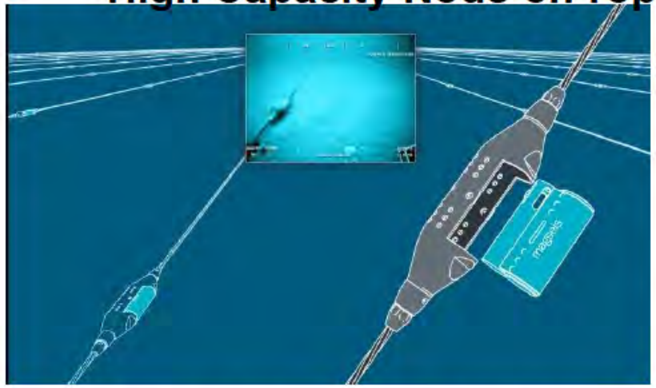


Potential Node Handler (M/V Ocean Pearl)

- Lays/Picks up nodes in very controlled fashion
- Can/does go close to installations
- “redundancy of propulsion/steerage”
    - Not necessarily DP (dynamic positioning)

Node & deployment on a rope

High Capacity Node-on-rope



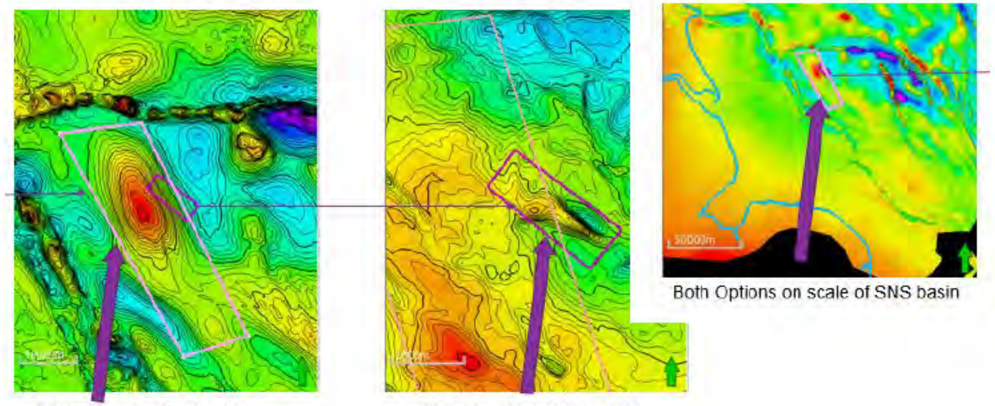
7kg node

- Cables hold sensors/ No electronics in cable
- Autonomous
- Vessel holds several hundred kms of cable
- Robotic back deck speeds up deployment/ removes manual handling
- Automatic data transfer

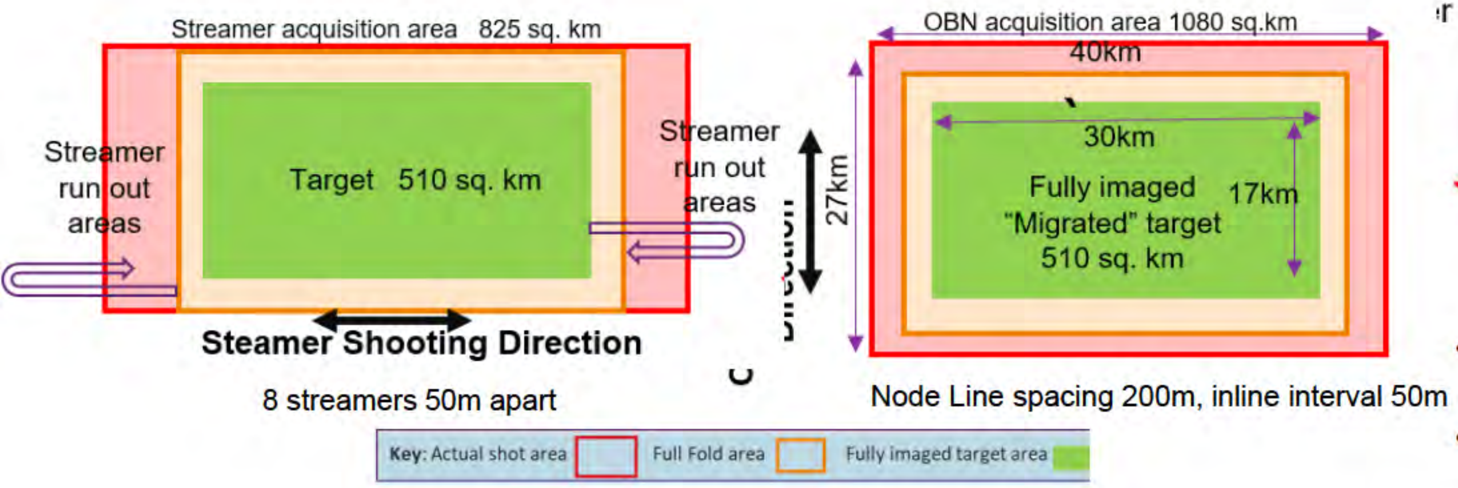
Modern efficient OBN acquisition

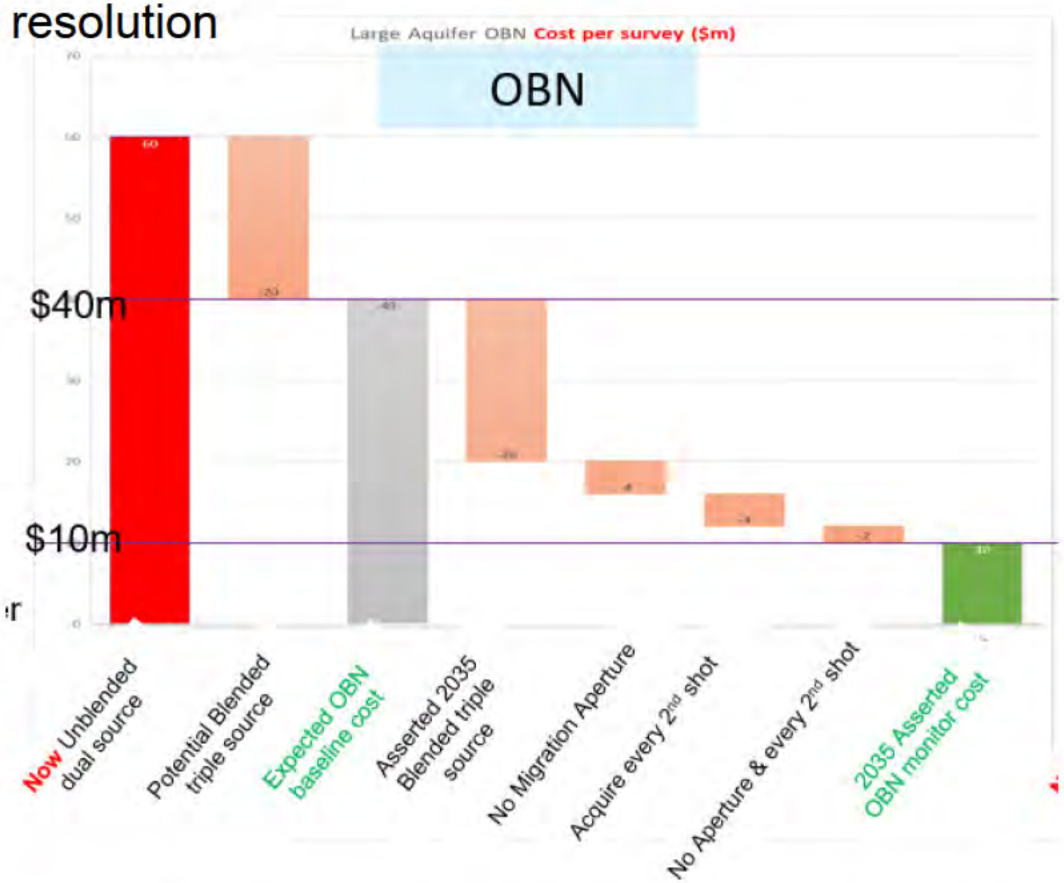
Acquisition cost comparison

- Compare generic large "aquifer" survey vs small "depleted gas" field
  - Using OBN & streamer configuration to give comparable resolution



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



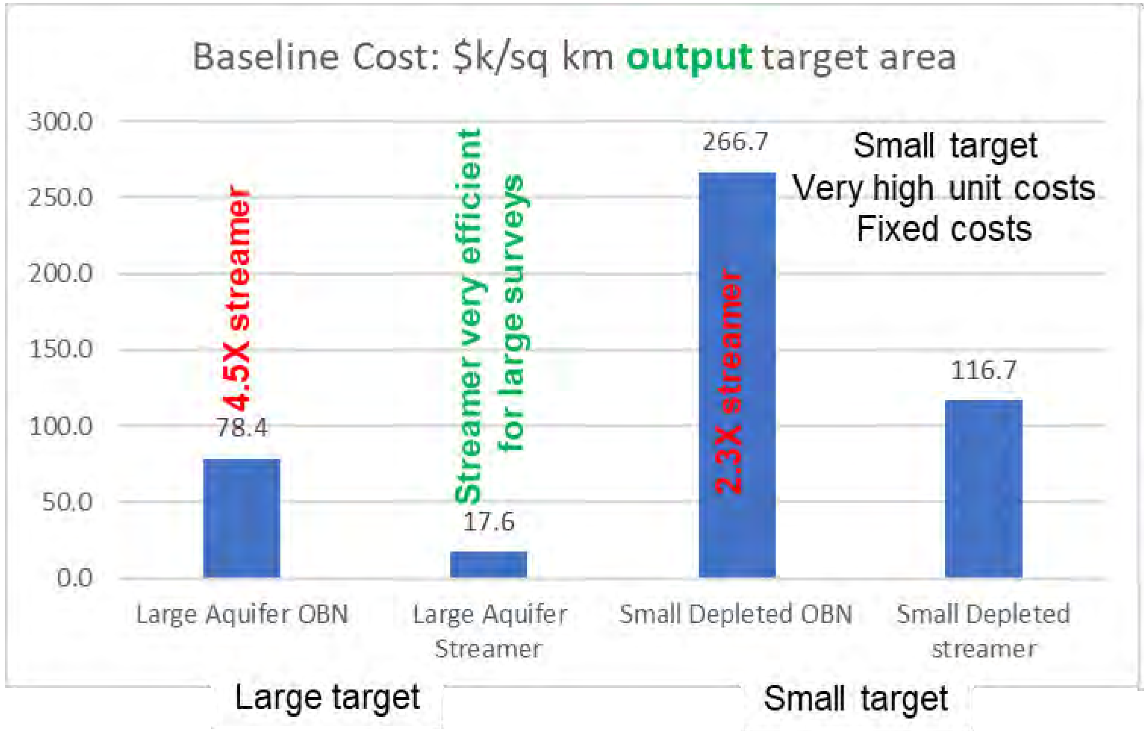


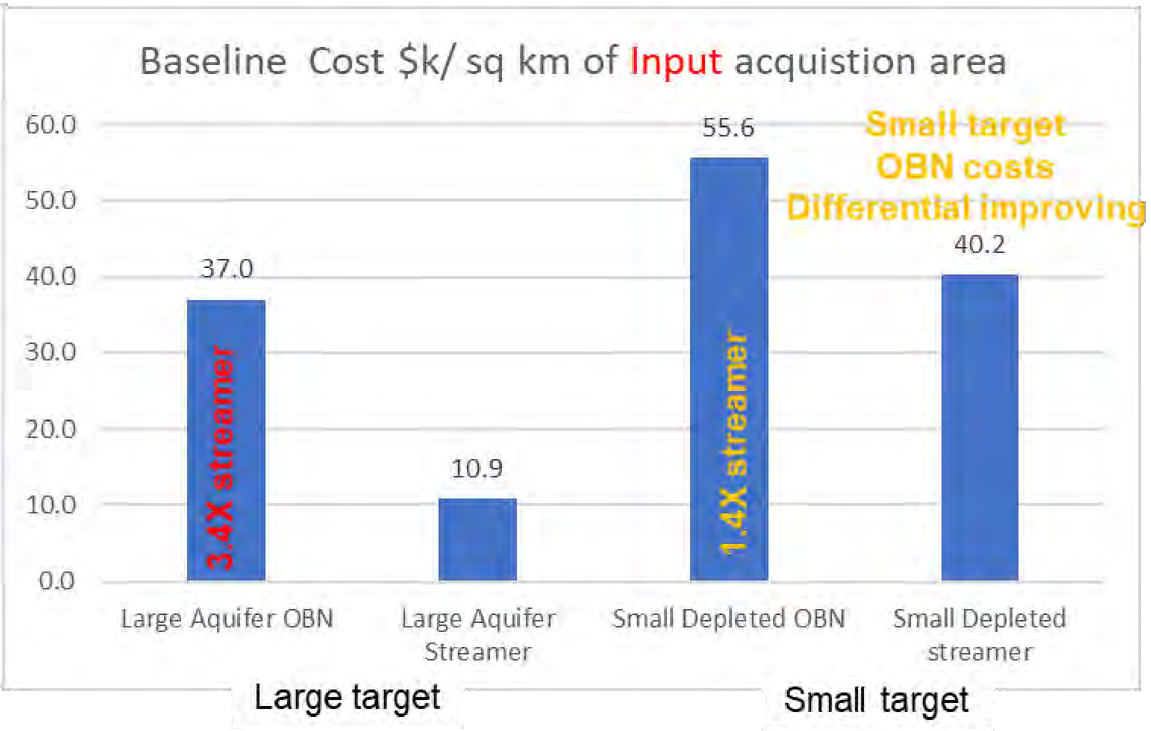
- OBN costs reduced by ~50% over last decade (automatic node handling)
- Some scope for further technology development / OBN will always be slower (and therefore more costly) than streamer

OBN has some scope for further cost reductions

Acquisition Cost model results

North Sea Transition Authority





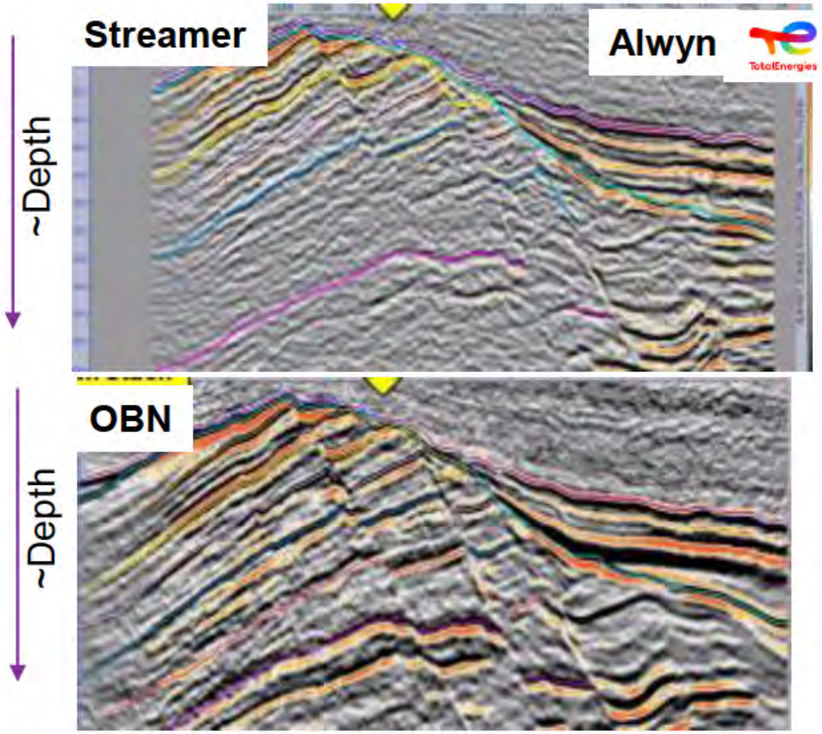
Total lifecycle Seismic Monitoring costs (assuming baseline 3D & 5 monitors + $1m processing for each)

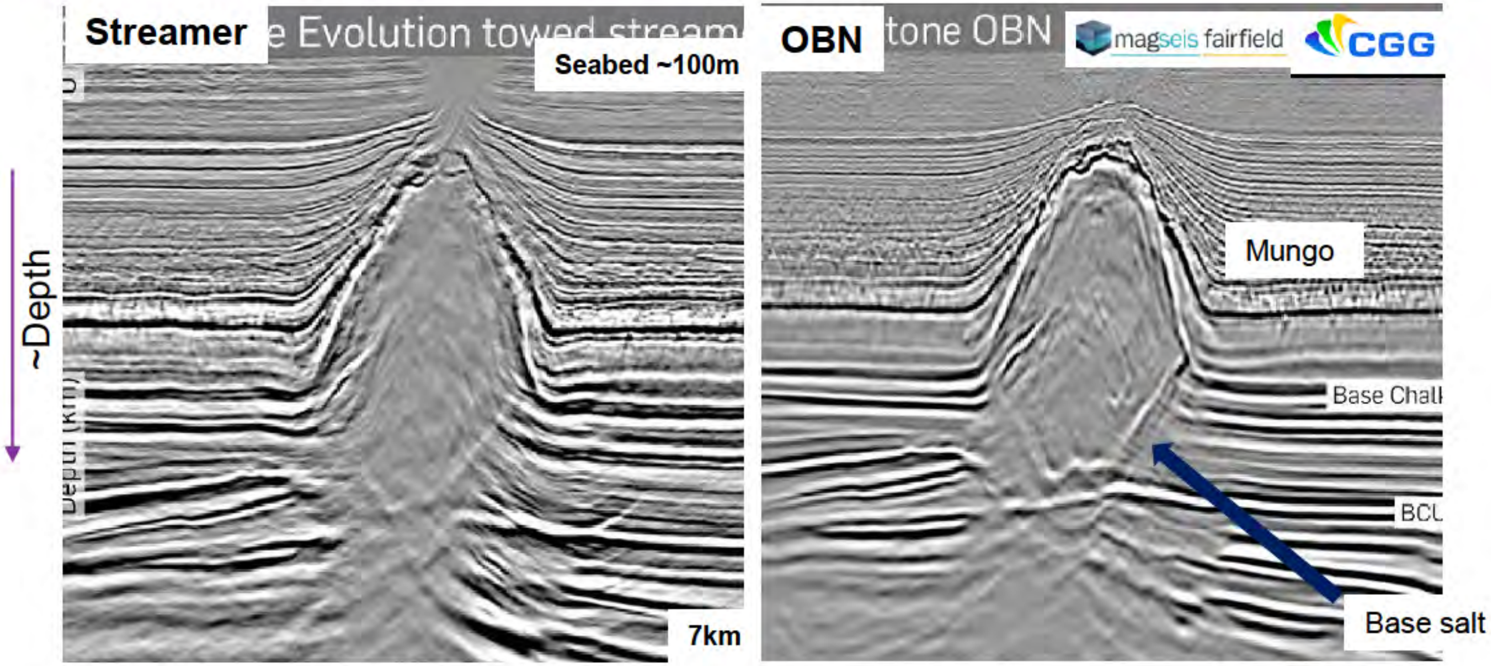
- Large Aquifer: $96-146m (OBN) or $54m (streamer) vs. Whole CCS project costs ~£5bn (1-2% of Capex)
- Small Depleted $34m (OBN) or $21m (streamer) vs Whole CCS project costs ~£1bn (2-3% of Capex)

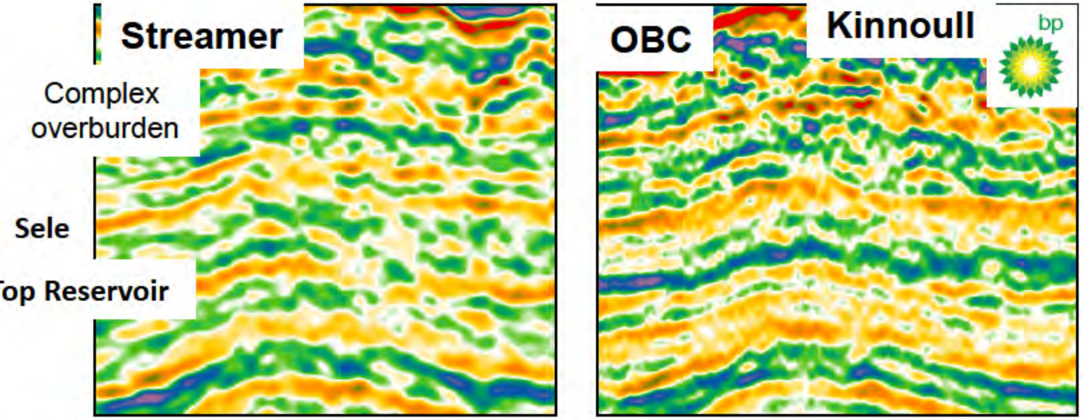
Seismic costs small proportion of total project capex, but very hard to justify the significant additional cost purely for marginal imaging improvement for most reservoirs

OBN will remain more operational complex, slower and more expensive than streamer

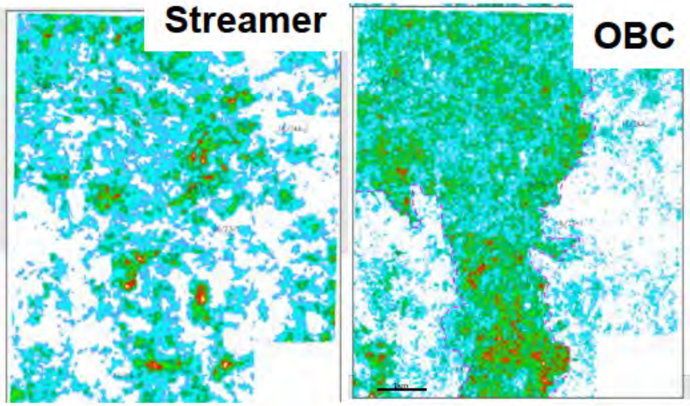
OBN Traditional: complex structures or overburdens







Seismic attribute map
(extract signal strength @ top reservoir)

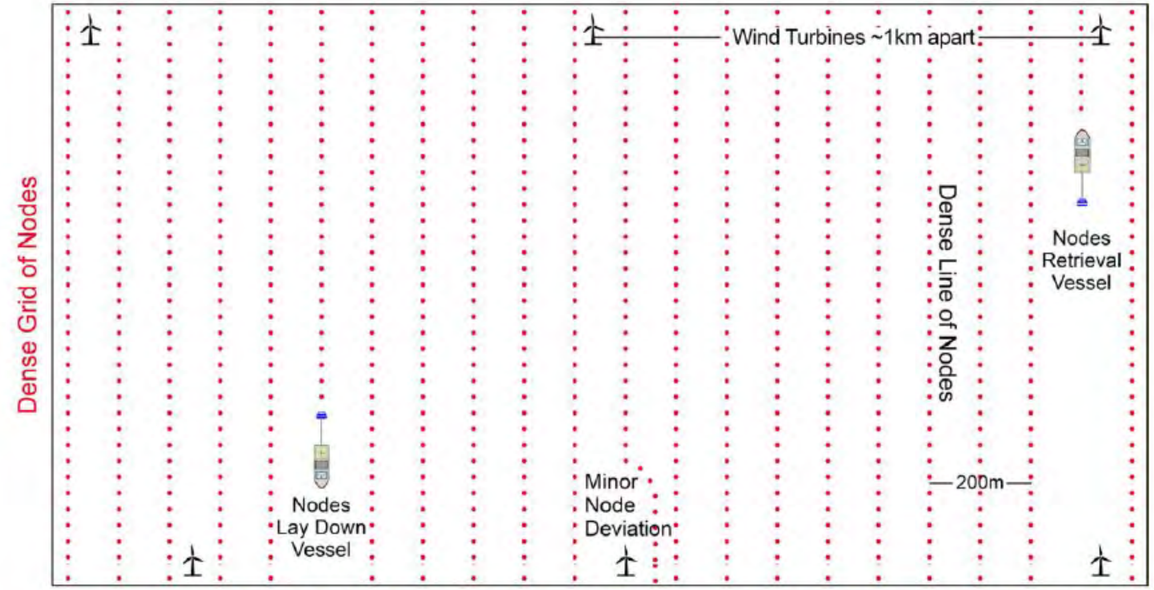


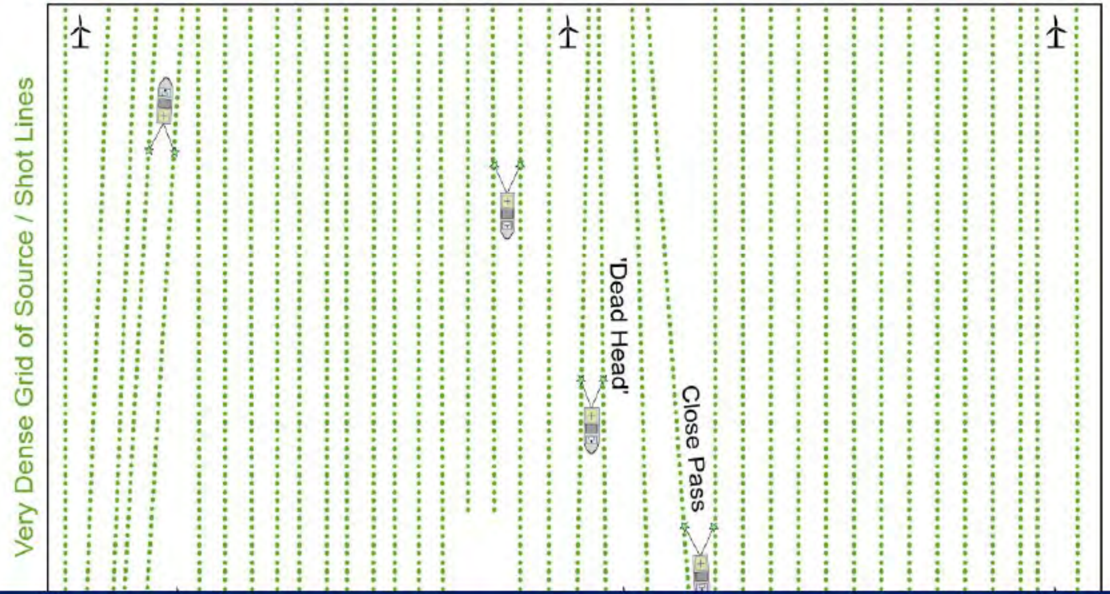
Many examples from UKCS where OBN has delivered superior image of subsurface e.g.

- Improved fault definition
- Increased horizon continuity
- Superior salt tectonic mapping
- 4D reservoir behaviour

OBN usually employed for complex targets/ Many excellent examples of geophysically superior imaging improvements

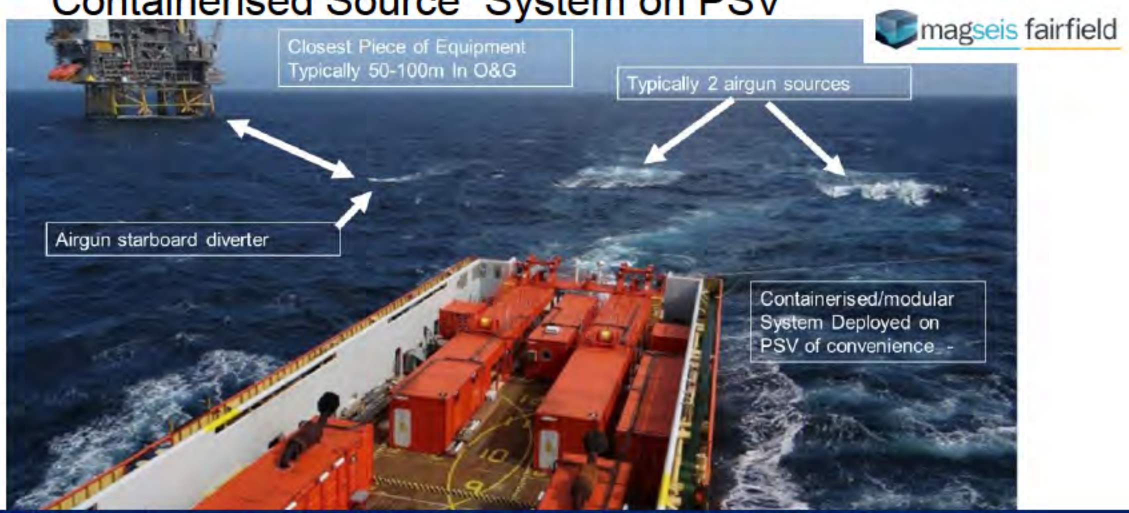
OBN acquisition Proximity to obstructions





Geowave Commander (node vessel) on close approach (~350m) to platform. Picture taken from source boat

Containerised Source System on PSV

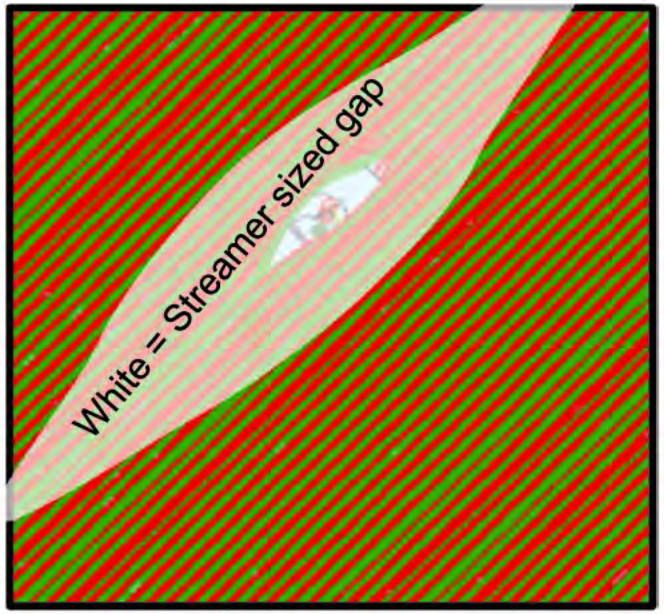


OBN can be acquired close to infrastructure

Streamer vs OBN around single platform

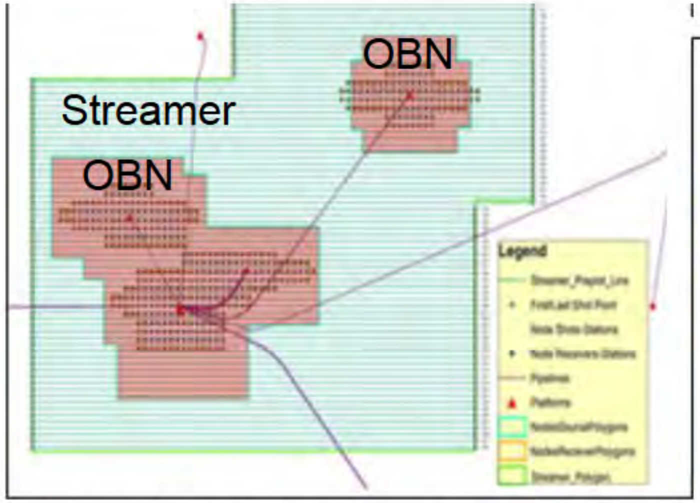
North Sea Transition Authority

Acquisition around single platform



Seismic source lines (alternating red & green direction, 25m apart) shooting into permanent installed nodes (PRM). Dead heads visible from NE

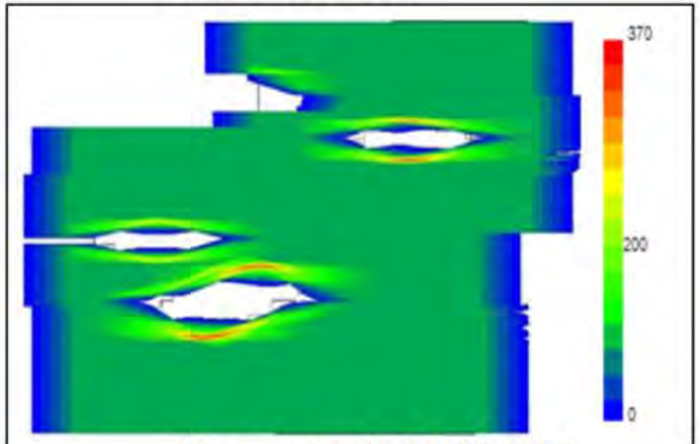
Hybrid streamer & OBN around platform (Malaysia)



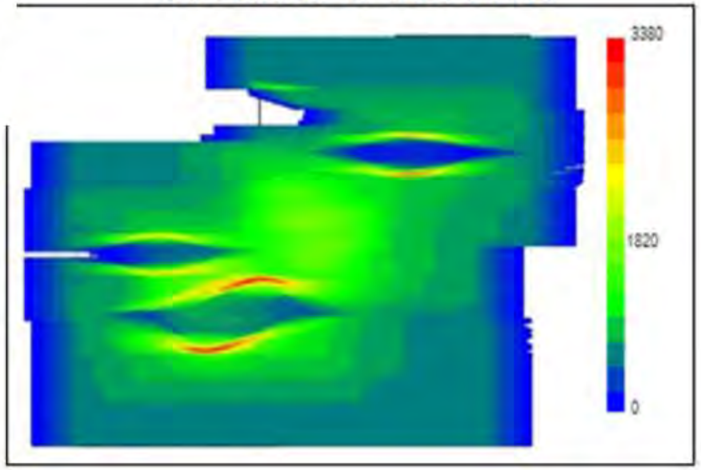
A cost-effective and efficient solution for marine seismic acquisition in obstructed areas – Acquiring ocean-bottom and towed-streamer seismic data with a single multipurpose vessel

Michelle Tham[1], Tim Brice[1], Artem Sazykin[1], Wai Leng Cheah[1], Stephen Winters[2], Nigel Jones[3], Sandeep Chandola[4], Shamsul Shukri[4], Subodh Kumar[4]*
[1]WesternGeco, [2]Roc Oil Company, [3]Dialog Resources Sdn. Bhd., [4]PETRONAS Carigali Sdn. Bhd.

Streamer fold



Streamer & OBN fold

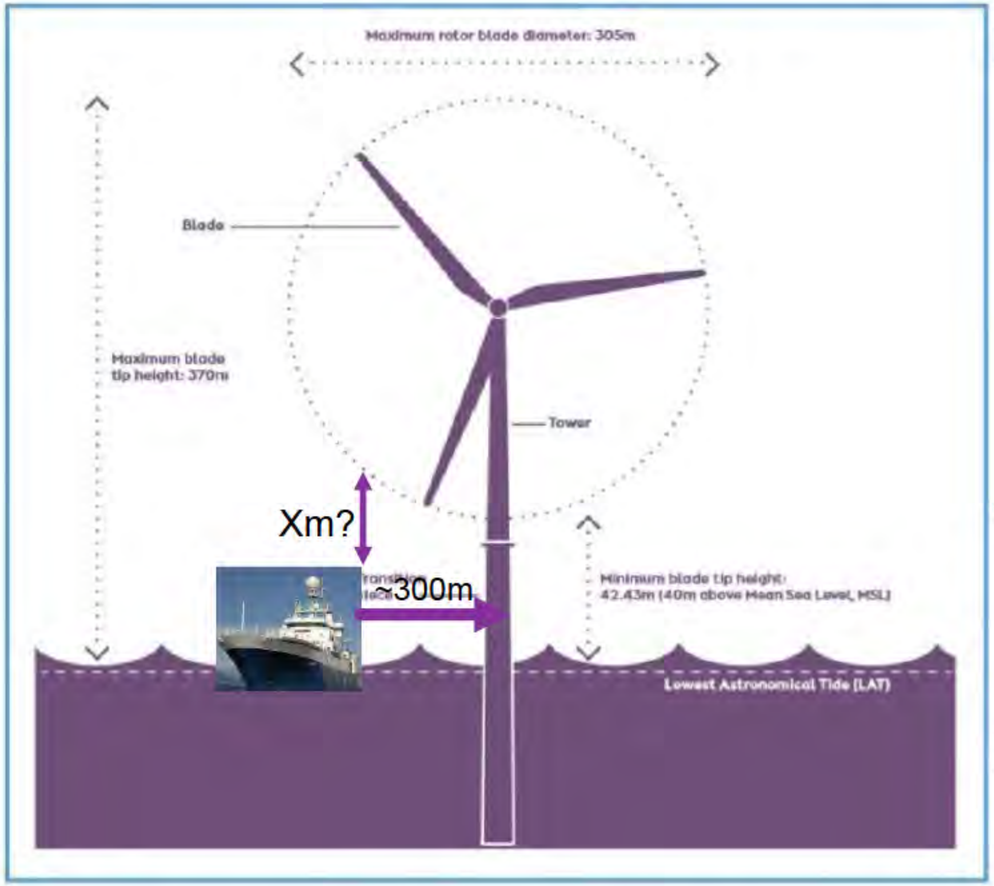


Claim hybrid survey ~25% cost of full OBN

Hybrid streamer and OBN may provide best of both efficiency & coverage

Future Operational considerations & Technology

North Sea Transition Authority



Intra-windfarm Cross disciplinary HAZID assessment

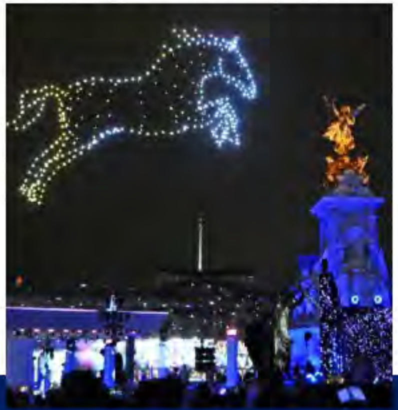
- Currently estimated seismic vessel- platform safety separation 250m (OBN) - 400m (Streamer)
- Seismic vessel Proximity to turbine?
  - Large turbines => longer blades
    - Impact on working beneath (e.g. radar domes)
  - Additional risks working within multiple obstructions
- Windfarm walk to work lessons

Technology development: size of vessel and towing equipment

Autonomous node

Further Autonomous receiver node development

- Increase Receiver mode density
- Analogous Drone choreography advancements



- Engineering Challenges for Autonomous seismic sources vision (RAM4D)
  - Source position, Obstacle avoidance and signal repeatability,
  - AUV endurance needs to be improved (>100km/day) / Limited OBN battery life
  - Additional power to energise source / Local Windfarm energy supply opportunity?

Further investigation into seismic operations in windfarms required

Reservoir 4D signal > seismic noise

The Signal > Noise See-Saw

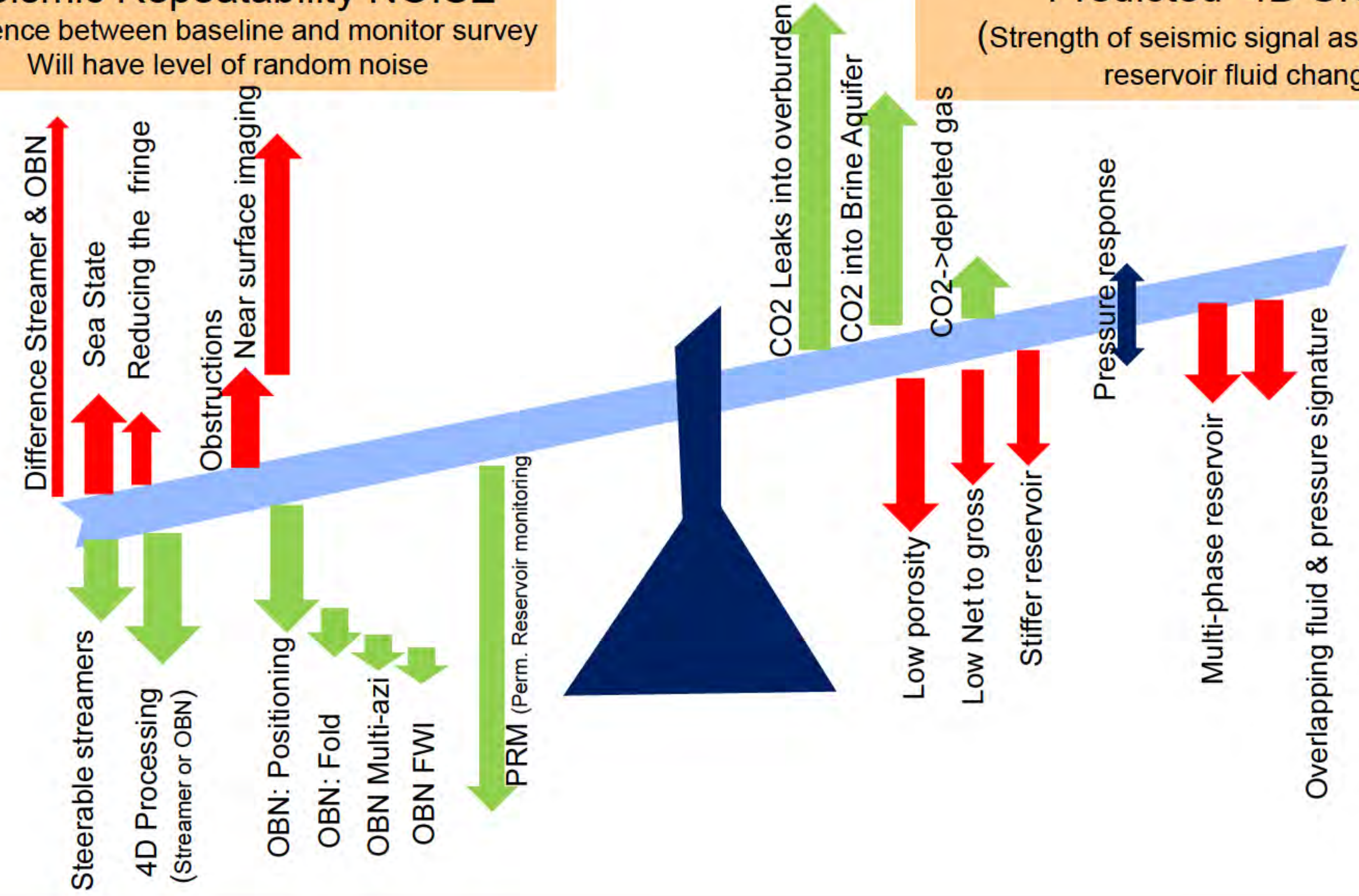
North Sea Transition Authority

Seismic Repeatability NOISE

Difference between baseline and monitor survey
Will have level of random noise

Predicted 4D SIGNAL

(Strength of seismic signal as a resulting of reservoir fluid changes)

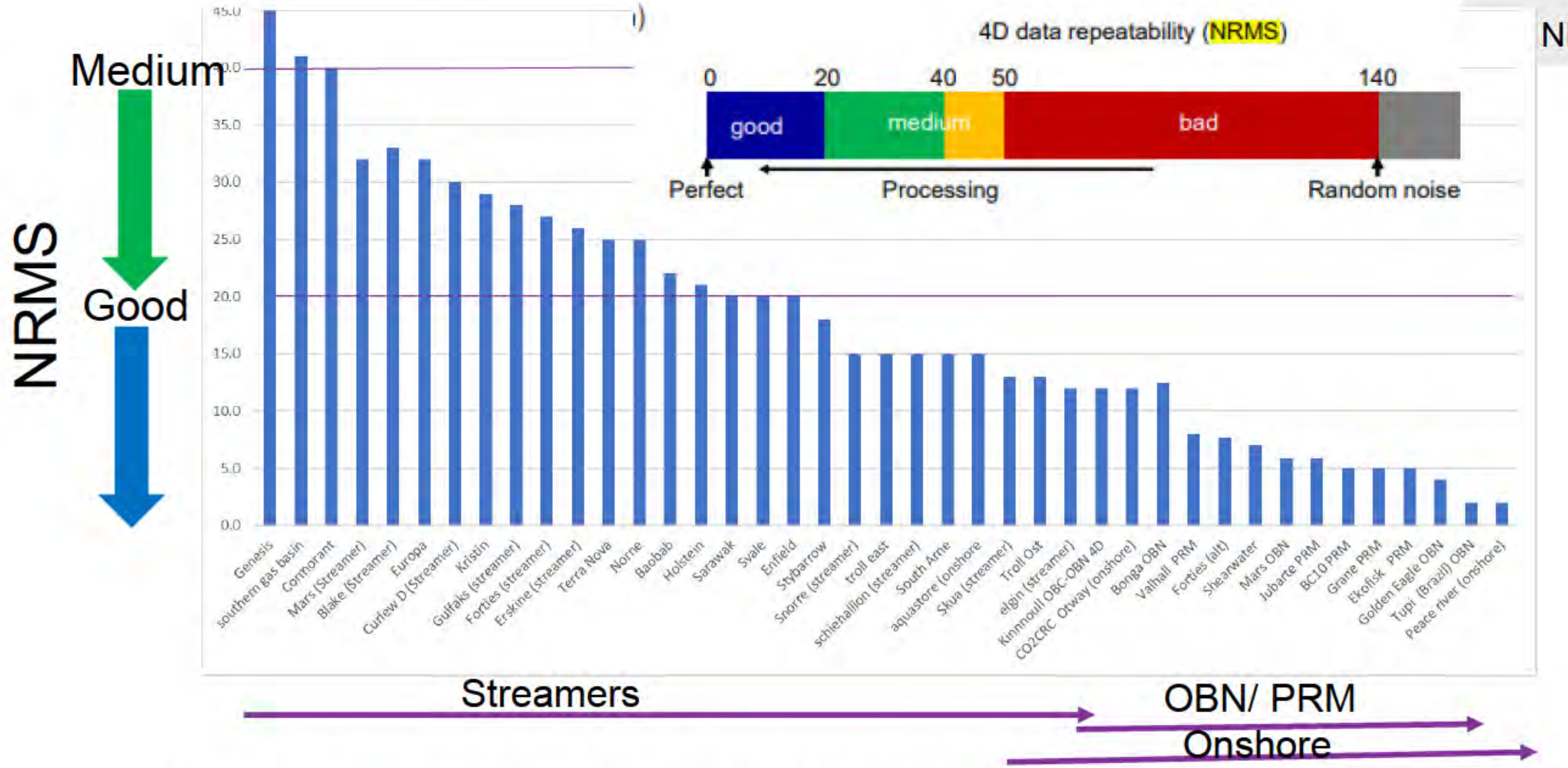


Critical to predict signal > noise before surveying

Seismic Repeatability & Noise: NRMS

North Sea Transition Authority

Seismic Repeatability NOISE
Difference between baseline and monitor survey
Will have level of random noise
NRMS (Normalised Root mean Squared)



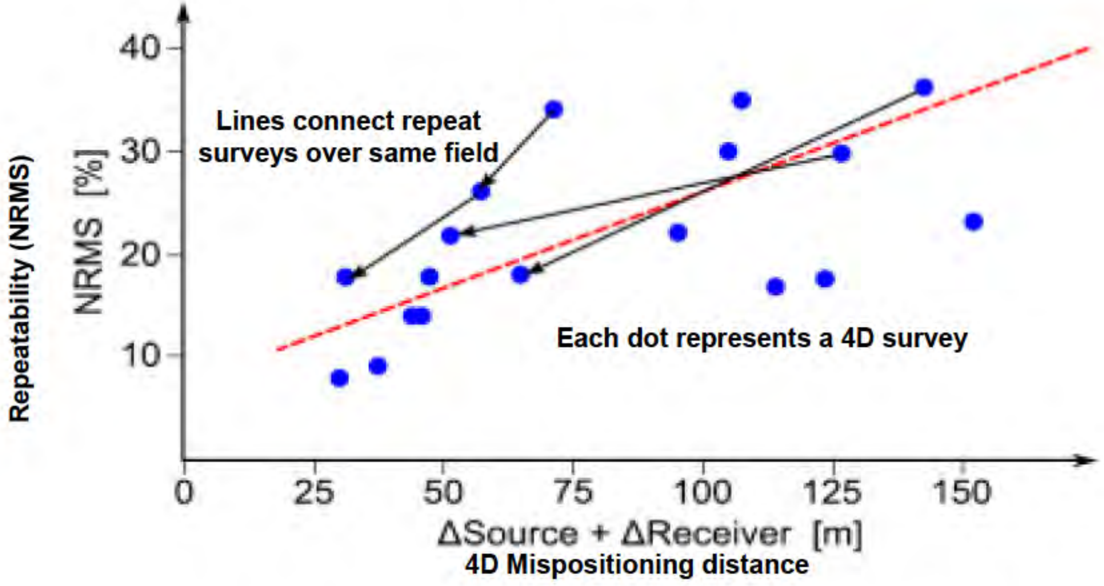
Modern Streamer data acquisition & Processing typically achieves NRMS ~15%
Modern OBN acquisition and processing achieves NRMS ~5%
Offshore PRM (Permanent reservoir monitoring) can achieve NRMS ~2%

OBN or PRM can significantly improve repeatability/ suppress the noise level

Role of offshore mispositioning and processing

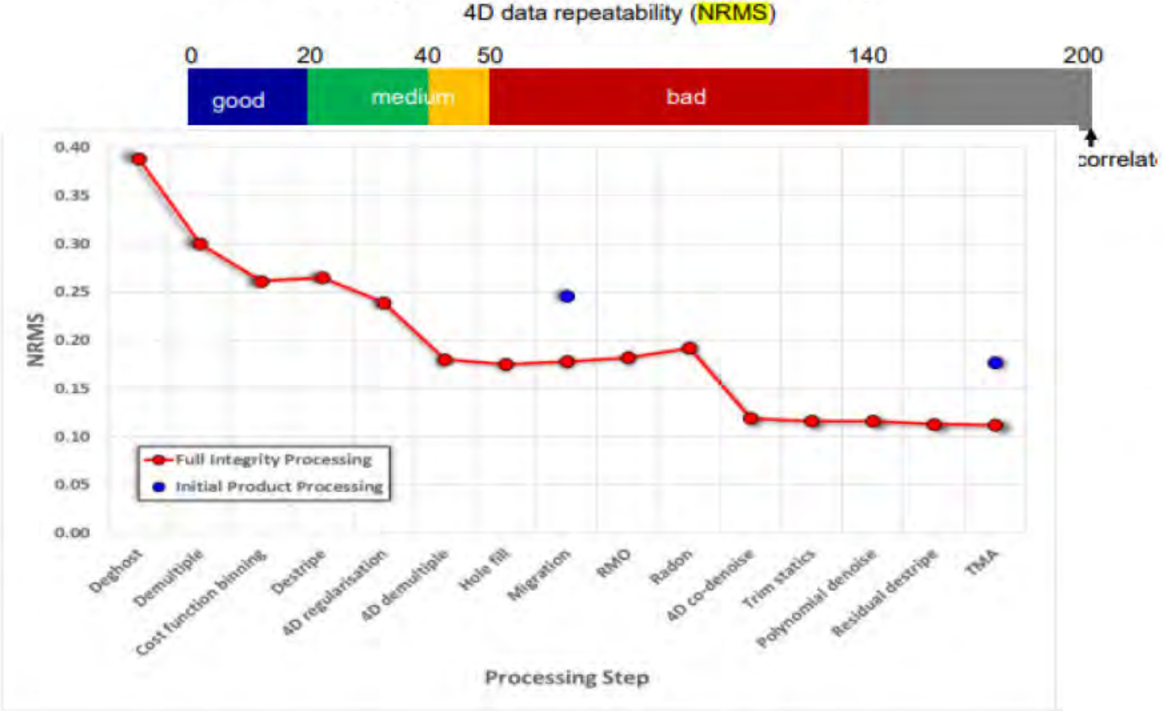
North Sea Transition Authority

Clear linkage between source & Streamer Repeatability vs NRMS noise



Improving Repeatability (lower NRMS) with better source and receiver positioning

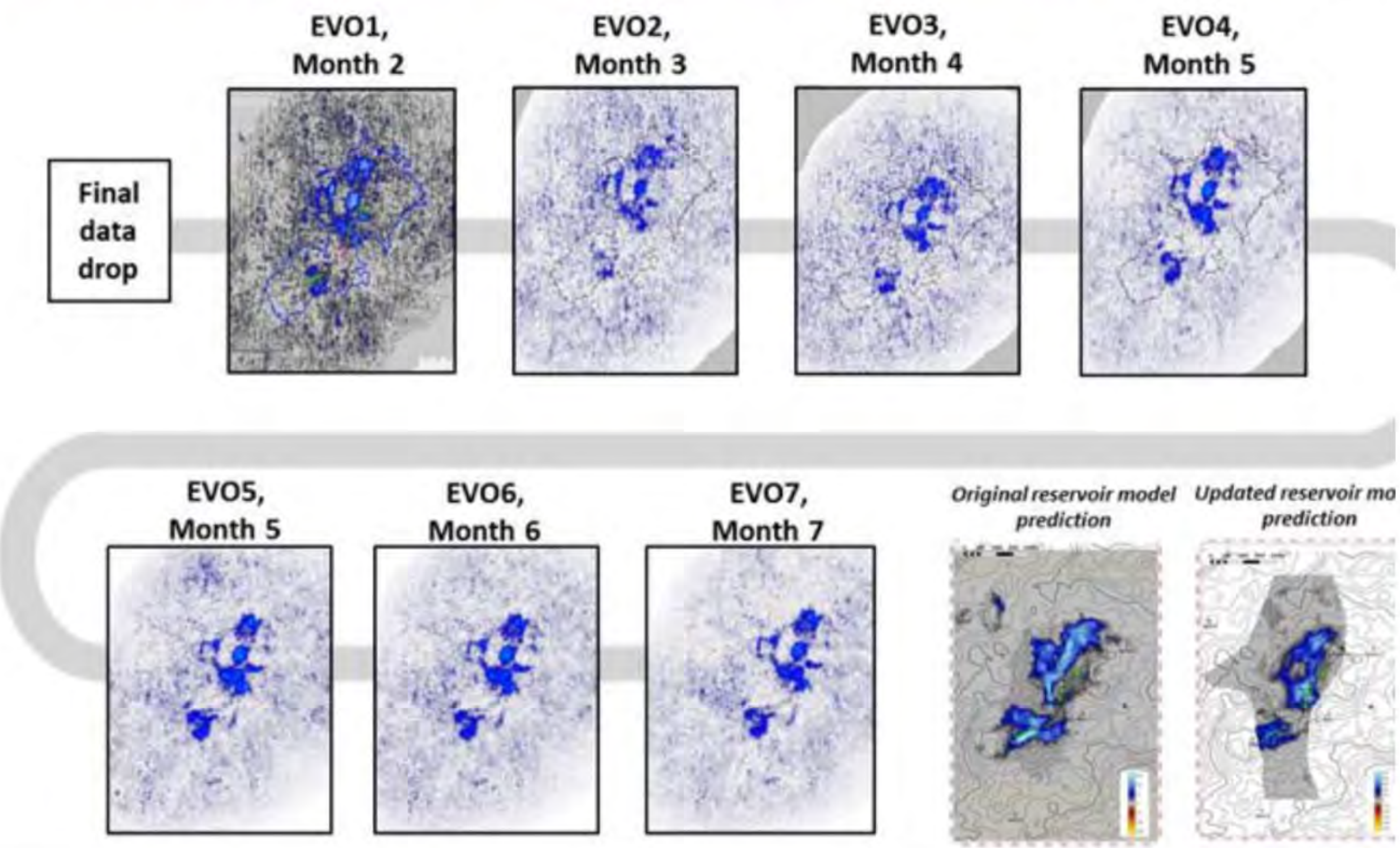
Processing can improve Repeatability



Certain processing steps improve repeatability

For comparison: OBN repeatability: 5m Node position 10m shots

Processing Stage: Sharpening the image



Kinnoull OBC-OBN
4D difference maps
By processing step

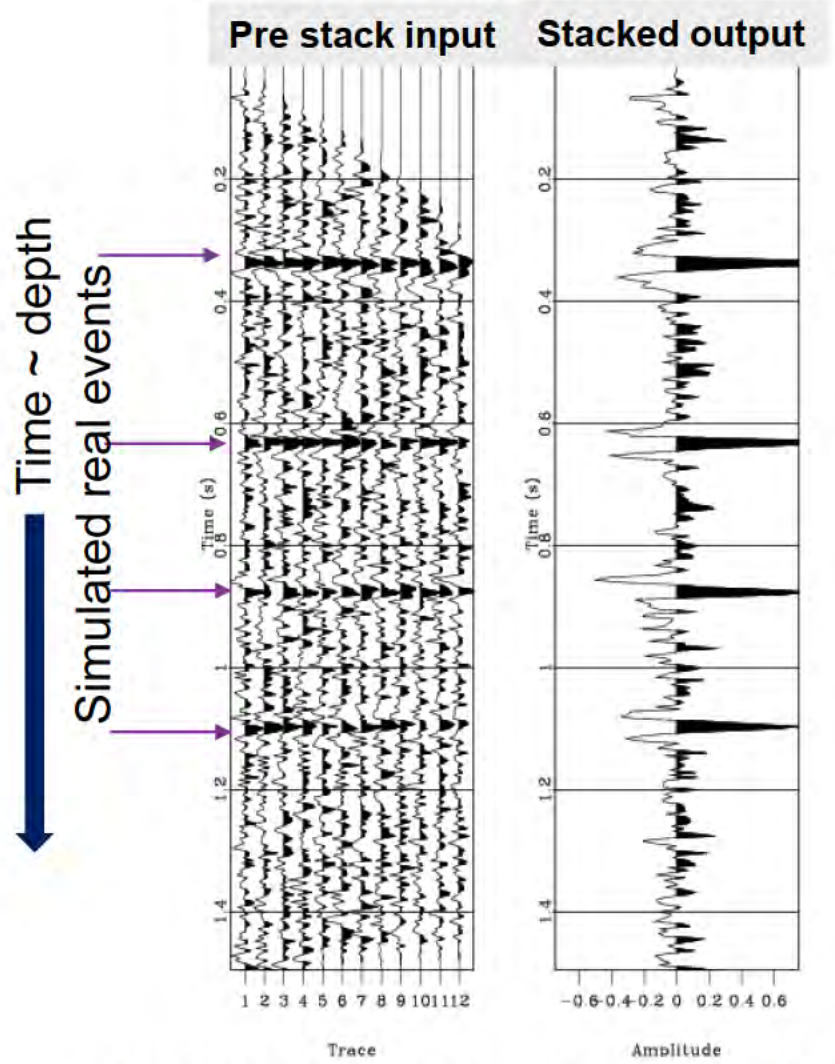
Full-cycle iterative processing: when is "good", good enough?
A 4D North Sea case study
M. Walker[1*], D. Davies[1], C. Hill[1], C. Page[2], P. Smith[2], A. Irving[2]

[1]BP, [2]CGG

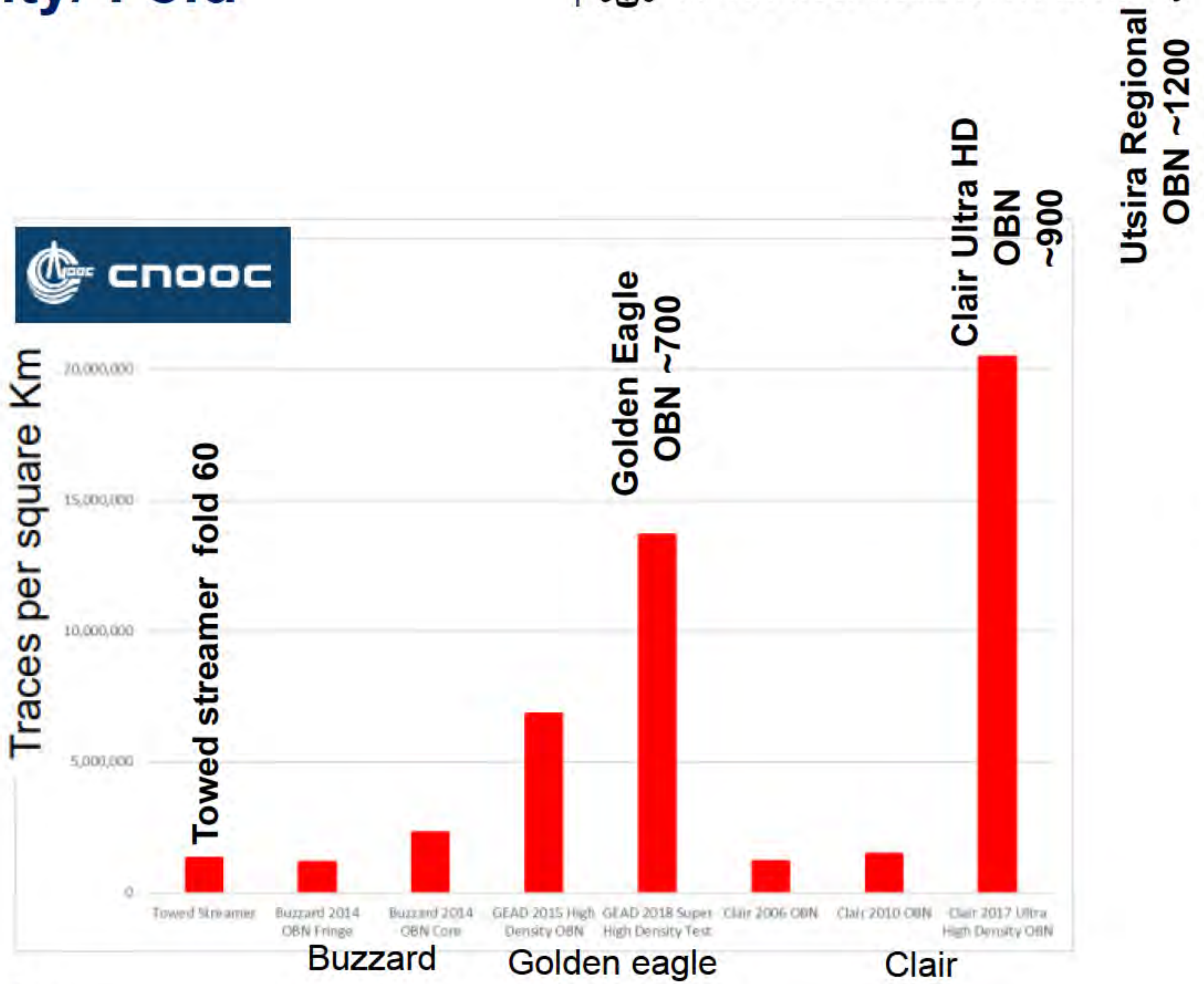
OBN very high trace density/ Fold

North Sea Transition Authority

The Power of the stack (simulation)



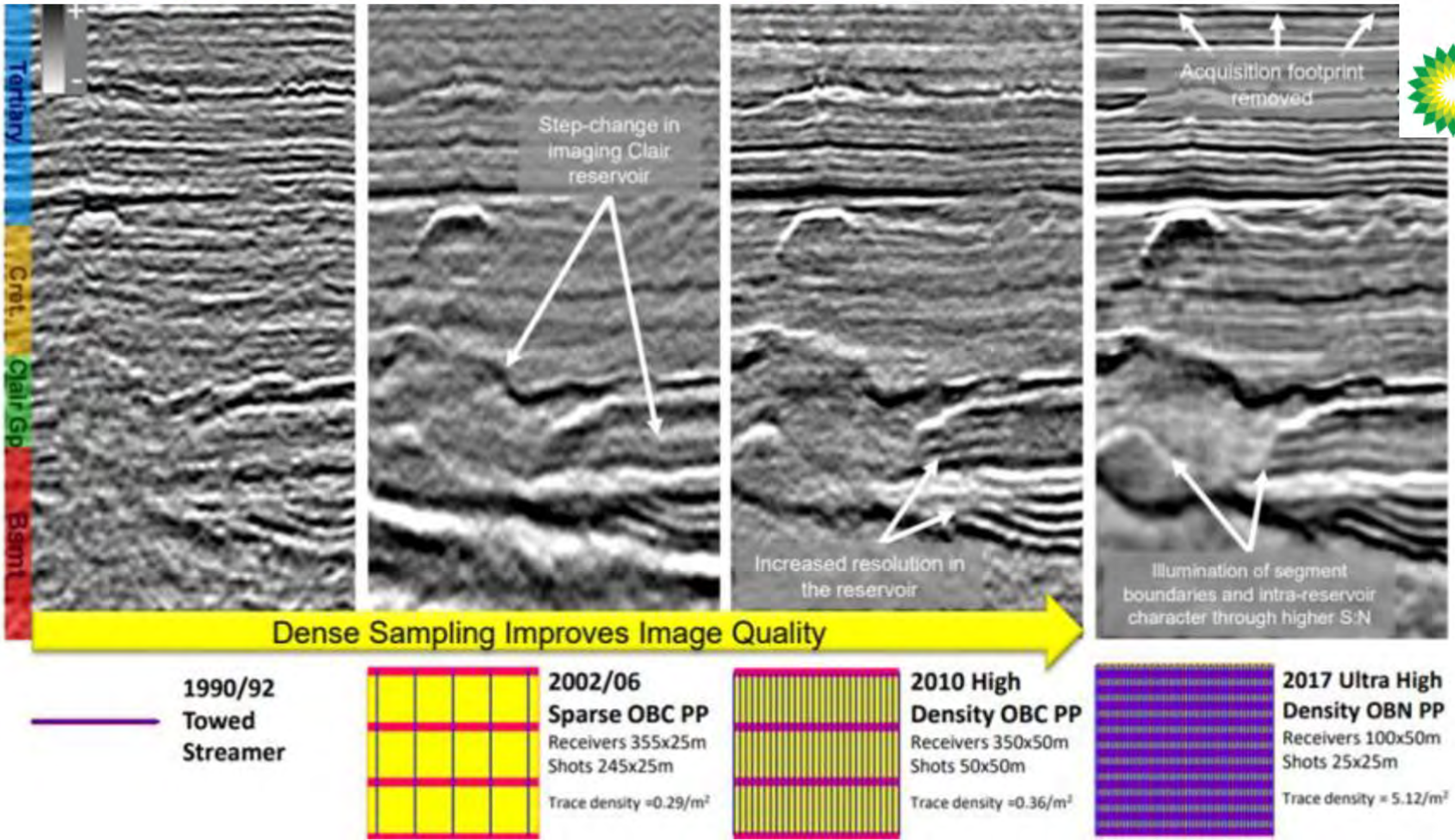
12 traces "fold" with simulated signal & random noise
Summing (stacking) improves signal/ noise



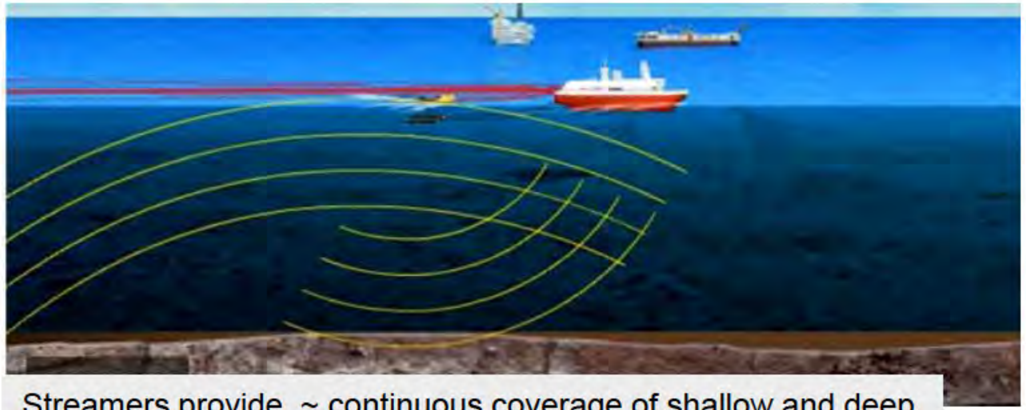
Signal to Noise improves Sqrt(Fold)
=> Golden Eagle OBN 4* Better signal/ noise than streamer

Clair Ridge: Towed Streamer to UH OBN

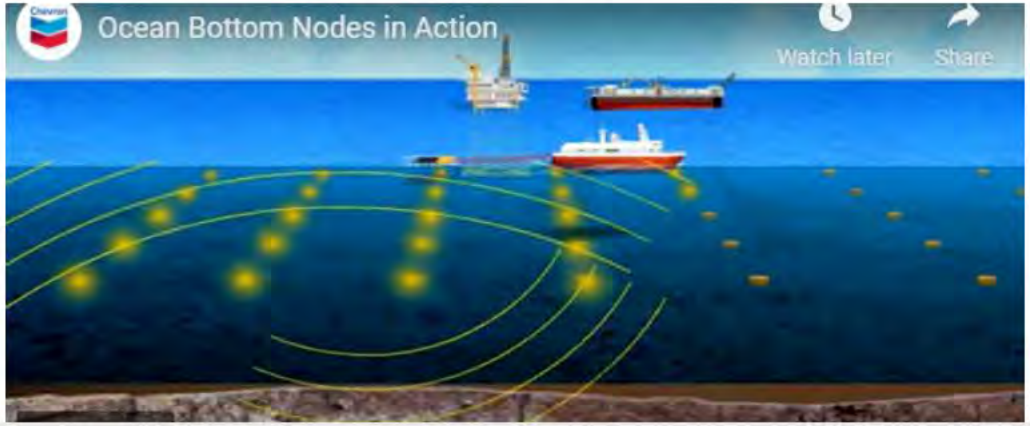
North Sea Transition Authority



Imaging the shallow section



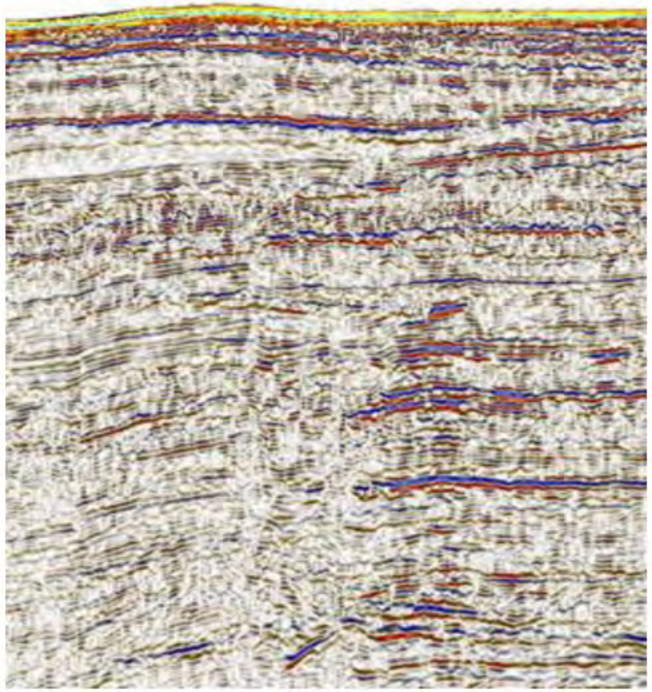
Streamers provide ~ continuous coverage of shallow and deep



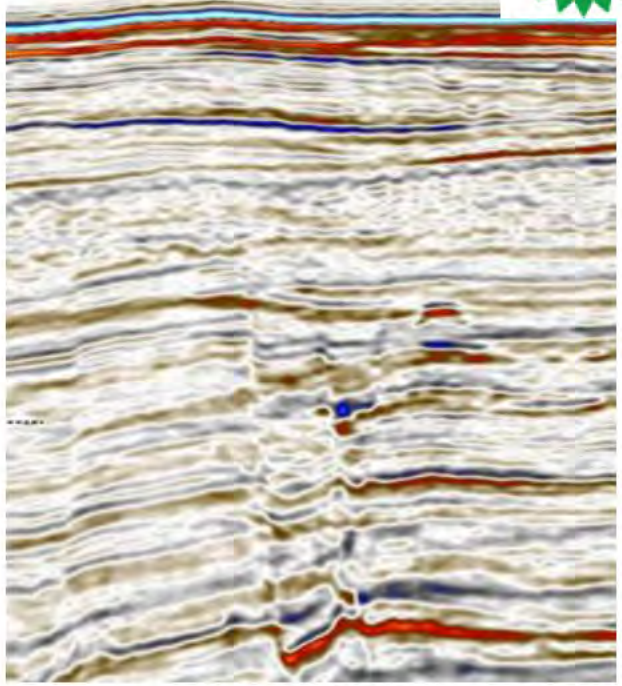
OBN gives continuous deep imaging, but leaves intra-node near surface gaps

Ocean-bottom node - SEG Wiki

Clair 2D HR Streamer



Clair UHD OBN 3D



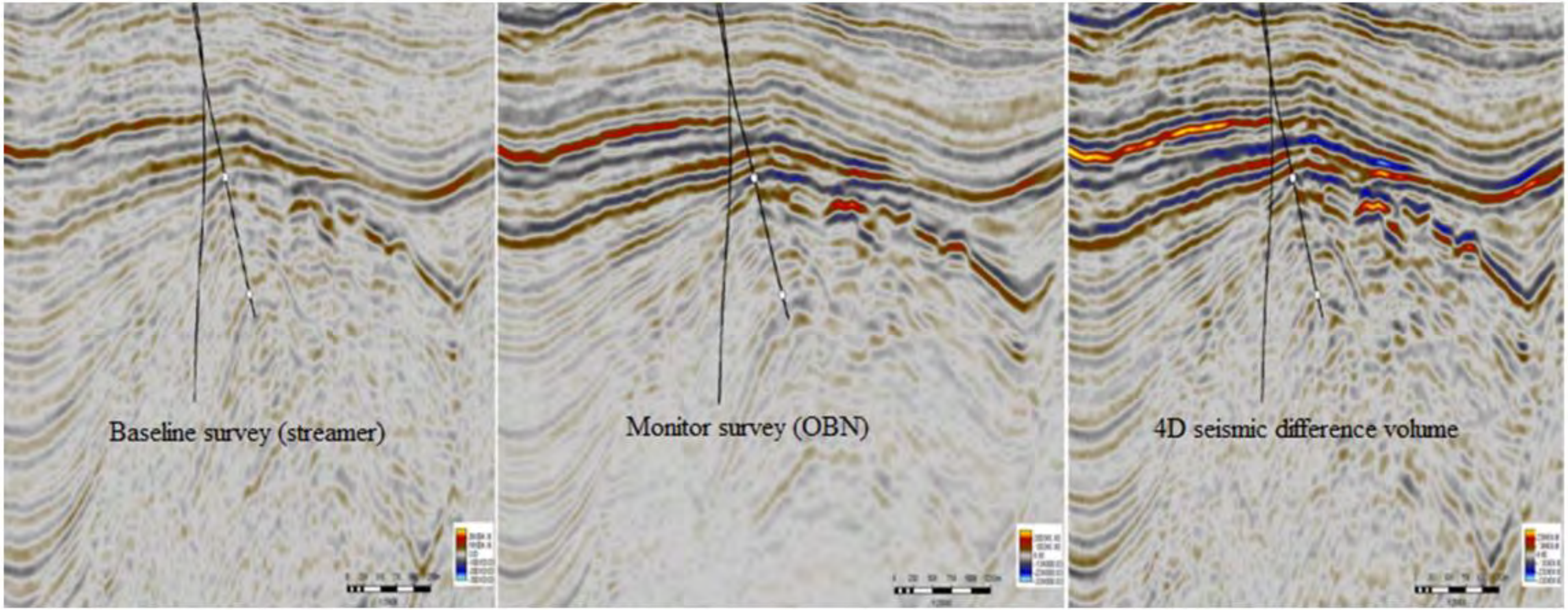
Ultra HD produces excellent near surface image

Clair Ridge: Learnings From Processing the Densest OBN Survey in the UKCS | Earthdoc

Streamer vs OBN difference: J-Field UKCS

North Sea Transition Authority

OBN improved imaging of Triassic J-Field but non-parallel processing yields 4D difference is very noisy



Considerable non-production related differences are apparent NRMS 129%
Unclear how much parallel processing would reduce NRMS

Differencing Streamer and OBN is currently unfeasible for 4D monitoring

OBN Project- Conclusions & Further considerations

North Sea Transition Authority

- OBN technology is
  - Becoming mature & mainstream in oil and gas
  - Employed in special situations: shallow water, complex structures, overlapping activity, small 4D signal

- OBN is advantageous in obstructed space (project focus on mono-pile)
  - Floating windfarms: Catenary cables & multiple anchor points, tension leg turbines?
  - Acquire baseline data before infrastructure installation
    - Impact repeatability?
    - Which has primacy: turbines or CCS baseline?
  - OBN acquisition feasibaility within an operational windfarm is unclear
    - Cross-disciplinary (CCS/Wind/Seismic/Marine) HAZID assessment workshop recommended

- OBN is a geophysically superior reservoir imaging technology
  - Many examples from UKCS (and worldwide) of improved **complex** subsurface imaging
  - Many successful hydrocarbon (Streamer & some OBN) 4D case studies

- Major OBN drawback remains cost differential compared to streamer
  - OBN costs have reduced by ~50% over last decade (automatic node handling)
  - OBN will always be slower (and therefore more expensive) than streamer seismic
    - OBN multiplier of 2-5X streamer does not justify the cost in most situations
- Hybrid Streamer and OBN could be a valuable co-location compromise

North Sea Transition Authority

Seismic Signal/ CO_2 Detection Project

Carbon storage reservoir distribution

North Sea Transition Authority

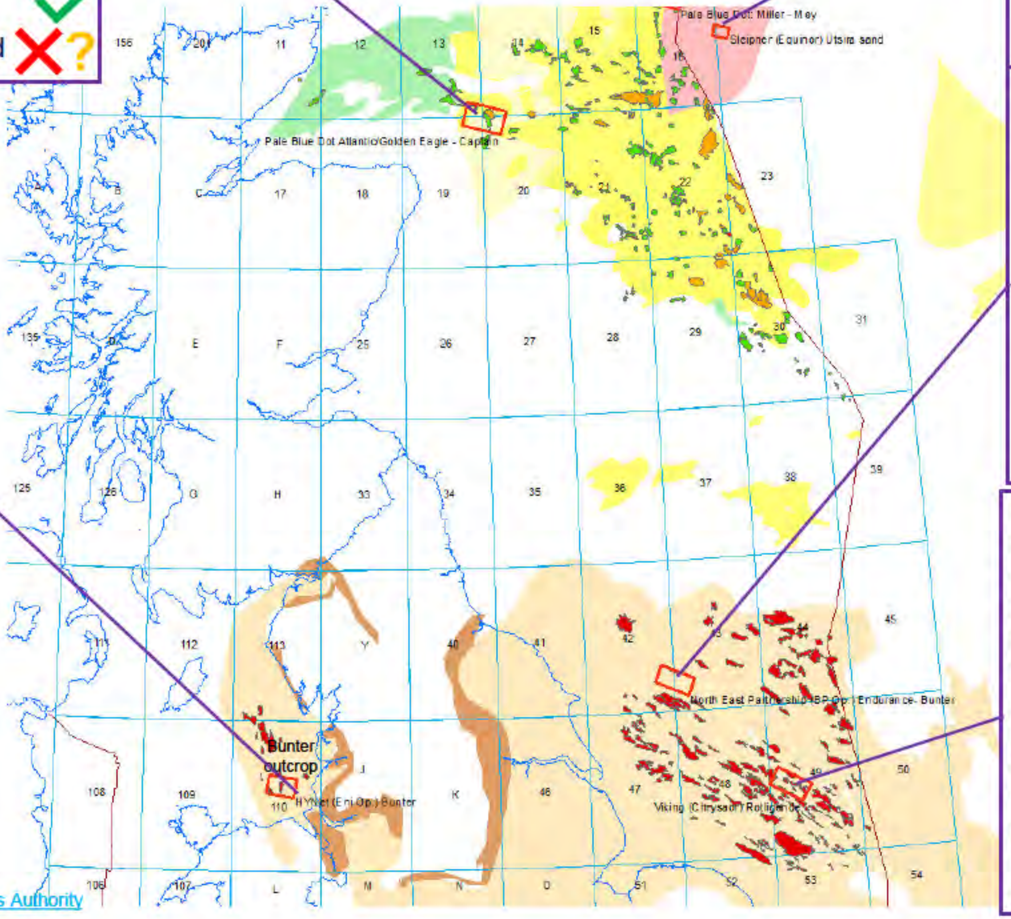
Licence: CS003 Acorn
Location: Goldeneye, Outer Moray Firth
Operator: Storegga
Reservoir Age: Lwr Cretaceous
Lithology: sandstone
Depth: 2860m MD
CS Type: Depleted Field
Well: 14/29a-3

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

Utsira/Miocene sand
Eocene/ Palaeocene(Inc. Forties/Mey)
Lower Cretaceous(Inc. Captain)
Triassic(Inc. Bunter)
Permian (Inc. Rotligende) NOT SHOWN

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) ✓



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 ✓

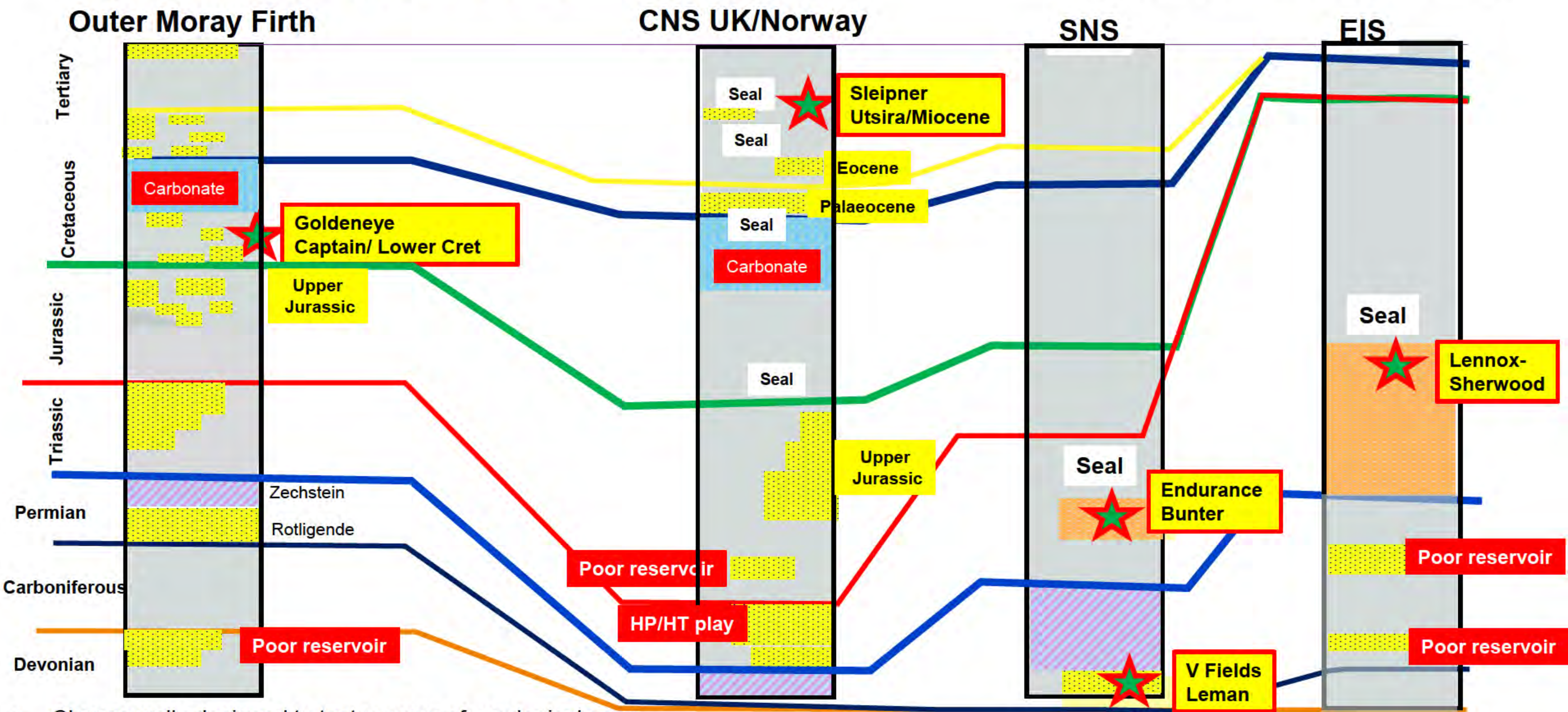
Licence: CS004 Hynet
Location: EIS
Operator: ENI
Reservoir Age: Triassic
Lithology: sandstone, consolidated, thick, high NTG, mid-low porosity, very low initial reservoir pressure
Depth: 1110m MD
CS Type: Depleted field
Well: 110/14-4

Results:
Injection into gas leg- Limited 4D response expected ✗
Migration into aquifer: observable response ✓

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 ?

Source NSTA (LR published maps), BGS & Equinor publications
OGA and Lloyd's Register UKCS Merged Regional Geological Maps (ArcGIS version) | Oil and Gas Authority

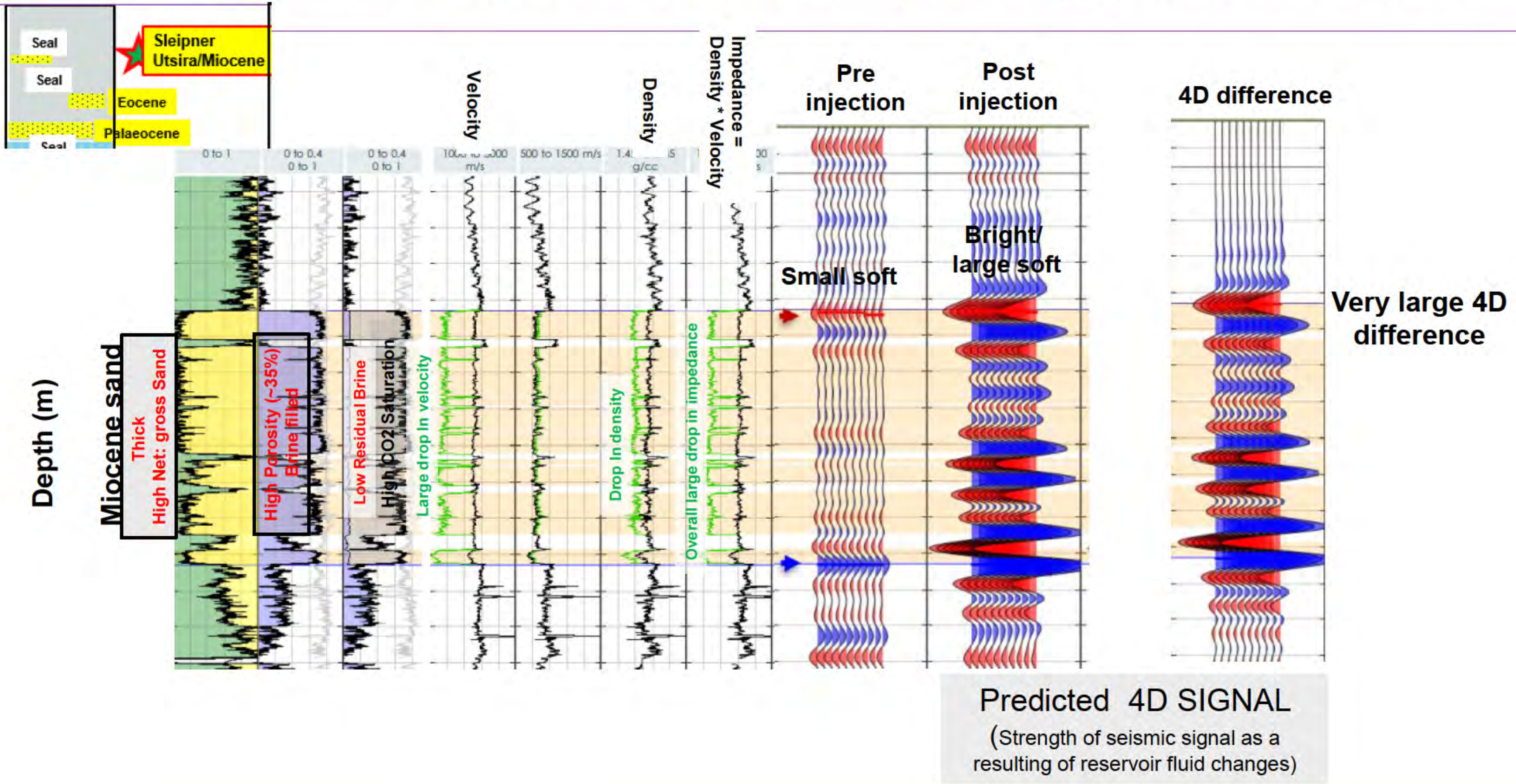
Carbon storage reservoirs by age



- Chosen wells designed to test a range of geological ages
- Some formations rejected as unlikely for CCS
- Potential future formation study options highlighted

“Easy 4D”: Sleipner CO2 injection/ “soft rock "aquifer

North Sea Transition Authority



Very large response, readily detectable

Real 4D example: Sleipner comparison

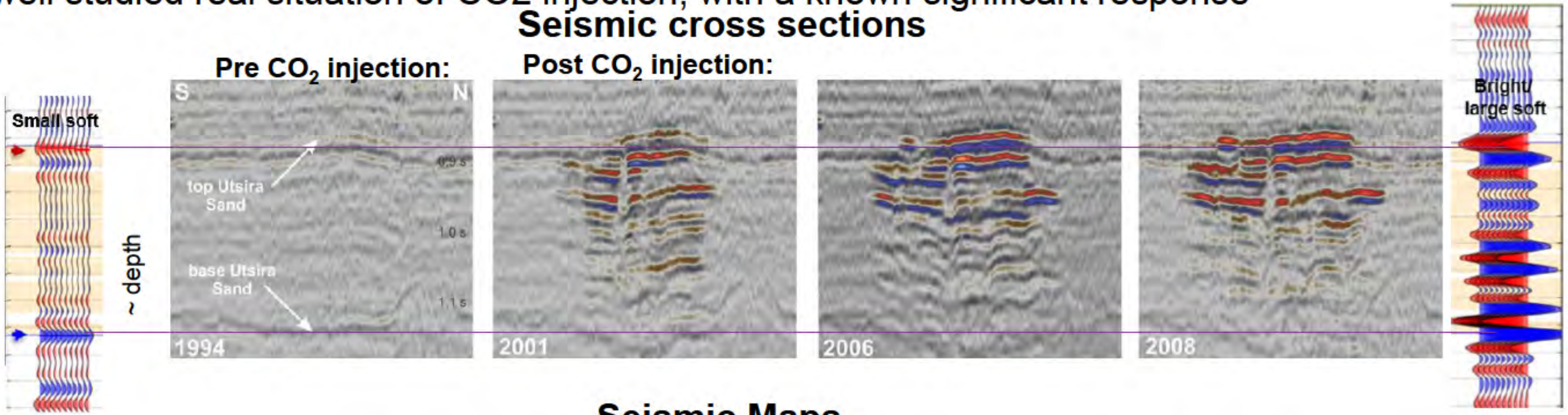
North Sea Transition Authority

- Sleipner is a well studied real situation of CO_2 injection, with a known significant response

Seismic cross sections

Pre CO_2 injection: Post CO_2 injection:

Real seismic
Also shows weak
Top & base
seismic response
Prior to CO2

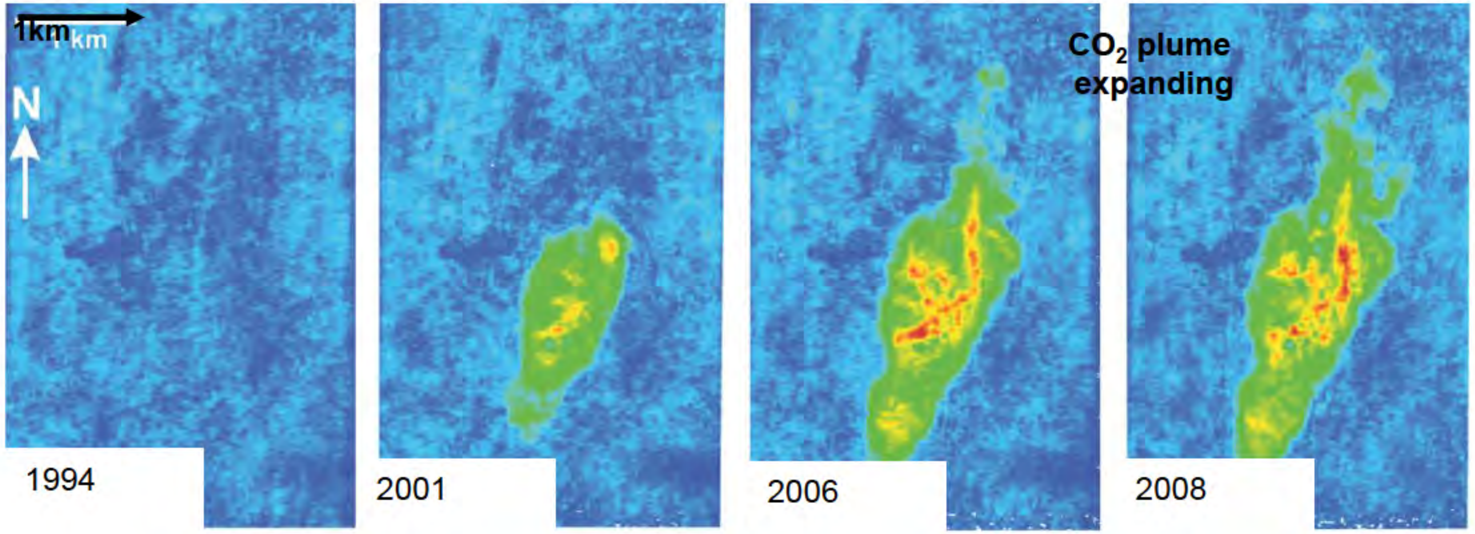


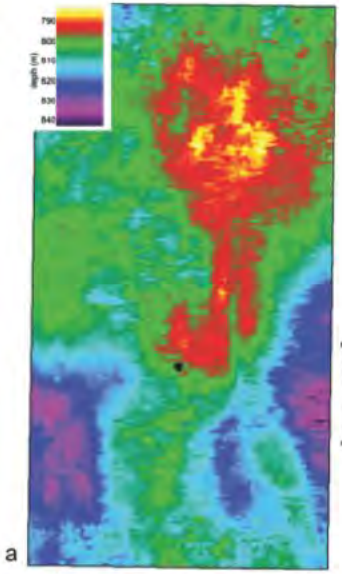
Shallow bright spots ~ Match real seismic

Deeper bright spots
Not present implies
CO2 not reaching
Base of reservoir

Seismic Maps

Mapping upper event
Shows CO2 migrating
In clear NNE direction



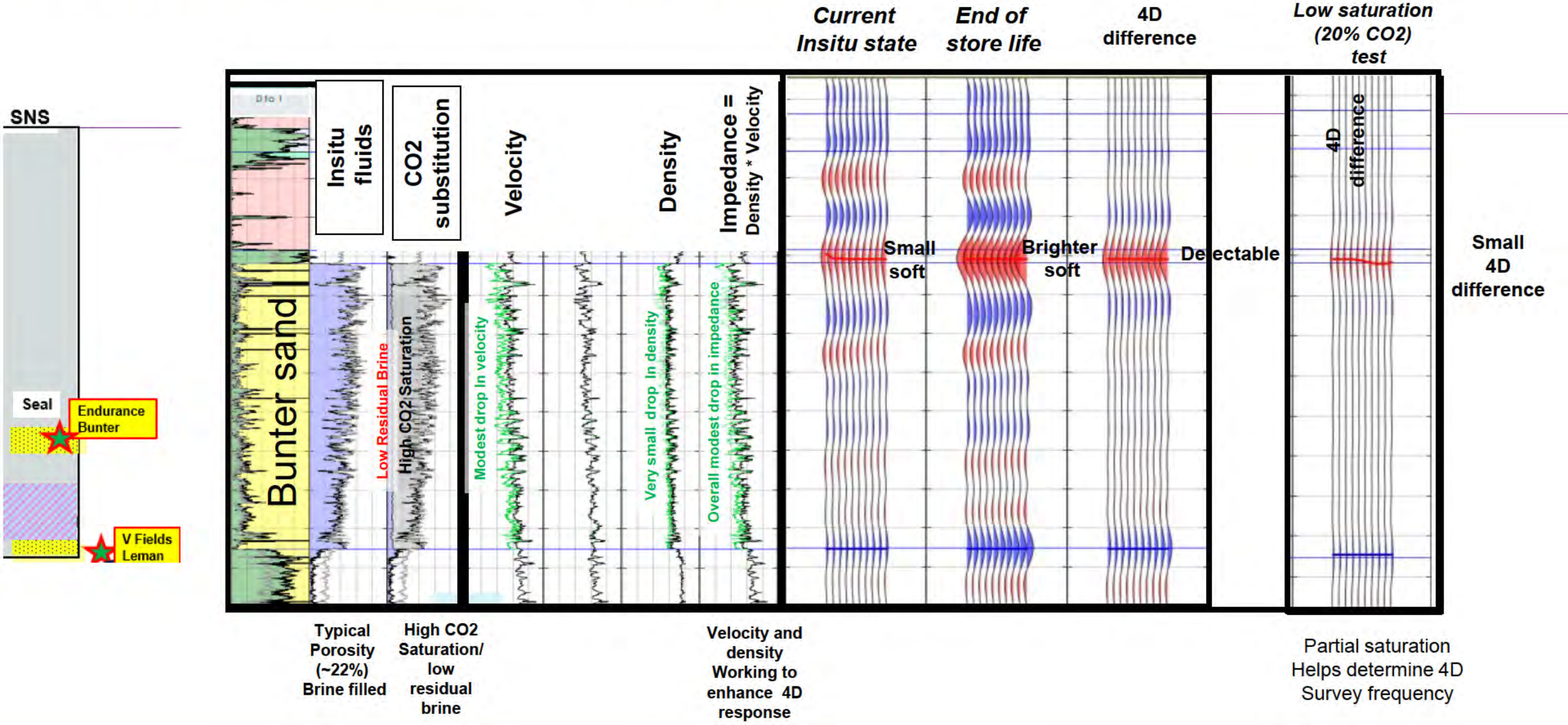


Structure map : not to scale

Proven CO2 site: Linking prediction modelling to real CO2 sequestration

"Medium 4D": Endurance (SNS) Triassic Aquifer

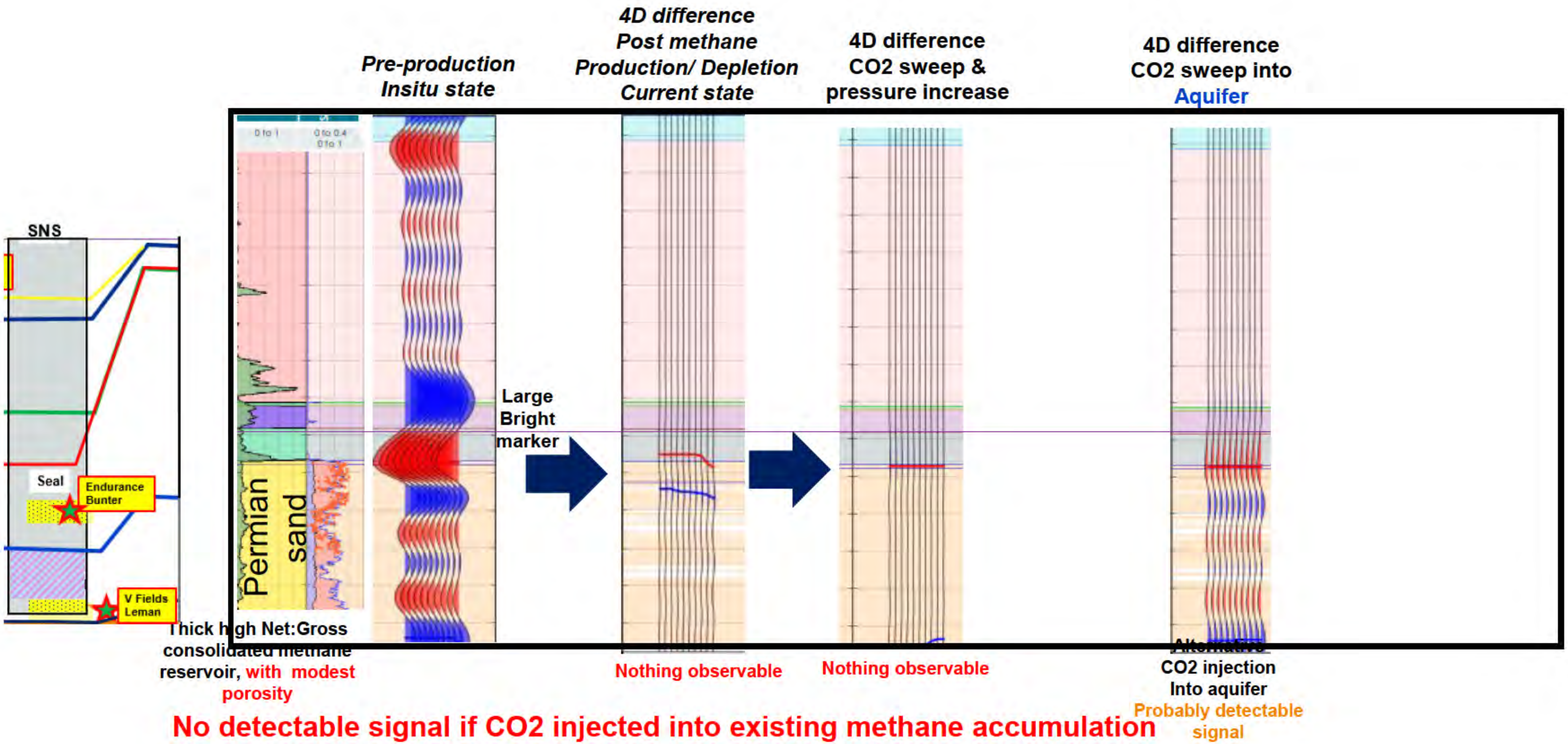
North Sea Transition Authority



Highly likely to be observable with streamer or OBN seismic acquisition

“Tough 4D” Low Porosity Permian V- Field gas field

North Sea Transition Authority



No detectable signal if CO_2 injected into existing methane accumulation

Possible small signal if CO_2 migrates into surrounding aquifer

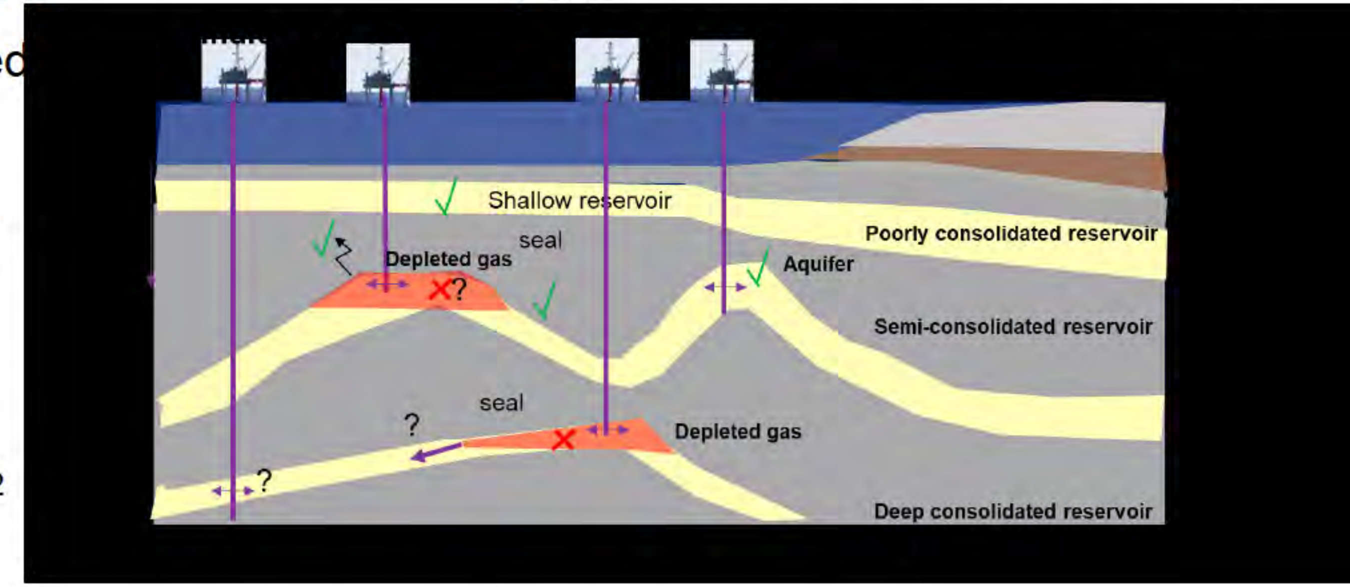
Consolidated reservoirs are probably below 4D seismic detectability

Modelled 4D signal Conclusions

North Sea Transition Authority

1) A significant 4D seismic signal should be anticipated in most situations where the CO_2
   a) Injected directly into an aquifer
   b) Laterally migrates into the surrounding aquifer or
   c) Leaks into a shallower/ overburden aquifer (e.g. Bunter secondary sand above Leman injection site)

2) The detection threshold is linked to the sand thickness, porosity, reservoir stiffness and level of CO_2 saturation at the time of surveying



3) Detection of a signal where CO_2 is injected into a pre-existing depleted methane fields is difficult

- Multi-fluid phase systems (e.g. brine, methane, oil and CO_2) are likely to provide ambiguous interpretations
- A large change in pressure does not produce an appreciable 4D response.
- Monitoring these reservoirs
  - Acquire higher specification seismic / improved repeatability to reduce the noise floor (e.g. OBN)
  - Await higher CO_2 concentrations / greater separation between surveys
  - **Assume seismic monitoring is not part of the reservoir MMV strategy**

Optional next steps: test a) 3 additional formations b) depleted oil fields & c) modelling study link seismic noise thresholds and CO_2 signal:

Seismic monitoring is likely to be a key tool in many situations

North Sea Transition Authority

CCS MMV & Spatial Co-Location Project

Nick Richardson & Ronnie Parr

26 Jul 22

Agenda

- Introductions (CCSA/NSTA) – 5 minutes
- NSTA priorities and current regional/high level activities (relating to CO_2 storage) and discussion (Nick Richardson) – 20-30 mins
- NSTA technical deep dive and discussion (Ronnie Parr) - 80-90 mins
  - MMV report

Break – 5 mins

  - Ocean Bottom Node project
  - Seismic Signal/CO_2 detection project
  - Windfarm Noise
  - Discussion over what next?

NSTA CCS role: overview

North Sea Transition Authority

NSTA CCS role

Licensing and permitting authority for offshore carbon storage

Stewardship of issued carbon storage licences

Assess and understand UKCS regional carbon storage in support of CCS build out and spatial planning

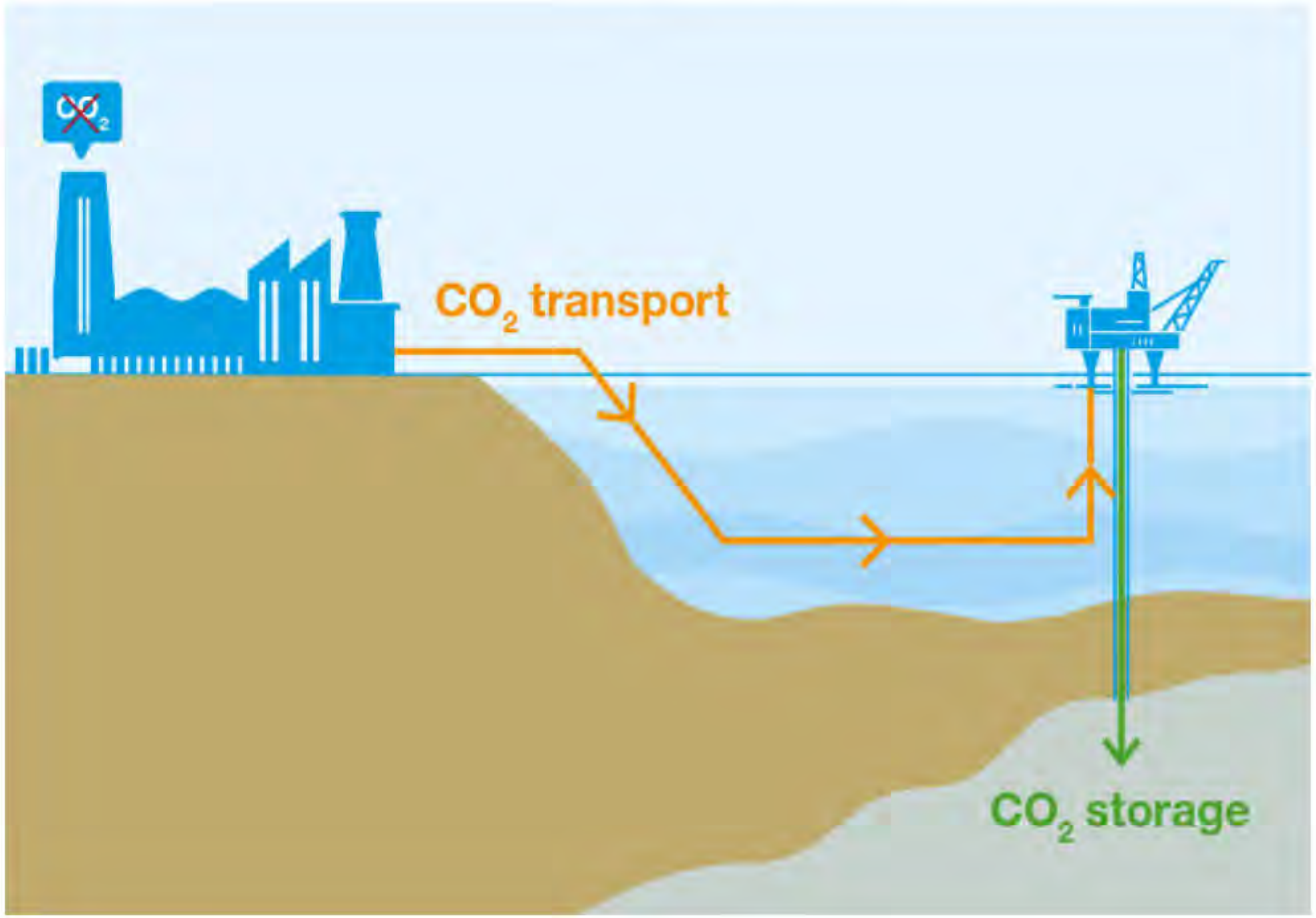
Encourage re-use as part of NSTA Cessation of Production process

Consultee to OPRED on operators' decommissioning plans

Regulatory coordination, including on co-location

Exploring role of CO_2 EOR

Maintain carbon storage public register



78 $GtCO_2$ total UKCS CO_2 storage resource estimate

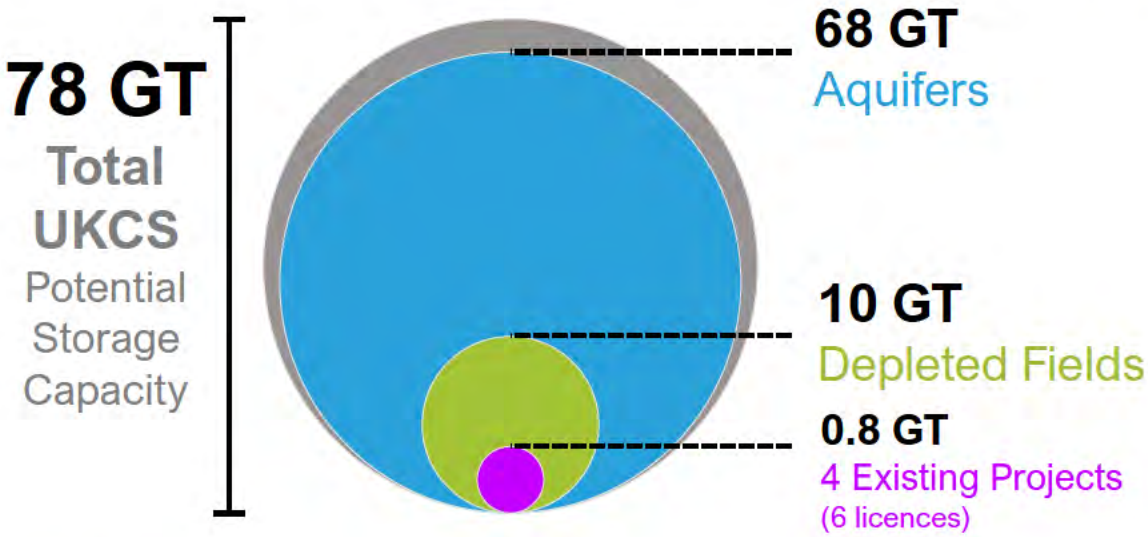
75-175 $MtCO_2$ CCC estimate of annual requirement in 2050

10 $MtCO_2$ UK govt 2030 annual target (Ten Point Plan)

UKCS carbon storage potential

North Sea Transition Authority

UKCS estimated to hold ~78Gt of potential CO_2 storage capacity, in >560 subsurface stores. Capacity could potentially cover UK needs for 100s of years, though more work is needed to understand effective UKCS CO_2 storage potential.

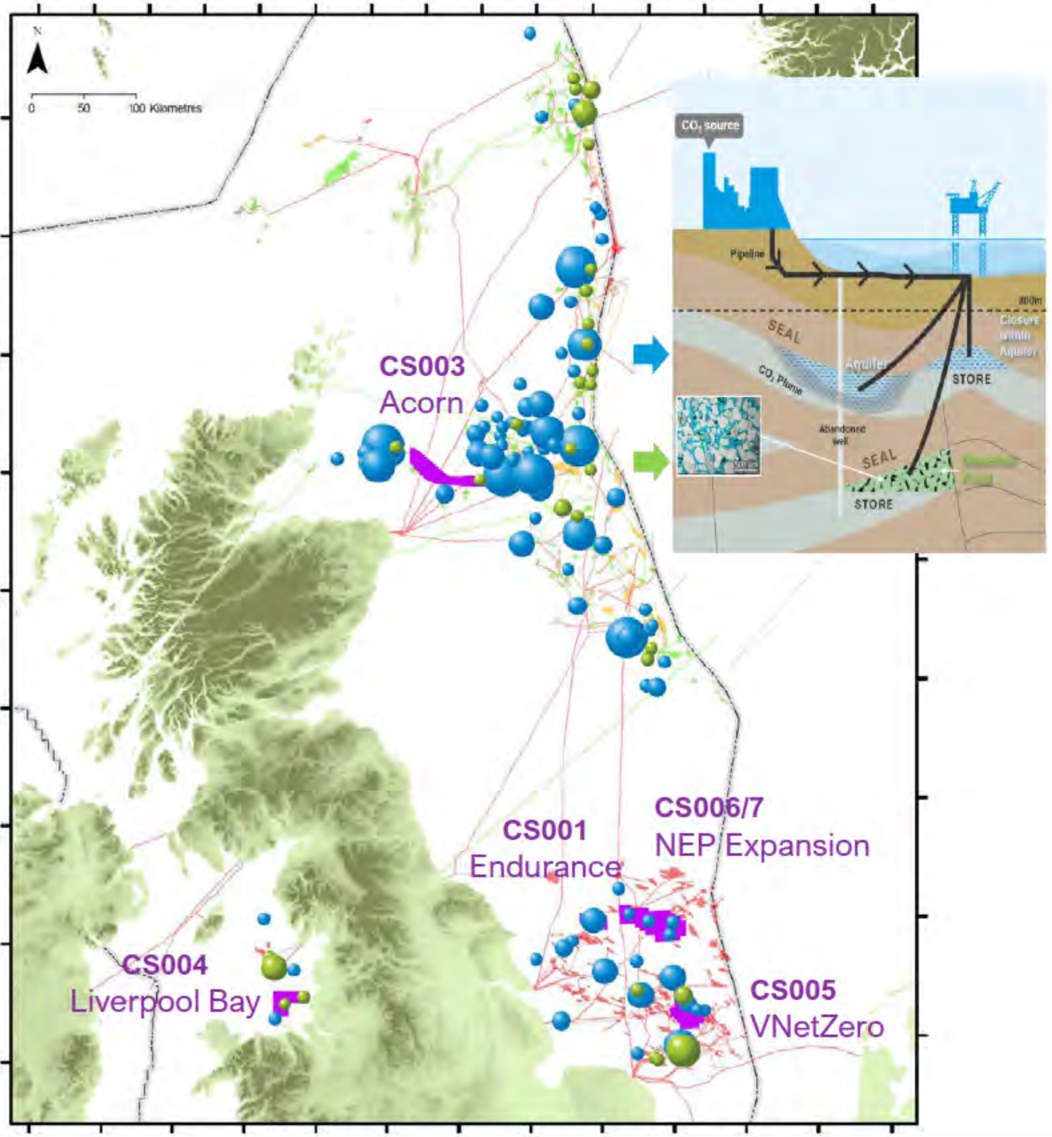


Aquifers

- Significantly larger size
- Greater subsurface uncertainty
- Requirement for new data & appraisal
- Potentially lower well-integrity risk

Depleted Fields

- Many small stores
- Potential to re-use infrastructure
- Existing data can provide baseline
- Legacy well-integrity risk

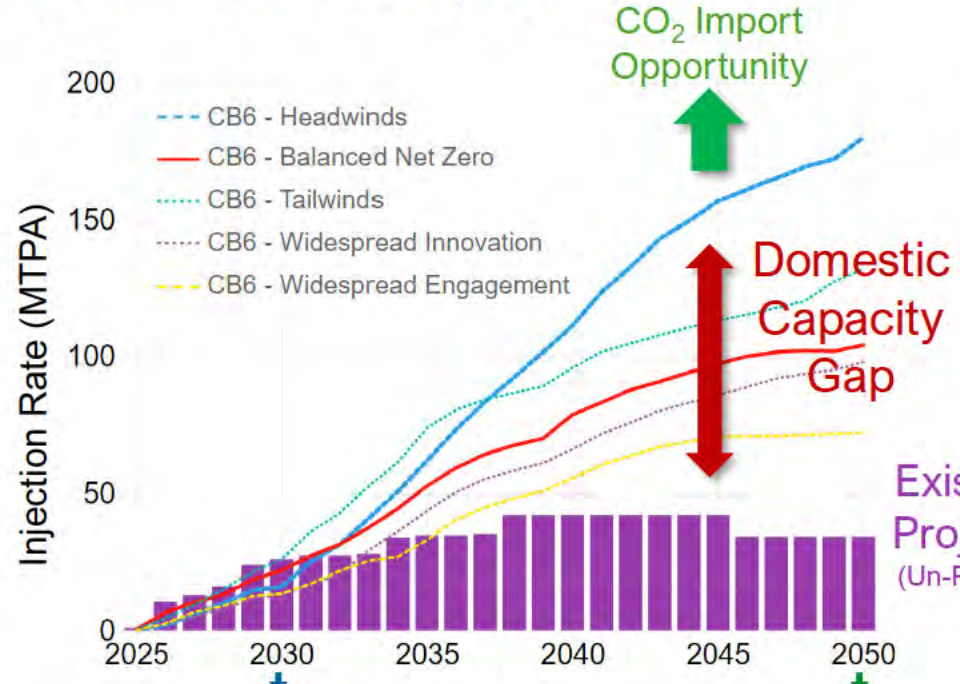


* CO2Stored Database P50 total capacity

Trajectory to meeting Sixth Carbon Budget (CB6) targets

North Sea Transition Authority

Headwinds Pathway Scenario



Existing Projects (Un-Risked)

Headwinds Scenario Domestic Requirement **180 Mt/year in 2050** (Carbon Budget 6)

140 Mt/year Gap to Headwinds 2050 Target

40 Mt/year Peak Carbon Storage Injection Rate from current 4 projects

requires:

80 stores maximum estimate

57 operational stores

37 stores minimum estimate

How many stores may we need?

Mid-range estimate based on average 2.8 Mt/year injection rate (4 wells per store at 0.7 Mt/year each)

2030 Targets

- **50% reduction** in oil and gas upstream GHGs
- **50GW** of offshore wind
  5GW of floating offshore wind
- **10 GW** of hydrogen production capacity
- Deliver 4 CCUS clusters, capturing **20-30 $MtCO_2$/year** across the economy, including 6 $MtCO_2$/year of industrial emissions capture.

2050

CCC recommendation - **75GW** offshore renewables capacity

180 Mt/year Carbon Storage Injection Rate (Headwinds)

- Appraisal timescales likely to be 6 to 10+ years from licence award to first injection
- To keep on track, NSTA launched a **Carbon Storage Licence Round** 14 June 2022

Activities

North Sea Transition Authority

Working with government and industry

Supporting government and others to identify existing infrastructure with reuse potential for CCS or hydrogen projects

Validating CCS facility plan costs using OGA offshore facility capex and opex benchmarks

Engaging with CCS project developers

Guiding and stewarding developers and applicants through OGA processes

OGA Digital Energy Platform

OGA, incl. through its National Data Repository, collects, holds and shares CCS relevant data – seismic, wells, etc. – and publishes data packages to support/promote licensing rounds

Interactive app mapping all UKCS energy sites – O&G infrastructure, wind, cables, CCS

Current project identifying CCS data gaps on regional basis

Technical Projects

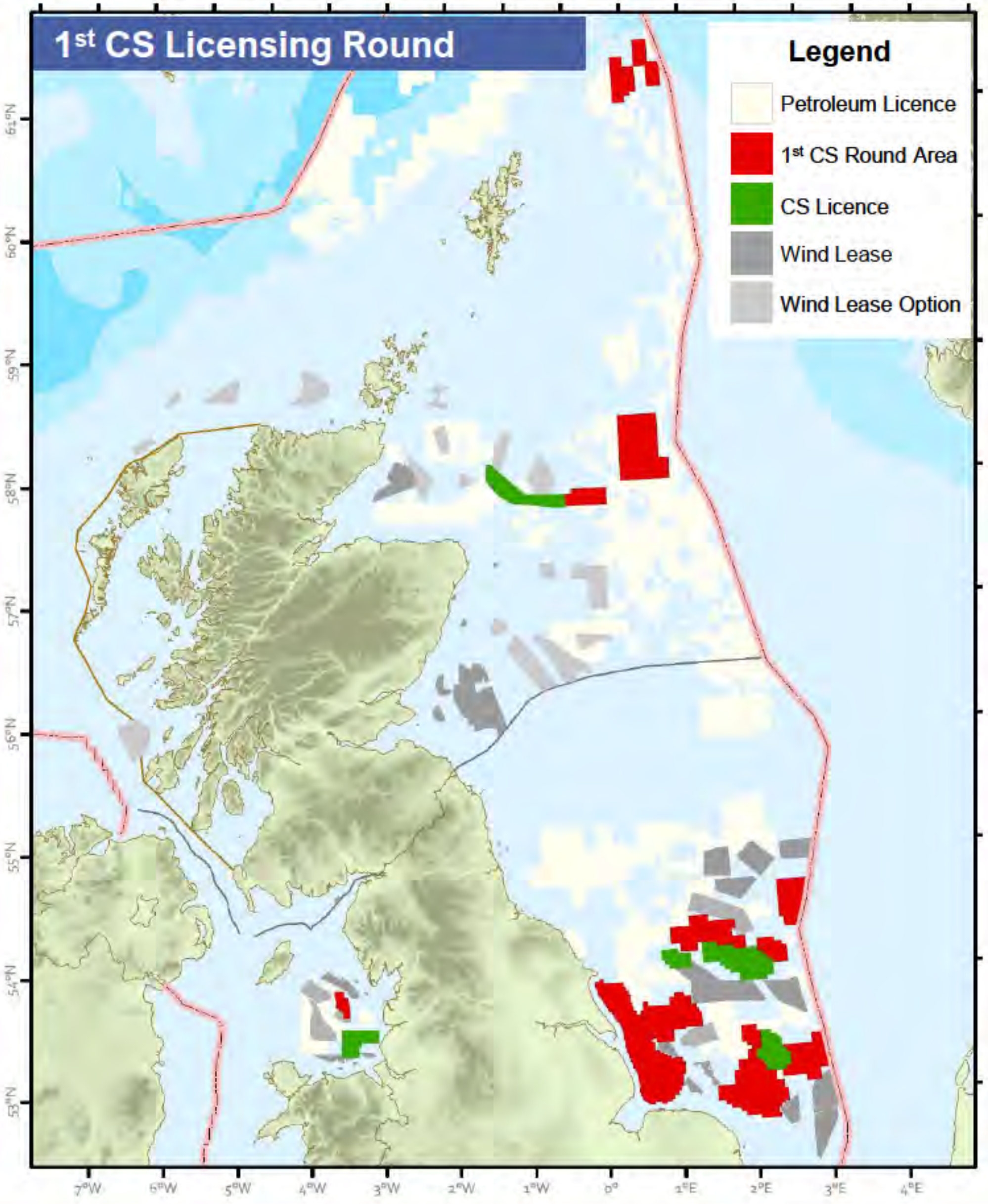
NSTA Project SPICE mapping UKCS storage potential and capacity estimation

'BOOST' (Best Opportunities Of Storage) initiative Objective to provide range of carbon storage capacities/injection in support of spatial planning considerations

NSTA participation in TCE Offshore Wind/CCS Co-location Forum NSTA leads on reviewing CCS MMV seismic acquisition issues, exploring alternative seismic technology (ocean bottom nodes) to reduce spatial conflict; study on turbine motion impact on seismic activity; study on predicted seismic detection threshold

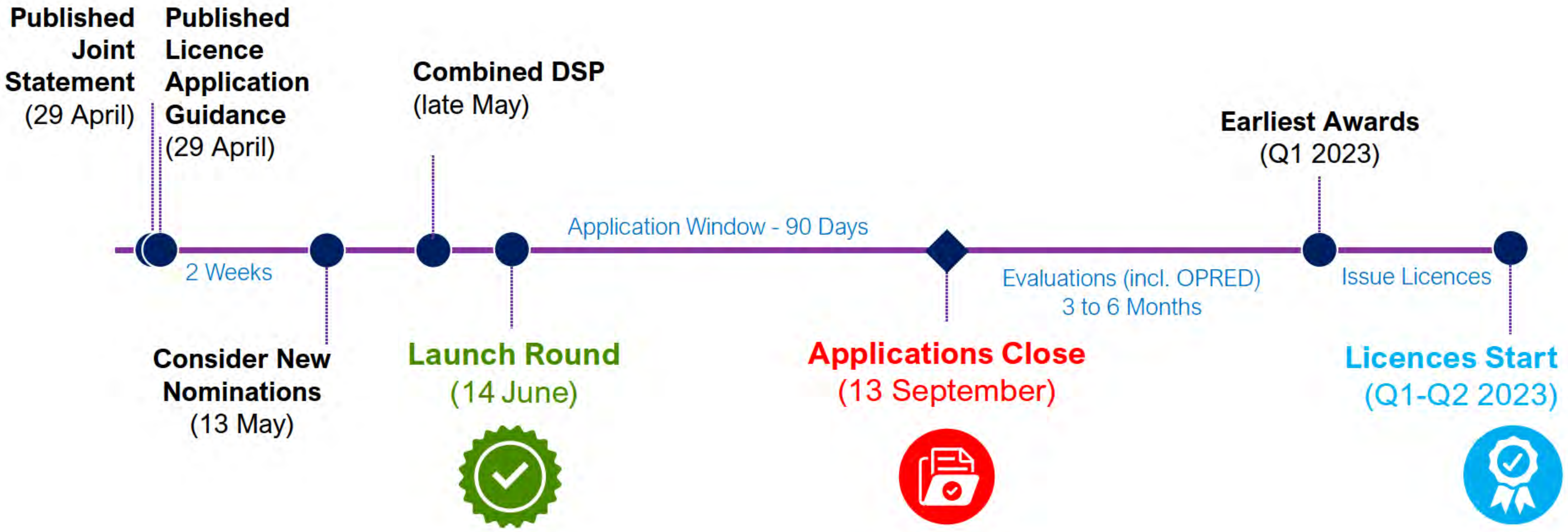
NSTA engagement with Defra marine planning programmes Engagement with Marine Spatial Prioritisation framework development

Well integrity and P&A – for legacy wells and decommissioning plans, including data reporting



First CS Licensing Round – Timeline

North Sea Transition Authority



UK Marine Planning Bodies

Marine planning is devolved across the UK and each administration has developed a different approach to managing activities in the marine environment suited to their own administrative, political and geographical needs.

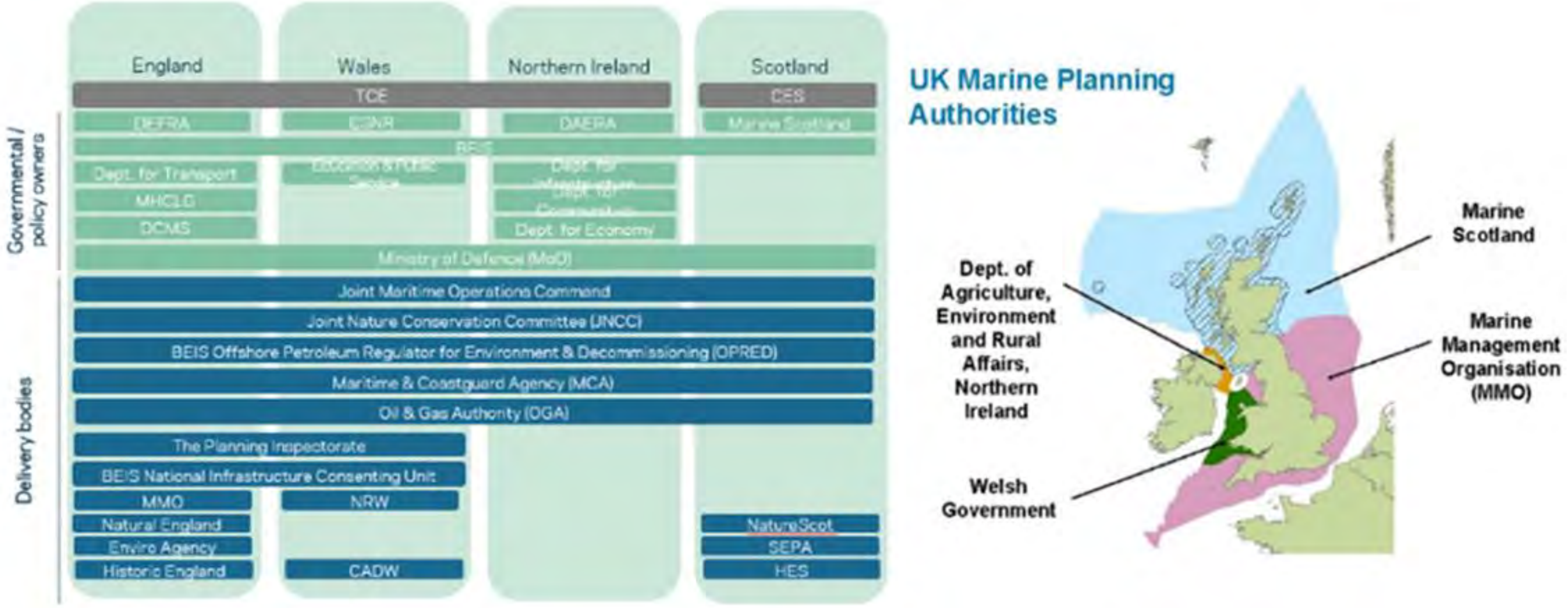


Figure from The Crown Estate

NSTA Projects Overview (Jan 2021- Mid 2022)

North Sea Transition Authority

- **1) MMV (Monitoring Measurement Verification)** — NSTA Publication summer 2022
  - Specific consideration to co-location issues
- **2) 4D CCS examples**
- **3) 4D OBN seismic** — Publication ~ end 2022
  - Seismic acquisition review
  - Processing, Case studies & Assimilation
- **4) Seismic signal vs noise**
- **5) Predicted 4D Seismic Signal/ CO_2 Detection Project** — Publication ~ end 2022
  - 5 Wells: Petrophysics & Fluid substitution (Brine, Methane and CO_2) — Completed
- **Windfarm noise (Heriot Watt/ Colin Macbeth**) — Reaching completion

Acknowledgements

North Sea Transition Authority

2021 MMV study

allton, bp, The Crown Estate, Department for Business, Energy & Industrial Strategy, ebn, eni, equinor, Fugro

Gardline, Heriot Watt University, magseis fairfield, Net Zero Teesside & Zero Carbon Humber – Northern Endurance Partnership, OGTC, Catapult Offshore Renewable Energy, Ørsted

NCS SubSea, new wave energy, PGS, Storegga, Schlumberger, Shell, Shearwater

STEMM-CCS, TGS

2022 OBN study

AGS, AkerBP, Blue Ocean Seismic Services, CNPC BGP, bp, CGG, cnooc

ion, Energeo Alliance, equinor, magseis fairfield, Ørsted

PGS, PXGEO, Schlumberger, Shearwater, Signum Geophysical Ltd

TGS, TotalEnergies

2022 Seismic Detection

bp, eni, equinor, Harbour Energy

Ikon Science, Shell, Storegga

2022 windfar e

Heriot Watt University, Spirit Energy

The NSTA is grateful to all individuals & organisations and who willingly provided expertise, insights and data

MMV Summary

There are no one-size-fits all solutions.

Seismic is the key geophysical monitoring technology providing best resolution.
Surveying activities in and **around offshore windfarms** can be extremely challenging,
unacceptable collision risk if deploying long towed seismic streamers
Some potential mitigating seismic solutions (e.g. Ocean Bottom Nodes OBN) at higher cost

---

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**,

---

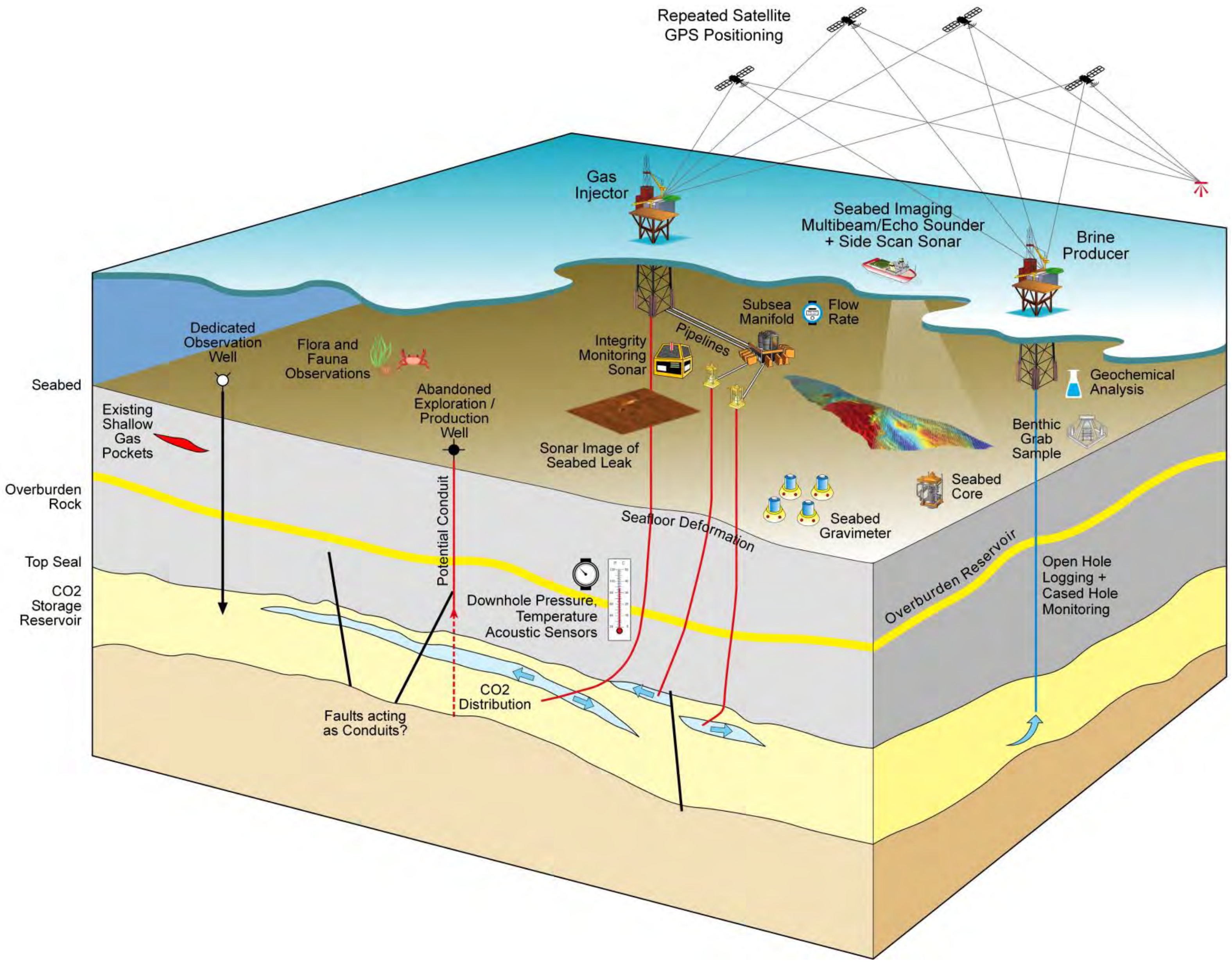
First-of-a-kind (FOAK) projects may be expected to be potentially over-engineered, particularly as MMV methods are tested and certified, and maintaining public confidence is crucial. Each project requires a robust environmental baseline.

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.

CCS Portfolio of MMV (Measurement, monitor, verification)

North Sea Transition Authority



Well surface & Downhole
Flora and Fauna
Benthic grab
Geochemistry
Sonar
Seeps
Ground deformation
Seabed gravity
Controlled source EM

Wide range of non-seismic monitoring technologies available

4D seismic monitoring context

- Seismic is expected to be an important component of the broader MMV (measurement, monitor, verification) technology portfolio.

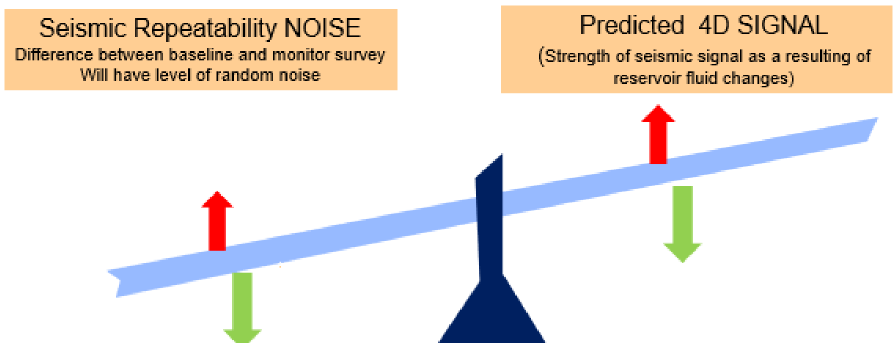
- CCS complex operator identifies a number of risks & uncertainties that could be mitigated by repeated seismic observations of the rock and fluid response to CO_2 injection.

Important considerations:

1) Magnitude of reservoir **signal** generated by production/injection between the baseline & monitor surveys

2) Sufficiently low level **noise** (non- production) differences between the seismic surveys

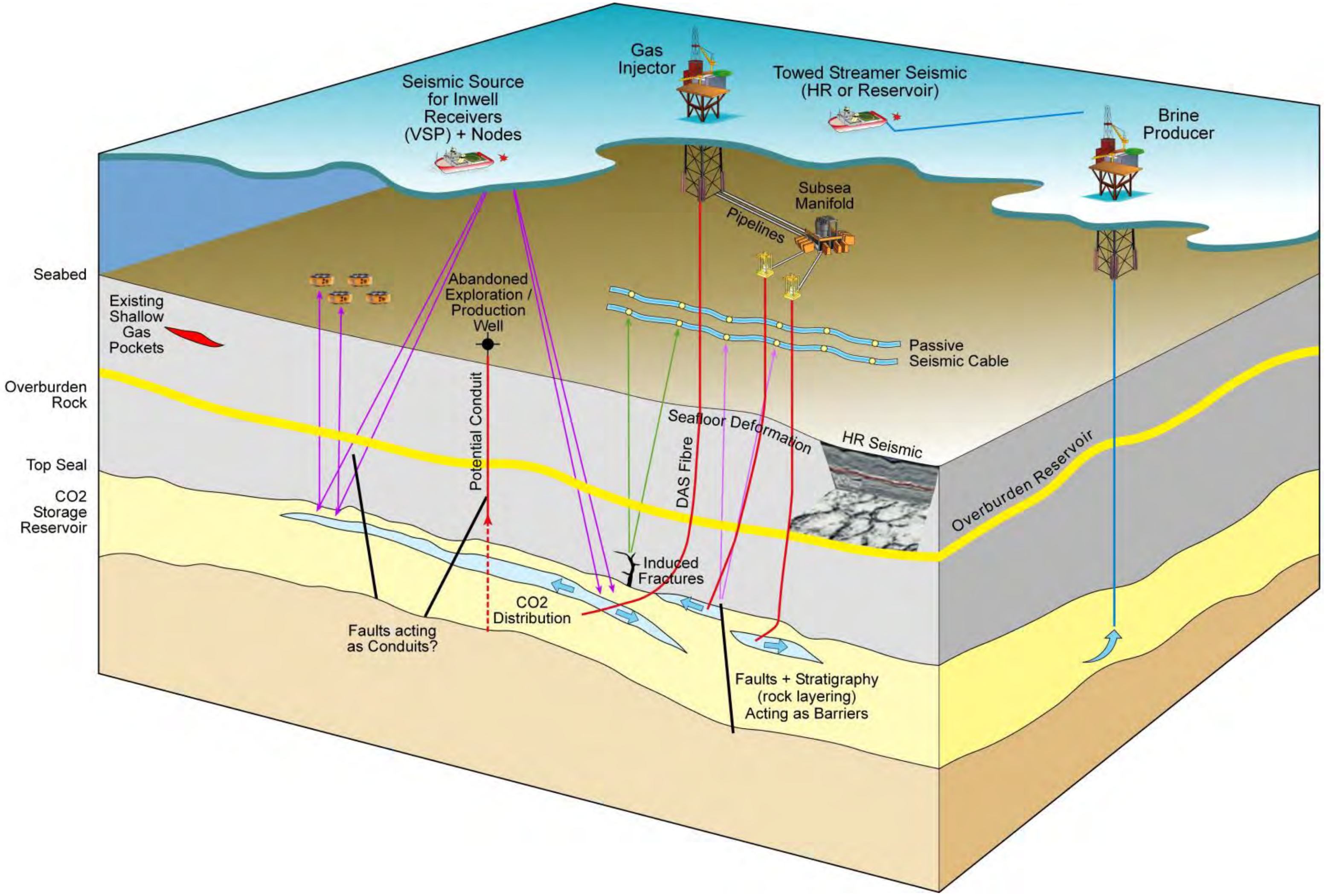
3) There are clear plans to use the monitoring data to mitigate specific risk and uncertainties



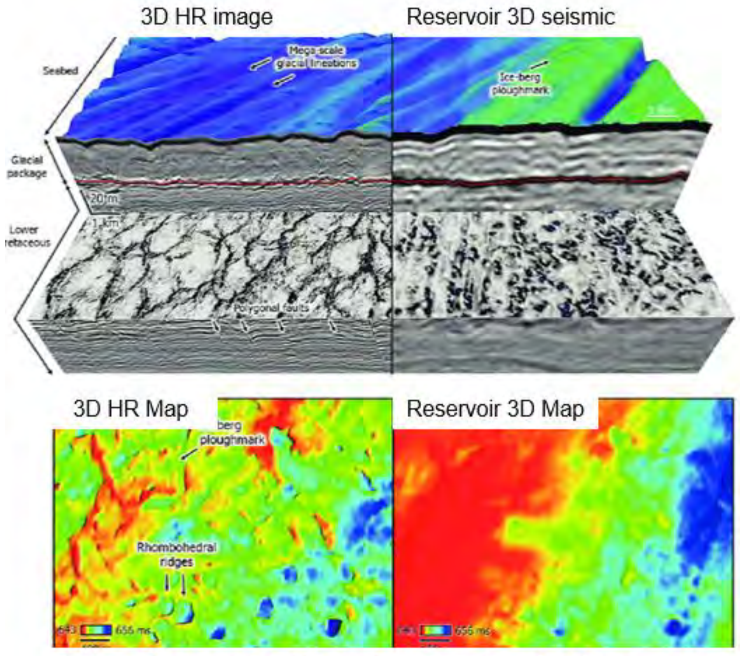
OBN (Ocean Bottom Node) seismic is

- **A geophysically superior reservoir imaging technology especially for complex imaging targets**
- **or within a constrained/ co-location environment**
- **The cost of each OBN 4D survey (baseline & every monitor) is 2 to 5 times more expensive than its streamer equivalent.**
- **This remains a major drawback and cannot justify the cost in most CCS situations.**

Range of Seismic technologies



- **Active seismic (Streamer or OBN acquisition)**
- **Reservoir or shallow (HR) targets**
- **Passive seismic (Microseismic)**
- **In-well seismic (VSP or DAS)**

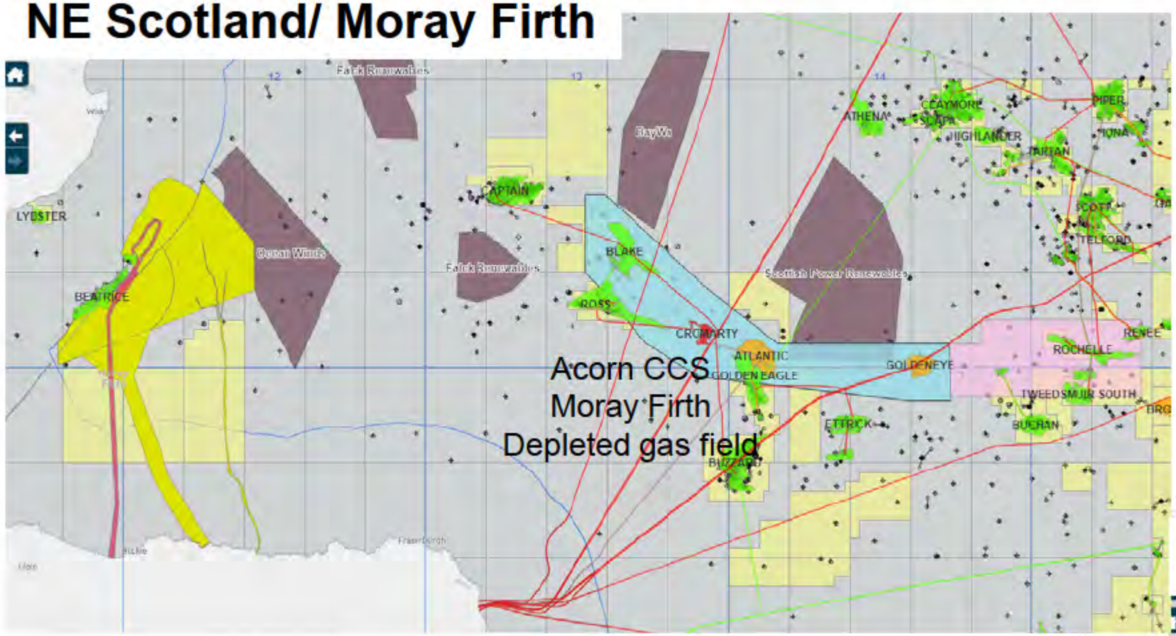


Comparison of 3D HR and reservoir seismic Reference (7)

CCS Projects investing in quality active 3D / Baseline 4D monitoring

UK Offshore Current Co-location areas

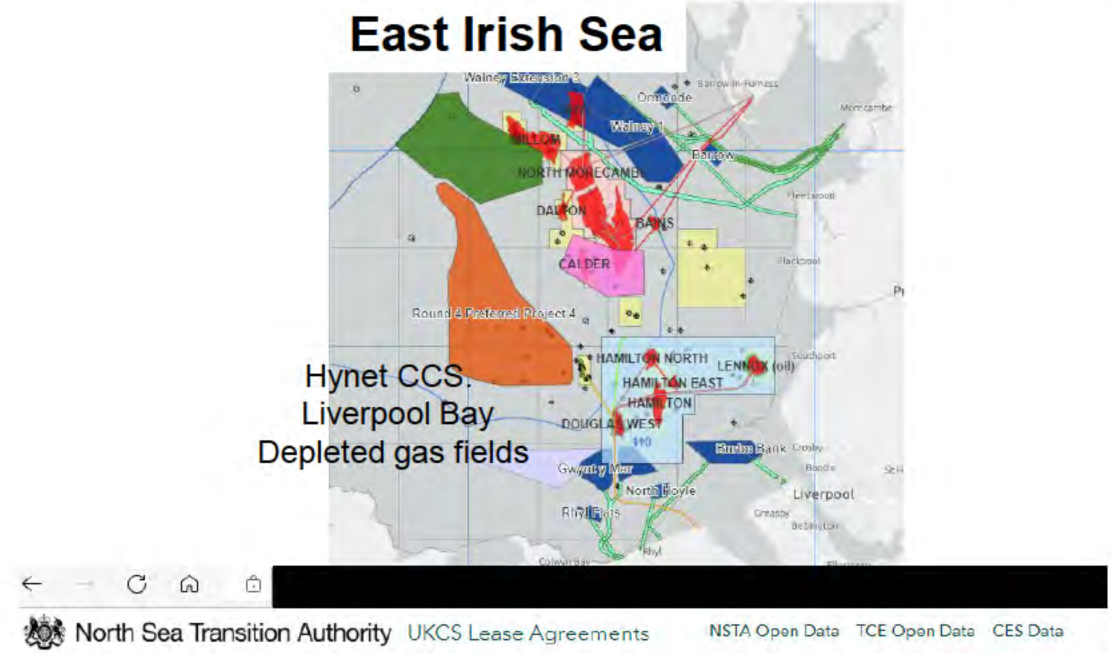
North Sea Transition Authority

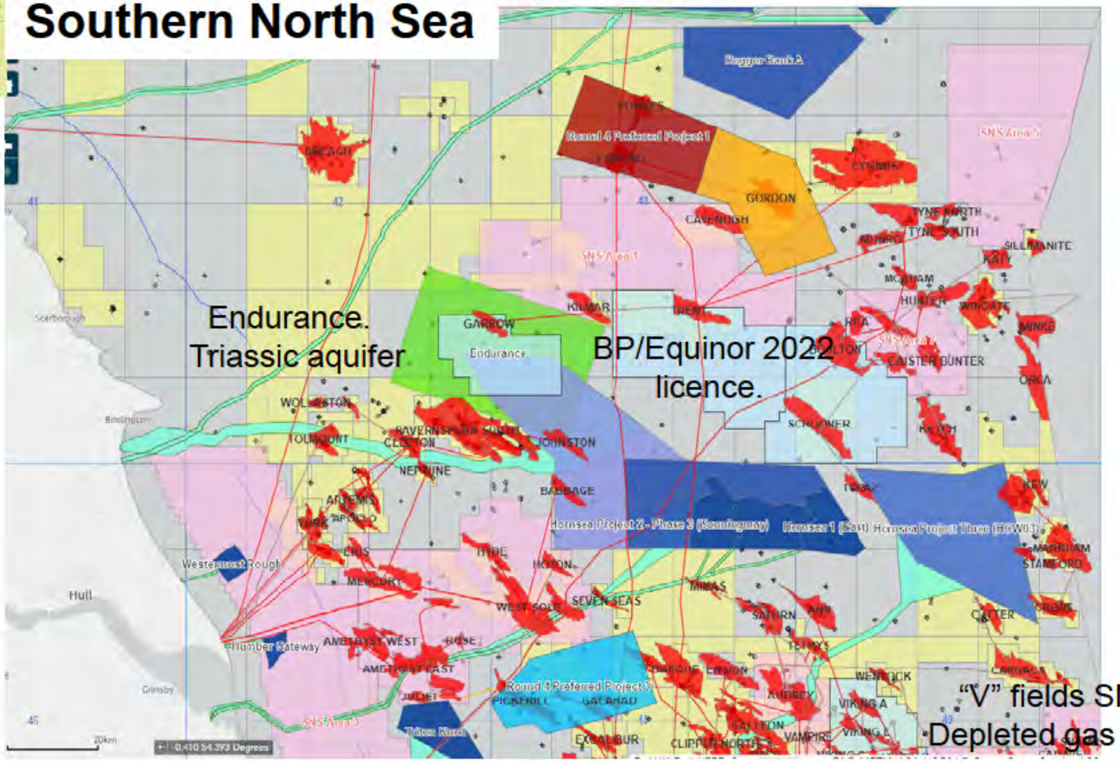


Offshore wind boom risks North Sea fishermen being 'crowded out'

ENERGY VOICE

Fisheries fleets risk being sidelined as offshore wind booms across UK waters

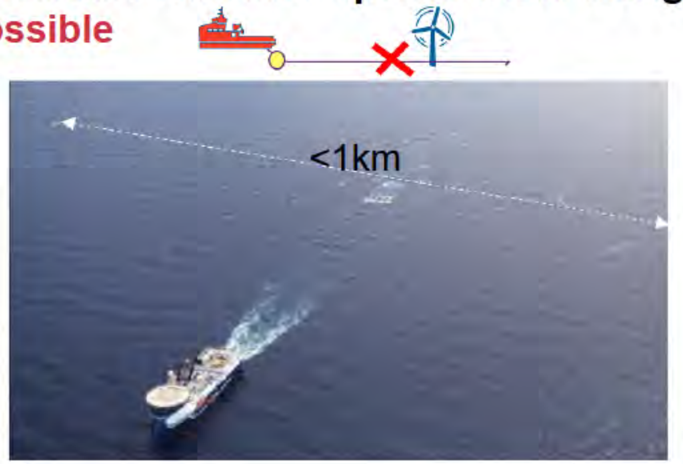




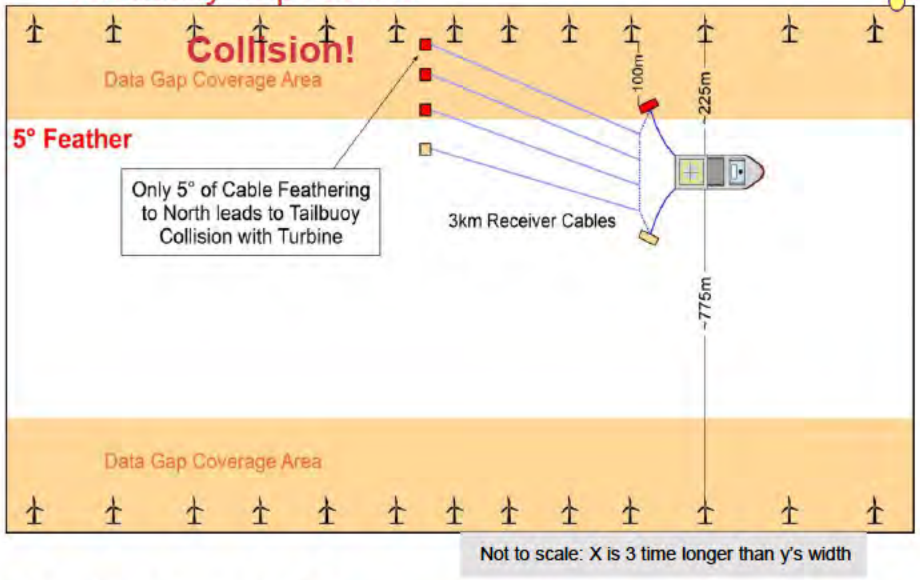
Marine Seismic Operations around Windfarms #1

North Sea Transition Authority

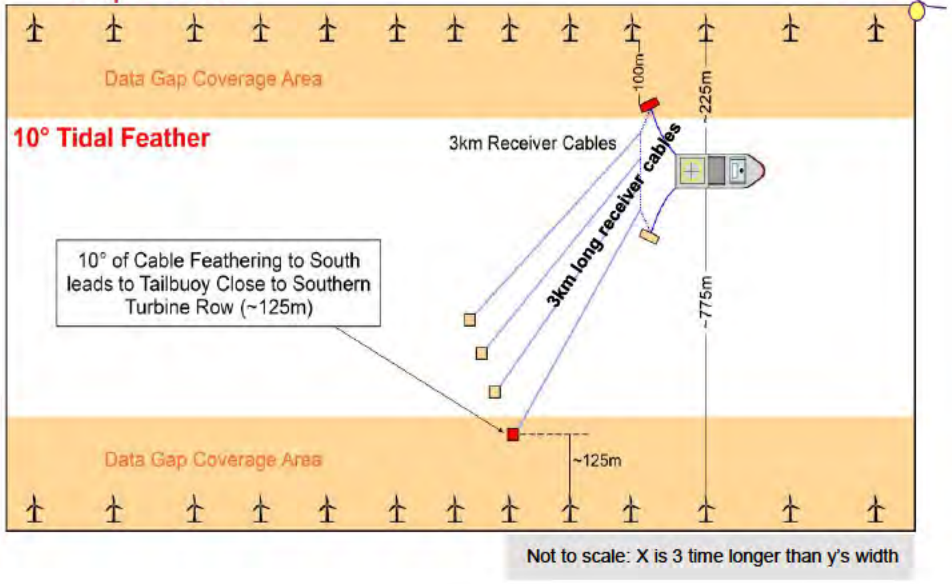
Conventional streamer spread width along turbine corridor:
Impossible



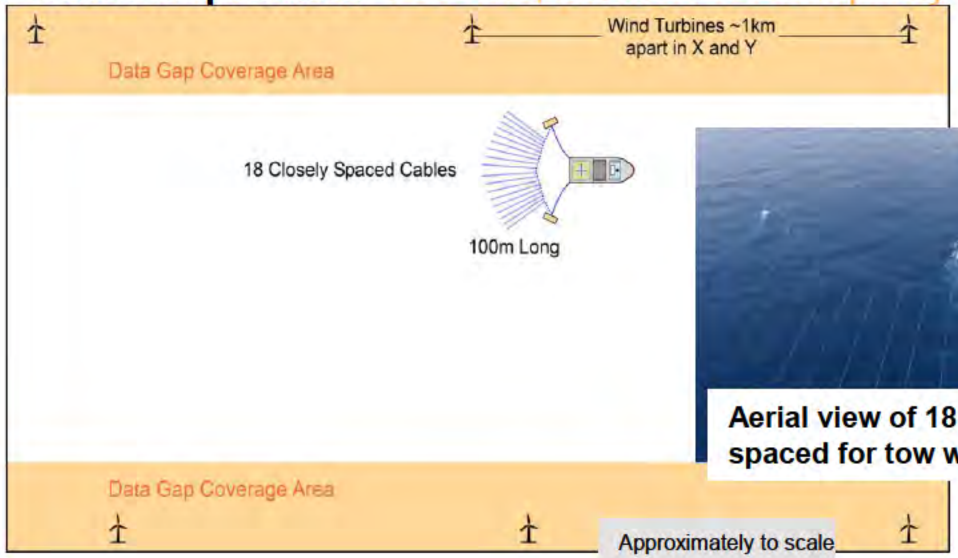
Very much reduced equipment spread.
Practically impossible



High or unpredictable currents -> moderate/large feather:
Impossible



P-Cable acquisition: Possible, but inferior data quality



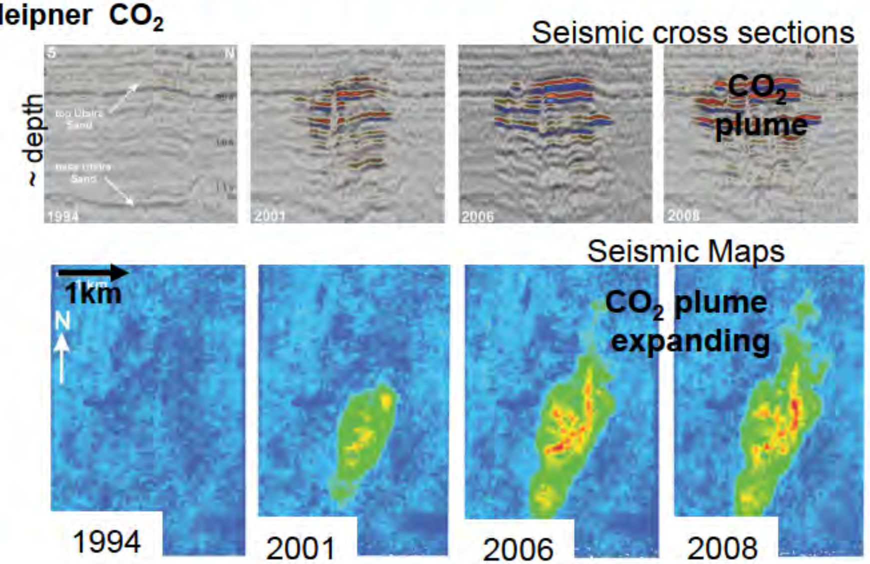
Aerial view of 18 x 100m cables closely spaced for tow width of about 200m

2. 4D examples

Very Few Real world 4D CCS examples

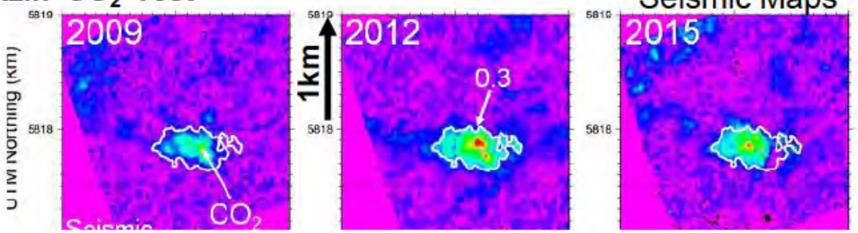
North Sea Transition Authority

Sleipner CO_2



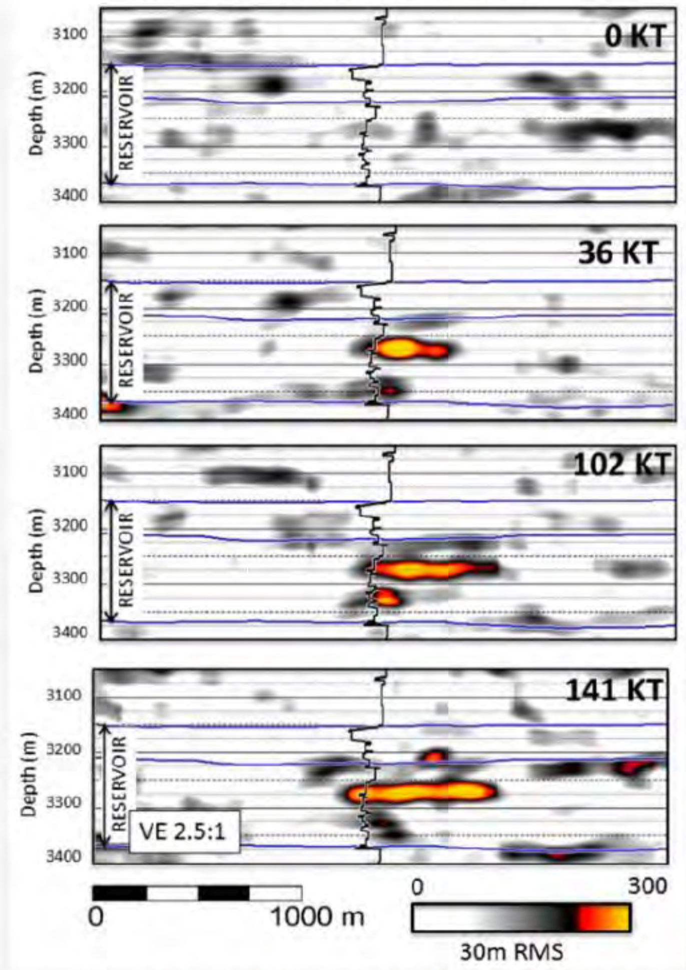
Pre CO_2 injection: weak seismic response
Post injection surveys: Complex CO_2 "bright spots"
Direct detection of CO_2 plume distribution

Ketzin CO_2 Test



Post Injection plume increase with time & CO_2
2015 Shrinking response = fast dissolution of the CO_2.
Could only be detected with an intermediate (2012) survey

Seismic Cross section
DAS-VSP Time lapse difference



As volume of injected CO^2 increase the amplitude relative to baseline increases

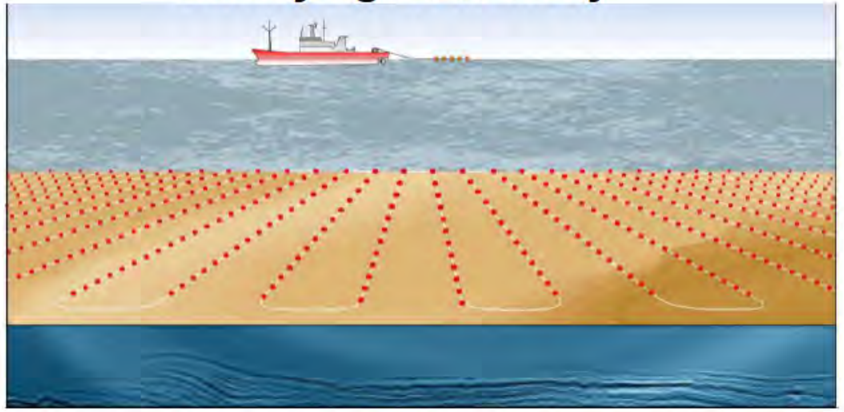
Important Notes: Very few actual CCS studies worldwide to underpin guidelines

- **Guidance based around 20 years 4D technology deployment in O&G industry**
- **CO_2 has a complex behaviour in the subsurface (e.g. dissolution)**

3. OBN (Ocean Bottom Node) Seismic Project

OBN acquisition methodology

Surveying node array

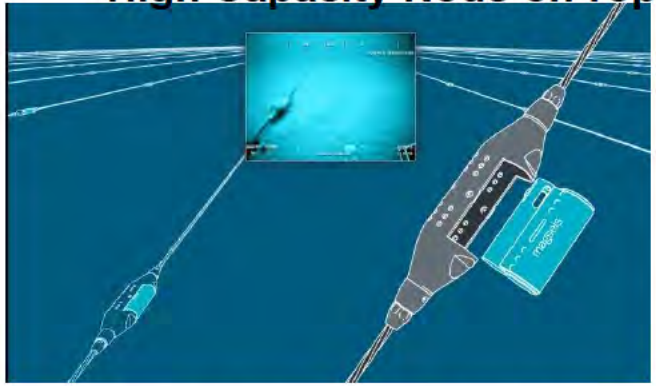


Potential Node Handler (M/V Ocean Pearl)

- Lays/Picks up nodes in very controlled fashion
- Can/does go close to installations
- “redundancy of propulsion/steerage”
    - Not necessarily DP (dynamic positioning)

Node & deployment on a rope

High Capacity Node-on-rope



7kg node

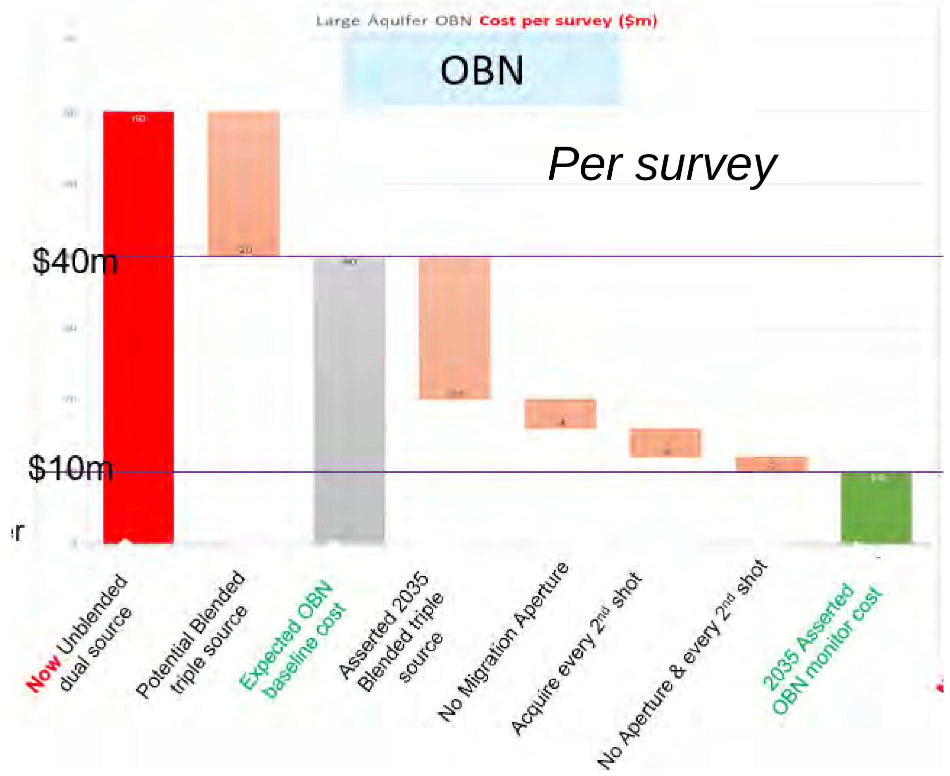
- Cables hold sensors/ No electronics in cable
- Autonomous
- Vessel holds several hundred kms of cable
- Robotic back deck speeds up deployment/ removes manual handling
- Automatic data transfer

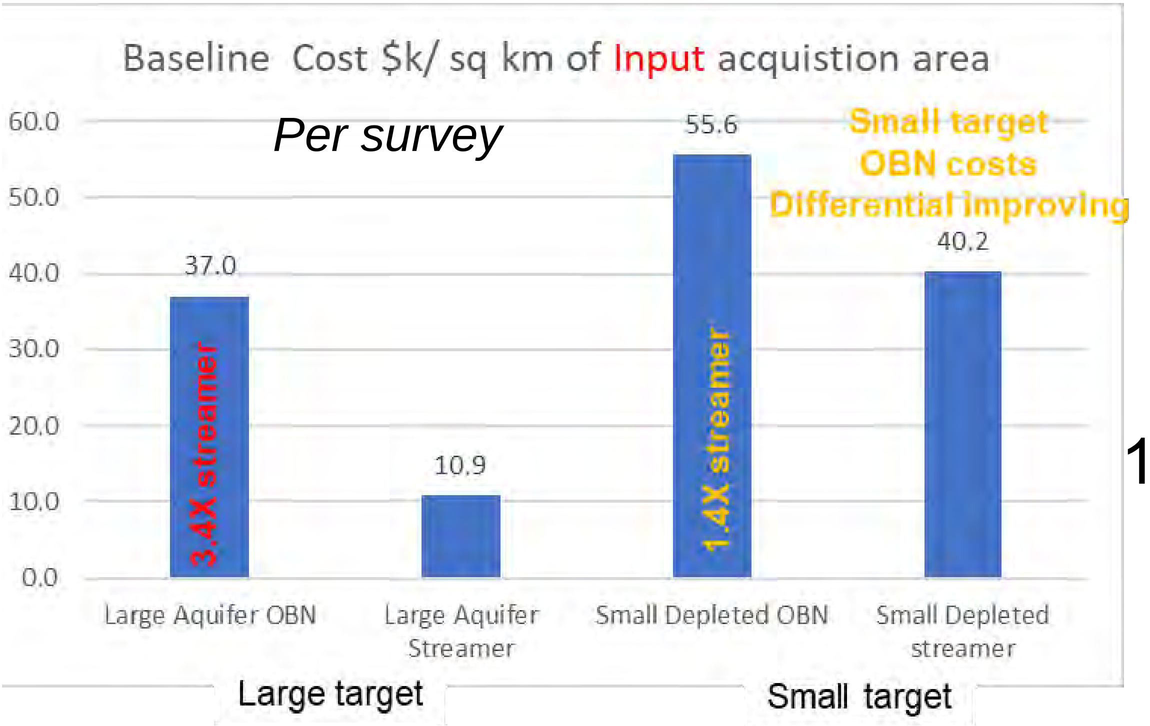
Modern efficient OBN acquisition

Acquisition cost comparison

North Sea Transition Authority

- Using OBN & streamer configuration to give comparable resolution
- generic large "aquifer" survey vs small "depleted gas" field





Total lifecycle 4D: Large Aquifer: $96-146m (OBN) or $54m (streamer) vs. Whole CCS project costs ~£5bn (1-2% of Capex

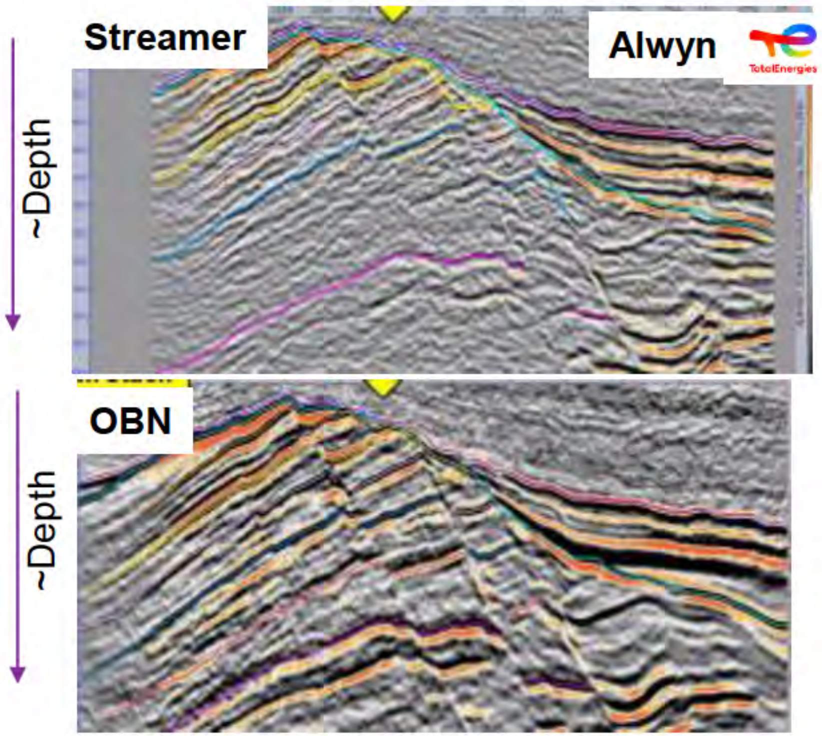
- OBN costs reduced by ~50% over last decade
- Some scope for further technology development
- OBN will always be slower (and more costly) than streamer

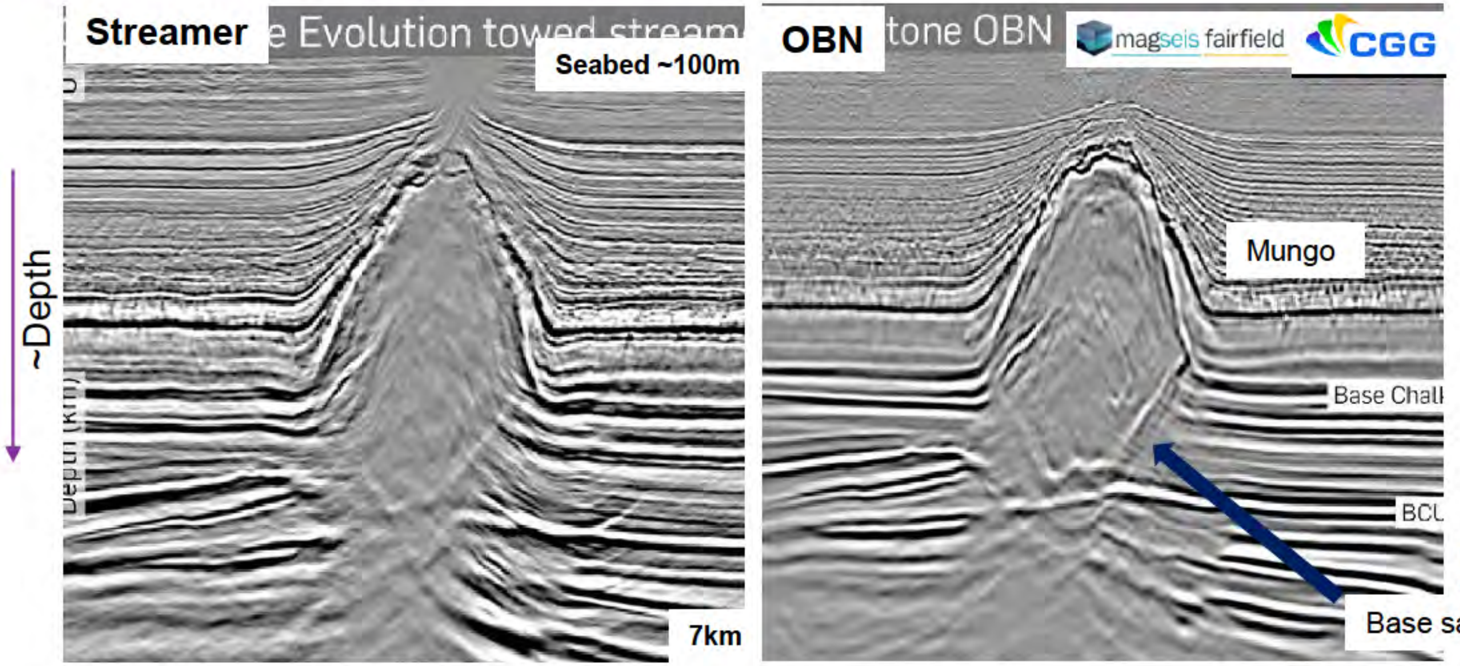
Seismic costs small proportion of total project capex, but very hard to justify the significant additional cost purely for marginal imaging improvement for most reservoirs

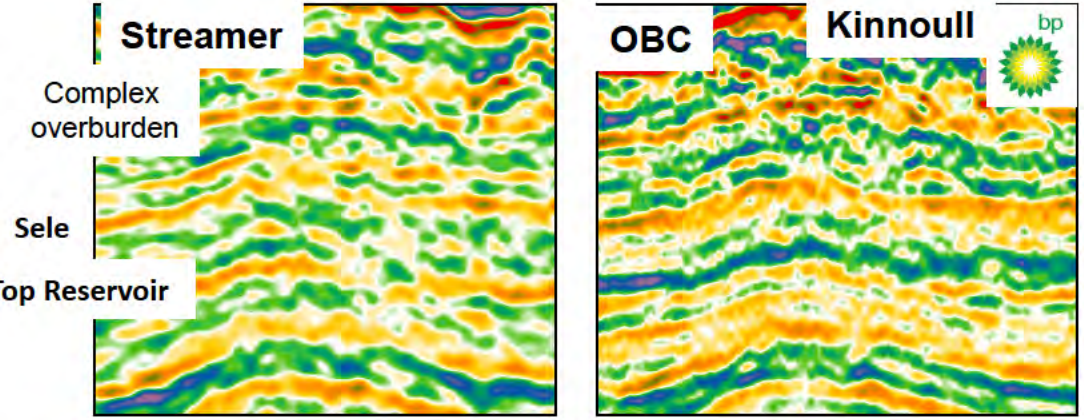
OBN has some scope for further cost reductions

OBN Traditional: complex structures or overburdens

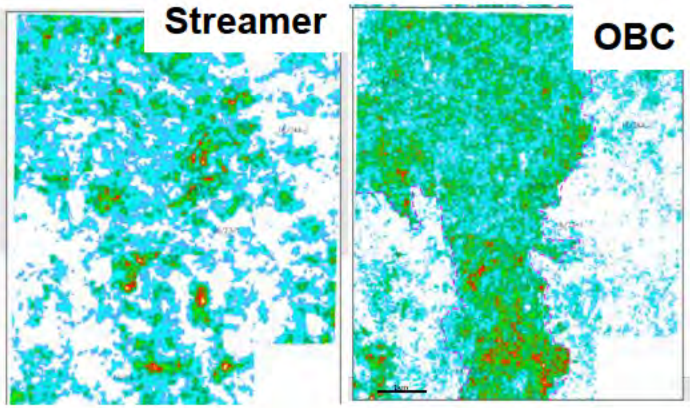
North Sea Transition Authority







Seismic attribute map
(extract signal strength @ top reservoir)



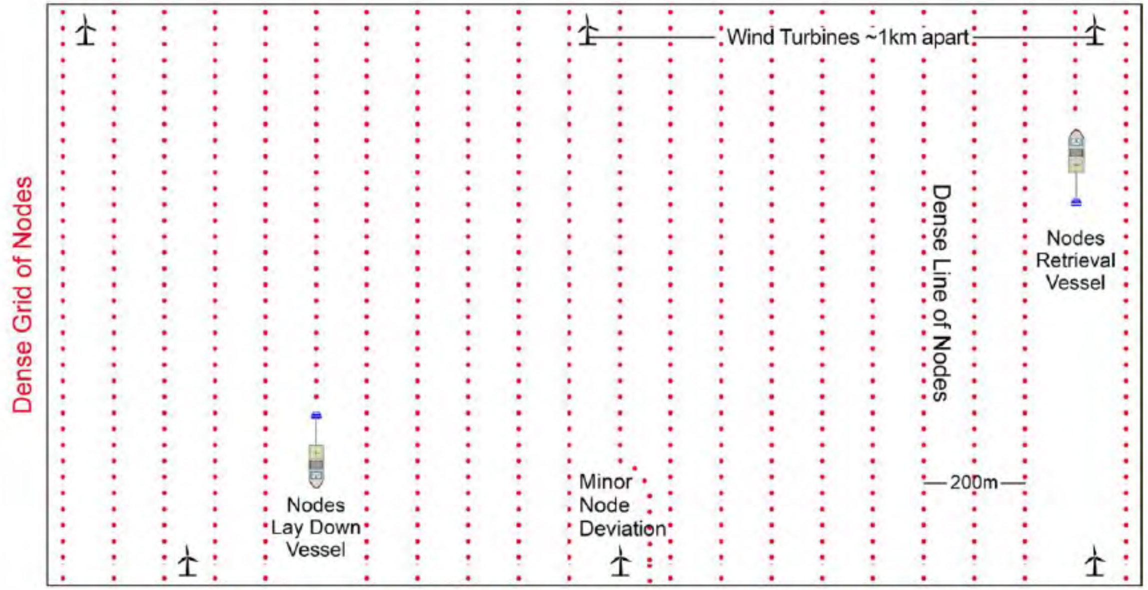
Many examples from UKCS where OBN has delivered superior image of subsurface e.g.

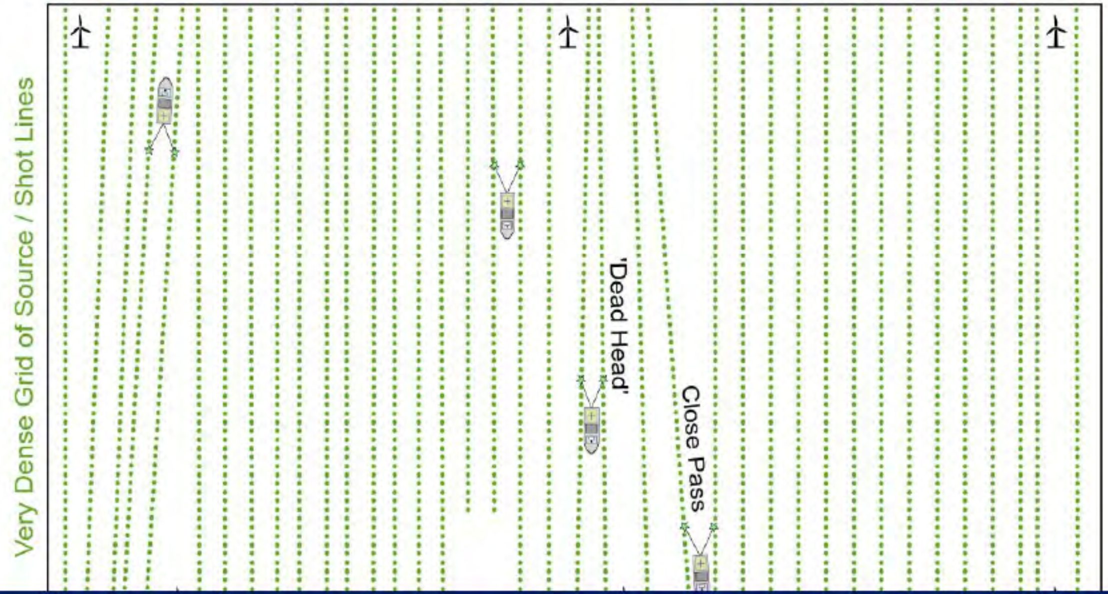
- Improved fault definition
- Increased horizon continuity
- Superior salt tectonic mapping
- 4D reservoir behaviour

OBN usually employed for complex targets/ Many excellent examples of geophysically superior imaging improvements

OBN acquisition Proximity to obstructions

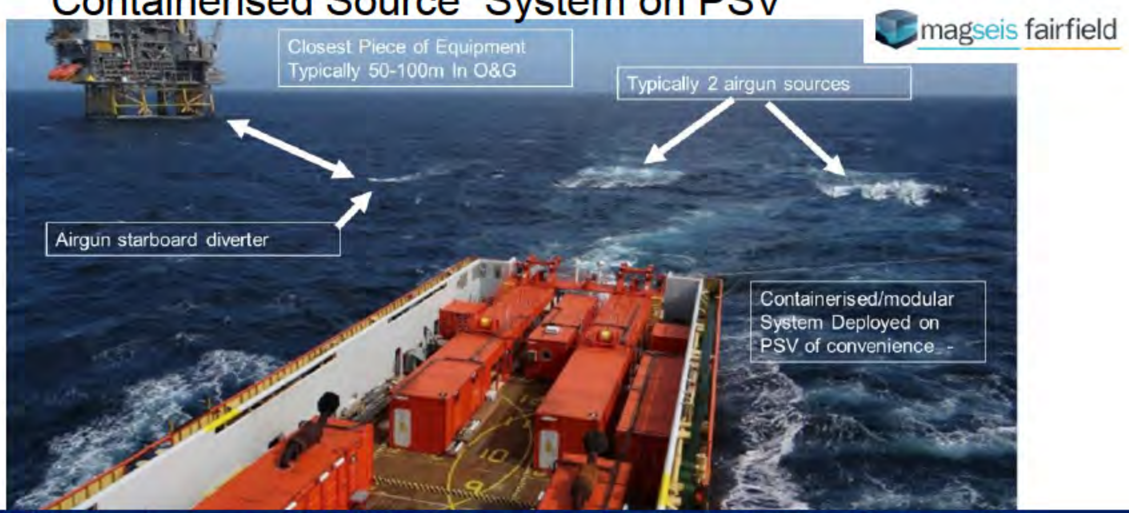
North Sea Transition Authority





Geowave Commander (node vessel) on close approach (~350m) to platform. Picture taken from source boat

Containerised Source System on PSV

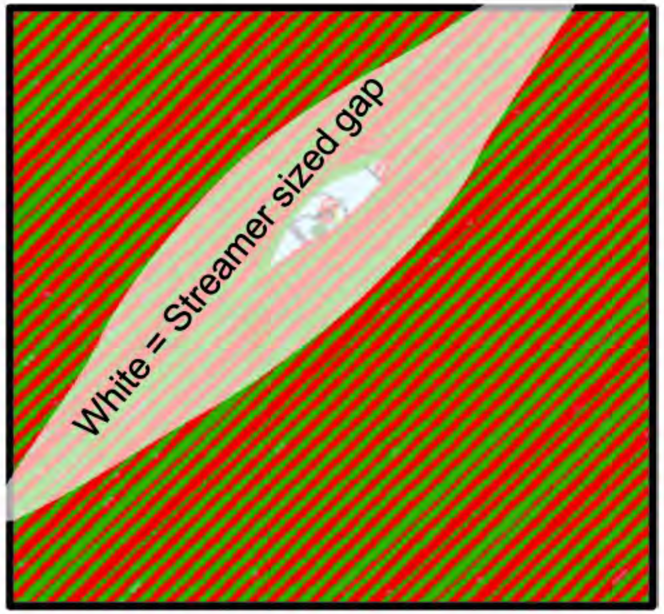


OBN can be acquired close to infrastructure

Streamer vs OBN around single platform

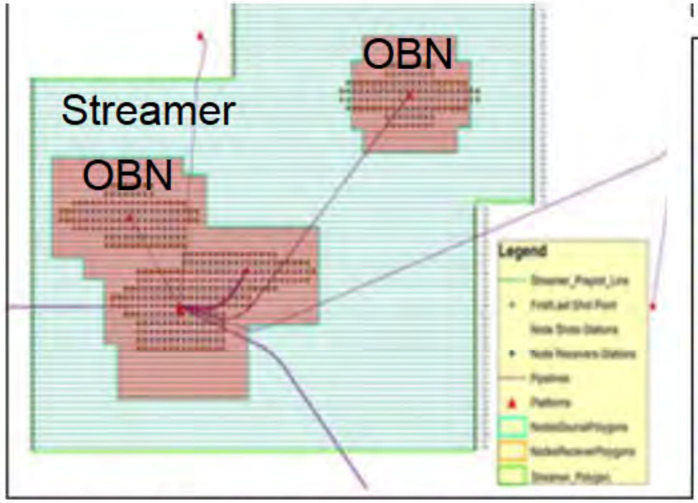
North Sea Transition Authority

Acquisition around single platform



Seismic source lines (alternating red & green direction, 25m apart) shooting into permanent installed nodes (PRM). Dead heads visible from NE

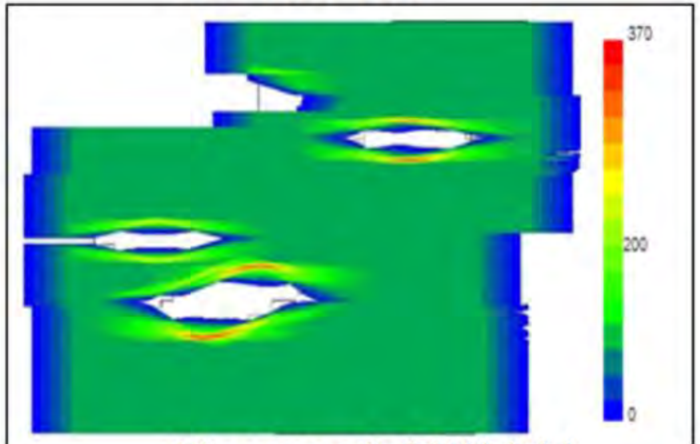
Hybrid streamer & OBN around platform (Malaysia)



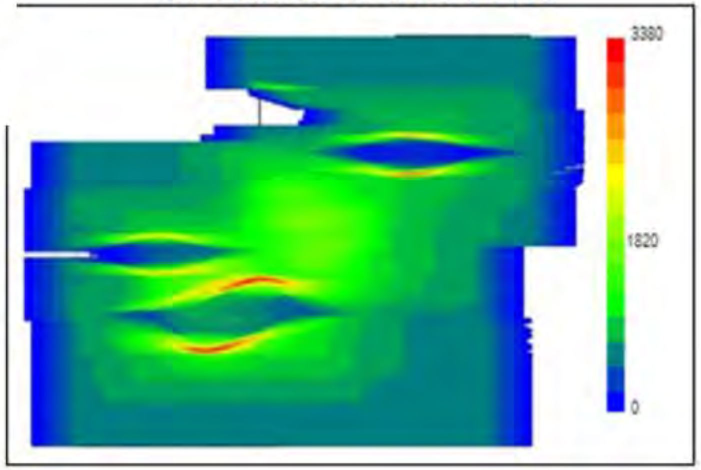
A cost-effective and efficient solution for marine seismic acquisition in obstructed areas – Acquiring ocean-bottom and towed-streamer seismic data with a single multipurpose vessel

Michelle Tham[1], Tim Brice[1], Artem Sazykin[1], Wai Leng Cheah[1], Stephen Winters[2], Nigel Jones[3], Sandeep Chandola[4], Shamsul Shukri[4], Subodh Kumar[4]*
[1]WesternGeco, [2]Roc Oil Company, [3]Dialog Resources Sdn. Bhd., [4]PETRONAS Carigali Sdn. Bhd.

Streamer fold



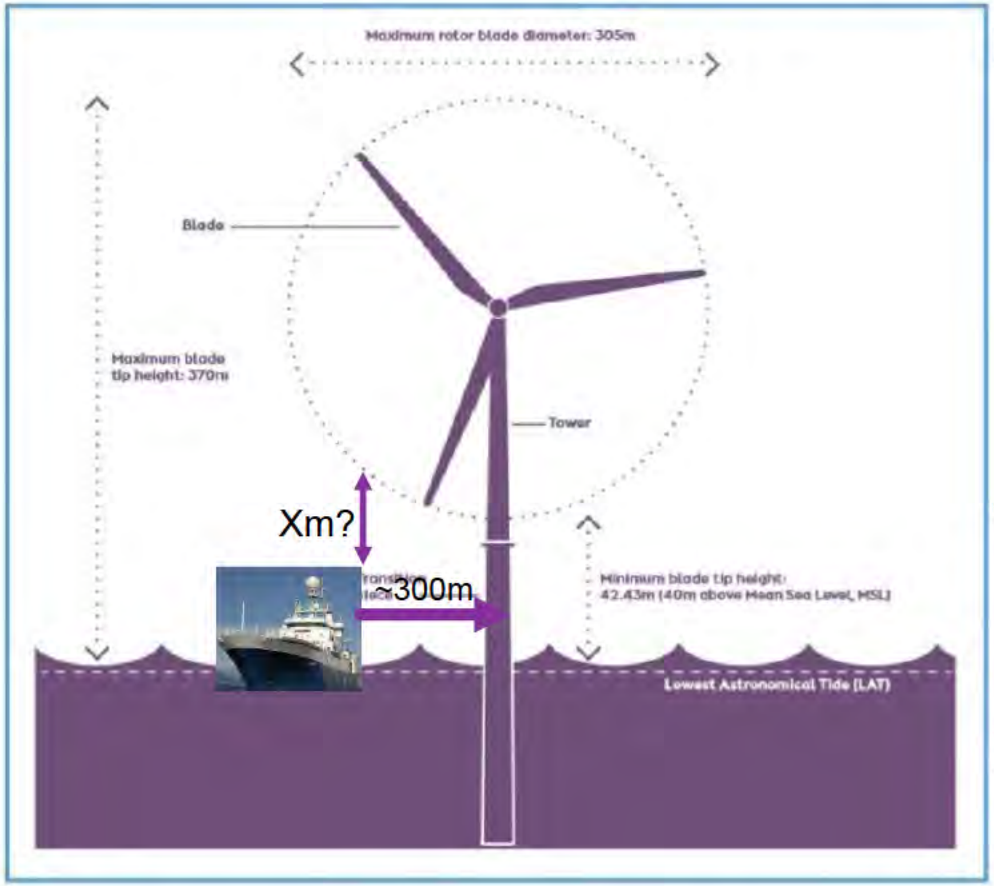
Streamer & OBN fold



Claim hybrid survey ~25% cost of full OBN

Hybrid streamer and OBN may provide best of both efficiency & coverage

Future Operational considerations & Technology



Intra-windfarm Cross disciplinary HAZID assessment

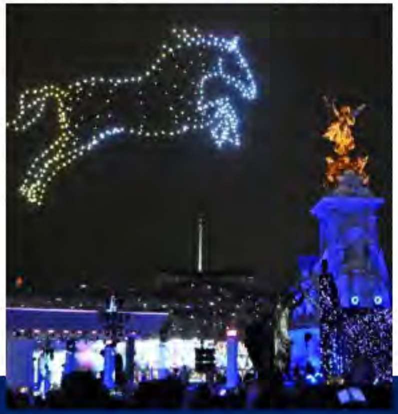
- Currently estimated seismic vessel- platform safety separation 250m (OBN) - 400m (Streamer)
- Seismic vessel Proximity to turbine?
  - Large turbines => longer blades
    - Impact on working beneath (e.g. radar domes)
  - Additional risks working within multiple obstructions
- Windfarm walk to work lessons

Technology development: size of vessel and towing equipment

Autonomous node

Further Autonomous receiver node development

- Increase Receiver mode density
- Analogous Drone choreography advancements



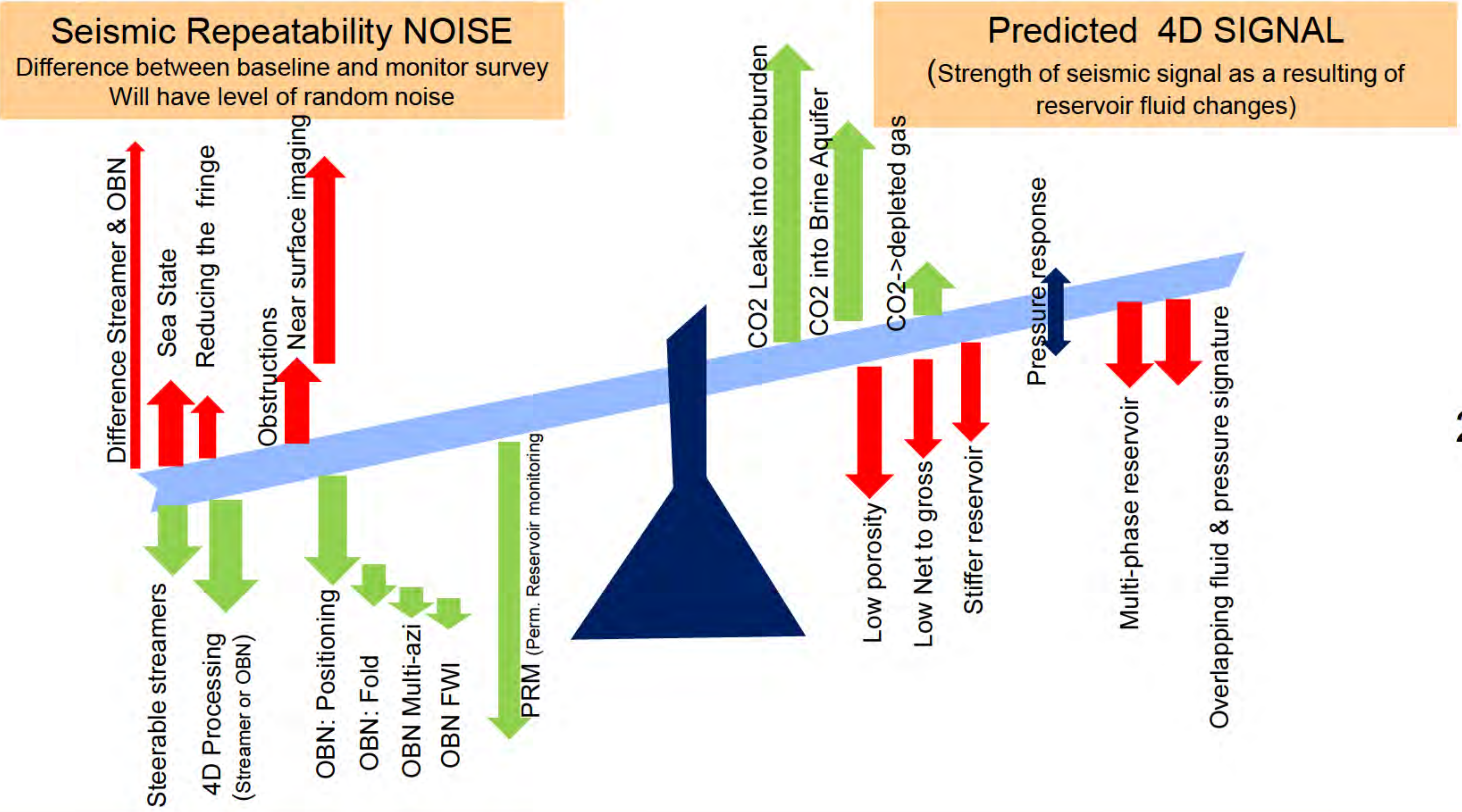
- Engineering Challenges for Autonomous seismic sources vision (RAM4D)
  - Source position, Obstacle avoidance and signal repeatability,
  - AUV endurance needs to be improved (>100km/day) / Limited OBN battery life
  - Additional power to energise source / Local Windfarm energy supply opportunity?

Further investigation into seismic operations in windfarms required

4. Reservoir 4D signal > seismic noise

The Signal > Noise See-Saw

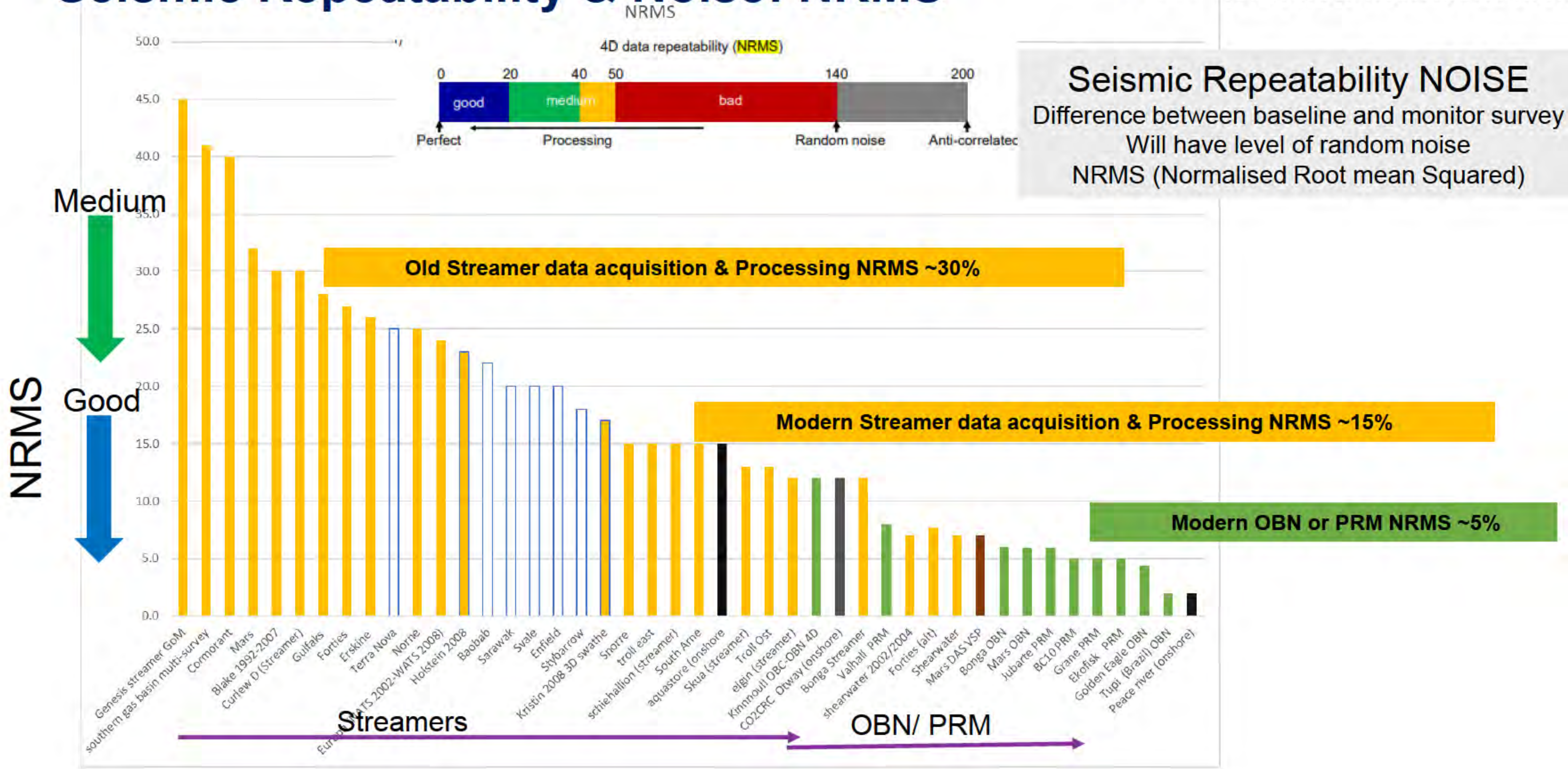
North Sea Transition Authority



27

Critical to predict signal > noise before surveying

Seismic Repeatability & Noise: NRMS



Seismic Repeatability NOISE

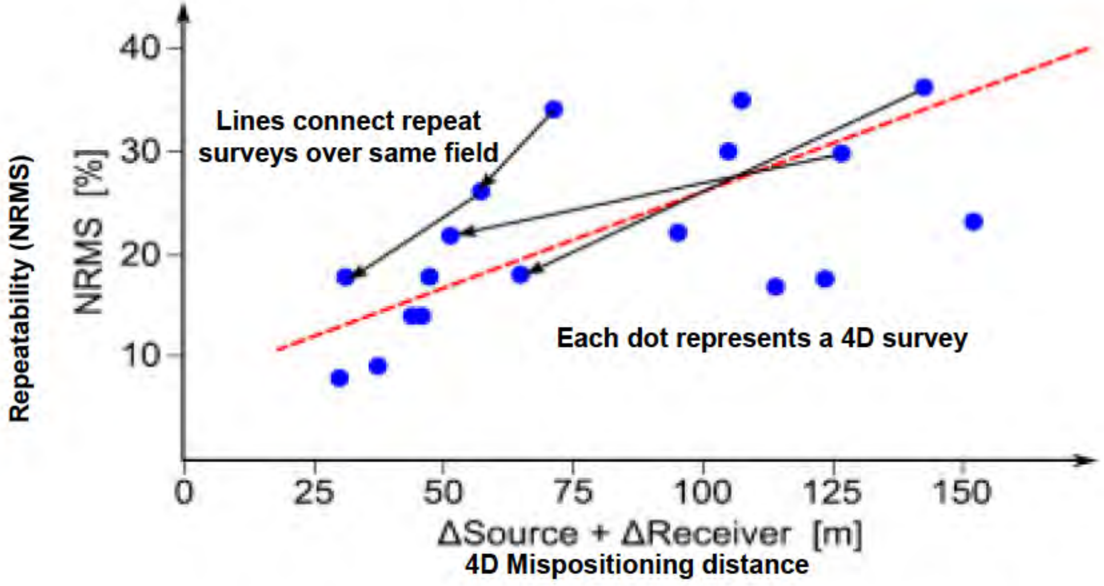
Difference between baseline and monitor survey
Will have level of random noise
NRMS (Normalised Root mean Squared)

OBN or PRM can significantly improve repeatability/ suppress the noise level

Role of offshore mispositioning and processing

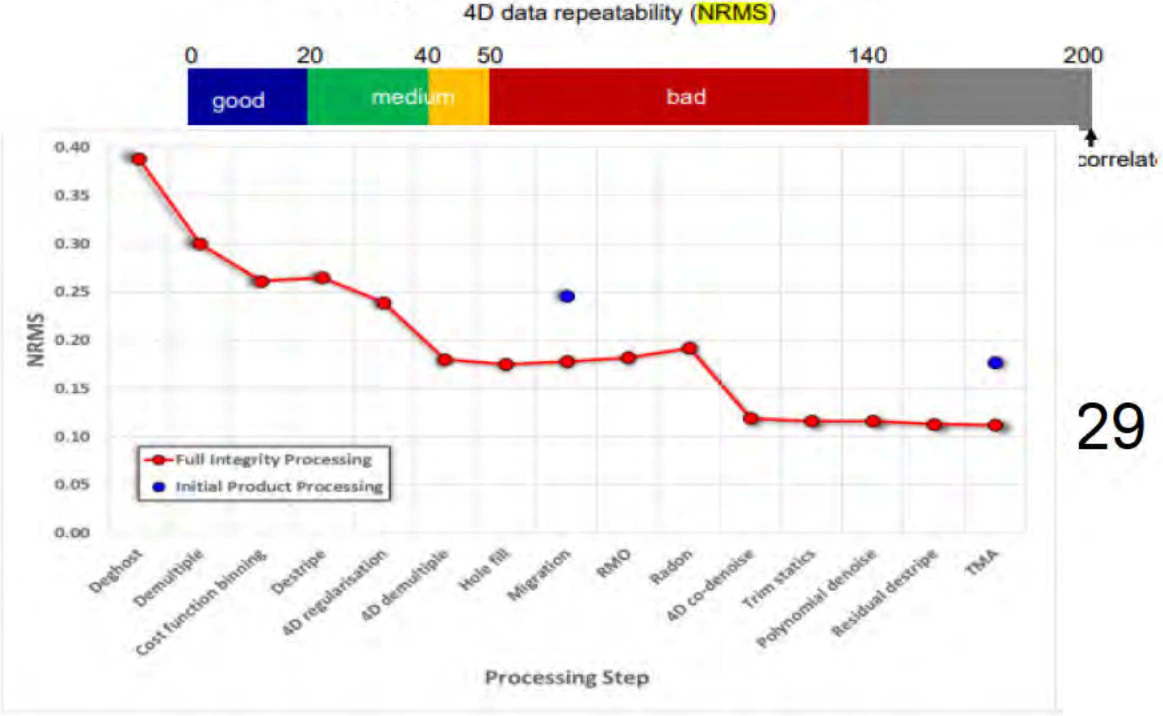
North Sea Transition Authority

Clear linkage between source & Streamer Repeatability vs NRMS noise



Improving Repeatability (lower NRMS) with better source and receiver positioning

Processing can improve Repeatability



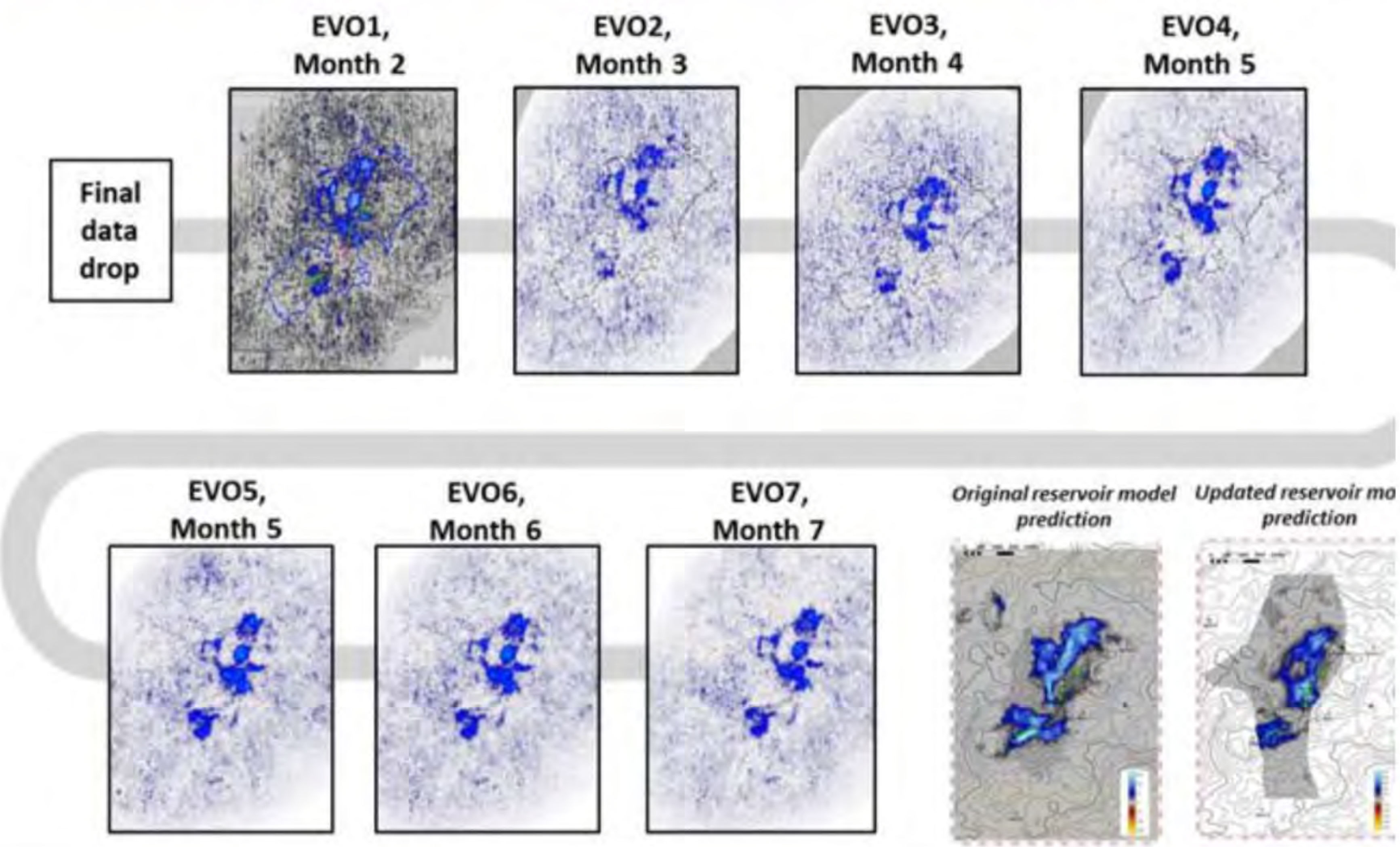
Certain processing steps improve repeatability

For comparison: OBN repeatability: 5m Node position 10m shots

Processing Stage: Sharpening the image

North Sea Transition Authority

bp



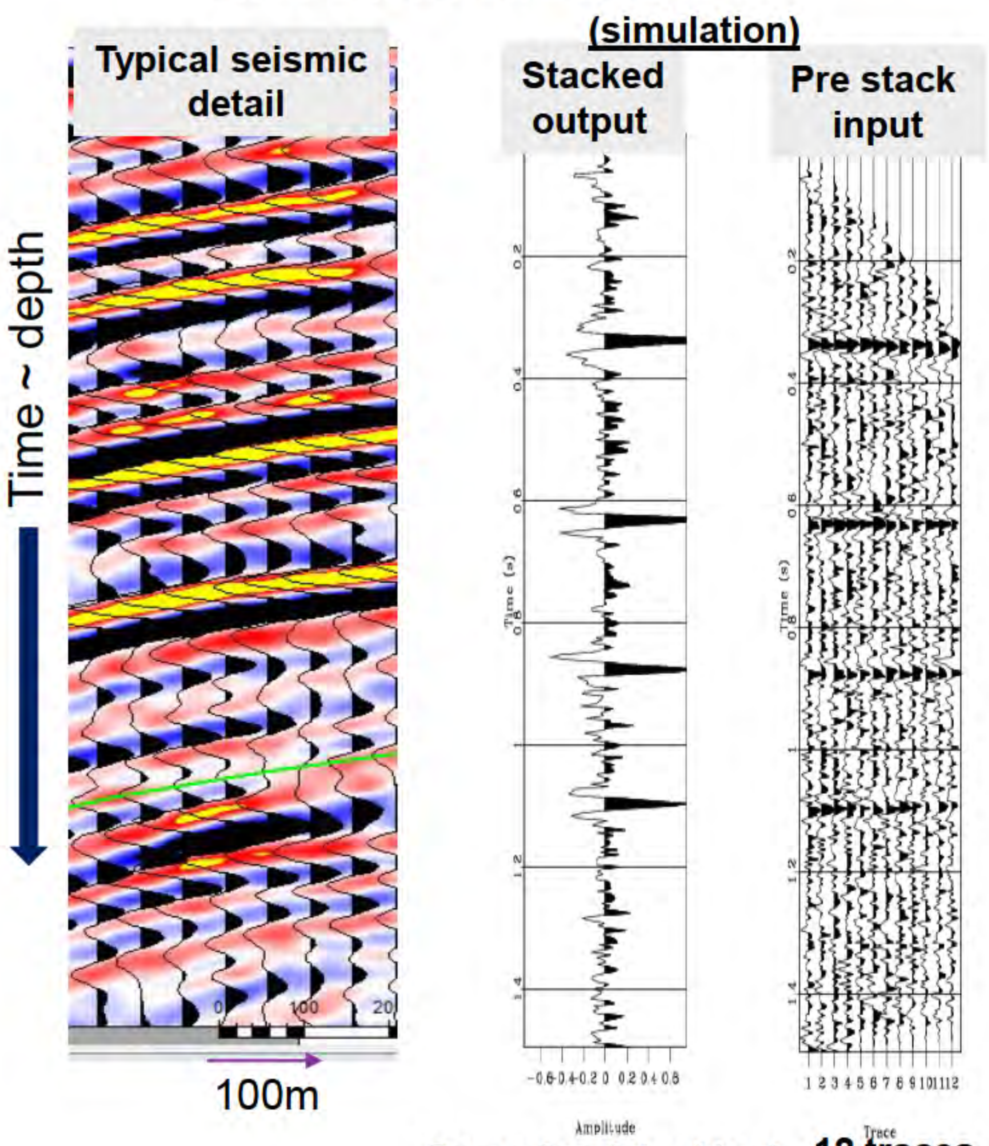
Kinnoull OBC-OBN
4D difference maps
By processing step

Full-cycle iterative processing: when is "good", good enough? A 4D North Sea case study
M. Walker[1*], D. Davies[1], C. Hill[1], C. Page[2], P. Smith[2], A. Irving[2]
[1]BP, [2]CGG

OBN very high trace density/ Fold

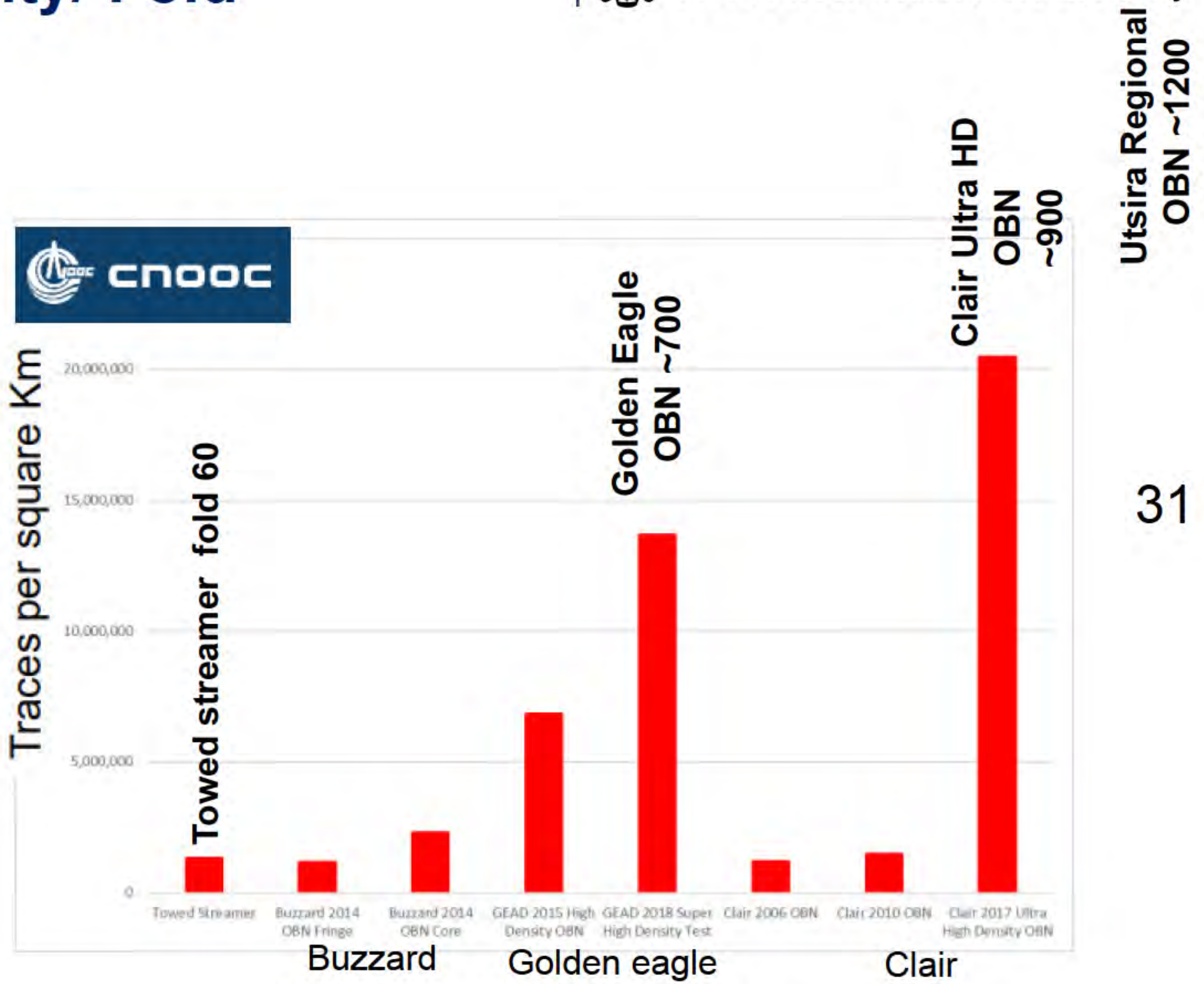
North Sea Transition Authority

The Power of the stack



Summing (stacking) improves signal/ noise

12 traces "fold"

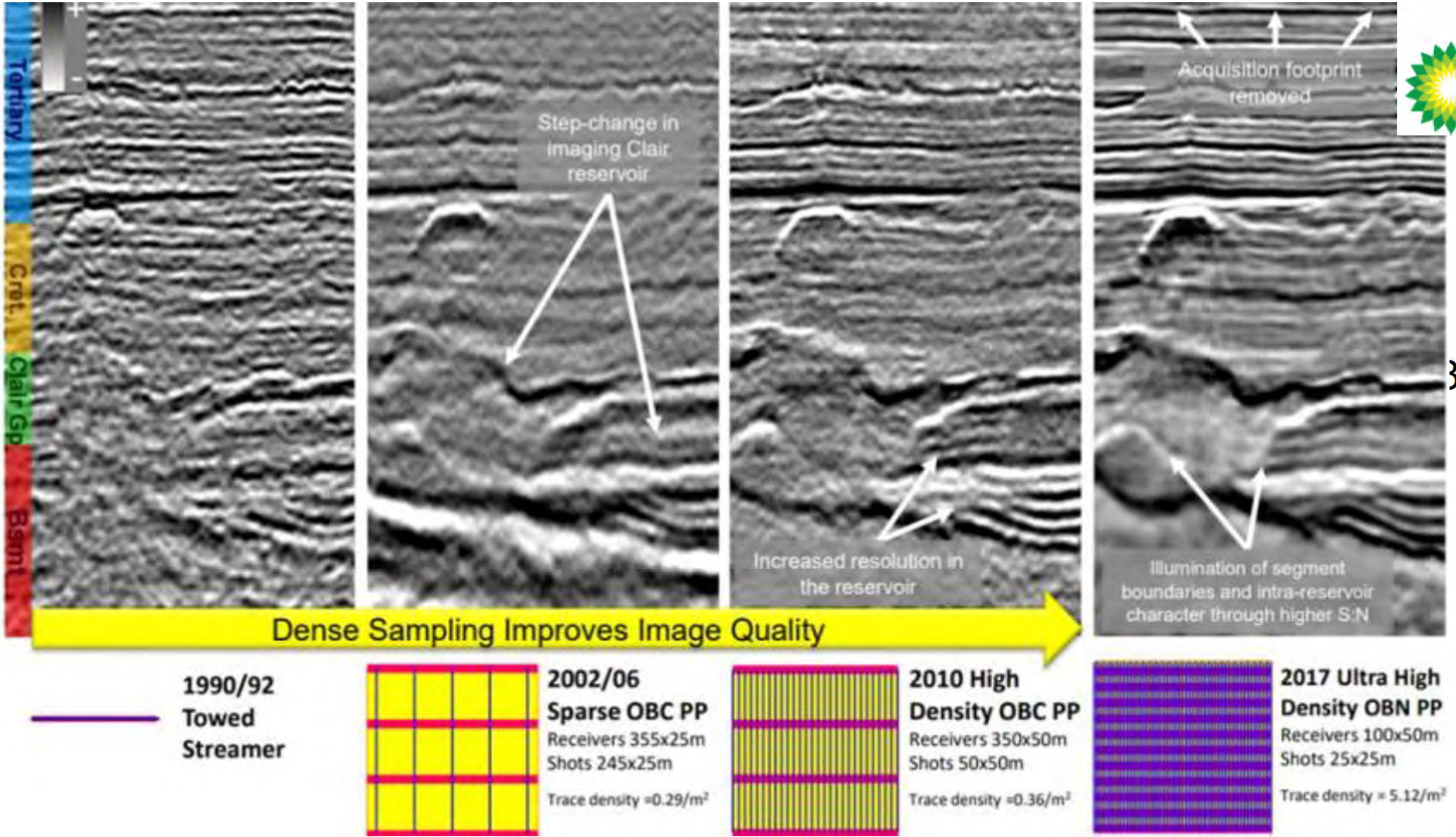


Signal to Noise improves Sqrt(Fold)

=> Golden Eagle OBN 4* Better signal/ noise than streamer

Clair Ridge: Towed Streamer to UHD OBN

North Sea Transition Authority



32

OBN Project- Conclusions & Further considerations

North Sea Transition Authority

- OBN technology is
  - Becoming mature & mainstream in oil and gas
  - Employed in special situations: shallow water, complex structures, overlapping activity, small 4D signal

- OBN is advantageous in obstructed space (project focus on mono-pile)
  - Floating windfarms: Catenary cables & multiple anchor points, tension leg turbines?
  - Acquire baseline data before infrastructure installation
    - Impact repeatability?
    - Which has primacy: turbines or CCS baseline?
  - OBN acquisition feasibility within an operational windfarm is unclear
    - Cross-disciplinary (CCS/Wind/Seismic/Marine) HAZID assessment workshop recommended

- OBN is a geophysically superior reservoir imaging technology
  - Many examples from UKCS (and worldwide) of improved **complex** subsurface imaging
  - Many successful hydrocarbon (Streamer & some OBN) 4D case studies

- Major OBN drawback remains cost differential compared to streamer
  - OBN costs have reduced by ~50% over last decade (automatic node handling)
  - OBN will always be slower (and therefore more expensive) than streamer seismic
    - OBN multiplier of 2-5X streamer does not justify the cost in most situations
- Hybrid Streamer and OBN could be a valuable co-location compromise

5. Seismic Signal/ CO_2 Detection Project

Carbon storage reservoir distribution

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 ✗ ?

Utsira/Miocene sand
Eocene/ Palaeocene(Inc. Forties/Mey)
Lower Cretaceous(Inc. Captain)
Triassic(Inc. Bunter)
Permian (Inc. Rotligende) NOT SHOWN

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

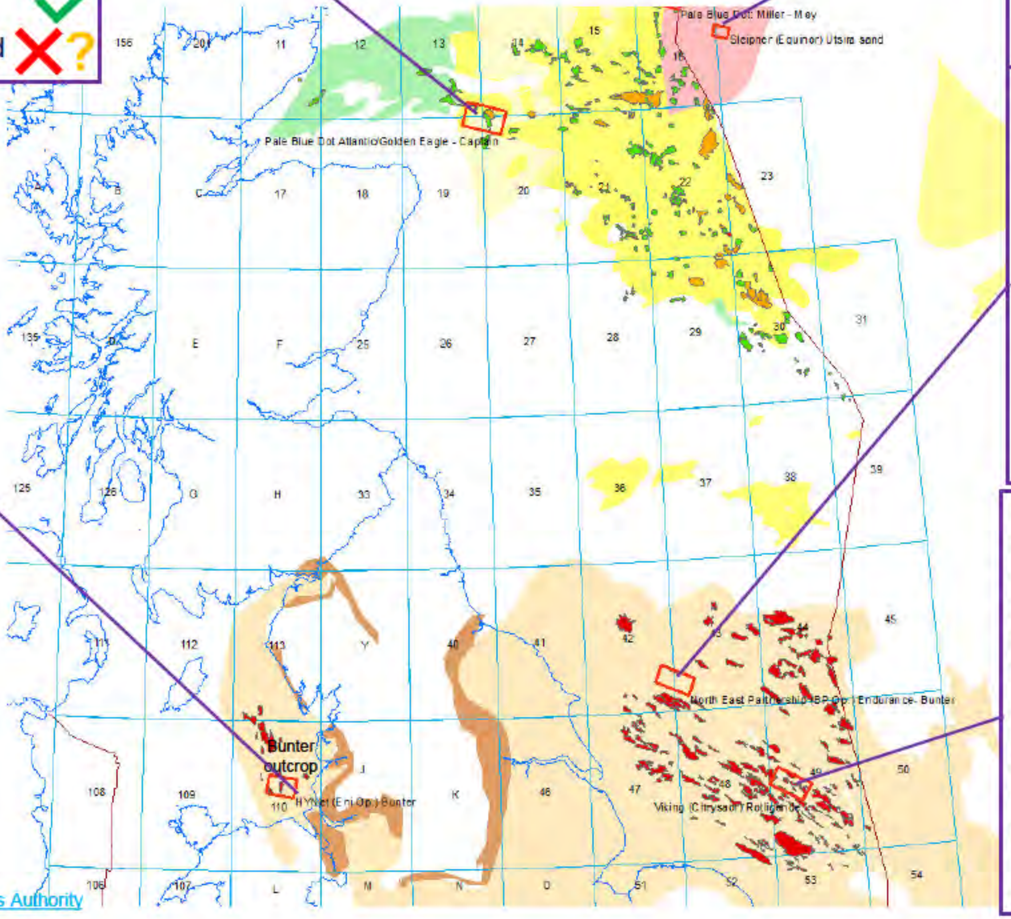
Results:
Injection into aquifer- large 4D response expected (& observed, 1 Mtpa since 1996) ✓

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 ✓

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

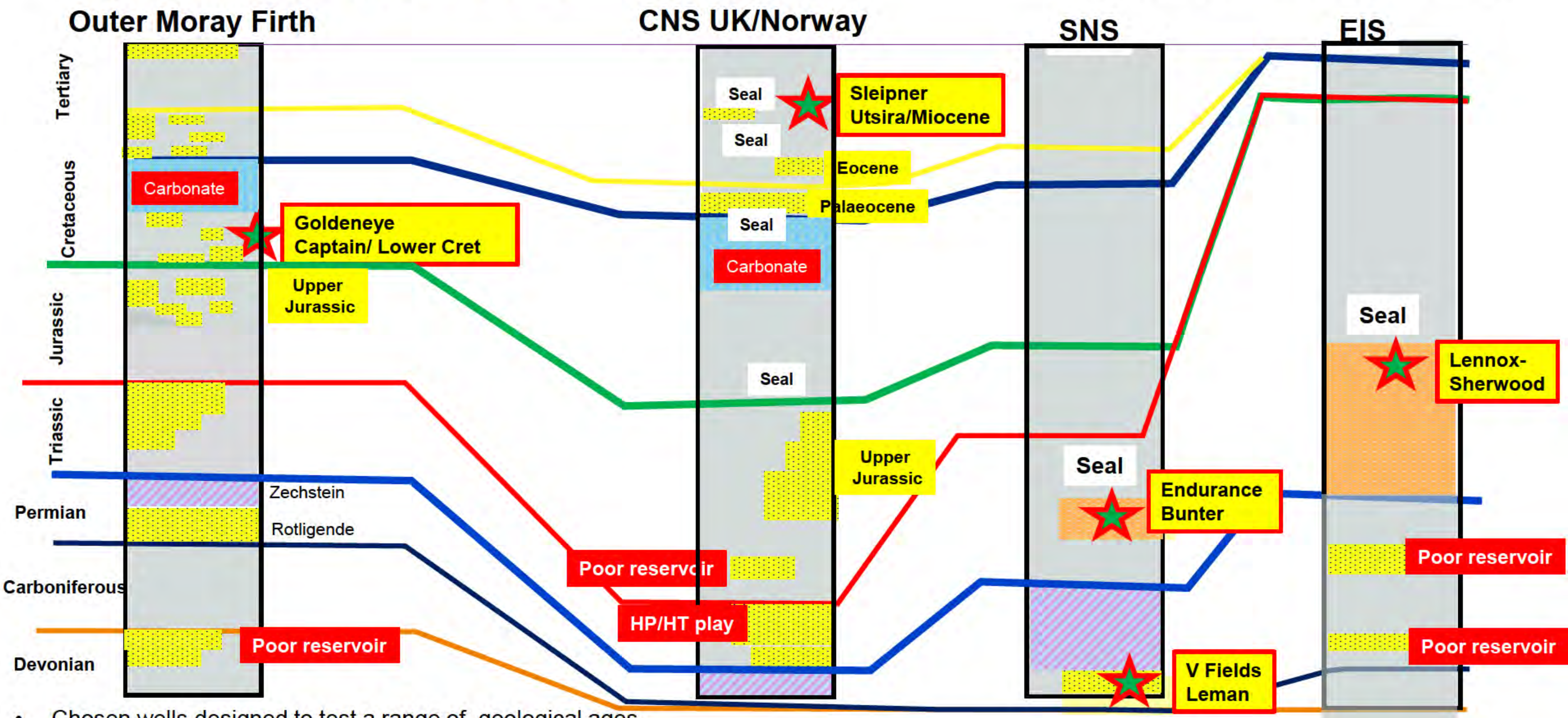
Results:
Injection into gas leg- Limited 4D response expected ✗
Migration into aquifer: observable response ✓



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 ?

Source NSTA (LR published maps), BGS & Equinor publications
[OGA and Lloyd's Register UKCS Merged Regional Geological Maps (ArcGIS version) | Oil and Gas Authority]

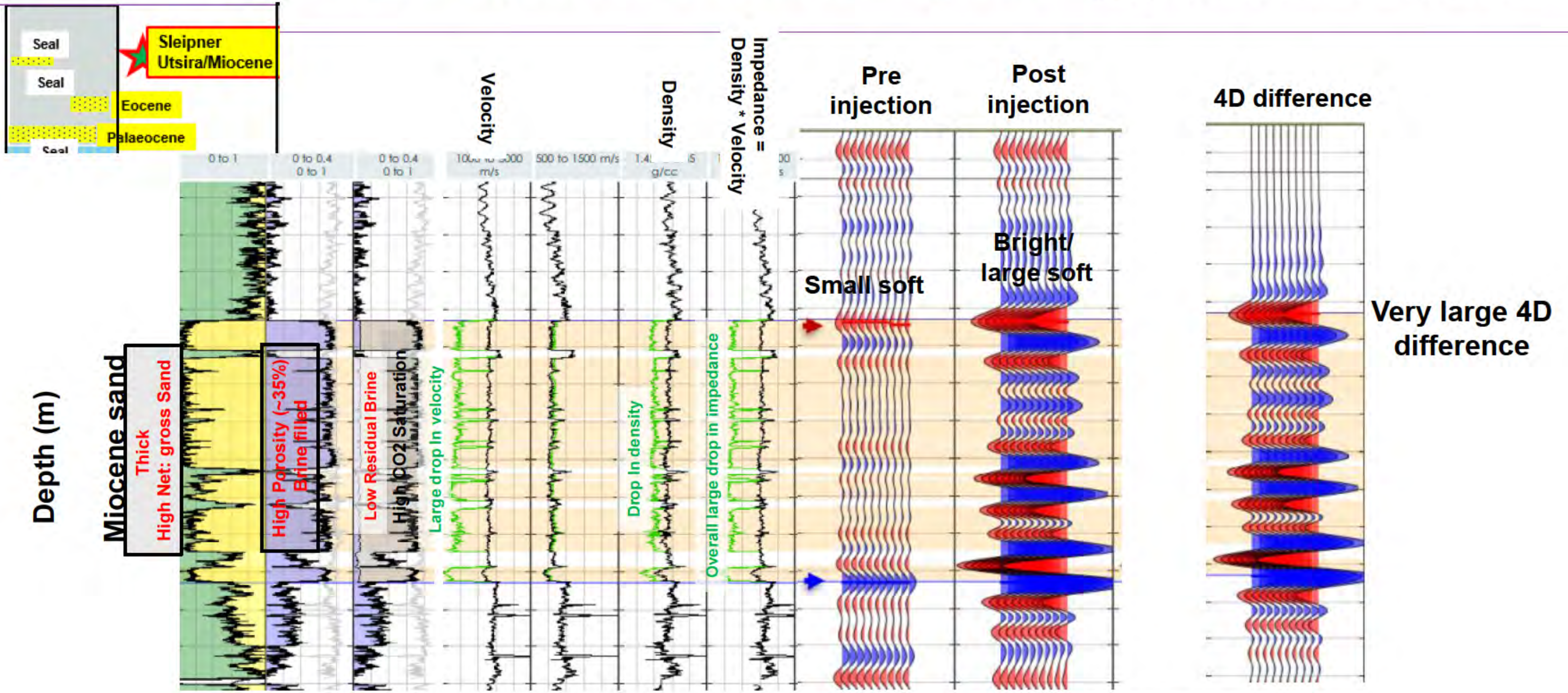
Carbon storage reservoirs by age



- Chosen wells designed to test a range of geological ages
- Some formations rejected as unlikely for CCS
- Potential future formation study options highlighted

“Easy 4D”: Sleipner CO2 injection/ “soft rock "aquifer

North Sea Transition Authority



Predicted 4D SIGNAL

(Strength of seismic signal as a resulting of reservoir fluid changes)

Very large response, readily detectable

Real 4D example: Sleipner comparison

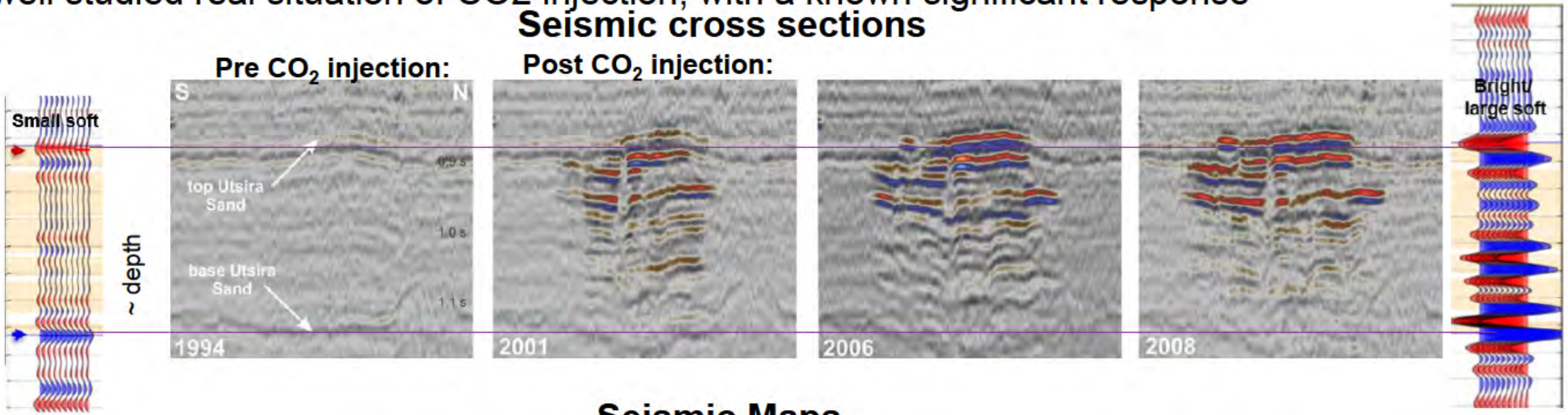
North Sea Transition Authority

- Sleipner is a well studied real situation of CO2 injection, with a known significant response

Seismic cross sections

Pre CO_2 injection: **Post CO_2 injection:**

Real seismic Also shows weak Top & base seismic response Prior to CO2

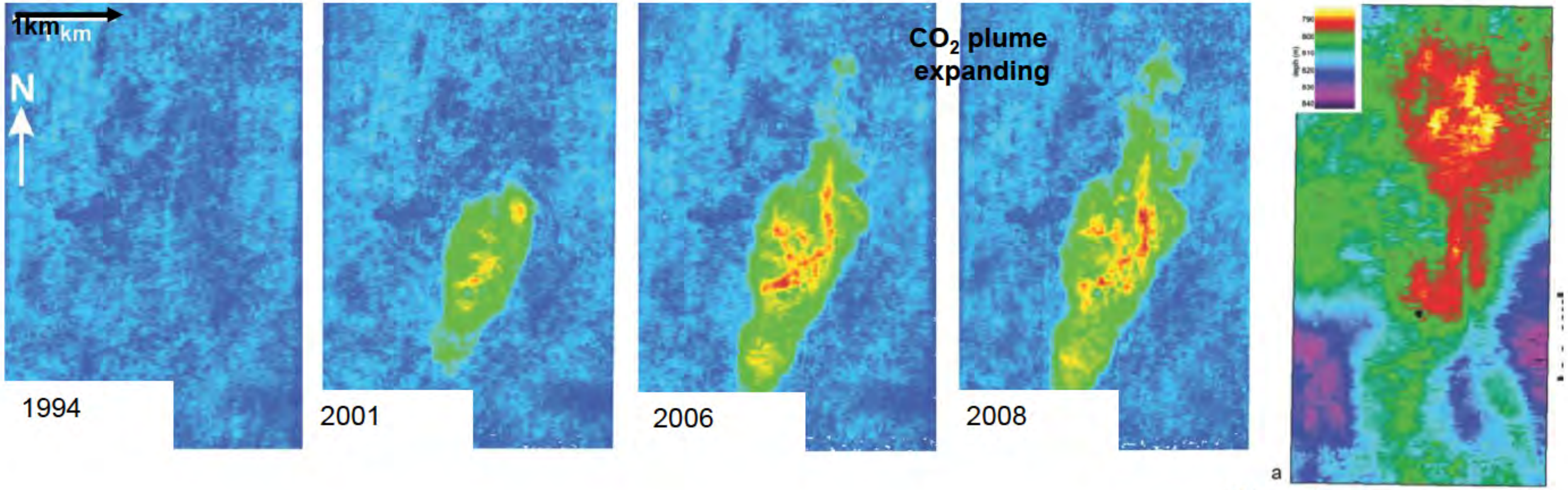


Shallow bright spots ~ Match real seismic

Deeper bright spots <u>Not present</u> implies CO2 not reaching Base of reservoir

Seismic Maps

Mapping upper event Shows CO2 migrating In clear NNE direction

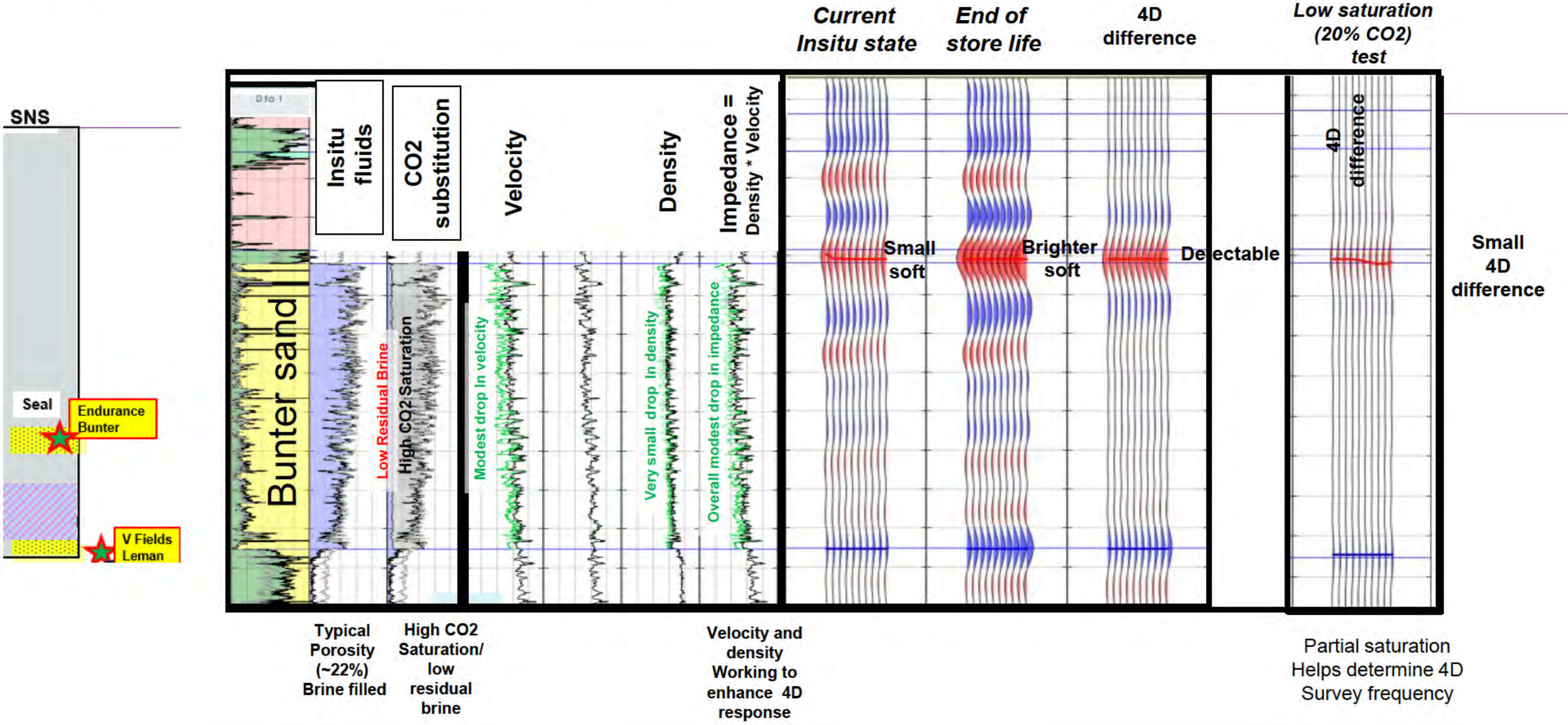


Structure map : not to scale

Proven CO2 site: Linking prediction modelling to real CO2 sequestration

"Medium 4D": Endurance (SNS) Triassic Aquifer

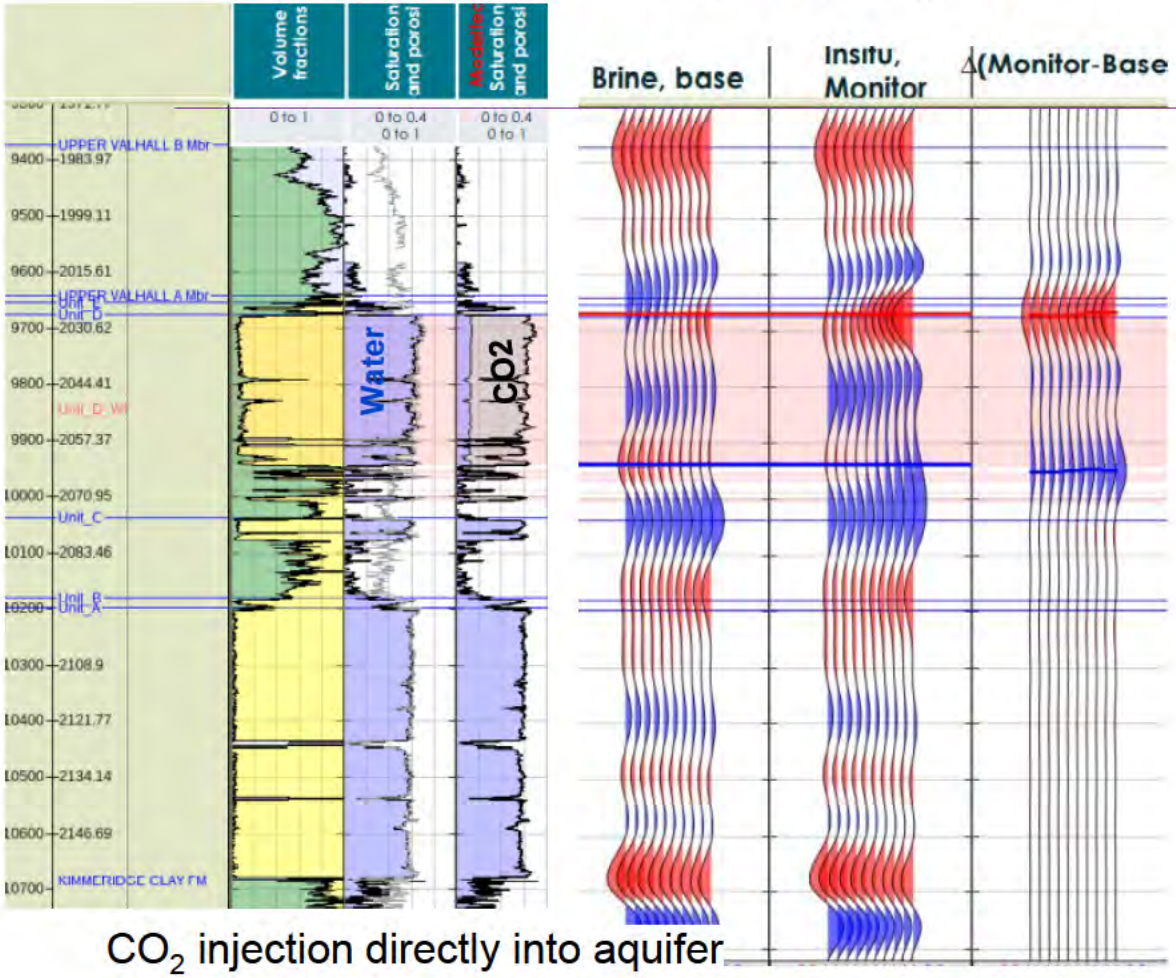
North Sea Transition Authority



Highly likely to be observable with streamer or OBN seismic acquisition

“Medium” Goldeneye Aquifer vs depleted gas reservoir

If CO_2 injected directly into aquifer

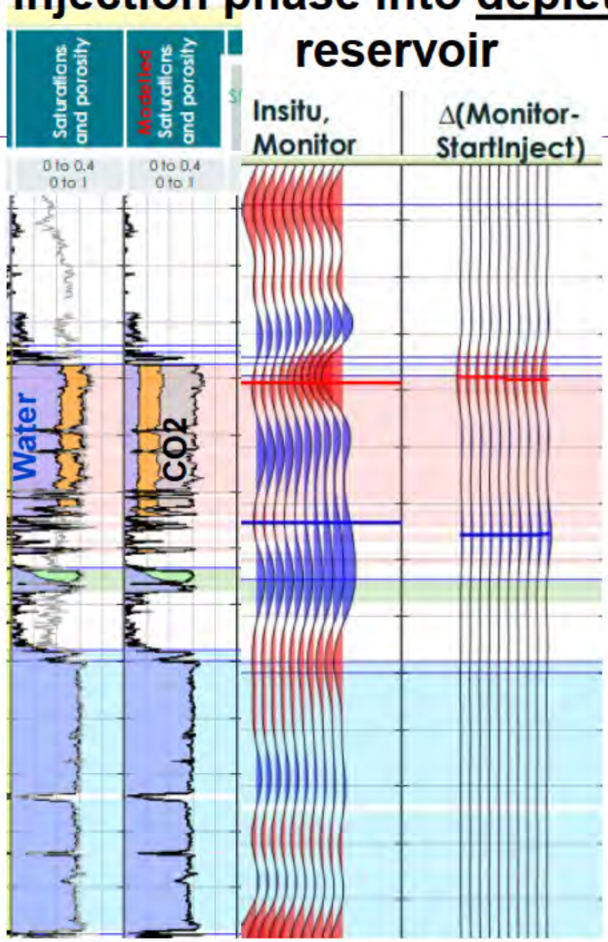


Significant Softening

CO_2 injection directly into aquifer

- Expected to be detectable with conventional seismic

CO_2 injection phase into depleted methane reservoir



Weak Softening

Post CO_2 injection with residual methane and water

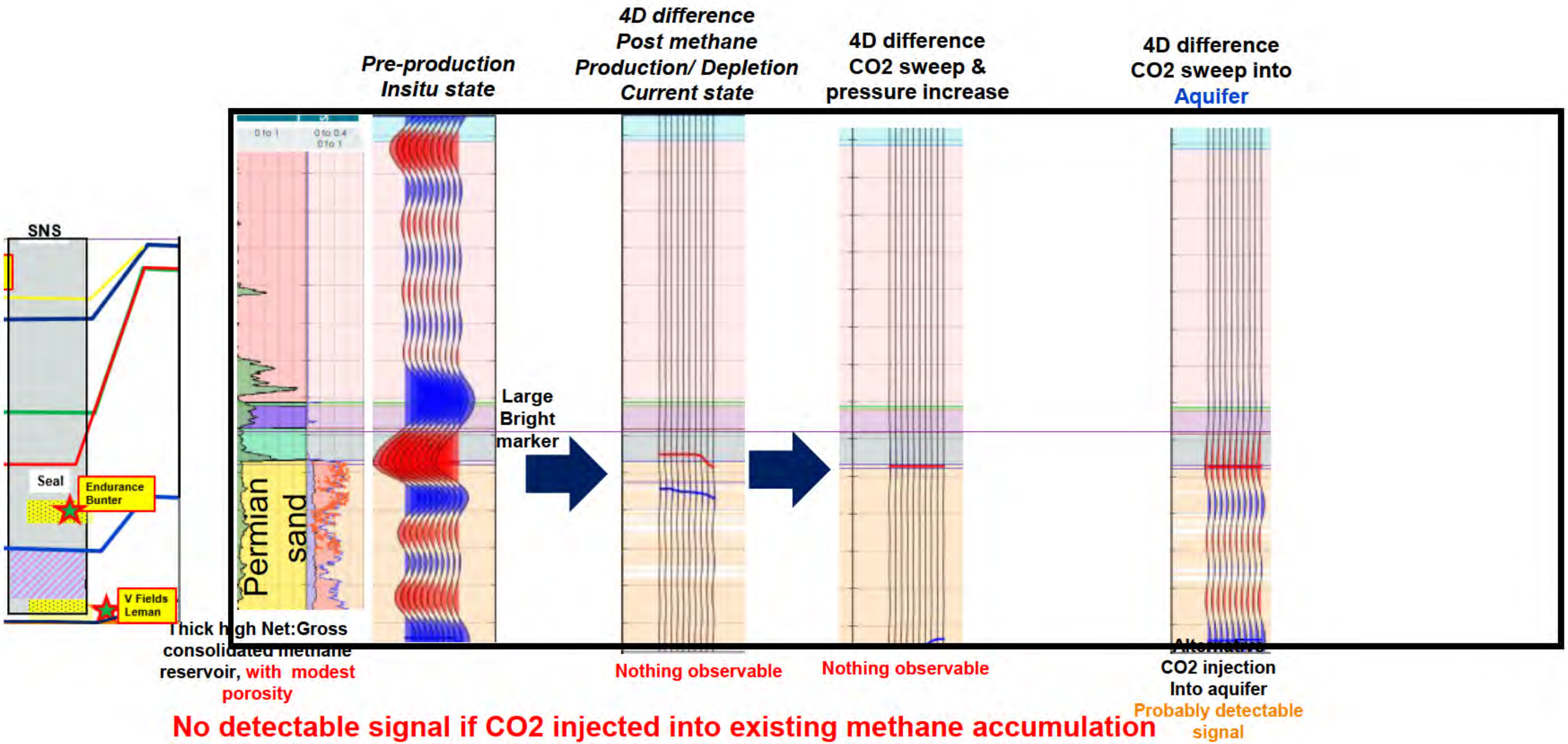
- Difficult to detect.

Significant expected response

CO2 into depleted gas difficult to detect

“Tough 4D” Low Porosity Permian V- Field gas field

North Sea Transition Authority



No detectable signal if CO_2 injected into existing methane accumulation

Possible small signal if CO_2 migrates into surrounding aquifer

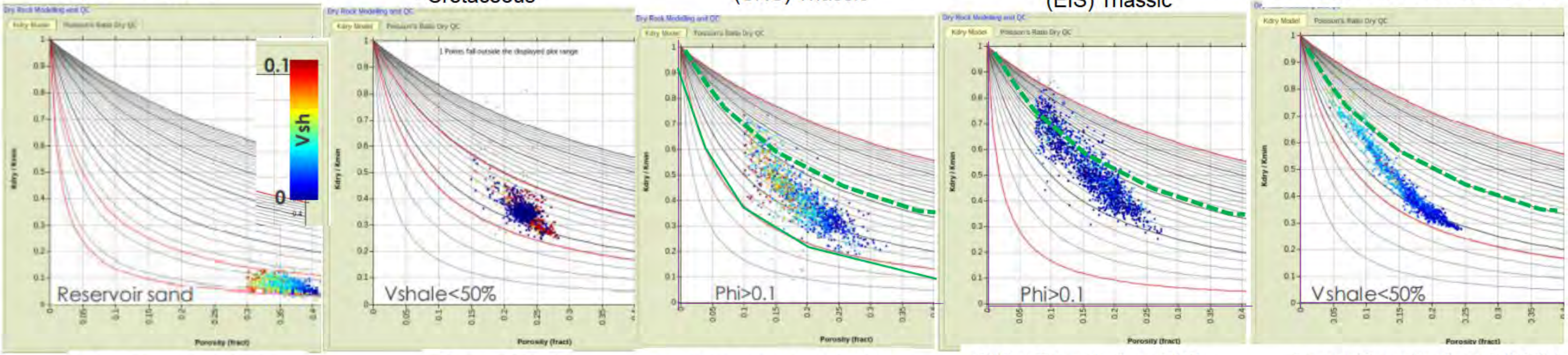
Consolidated reservoirs are probably below 4D seismic detectability

Influence of Dry Rock Frame/ Stiffness

- The dry rock frame (friable to consolidated & cemented sand) has a major influence on the magnitude of the seismic fluid effect response

Porosity vs rock frame plots

Sleipner- Miocene | Goldeneye (Moray Firth) - Cretaceous | Endurance- Southern North Sea (SNS) Triassic | Lennox- East Irish Sea (EIS) Triassic | V Fields- SNS Permian Leman

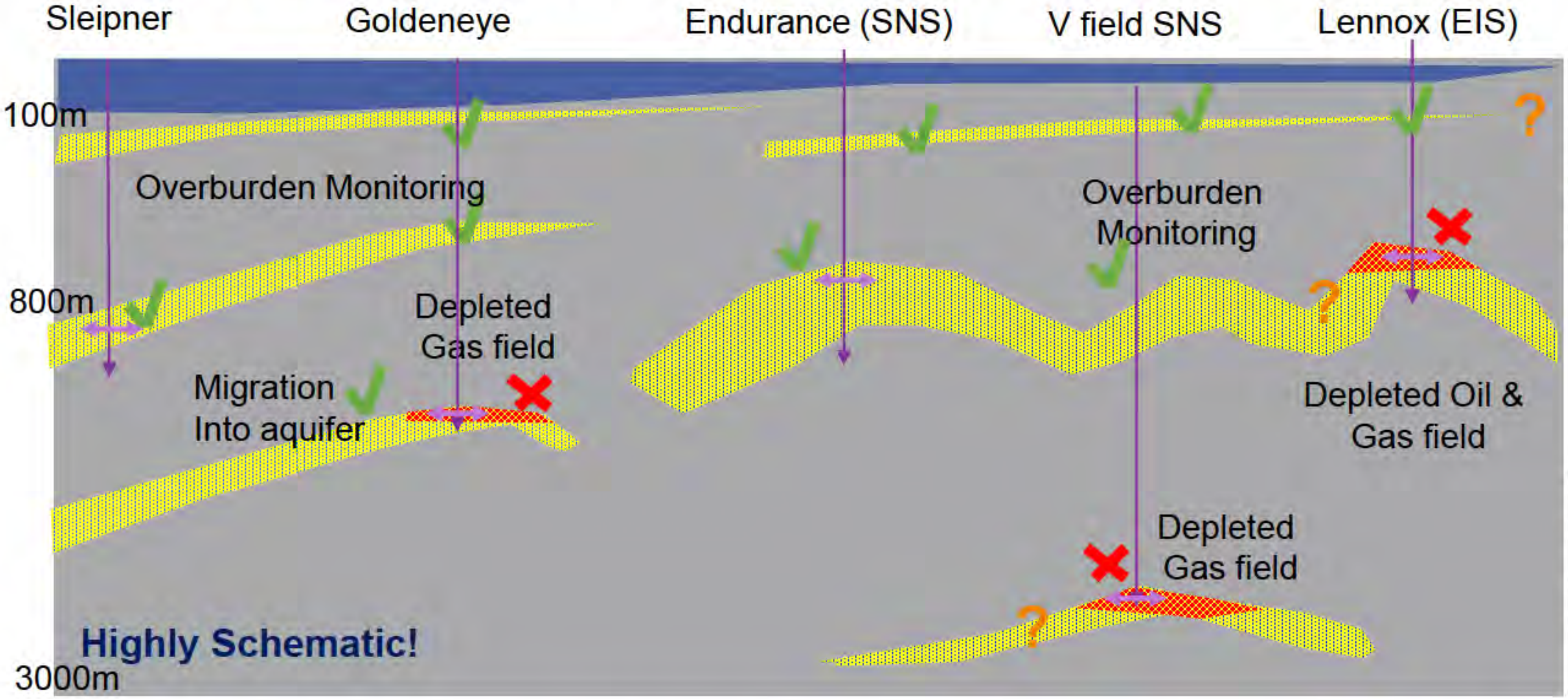


High Porosity, Friable & Very unconsolidated | Consolidated | Further porosity reduction With more stiffer frame | Stiffer Triassic than SNS Greater burial & uplift in EIS? | Lower Porosity than SNS Triassic Greater reservoir depth

Understanding dry rock frame is key to predicting 4D response

4D seismic monitoring summary

North Sea Transition Authority



1) A significant 4D seismic signal should be anticipated in most situations where the CO_2
   a) Injected directly into an aquifer
   b) Laterally migrates into the surrounding aquifer or
   c) Leaks into a shallower/ overburden aquifer

2) The detection threshold is linked to the sand thickness, porosity, reservoir stiffness and level of CO_2 saturation at the time of surveying

3) Detection of a signal where CO_2 is injected into a pre-existing hydrocarbon fields is difficult

- Multi-fluid phase systems (e.g. brine, methane, oil and CO_2) are likely to provide ambiguous interpretations
- A large change in pressure does not produce an appreciable 4D response.
- Monitoring these reservoirs
  - Acquire higher specification seismic improve the signal to noise: — Higher cost for small signal difficult to justify
  - Await higher CO_2 concentrations / greater separation between surveys — Too Late to influence?
  - **Assume seismic monitoring is not part of the reservoir MMV strategy** — **HR seismic still required for overburden?**

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

Windfarm noise (Heriot Watt)

North Sea Transition Authority

- Onshore Literature review.
  - No published offshore experience. Large Gap in knowledge
  - UKCS One intra-windfarm streamer survey.

- Turbine generated noise is low within the seismic bandwidth(>1Hz)
  - "less than an 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

Conclusions: Windfarms are a clear operational hazard to active seismic acquisition, but ***appear to be*** a low level acoustic noise source within the seismic survey spectrum

Next steps:

- Develop operational OBN acquisition procedures?
- Acquire marine seismic background & environmental measurements?

Thank You!

So….. What next?

North Sea Transition Authority

TECHNICAL REPORT

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

A technical study on the Monitoring, Measurement and Verification (MMV) Activities with reference to the co-existence of Offshore Carbon Capture Storage Wind and Oil/Gas Projects

July 2022

Contents

North Sea Transition Authority

1. Executive Summary

Executive Summary

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.

2. Project Scope

Project scope

North Sea Transition Authority

The primary objective of this project was to identify and scope specific issues associated with offshore geological/geophysical surveying and monitoring activity.

Technical Study Aims

Provide a general view of MMV activities for carbon storage sites in proximity to offshore wind farms. It is not specific to any particular carbon storage site, Offshore Windfarm, or Oil/Gas project, however, individual project developers have contributed key learnings and insights from existing and planned projects.

- Build on work undertaken by the OGA/NSTA-led Energy Integration Project and with The Crown Estate's 'Project Vulcan', covering generic CCS vs Offshore Wind engineering interactions. (Reference 1)
- While this project identified potential solutions, the intent was to identify further studies that could provide more detailed recommendations or actionable results in support of industry and regulatory activities.

Report Method

This report is largely based upon insights gleaned and distilled from ~ 30 meetings with a selection of over 20 relevant and interested parties in early 2021

- Parties ranged over oil and gas operators and others with CCS licences/leases (or an intent to enter this market), seismic/geophysical contactors, site survey contractors, academia, other regulators/government bodies, geophysical service analysis providers, wind farm operators, suppliers of novel geophysical acquisition and processing techniques.
- Whilst not every possible interested party was consulted, it is believed that a fair cross-section of views was likely sampled.
- This MMV report was revised, prior to public release, after a subsequent 2022 project considering OBN technology.

North Sea Transition Authority

3. Background & Acknowledgements

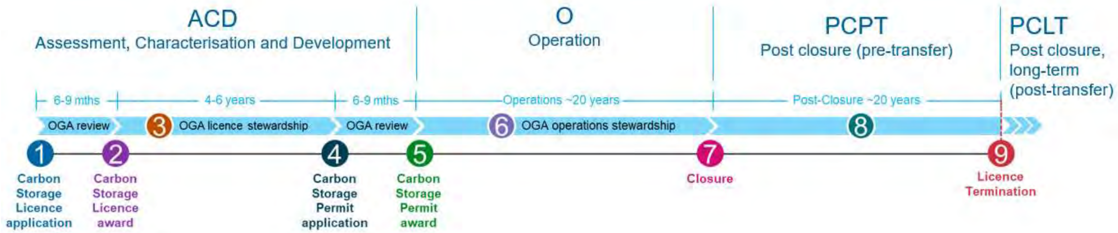
Background: CO_2 storage

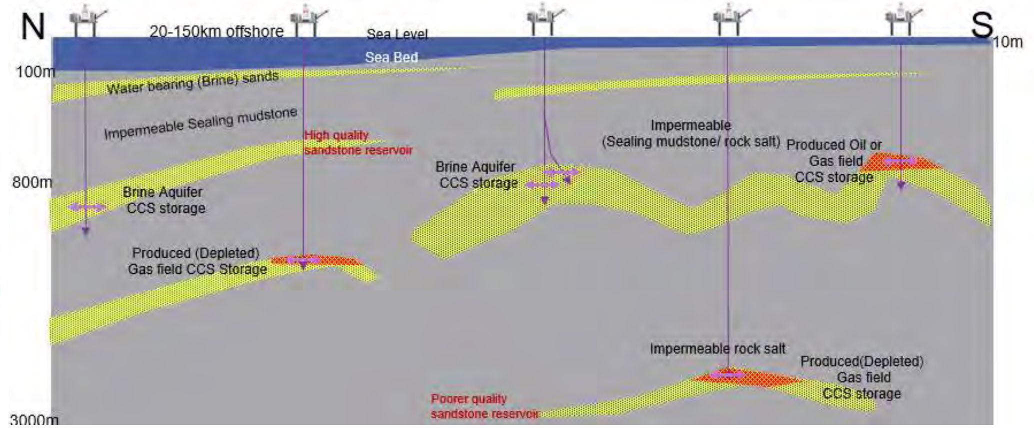
North Sea Transition Authority

The UKCS is a critical energy and carbon storage resource, with oil and gas exploration and production, offshore wind generation, and significant potential for carbon storage and energy hubs integrating these activities. With government's ambitious net zero targets, the demands on the seabed are expected to increase – while there are huge opportunities for energy transition, there will also be challenges around the spatial and temporal coordination through the project lifecycles.

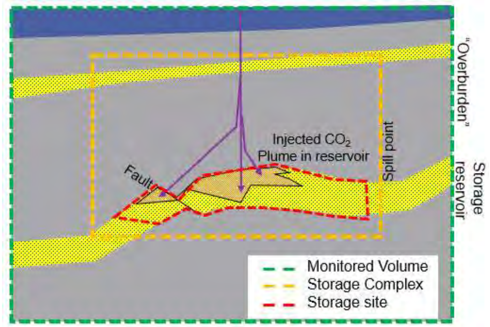
Offshore subsurface carbon storage sites cover a significant area of seabed, that will require ongoing surveying and monitoring. Before the NSTA can award a Carbon Storage (CS) permit, a licence holder needs to complete a full geological characterisation of the storage site and provide an MMV monitoring plan to understand and verify if the distribution of injected CO_2 within the reservoir rocks matches modelled predictions, and identify any potential risks which may lead to leakage from the wider storage complex.

Monitoring, Measurement and Verification (MMV) Activities will be required throughout the lifecycle of a CS Licence, including prior to the CS Permit award and following site closure. The total duration of activities can therefore be well in excess of 40 years.





Collectively, the operational Monitoring, Measurement and Verification (MMV) plan is used to demonstrate that the storage site performance and the wider storage complex complies with regulations. This means monitoring for the duration of the site operation (~ 25 years), and to ensure environmentally safe storage of the carbon dioxide a further ~20 years post-injection.

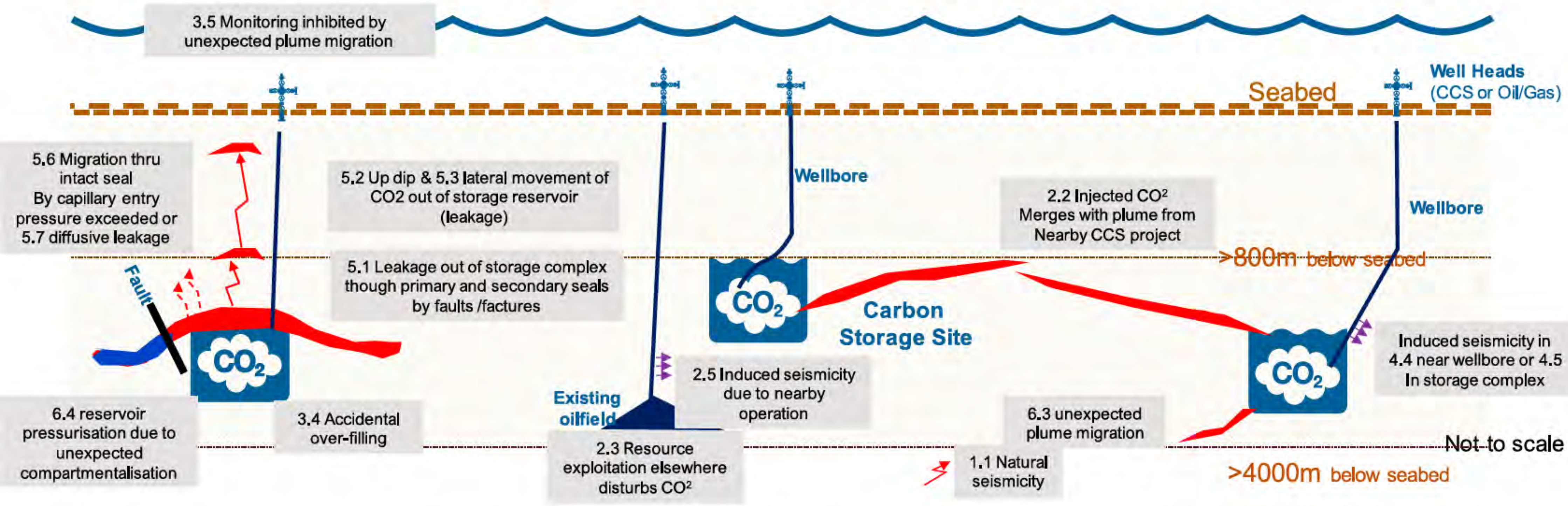


Schematics showing Range of UKCS storage sites & more detailed CO2 injection site configuration

Potential Risks which can be monitored by seismic

North Sea Transition Authority

The MMV plan establishes the pre-injection baseline data acquisition, and describes periodic monitoring required during the injection phase. This is undertaken with a spectrum of MMV technologies, but most likely a combination of "remote sensing" geophysical data acquisition and physical/chemical measurements and sampling. These data are used to assess and verify conformance with reservoir fluid distribution computer models; early identification of any unexpected behaviour of CO_2 allows corrective measures for storage risks within and around the complex to be implemented. The OGA/NSTA-sponsored report led by Quintessa indicates the range of potential risks that may require monitoring throughout the lifecycle of a Carbon Storage project. **(Reference 2)** Quintessa Merlin TNO innovation for life



The area of the carbon storage complex will require careful consideration of any co-location interfaces and impacts with other users of the sea-bed, such as offshore wind farms, to avoid undue interference with other surrounding users.

Acknowledgements

North Sea Transition Authority

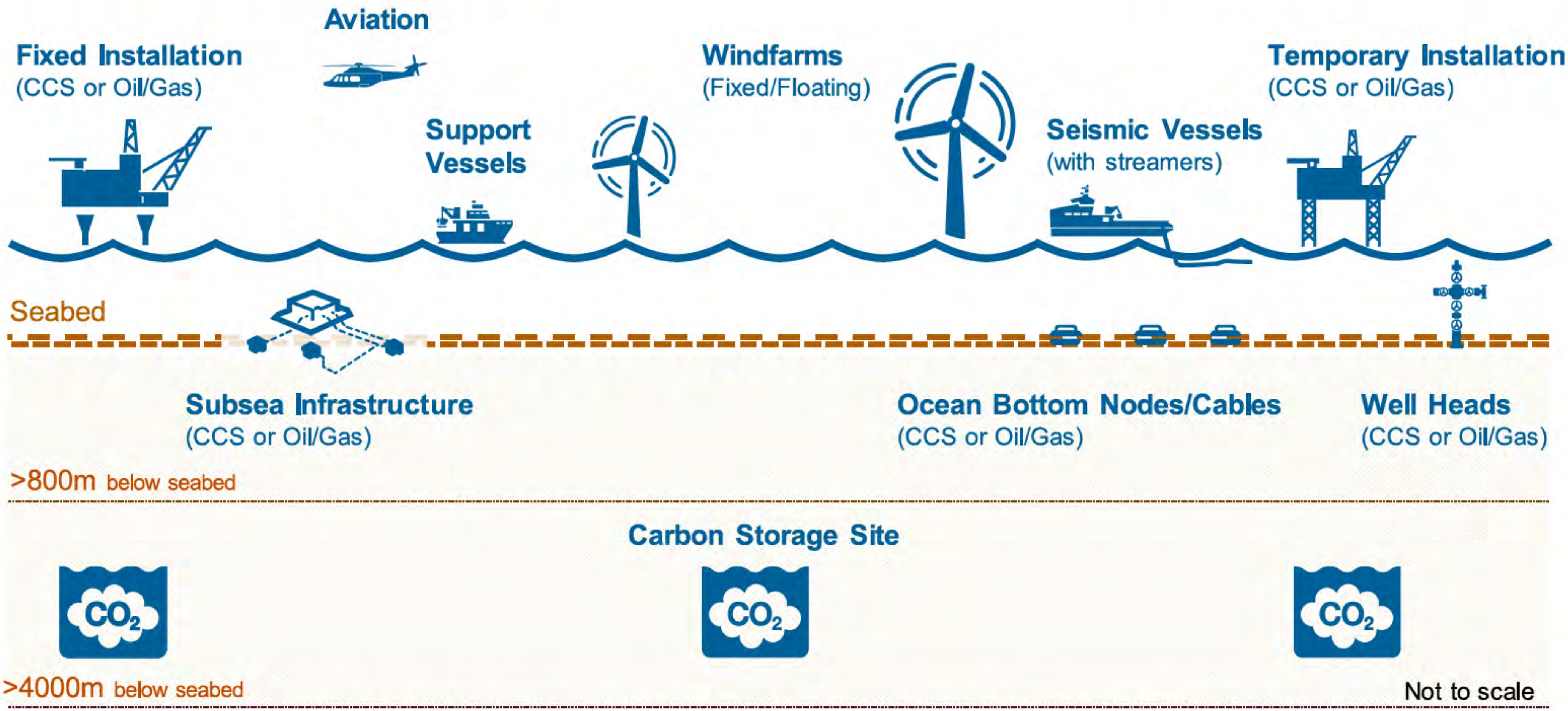
Engagements with the following companies and organisations helped to inform the content of this report, and the NSTA gratefully acknowledges all consultees for the time, effort, and insights freely and openly given. However the final content and conclusions are those of the NSTA.

North Sea Transition Authority

4. Operational Scenarios & Monitoring Objectives

Operational Scenarios

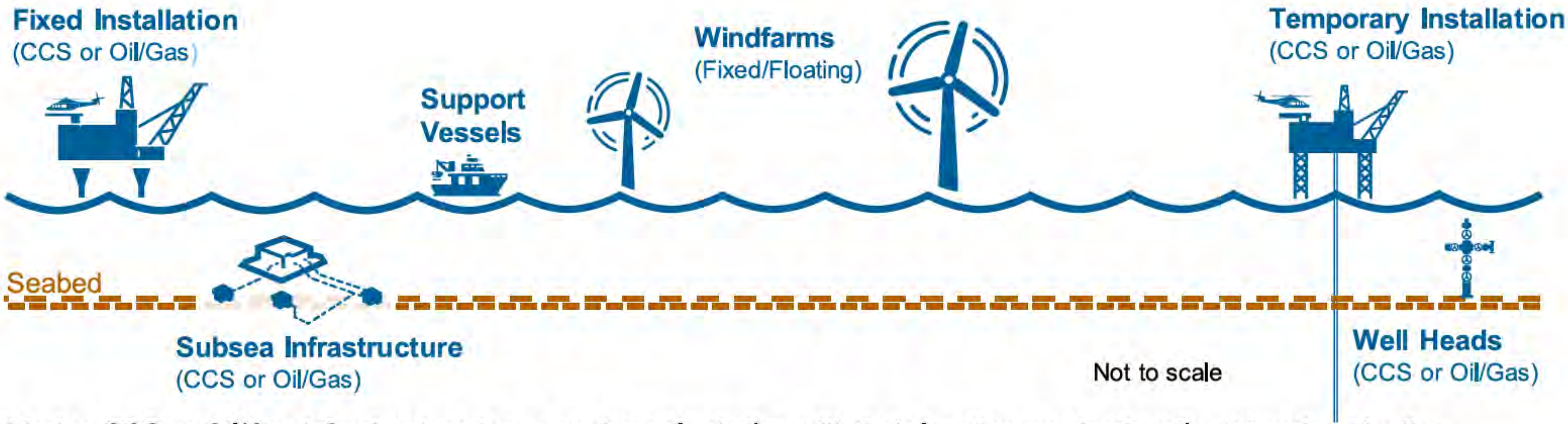
North Sea Transition Authority



There is no one-size-fits all MMV solution. Monitoring every offshore co-location scenario have different critical risks to be managed and different geometric arrangements including 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.

Operational Scenarios - Infrastructure

North Sea Transition Authority

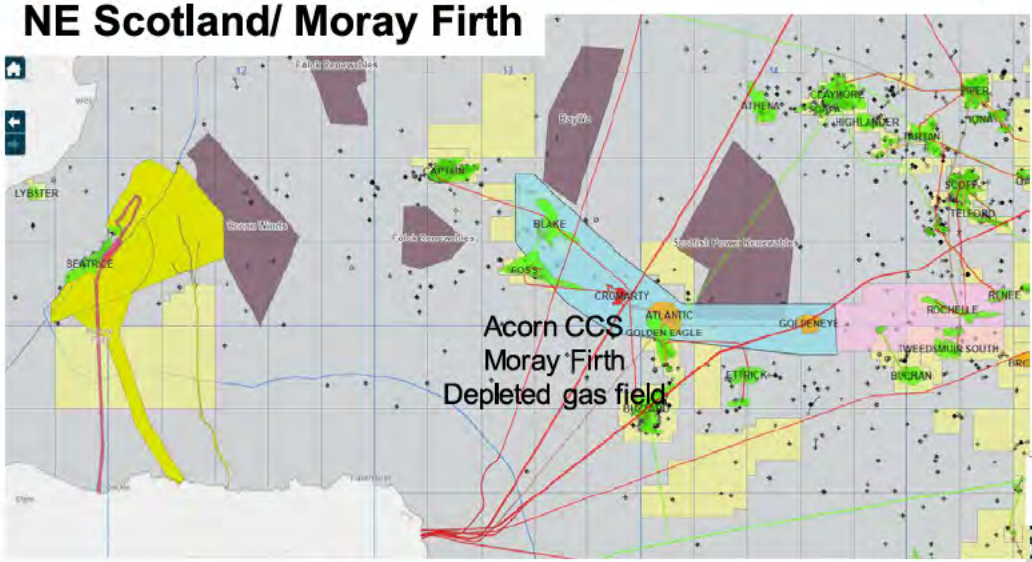


- Marine CCS or Oil/Gas infrastructure types are broadly similar, with their location predominantly determined by the location of the subsurface fields or stores (immovable).
- Offshore windfarms can be fixed or floating depending on the water depths, and the locations are predominantly determined by wind conditions and environmental constraints. Current turbine spacings areup to ~1km, and arrays can spread over large areas. They are generally on a regular grid, but additional turbines can be located around the edge to maximise yield.
- All operation types require vessel and aviation support/supplies.
- CCS or Oil/Gas operations require the drilling of wells, initially with temporary installations, but with fixed surface installation or subsurface equipment during injection/production.
- Wells require a clear zone around them for maintenance and emergency operations, including the drilling of relief wells and final abandonment.

UK Offshore Current Co-location areas

North Sea Transition Authority

NE Scotland/ Moray Firth



NSTA Offshore Fields
- Condensate Field
- Gas Field
- Oil Field

NSTA Offshore Carbon Capture Storage Licences

CES Carbon Capture Storage Sites

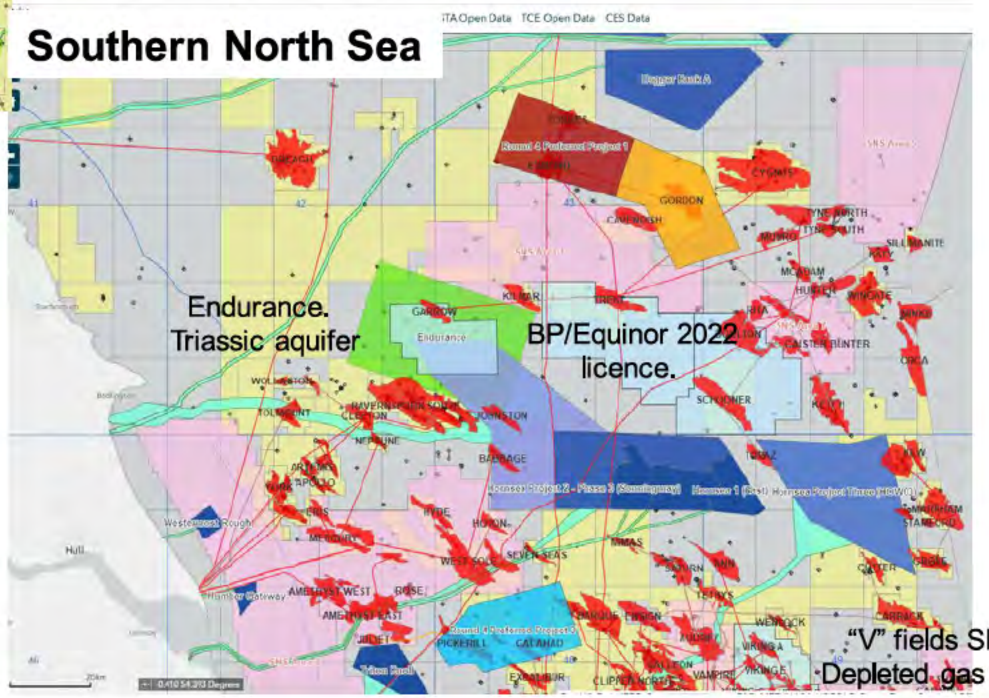
NSTA Carbon Storage Areas Offered for Application

TCE Offshore Wind Farms
- Government Support on Offer
- Active/In Operation
- Under Construction
- Consented
- In Planning
- Pre-planning Application
- Area of Search

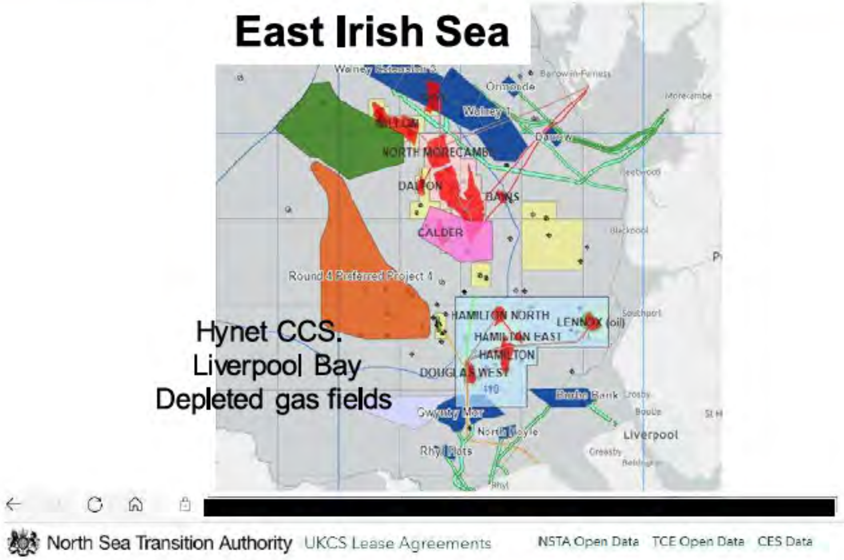
TCE Offshore Wind Leasing Round 4 Preferred Projects
- 1 - RWE Renewables, 1500 MW Capacity
- 2 - RWE Renewables, 1500 MW Capacity
- 3 - Green Investment Group - Total, 1500 MW Capacity
- 4 - Consortium of EnBW and BP, 1500 MW Capacity
- 5 - Offshore Wind Limited, a Joint Venture between Cobra Instalaciones y Servicios, S.A. and Flotation Energy plc, 480 MW Capacity
- 6 - Consortium of EnBW and BP, 1500 MW Capacity

CES ScotWind Offers

Southern North Sea



East Irish Sea



Operational Scenarios - Aviation

The details of aviation constraints were beyond the scope of this study. This requires further engagement with the CAA.

CAA Policy and Guidelines on Wind Turbines (CAA 764) References (4& 5)

Consultation zones around offshore helidecks

3.30. For many years, the CAA has emphasised the importance of operators and developers taking into consideration all existing and planned obstacles around offshore helicopter destinations that might impact on the safe operation of associated helicopter low visibility approaches in poor weather conditions. In order to help achieve a safe operating environment, **a consultation zone of 9 NM radius exists around offshore helicopter destinations.** This consultation zone is not a prohibition on development within a 9 NM radius of offshore operations, but a trigger for consultation with offshore helicopter operators, the operators of existing installations and exploration and development locations to determine a solution that maintains safe offshore helicopter operations alongside the proposed development. This consultation is essential in respect of established developments. However, wind energy lease holders, oil and gas developers, and petroleum licence holders are advised to discuss their development plans with each other to minimise the risks of unanticipated conflict at a later date.

Topics for discussion within any such consultation should include, but are not limited to:

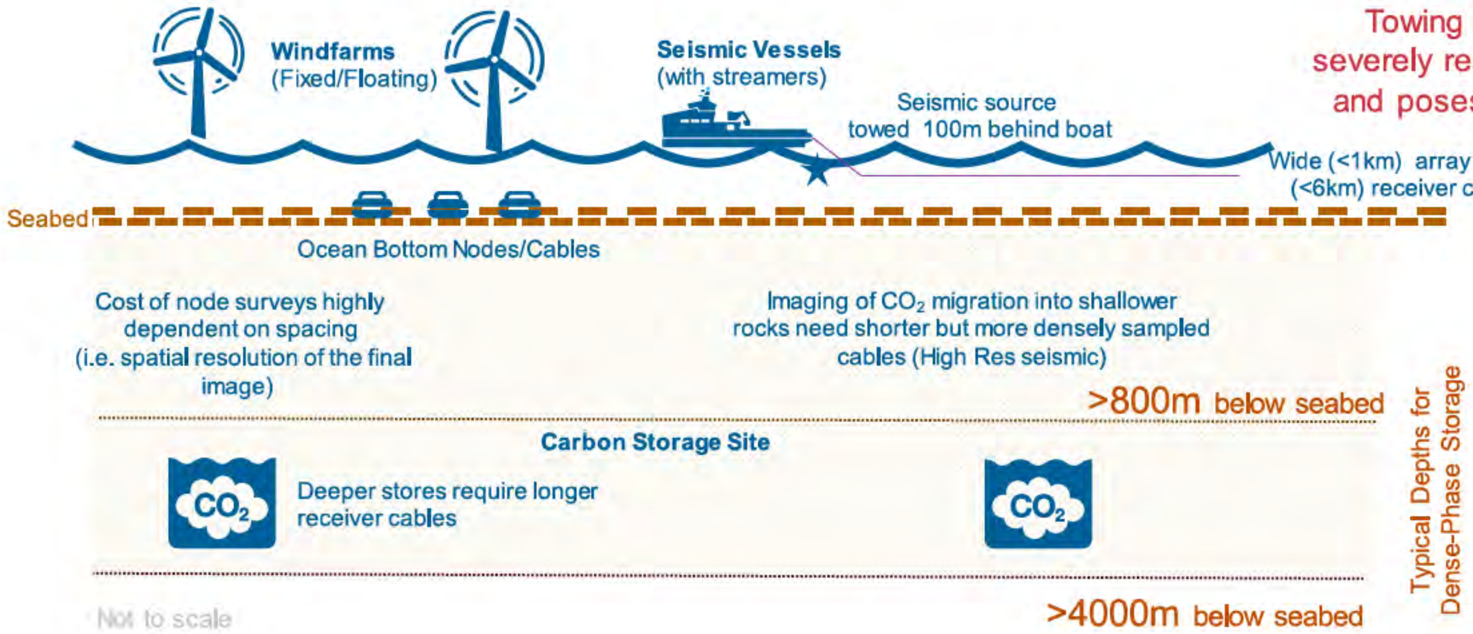
1. Prevailing weather conditions, including predominant wind direction;
2. Manning status of the installation;
3. Frequency of flights to the installation and predominant routes;
4. Performance limitations of offshore helicopter types utilising the helideck;
5. Established helicopter instrument and low visibility approach procedures;
6. Mandated constraints on approaches to helidecks on installations;
7. Long term access to well and subsea infrastructure;
8. Concurrent wind farm operations and oil and gas operations to well and subsea infrastructure;
9. SAR operations to the installation in the event of an emergency;
10. Location and height of potential obstacles including proposed wind turbines

5. Seismic Surveys and Monitoring

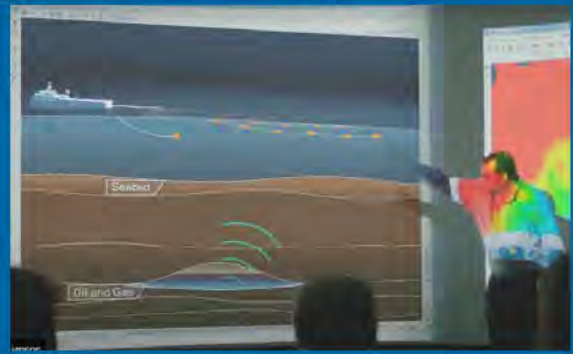
Operational Scenarios – Seismic Surveys

North Sea Transition Authority

- Seismic surveys remain the primary geophysical tool of choice for imaging the subsurface.
  - Essential for mapping the geometry and extent of storage sites and complexes which underpins dynamic fluid prediction models.
  - A high-quality baseline survey is expected for all CO_2 Storage Sites, since this data will be used for decades beyond post-closure Seismic Acquisition parameters will depend on the subsurface scenarios that need to be addressed
  - Reprocessed old surveys (>~15 years) are unlikely to adequately address risks.
  - Streamer surveys are lower cost, but use of **long streamers are impossible** close to & within dense turbine infrastructure
  - Ocean Bottom receivers (nodes) surveys are available at a much higher cost. They can be deployed within infrastructure, if seabed conditions are conducive. A high specification/more manoeuvrable (dynamically positioned) seismic source boat is still required.
- **<u>In some situations</u>**, seismic may also be able to directly image fluids (inc. CO_2)
  - Time lapse **<u>monitoring</u>** its movement in the subsurface (a.k.a. 4D seismic)



Towing large array of equipment severely restricts vessel manoeuvrability and poses unacceptable collision risk

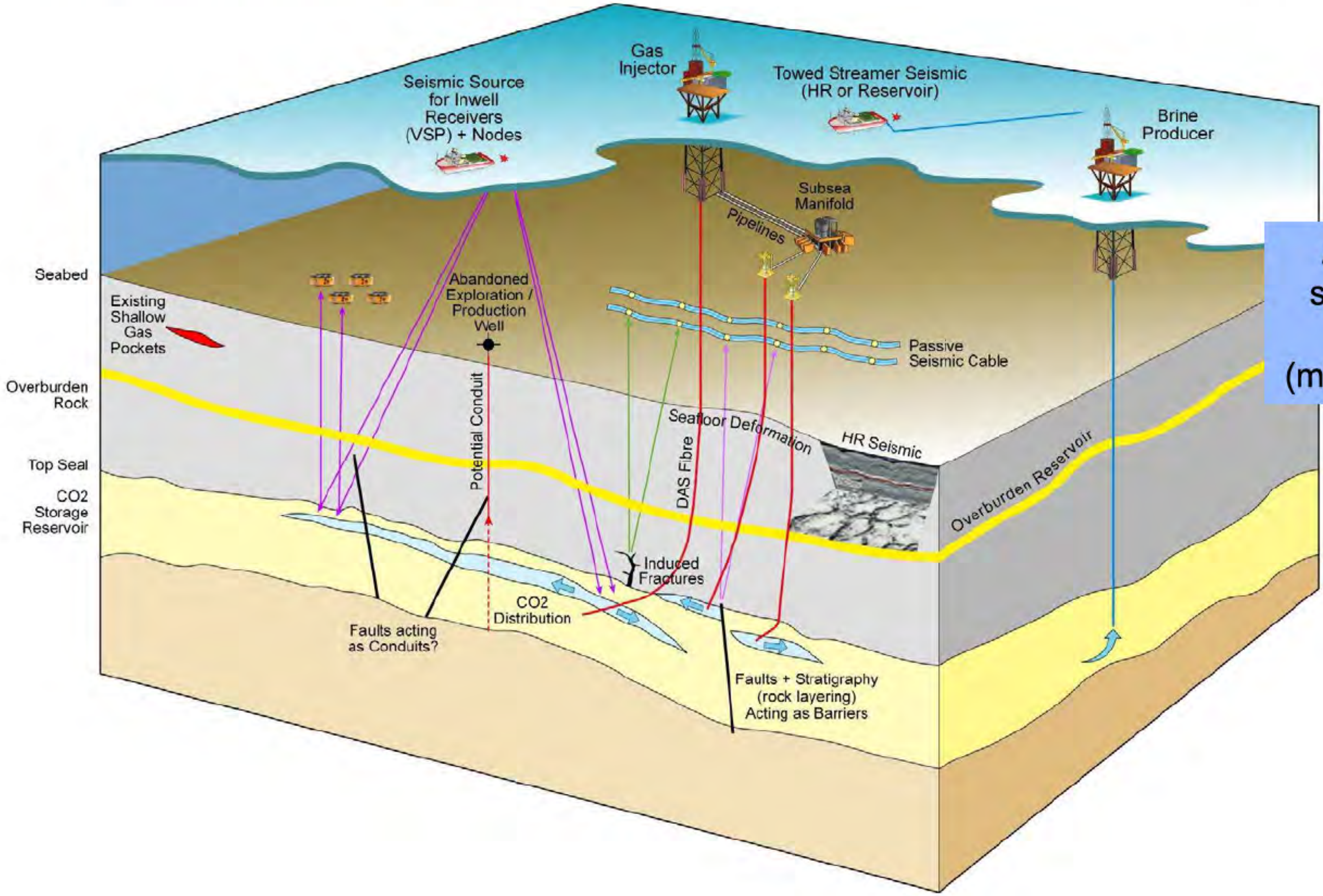


<u>Introduction to Seismic video</u>

Reference (6)

Seismic MMV summary

North Sea Transition Authority



Active source (towed streamer, OBN, in-well VSP) and passive (microseismic) monitoring

Seismic – Regulatory Requirements

North Sea Transition Authority

Framework

- Legislation is not prescriptive with respect to specific MMV solutions
- MMV scope is subject of NSTA stewardship discussions up to the Carbon Storage Permit stage
- Ensures a fit-for-purpose approach according to specific site and complex risks

Geophysical Monitoring

- Most potential UK CCS operators are *assuming* that repeating seismic is the main tool for ongoing MMV
- Seismic monitoring widely accepted as a hydrocarbon field management tool, for many, but not the majority of fields.
        - Some O&G fields were developed after 4D seismic technology invented (late 1990's)
        - Some fields and future CCS stores will not have sufficiently detectable response
    - Mixed approach non-UK CCS pilot projects:
        - Onshore US: expected to have time lapse 4D
        - Dutch sector: Emphasis on classical reservoir engineering (pressure, temperature, volume of fluids) with minimal seismic
    - The NSTA and UKCS operators generally acknowledged FOAK surveys should be over-engineered
    - Non-seismic geophysical remote sensing techniques can complement, but are unlikely to replace active seismic acquisition

Monitoring objectives & specification need to be closely aligned to anticipated risk/uncertainties from project register

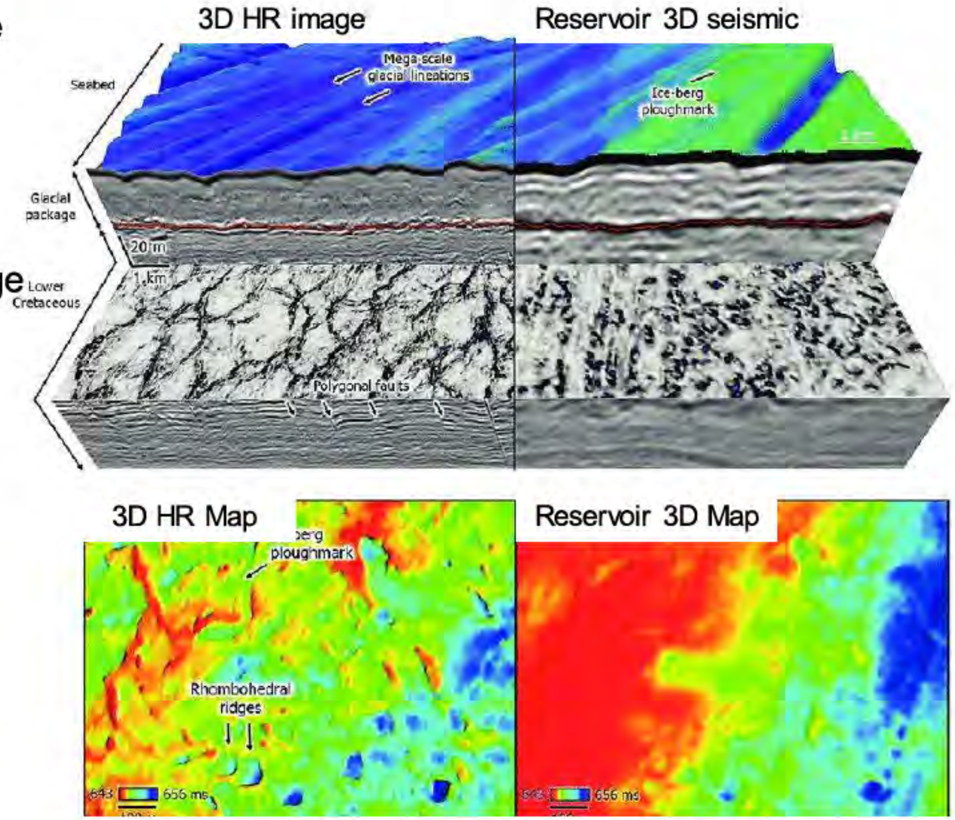
- A *large 4D* be acquired across the entire site closure for direct fluid detection? OR / AND
- More *targeted monitoring* to help calibrate reservoir simulator calibration near an injection site? OR / AND
- A single survey imaging from seabed to base reservoir? OR
- 2 separate surveys: deep reservoir seismic and contingent HR overburden?
- Role of In-well seismic? : Excellent vertical resolution, but very limited spatial extent
- Can Gravity and passive seismic play an intermediate role?

Seismic Vertical (Temporal) and Spatial Resolution | North Sea Transition Authority

- Seismic surveys fall into 2 broad types: Reservoir/Deep imaging & Site Survey/High resolution (HR)

- Modern reservoir 3D seismic is critical for characterisation of the deeper injection site
  - Detailed vertical (~10m) & spatial (12.5x12.5m) 3D-subsurface image
  - Can be acquired via streamer or OBN receivers

- HR3D provide higher vertical & spatial resolution for upper 2km
  - Higher frequencies (<400Hz) imposes depth restrictions
  - Short offset (Small distance between seismic source & receiver) acquisition
    - Nosier image (Lower fold & processing/ demultiple challenging)
    - No AVO (Amplitude vs Offset a.k.a. no advanced geophysical analysis)



Comparison of 3D HR and reservoir seismic Reference (7)

Seismic Streamer surveys remain the obvious choice where clear water access is available

(i.e. there are no windfarms anticipated over CCS site)

Seismic Signal Detection Capability

North Sea Transition Authority

- Undepleted aquifer CO_2 site: **Clear rationale for seismic monitoring**
  - Uncertainty about vertical distribution,
  - Lateral containment,
  - Pressure build-up
  - *Expecting "should see"* time lapse effects (like Sleipner & Ketzin examples)
  - Seismic monitoring expected to provide critical role in MMV strategy

- Depleted Gas Field injection site: **More difficult justification**
  - Prior Gas containment supporting CO_2 containment model
  - Underfilled & low-pressure structural closure provides injection limits
  - <u>*Marginal*</u> seismic detectability,
    - CO_2 injected into residual gas <u>*expected*</u> to generate small seismic signal
    - **Main benefit any displaced hydrocarbons/CO_2 into aquifer**

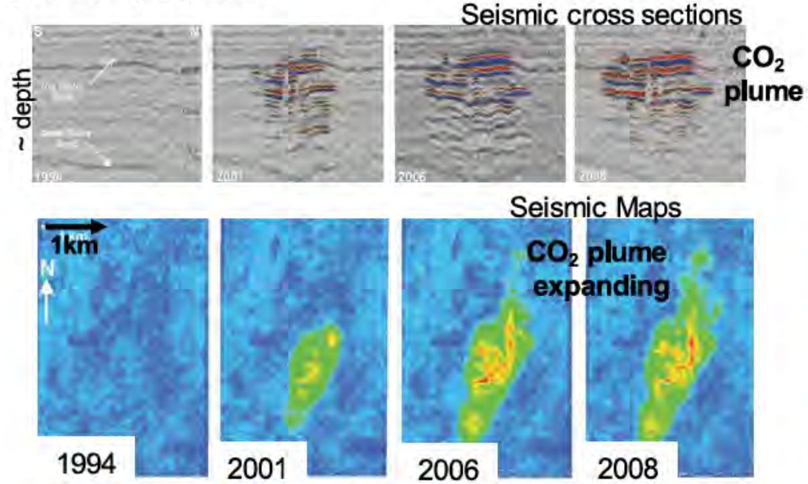
- Overburden Monitoring: **Technically sound reasoning**
  - If CO_2 has significantly escaped expected into an overlying aquifer
    - Potential for fault or near well bore escape imaging
  - Expecting high resolution "should see" effects
  - Baseline critical to rule out natural pre-existing shallow gas pockets

Important Notes: Very few actual CCS studies worldwide to underpin guidelines

- **Guidance based around 20 years 4D technology deployment in O&G industry**
- **CO_2 has a complex behaviour in the subsurface (e.g. dissolution)**
- **Limited rock/ fluid substitution examples to predict response**
  - **NSTA Seismic Detection study in prep (2022)**

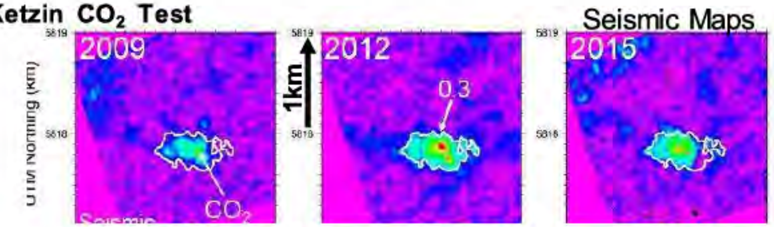
Two examples of direct CO_2 Seismic Detection

Sleipner CO_2 injection



Pre CO_2 injection: weak seismic response
Post injection surveys: Complex CO_2 "bright spots"
Direct detection of CO_2 plume distribution

Ketzin CO_2 Test



Post Injection plume increase with time & CO_2
2015 Shrinking response = fast dissolution of the CO_2.
Could only be detected with an intermediate (2012) survey

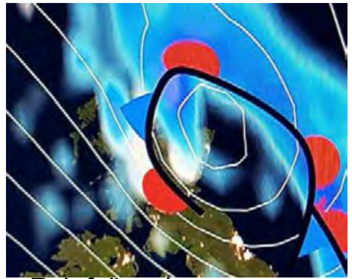
(References 8 & 9)

Seismic Monitoring for CCS

North Sea Transition Authority

Weather analogue

Predictive reservoir model



Rainfall radar

Simulation models are most accurate with regular update of direct observations

4D (Time Lapse 3D) seismic remains the principal, proven, reliable monitoring method supporting

- Conformance/ Reservoir management- Where is the CO_2 distributed within the reservoir?
    - Weather Analogue: Modelling predicts fluid distribution, rainfall radar verifies
- In-fill well targeting: Which subsurface locations have not yet been CO_2 saturated?
- Containment: Is fluid migrating laterally outside planned site, or vertically into overlying rock?
- Public awareness: 4D seismic images can be intuitive (c.f. time lapse photography)

There are two approaches to demonstrating conformance:

1) **Data Led Conformance** Demonstrate agreement between predictive reservoir models & monitoring observations
    - Very difficult to match predictive fluid distribution models solely with **well based monitoring**
        - A perfect, unique match to injected flow rate and pressure is virtually impossible to achieve
    - **Seismic monitoring** always shows unexpected fluid distributions, usually within an acceptable range
    - CO_2 sequestration & hydrocarbon extraction projects both have the same issues.
2) **Refresh Predictive model with monitoring data**
    - Progressively improve predictive reservoir simulation modelling capability as more dynamic data becomes available
    - Seismic monitoring indicates the geological and simulation model assumptions are basically robust
        - Additional data leads to progressive model improvement and refinement
        - Provides increasing confidence and potentially decreasing need for mid/late life seismic

The latter is the generally accepted approach in hydrocarbon reservoir management & applied to Sleipner CO_2 **(Reference 8)**

- **Implications for future MMV regulations**

CCS Seismic Monitoring Considerations

North Sea Transition Authority

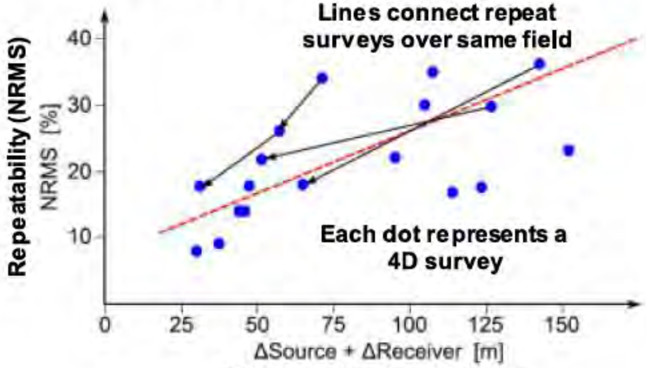
Seismic monitoring reliant upon consistent, repeatable acquisition & careful processing

Quality of differences will be driven by (pre injection) baseline acquisition specification is not prescribed, assumes

- Post 2010 broadband acquisition (broad range of seismic source frequencies) &
- Accurate source/receiver positioning
- Modern Pre-Stack Depth Migration processing

NRMS is a measure of repeatability

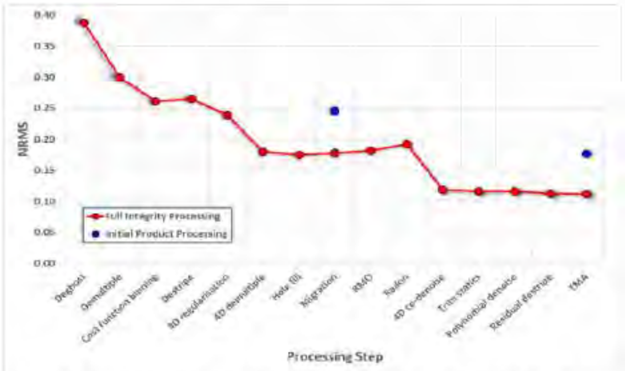
Minimise Towed Seismic 4D Geometrical differences improves repeatability



Improving Repeatability (lower NRMS) with better source and receiver positioning

(Reference 10)

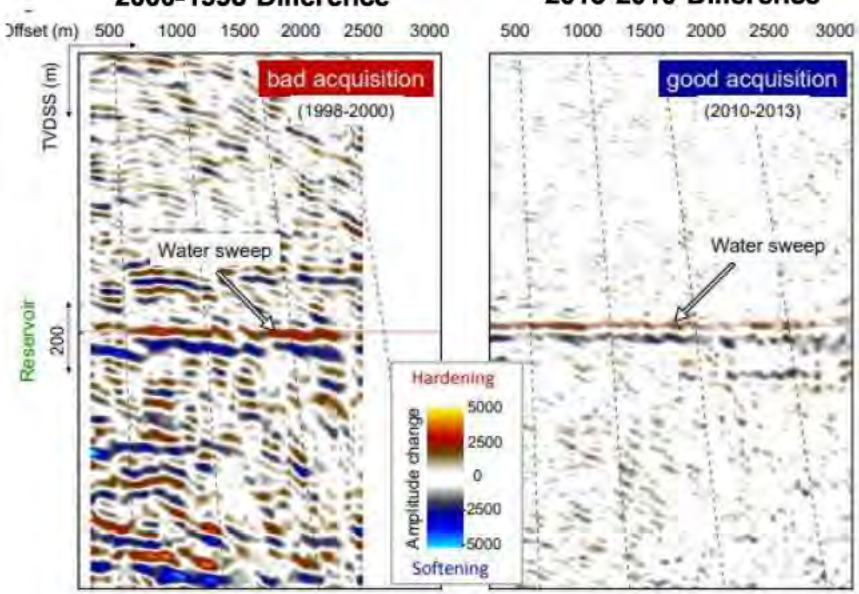
Processing can improve Repeatability



Certain processing steps improve repeatability

(Reference 11)

Forties oil field 4D repeatability



Legacy 3D technology Water swept response subtle Above considerable background noise

Steerable streamers replicate positions Very clear 4D seismic difference

(Reference 10)

North Sea Transition Authority

6. Seismic Surveys Around Windfarms

Seismic Options around Offshore Windfarms

North Sea Transition Authority

- **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

- **Potential monitoring acquisition options**

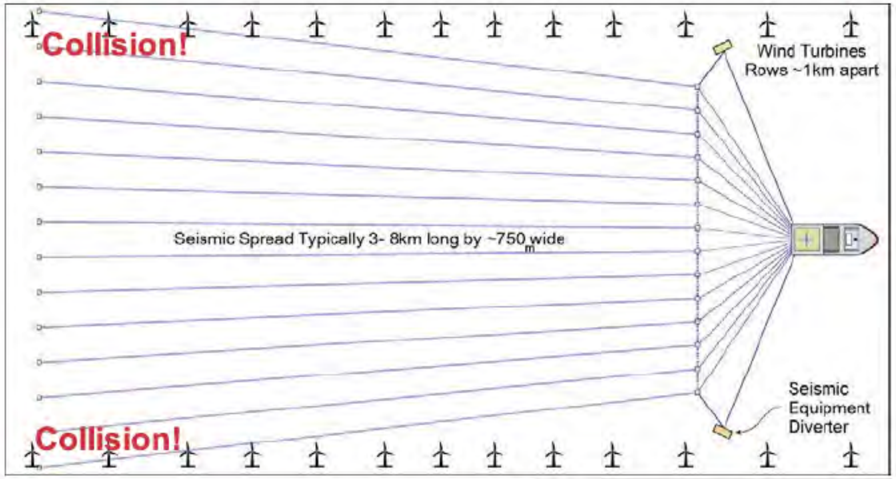
  - Very Restricted **HR towed source only or very short streamer length** seismic **may** work amongst turbines.
    - Requires shallow targets with large expected response
      - Short offset HR seismic which may not deliver reservoir image
      - Cannot provide fieldwide 4D
    - HR contractors currently **hesitant to commit** to minimal HR scope (any more than 1 x 600m cable) between turbines
    - Alternative P-Cable arrangement (multiple ultra-short cables) / still does not present full spatial data
    - “2.5D” monitoring gives very limited image

  - Ocean Bottom nodes (OBN) could be deployed amongst turbines
    - Differencing Baseline Streamer & Monitor OBN currently not effective.

Marine Seismic Operations around Windfarms #1

North Sea Transition Authority

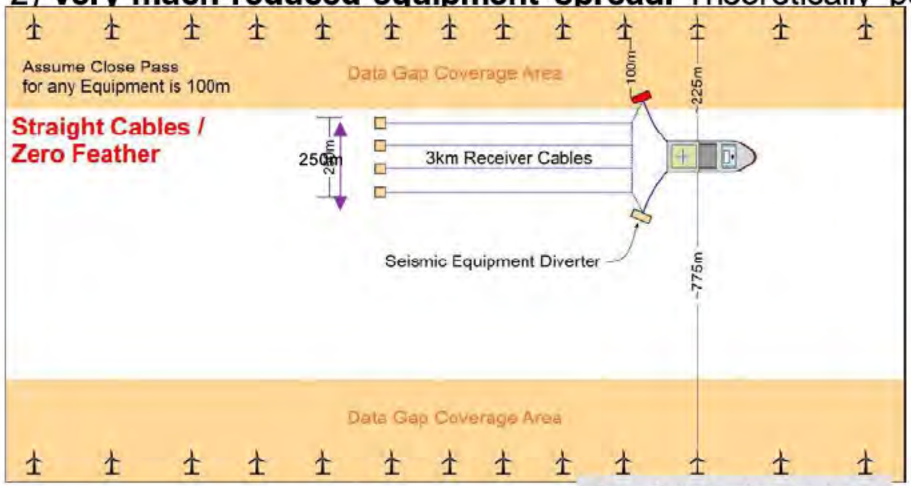
1) **Streamer spread width along turbine corridor:** Impossible



Not to scale: X is 3 time longer than y's width

- 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

2) **Very much reduced equipment spread.** Theoretically possible, but practically impossible



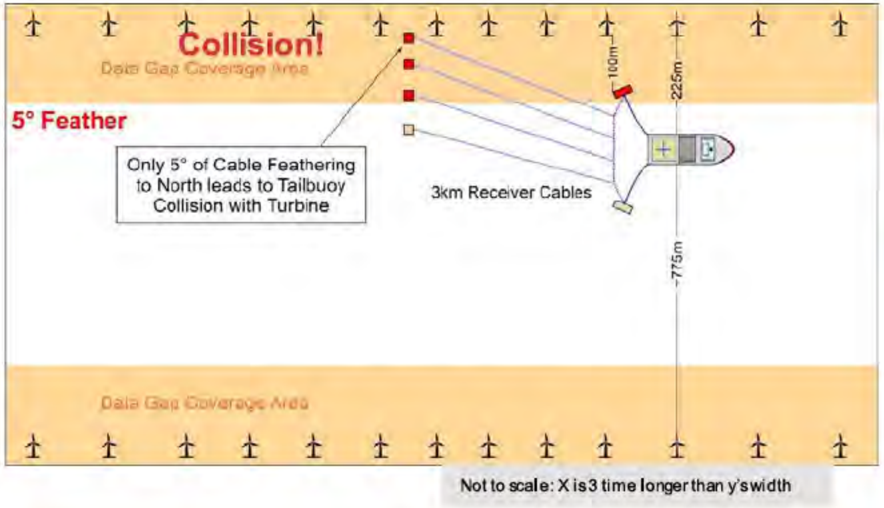
Not to scale: X is 3 time longer than y's width

- Transition point to HR contractors
- Even with zero feather->
- Furthest point for vessel is only 775 m

Significant data gaps
Still very little escape room

Marine Seismic Operations around Windfarms #2

North Sea Transition Authority



3) **Very small & predictable feather:**

May be acceptable in exceptionally good situations, (less strong or more predictable tide)

Subject to risk assessment acquisition may be possible in low predicted feathering,

- Short as feasible streamers,
- large turning circle (2.5-3.5km radius)
- Acceptable vessel capability & escape routes.

Large data gaps remains

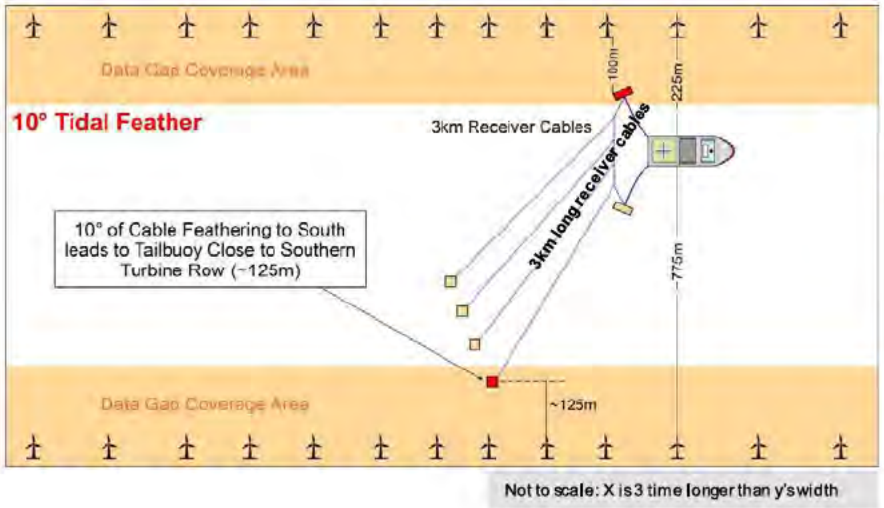
Note:

In high current/tidal areas (e.g. SNS) high feather often occurs

- > 5º feather-> collision would occur

Seismic contractor utilise tides to provide safe streamer drift to "south"

but this further enlarges the data- gap



4) **High or unpredictable currents -> moderate/large feather:** Impossible

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

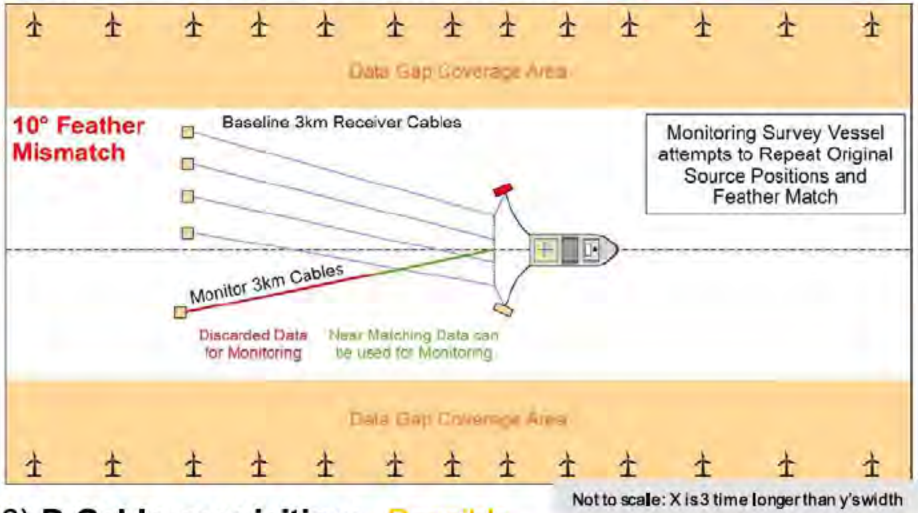
Note: all these scenarios are simplifications and do not show:
- Vessel escape routes and
- Turbines in more complex arrangements

NSTA is aware of only one, carefully planned field example of intra-windfarm 2D HR survey acquistion

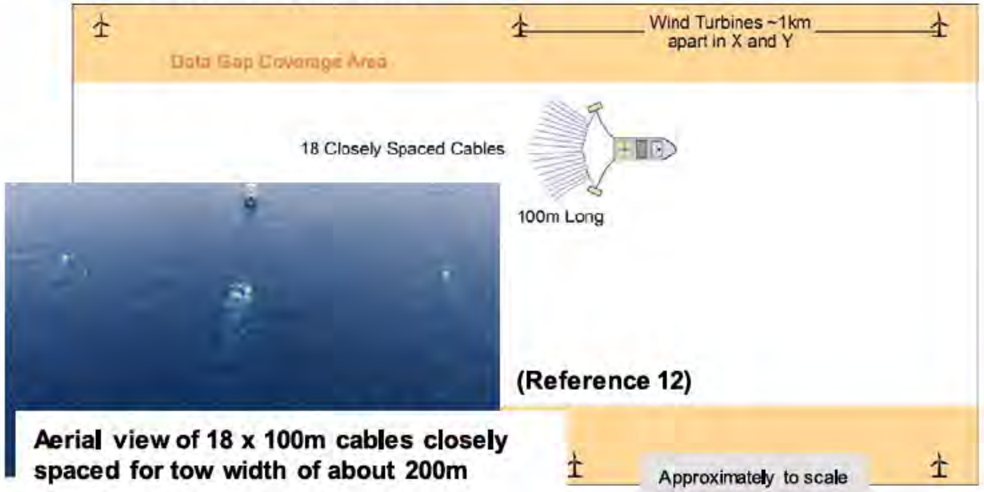
Marine Seismic Operations around Windfarms #3

North Sea Transition Authority

5) **Highly reduced (2.5D) <u>monitoring</u>**: Possible



6) **P-Cable acquisition:** Possible



Aerial view of 18 x 100m cables closely spaced for tow width of about 200m

1) If a clear water **baseline** streamer survey is acquired, then
2) A restricted 2.5D **monitor** survey may be acquired with turbines using selected subset of matching data with reduced acquisition

- 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
- May be more acceptable for Captain/Party Chiefs working amongst windfarms.
- Potentially very high resolution in shallow section
- 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

Ocean-Bottom Seismic

North Sea Transition Authority

Introduction to ocean bottom cables (OBC) and ocean bottom nodes (OBN)
Please see **References 13,14,15**

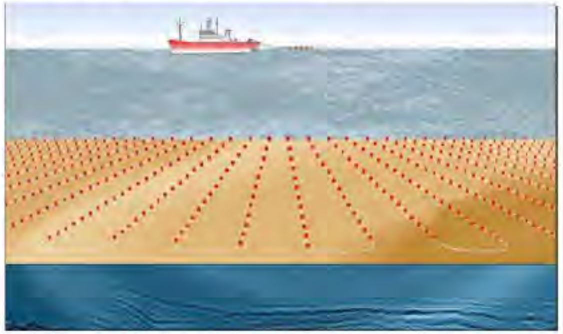
Ocean Bottom Node most likely provide robust & future proofed MMV co-existence solutions.

- **Technologies**
  - Ocean bottom cables
  - Nodes:
    - Autonomous recording unit
    - Contains a hydrophone and three directional geophones,
    - Lightweight nodes on rope OR
    - ROV placed carefully around infrastructure

- **Current developments**
  - Node count increasing/ Costs decreasing
  - Targeted/ localised intra-turbine solutions in development.
  - Hybrid: HR streamer or P-Cable with OBN may provide more widescale data
  - Autonomous Underwater Vehicles (AUV) **References 16& 17**
    - Small number of self- directing nodes “e.g. Spicerack" / Autonomous Robotics
    - Fully autonomous sources and nodes
  - Nodes on “parachute”

More detail on the status of OBN technology is available in a separate NSTA publication (2022 in prep.)

Surveying node array

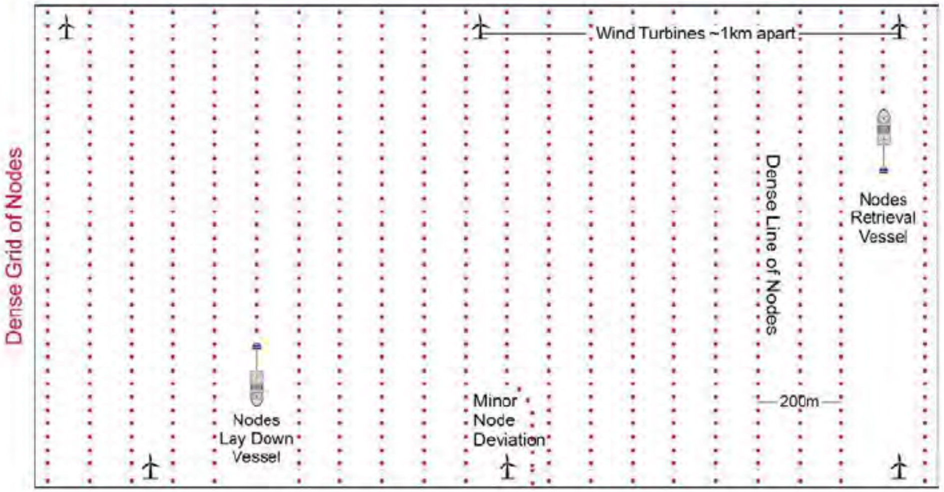


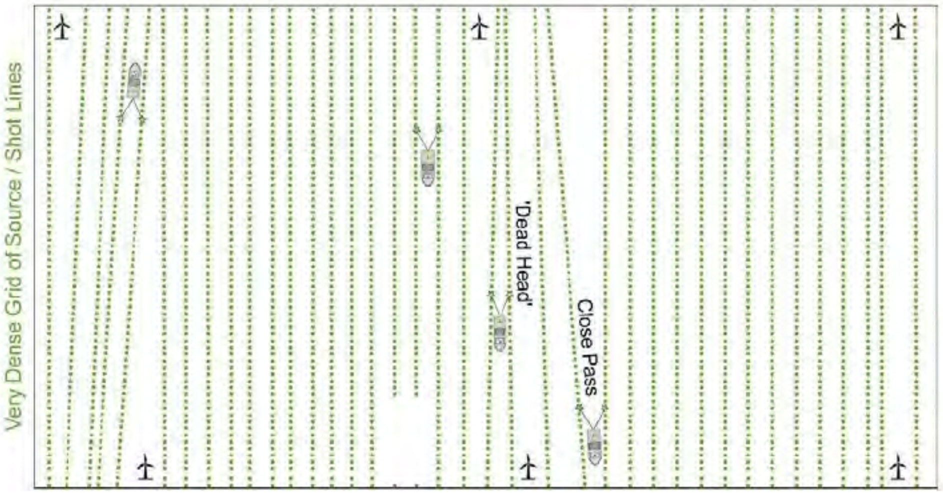
Node

Autonomous node

Node on rope

Ocean-Bottom Nodes Acquisition within Windfarm





Operationally challenging, but feasible

- High density /quality broadband baselines to enable future 4D differencing
- Vessels capabilities entering close turbines
- SIMOPS (Simultaneous Operations)

Positives

- 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
  - Increased data type collection: 4 Component data (Hydrophone + 3x geophone)
    - Useful for imaging below gas cloud (e.g. shallow CO_2 plume)
  - Complete illumination: Multi-azimuth seismic Quieter environment (no wave action)
  - Data can be acquired in very shallow water

Negatives

Cost & duration

- Deployment Speed
  - Placing receivers much slower than towing streamers
  - Ocean bottom nodes are much bulkier and heavier than cables
  - Individual placing/ retrieval by ROV deployment is very slow
- Multiple vessels (source, lay-down pick-up, guard)
- Completion of survey within seasonal weather window
- Coverage gaps @ seabed & shallow section
  - Needs High density/ very narrow receiver line spacing to compensate
  - Significant cost factor

Seismic Monitoring Considerations

North Sea Transition Authority

Frequency and timing of 4D surveying is project dependent

- CCS survey frequency determined case-by-case basis. Estimated 3-10 years
  - More frequent lower cost streamer vs Infrequent costly OBN
  - Identification of CO_2 dissolution within reservoir may require more frequent surveys (e.g. Ketzin Site Pilot)
  - Monitoring Survey frequency every 3-5 years typically assumed for **hydrocarbons**,
- Separate deep reservoir monitoring seismic and targeted overburden imaging?
  - As & when required HR to test if CO_2 migrated above the reservoir / into the top seal
  - Periodic low-density node for reservoir imaging/ initial fluid distribution

Future proofing technology for 60 years is a significant concern

- Pre-injection surveying (<5 years) + Active Site (25 years) + Post closure monitoring (30 years)
  - Seismic monitoring requires consistent acquisition and processing
    - Hydrocarbon 4Ds often have to reprocess *all surveys* to bring them to modern standards
  - Seismic Imaging and OBN acquisition still rapidly evolving
  - Contrast modern seismic acquisition, processing and imaging barely recognisable from 1960's:
    - Crude 2D Acquisition ->3D ->4D. Single -> 16 Streamers -> OBC-> OBN -> UAV/USV seismic
    - Limited manual Unmigrated Processing -> highly complex, computer intensive . Post stack-> Pre stack Time –> Pre stack depth migration
    - Fluid and lithology/ AVO analysis and inversion were not invented.

Environmental

To avoid collateral damage to marine environment CCS operators strongly encouraged to reduce seismic acoustic output

- Current surveys generally looking at smaller sound sources/ new technology development
- Shared noise budgets with windfarm operators likely
- Operator awareness of extended consent timeframe in SAC (Special Areas of Conservation)

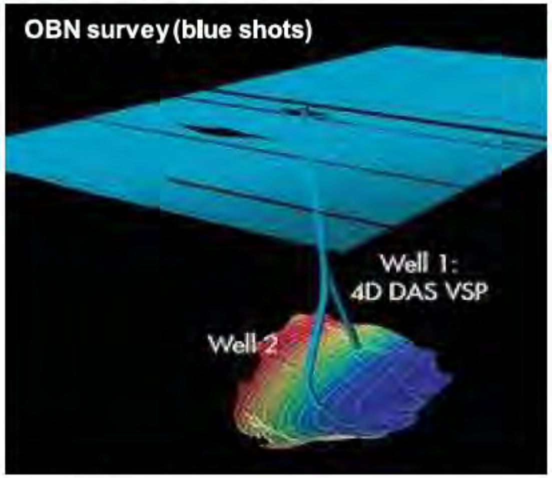
7. Other Active Seismic Options

Localised / Spot Seismic Monitoring

Rather than illuminating a full 3D volume of rock, it is possible to target a particular subsurface point, near a CCS well.

- Repeated VSP (Vertical seismic profiles)
  - Enabled by DAS cables & Surface seismic survey
  - Images a narrow corridor around a wellbore
- Soundsabre: **Reference 19**
  - Node based permanent reservoir monitoring system.
  - Vertical array of 4C sensors in shallow boreholes around specific well target
  - Possible for passive seismic monitoring
- Subsurface spot illumination **Reference 20**
  - Minimal source and receiver pairs,
  - Located upon 3D illumination study & sufficient repeated data (fold) to form a common spot gather.
  - Potential for continuous (e.g. daily) monitoring

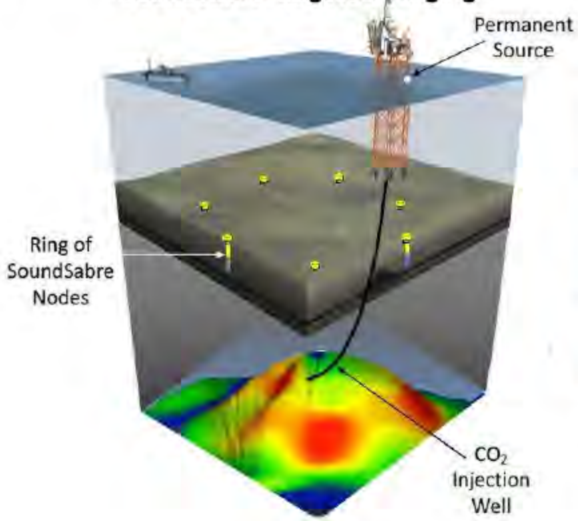
Monitor DAS VSP acquired during OBN

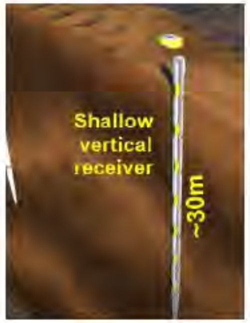


Dense shot carpet provides small 3D cube around wells

Reference 18

Soundsabre targeted imaging





Role of Un-crewed Surface Vessels (USV)

North Sea Transition Authority

Flotilla of smaller surface unmanned vessels be developed to provide a viable and safe surface tow replacement?

References 24, 25

Targeted illumination: build up coverage/fold with a low intensity over an entire acquisition season

Range of developing USV's

Reference 21

Reference 22

Reference 23

Analogous aerial drone swarms choreography

Flotilla of smaller USVs with short streamers provide targeted subsurface imaging

Medium sized USV towing a conventional air gun source or marine vibrator

Receivers maintain critical offset separation from source

Mother Duck and duckling concept

Permanent Reservoir Monitoring (PRM)

North Sea Transition Authority

PRM involves the fixed installation of monitoring equipment on the seabed for multi-season acquisition

- Useful for *frequent* monitoring when tracking very rapid fluid distribution changes
  - Aimed at 3-6 month frequency compared to 3-10 years with streamers
- Globally very few permanent installations only associated with very large scale projects . Clair in UKCS, Valhall and Ekofisk in Norwegian waters

Positives:

- Provides very high repeatability
- Lower repeat monitoring costs
- Containerised seismic source from supply vessel

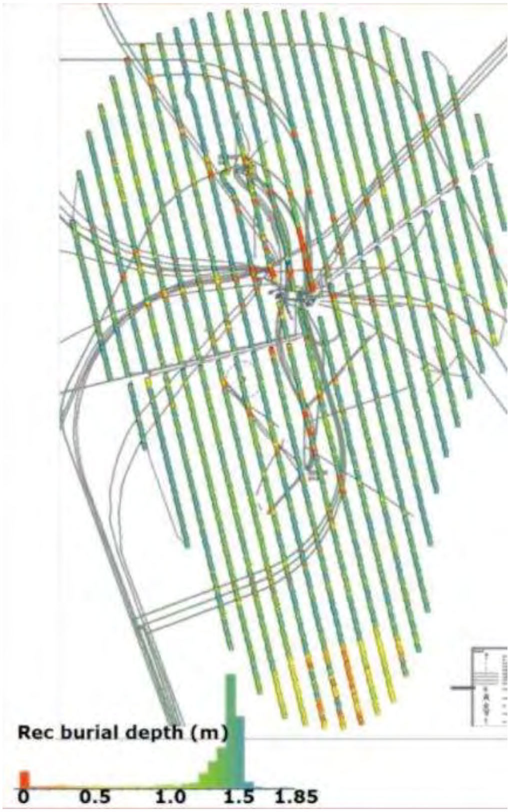
Negatives:

- **Very High up front capital expenditure,**
- Equipment durability,
- Cable based systems inflexible to expansion
- Permanent installation prevents CCS subsea development/ windfarm expansion
- **Seafloor PRM is likely to exacerbate the coexistence issue and is unlikely to have a significant role in congested areas.**

Possible Future Fibre optic development as PRM

- Currently used in-well
- Noisy seafloor environment for untrenched light weight cable

Ekofisk PRM array

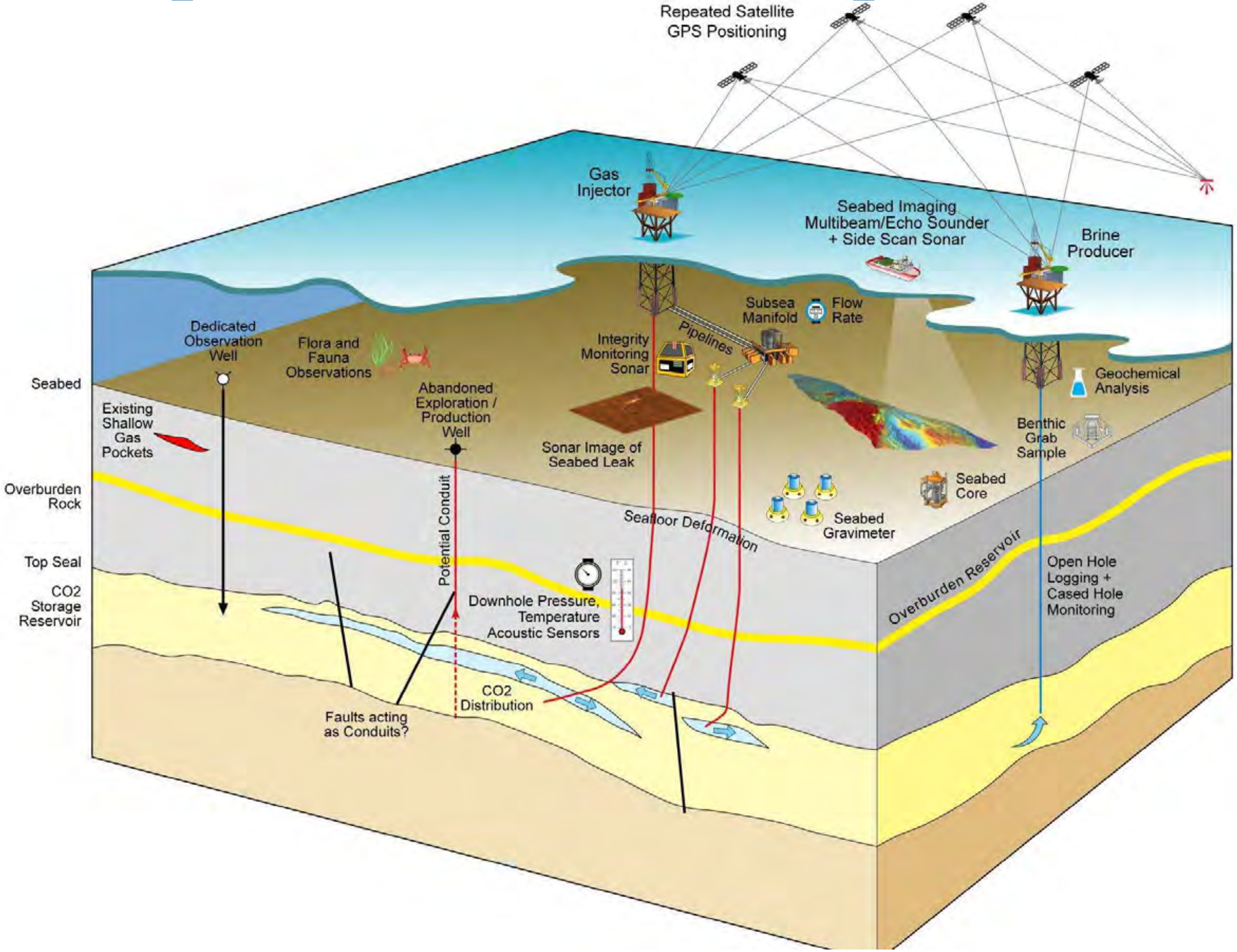


Reference 26

8. Wider Range of MMV Technologies

Range of Other MMV Technologies

North Sea Transition Authority



There is a broad range of complementary MMV technologies which could be routinely applied or could be applied for specific purposes.

Passive Seismic (Microseismic) Monitoring Technologies

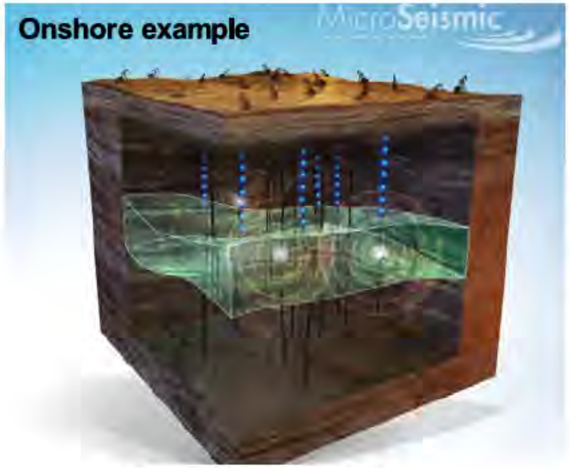
CO_2 Injection is likely to trigger extremely small earth tremors

- High pressure fluids break down lateral or vertical barriers.
- Continuous real time seismic monitoring
- Analysis of passive seismic events help track CO_2 plume migration

Passive Seismic Array

Reference 27

- UK seismometer network used for <u>onshore</u> fracture injection monitoring
  - Usually onshore receivers too remote from distant offshore CO_2 injectors
- Offshore Receivers can be located
  - Vertically in an observation well above/ close to the CO_2 storage reservoir to detect smallest tremors
  - Nodes located around an injection site
    - High marine noise environment?
    - Mobile seabed?
  - Semi-permanent or Permanently installed seabed array around reservoir to triangulate the position of the events
    - Cuttlefish Tenzor Geo



Fracture events create very small tremors, detectable with surface array or in-well seismometers

3 component seismometer and hydrophone receivers linked by fibre optic cable on seabed

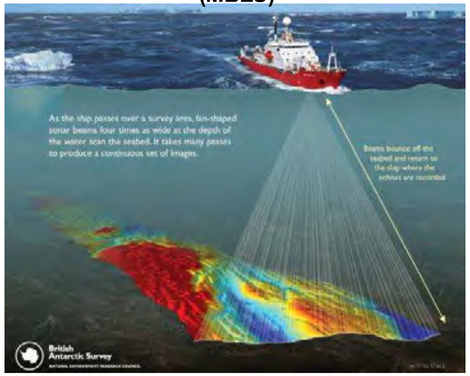
Reference 28

Marine Monitoring Technologies

North Sea Transition Authority

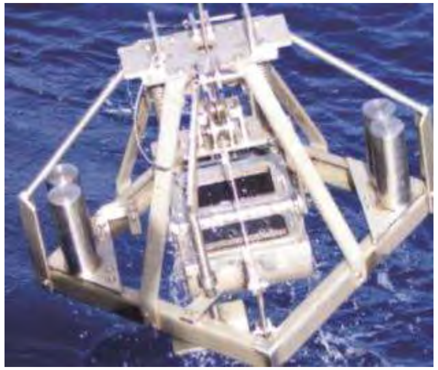
- Marine surveys investigate the water column/ seabed (Bathymetry)
- Collect samples of the flora and fauna to monitor marine habitat (benthic study)
- Form part of baseline environmental and geological data.

Bathymetry Multi Beam EchoSounder (MBES)



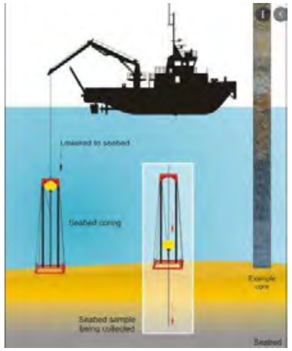
Reference 29

Benthic Grab Sample - Sea floor sampling



Reference 30

Seabed Coring

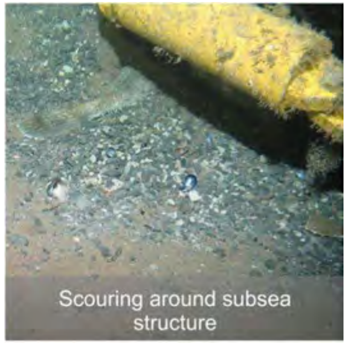


Reference 31

Sidescan Sonar (SSS) Detecting CO_2 plume leak trial

Reference 32

Examples of Benthic Studies

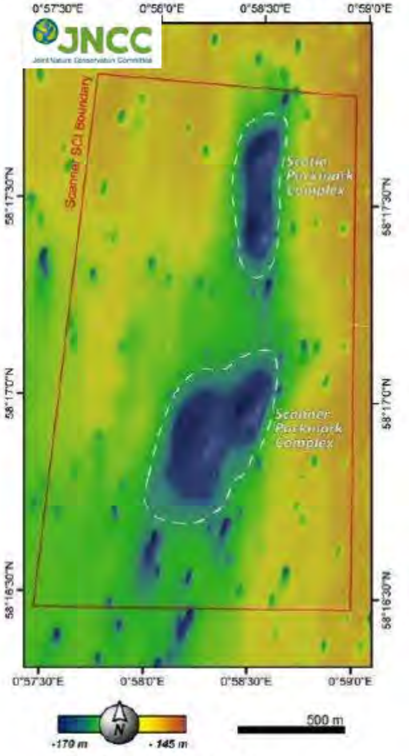


Reference 33

Understanding Shallow Migration Pathways | North Sea Transition Authority

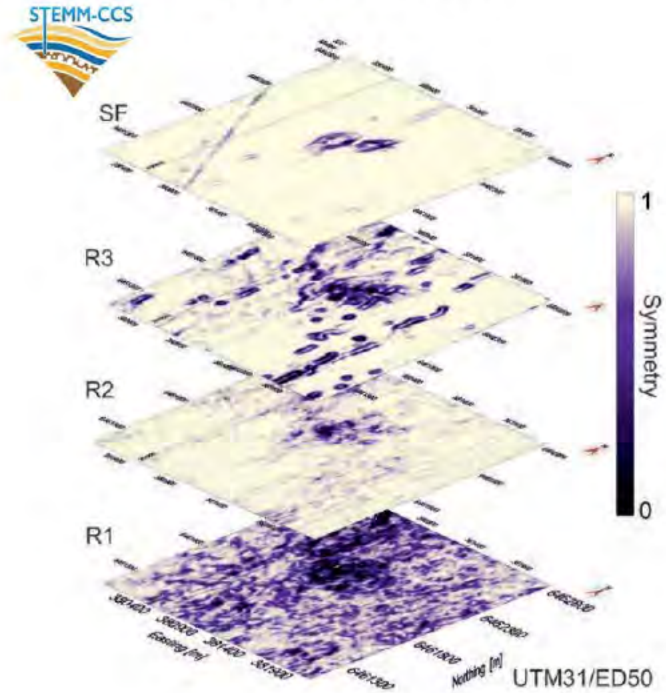
- Multi-beam & High resolution seismic can be used to identify pockmarks/ natural methane gas escape features on the seabed.
- Baseline surveys required to understand the pre-existing pathways, prior to potential CO_2 disruption

Multi-beam Depth Map



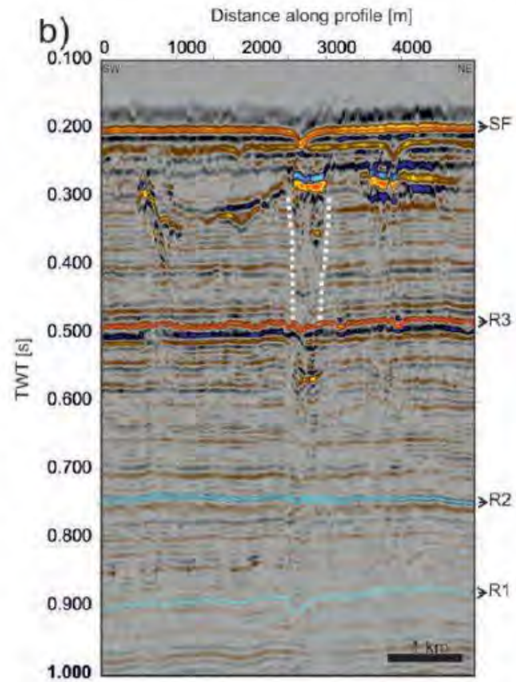
Reference 34

Slices through a 3D coherency cube



Reference 35

3D seismic image of the pipe structure underneath the Scanner pockmark

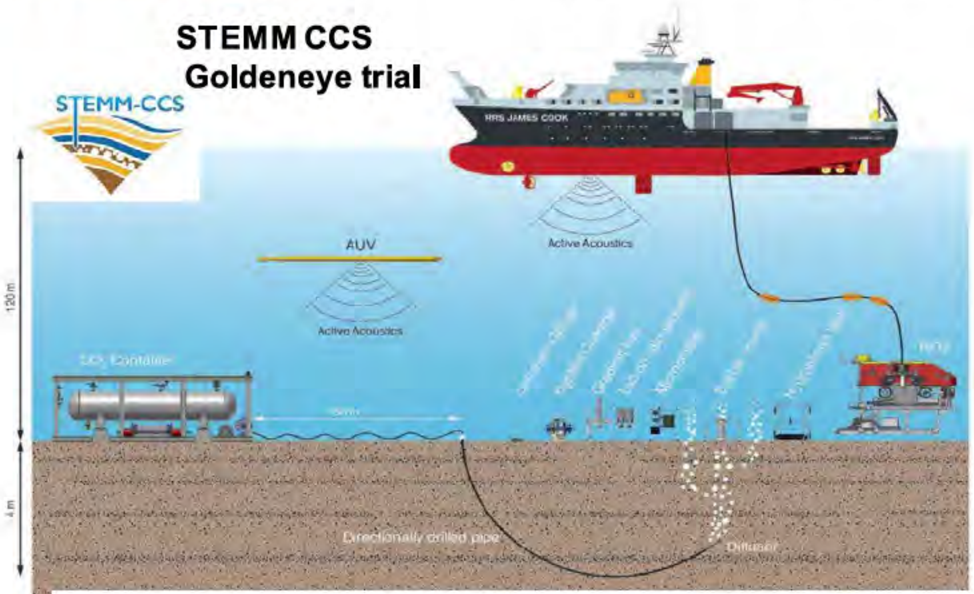


Water Column Monitoring Technologies

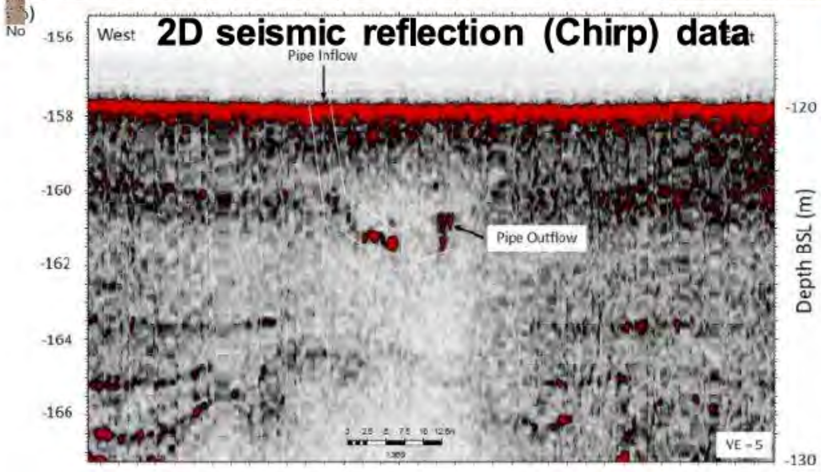
North Sea Transition Authority

- Geochemical sampling (laser) of water column to identify monitor leaks and seeps **Reference 36**
- Photographs of bubble stream
- Shallow Chirp profiler acquisition
- Laser measurements via AUV paired with surface USV
- Optodes measuring pH or pCO_2 (the partial pressure of CO_2) as indicators of CO_2 in both the water column and seafloor sediment.
- Goldeneye trial: CO_2 concentration greater than baseline and seasonal variation **Reference 37-42**

STEMM CCS Goldeneye trial



2D seismic reflection (Chirp) data



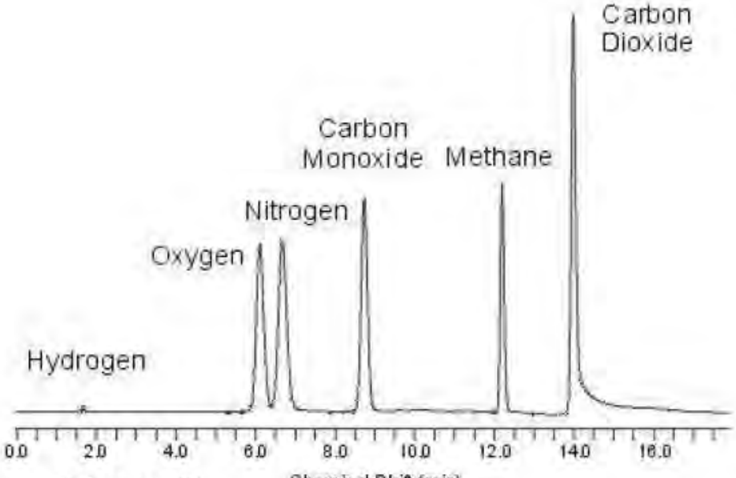
CO^2 outflow pipe experiment

Geochemistry/ Geochemical Analysis

North Sea Transition Authority

- CO_2 interacts with the rock and existing pore fluid
  - Dissolution and precipitation of minerals in the reservoir and seal rocks
  - Modification of the properties of mineral surfaces occurs
  - Effects occur on fluid flow and capillary trapping
- Geochemistry traces fluid-fluid interactions and fluid-rock processes
- Analysis includes:
  - Gas Ratio data
  - Carbon and Oxygen isotopes
  - Isotopic changes in Calcium and Magnesium in the rock
  - Trace metals in overlying aquifer waters
    - upward migration & acidification of CO_2 from storage forn

	Component	Mole%
H_2	Hydrogen	0.00
H_2S	Hydrogen sulphide	0.00
CO_2	Carbon dioxide	3.12
N_2	Nitrogen	0.21
C_1	Methane	76.25
C_2	Ethane	10.59
C_3	Propane	4.72



Reference 43

Downhole Well Monitoring Technologies

North Sea Transition Authority

- Baseline rock and fluid formation data is collected during and immediately after a well is drilled
  - Gives very high resolution, but only very close to well bore (<~5m)
  - Routinely collected "open-hole" prior to running production steel casing

- Injection/production well access can provide time lapse reservoir fluid saturation or production logging
  - **Restricted to very occasional access to offshore wells** (cost and risk)
  - Virtually no access to subsea wells

- CO_2 wellbore measurements have included:
  - CO_2 saturation in brine reservoirs estimated from decrease in sonic (P-wave) velocity & increase in resistivity (induction tool)
  - Repeat Reservoir Saturation Tool (RST) using pulsed neutron capture to determine changing brine saturation

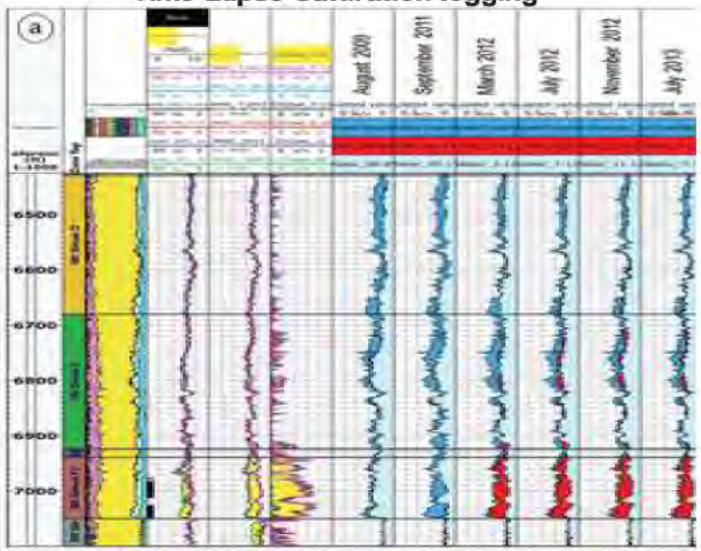
- Future downhole gravity may sense density changes further into reservoir

Reference 44

Downhole logging schematic

Downhole gravity tool

Time Lapse Saturation logging



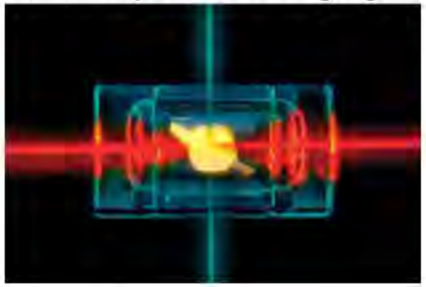
Reference 45 Saturation increasing with time

Realtime Wellbore Monitoring Technologies

North Sea Transition Authority

- Wellhead measurements routinely provide pressure and CO_2 injection rates
- Downhole gauges located near casing perforations (open sections to reservoir)
  - Usually provide continuous downhole pressure and temperature
  - Well pressure correlates between the injection rate vs. the reservoir pressure.
    - Ensures overall dynamic equilibrium within the reservoir.
- Distributed sensors continuously measure physical properties along an entire fibre optic cable.
  - Vibrations from the surrounding environment, disturb the light in the fibre and observed (Distributed Acoustic Sensing or DAS)
    - Permanent installation with well completion
    - Mitigate tube ringing noise: preferable deployed behind casing rather than via tubing
  - Detection of leaks/seeps in and near wellbore
  - Temperature (Distributed Temperature Sensing/ DTS) and
  - Strain (via Distributed Strain Sensing or DSS)
  - DAS – Vertical Seismic Profile (VSP) can provide early indications of CO2 plume development
- Risk of near wellbore leakage means that DAS could play a significant low cost monitoring role. **Reference 46**

Quartz Crystal Pressure gauge



Reference 47

Rig up for DAS installation

Reference 48

DAS- Vertical Seismic Profile

North Sea Transition Authority

DAS – Vertical Seismic Profile (VSP) can provide early indications near wellbore CO_2 plume development

Lower cost 2D "walkway" (from wellbore)

Reference 49 **Seismic Cross section**

DAS-VSP Time lapse difference

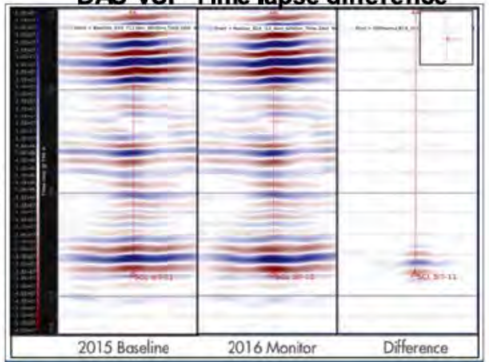


Figure 5. Time-lapse assessment after 6 months of injection of the North-South DAS walk-away VSP line at injection well 7-11. The difference between the 2015 baseline and 2016 monitor clearly shows the time lapse anomaly representing the CO_2 plume.

Map CO² Plume development from Sparse 2D walkaway VSP

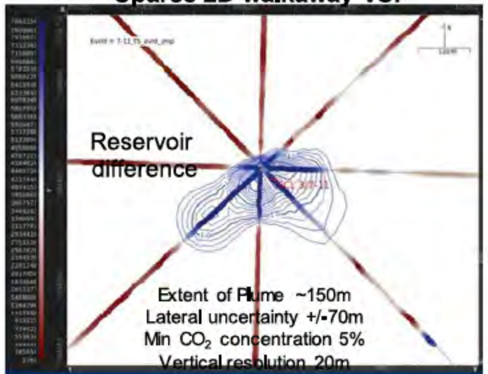
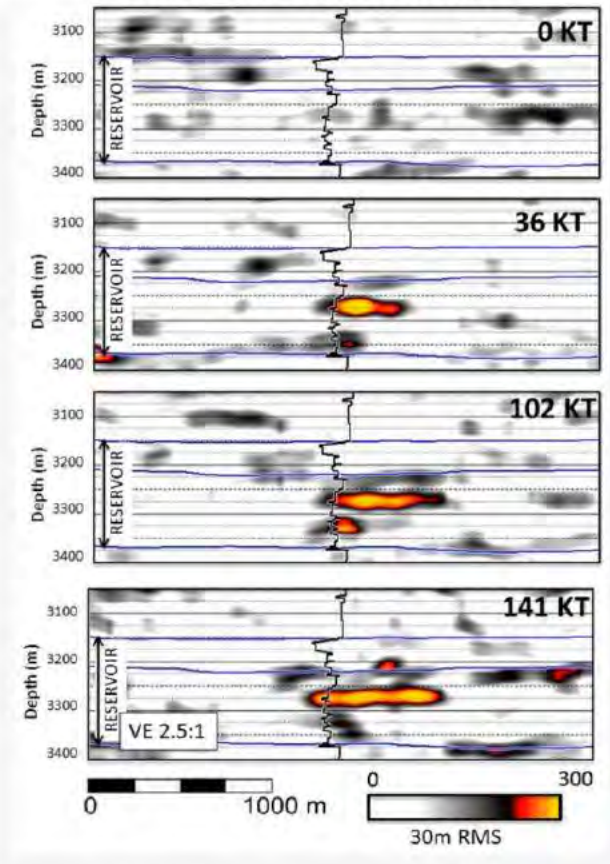


Figure 8. Minimum curvature interpolation of the amplitude difference between 2015 baseline and 2016 monitor in each VSP line, representing a map view of the seismic response to the presence of CO2 after 6 months of injection

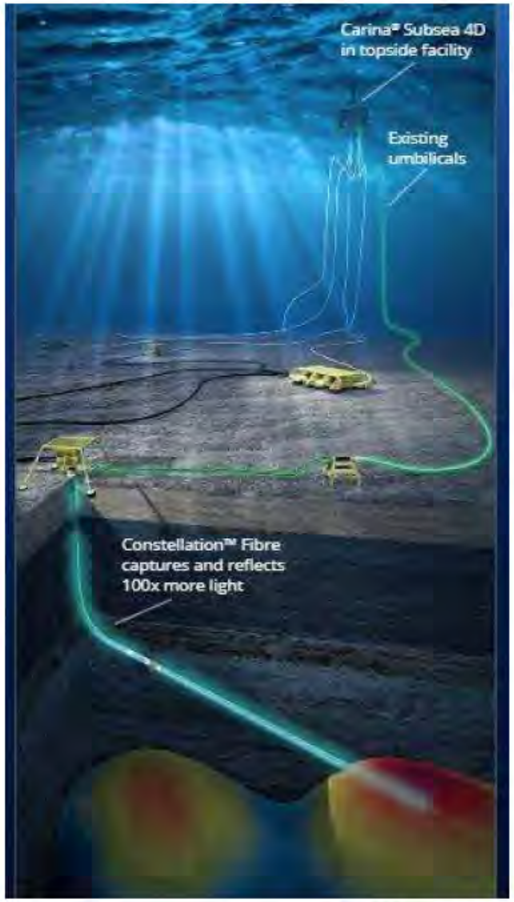
Reference 50 **Seismic Cross section**

DAS-VSP Time lapse difference



As volume of injected CO² increase the amplitude relative to baseline increases

Permanent In-well Seismic concept



Reference 51

Seafloor Deformation Monitoring

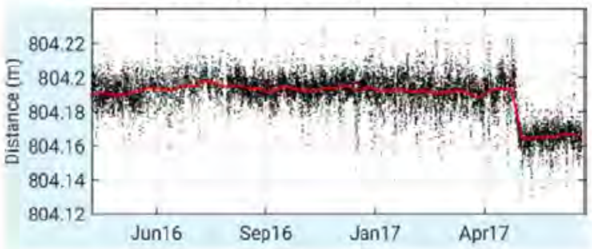
North Sea Transition Authority

Hydrocarbon extraction occasionally generates minor subsidence, expected that CO_2 injection/ sequestration may create seafloor *inflation.*

- Average **subsidence** Ekofisk 10-15cm/year, Deep water US/Brazil fields ~ 2-5cm/year
- CCS related predicted inflation has not been studied, but likely small

- Long term subsea seafloor deformation monitoring
  - Vertical displacement by Pressure Monitoring Transponder (PMT)
    - Self calibrating/ Currently being trialled on Ormen Lange
  - Autonomous Monitoring Transponder (AMT)
    - Pressure, Temperature, sound velocity and dual-axis inclinometer
    - Horizontal accuracy of <15mm
    - Long endurance: < three years deployment

Time series geodesy data (Mt Etna)

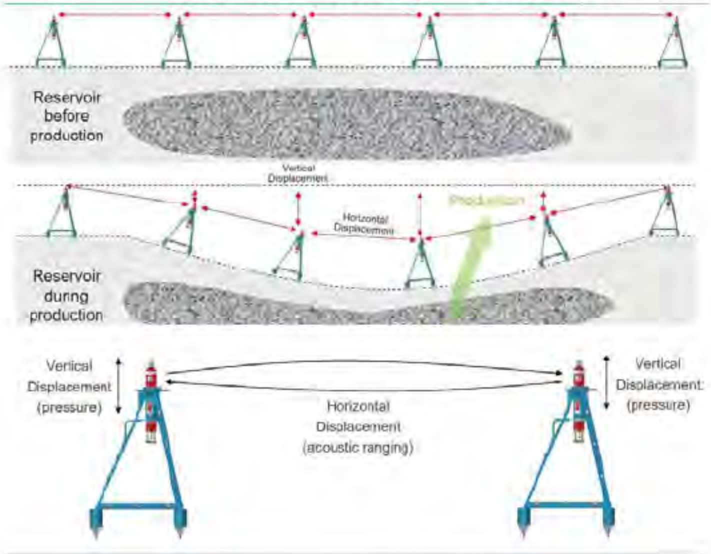


Volcano 4cm slip May 2017

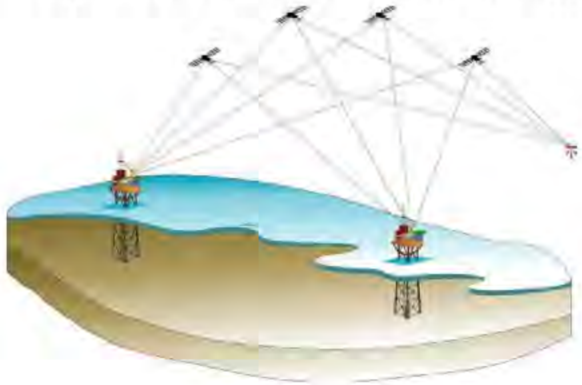
Reference 53

- Continuous satellite GPS on fixed platforms detect mm scale changes
  - Onshore: Humbly Grove **(Reference 54)**
  - Onshore InSar (Interferometric Synthetic Aperture Radar) measures ground deformation / In Salah CO_2 sequestration demonstration **(Reference 55)**
  - Offshore InSar provide low-resolution seabed topography data **(Reference 56)**
    - Probably insufficient definition for CCS monitoring

Marine Geodesy **Reference 52**



Repeated Satellite GPS Positioning



Seafloor Gravity Monitoring

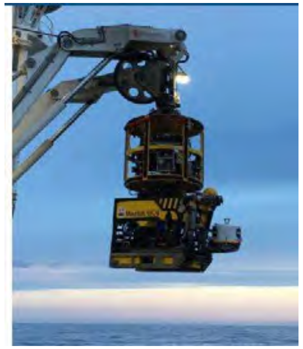
Seabed Gravimetry

- Periodic measurements of strength of the earth's gravitational field
  - Gravimeter deployment on concrete plinth to ensure repeatability.
    - May not be practical for very long term stability/ mobile seabed
  - Gross changes may be detectable/ subject to modelling

- Ormen Lange undertaken 7th G-watch survey
  - Claim 1/10 of the price of a 4D seismic survey and 1/3 of the delivery time.

OCTIO Gravitude

Reference 57-59



ROV holding gravity meter ready for deployment

Electromagnetic / CSEM

Electromagnetic measurements are routinely used in wellbore data acquisitions to determine the electrical resistance (resistivity) of the rock/fluid mixture.

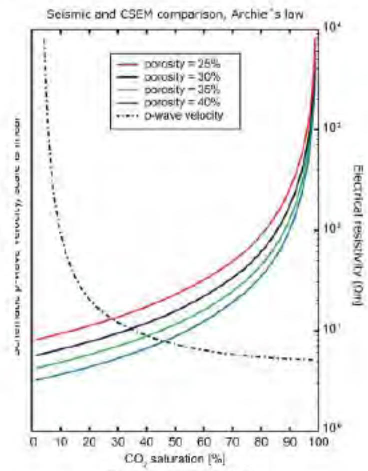
- Function of gas saturation, amongst other parameters.
- Rock physics models predict resistivity changes by several orders of magnitude with changing CO_2 saturation.

Controlled Source Electromagnetics (CSEM) used to measure large resistivity variations below the seabed

- Used on the onshore Ketzin CO2 storage site
- Very limited testing use offshore CCS (Sleipner)
- Tested on pockmark for shallow gas detection **Reference 62**

Impact of changing CO2 saturation on seismic and EM properties

High CO_2 gives High resistivity in good quality (high porosity) reservoirs



Reference 61

Usually employed as complementary technique to seismic

CSEM still requires towing significant source may be an operational problem in a constrained environment.

CSEM acquisition configurations

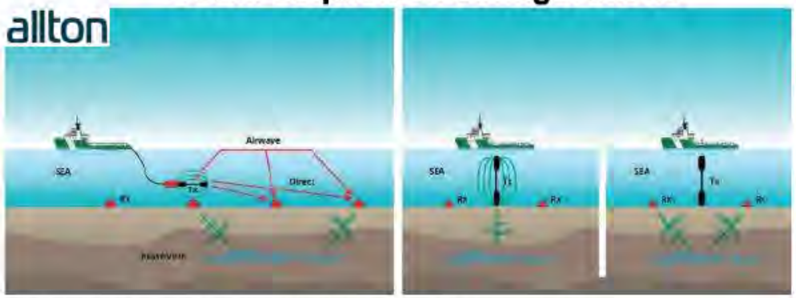
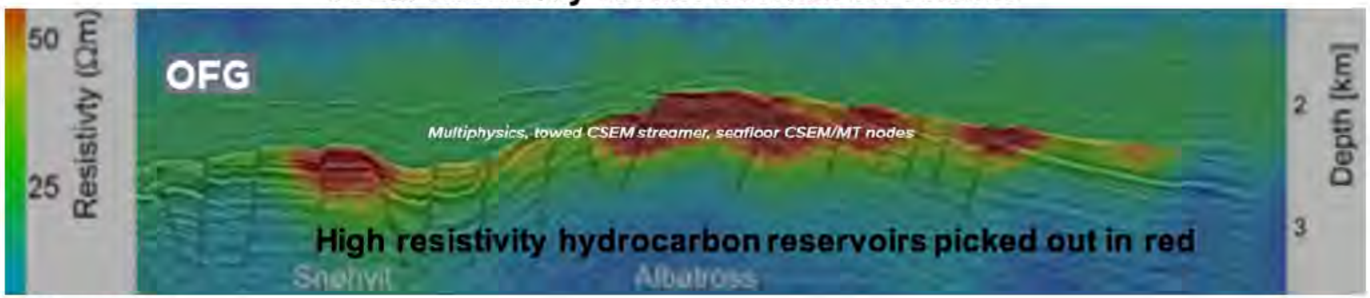


Figure 2 Controlled source electromagnetic signal propagation through subsurface with towed (left) or stationary source (right)

Reference 63

CSEM Resistivity results overlain on seismic



Reference 64

9. Conclusions and Next Steps

Conclusions & Recommendations

North Sea Transition Authority

Each carbon storage project has a different risk priority/ranking

- Carbon Storage Project Monitoring objectives will have a slightly different emphasis depending on subsurface and surface factors, and their relative risk.
- A consolidated list of monitoring objectives is recommended, cross-referenced to
  - subsurface risks and other project risks
  - monitoring technologies/techniques/tools and
  - their technology readiness levels (including availability and cost).
- Monitoring strategies will evolve over a project's lifetime
  - More frequent seismic monitoring will likely be required during early storage development, with learning and adaptation through the operational phase.

NSTA/TCE/CES to establish and publish 'Greater Working Areas' for Carbon Storage sites and complexes to

- Demarcate areas where surveying activities (especially using seismic streamers) can be expected.
- Areas should be established on a site by site basis in collaboration with the licence/lease holder.

Expansion of Project Vulcan co-location **risk assessments to include more operational disciplines** (e.g. operations geophysicists, marine & aviation experts, drillers, rig tow masters, hydrographic surveyors, fishing bodies, Nature Conservation bodies, etc).

Ongoing & Next Steps

North Sea Transition Authority

Current 2022 studies

- Ocean bottom seismic, technology assessment for the use for CO_2 storage monitoring
  - Operability, costs and ability to mitigate colocation issues with windfarms
- Rock Physics Fluid Substitution study,
  - Ability of seismic to detect CO_2 plume migration within CCS target intervals of interest
  - Across range of potential storage sites
- Review of literature and on the effect of windfarm noise on seismic acquisition

2023+ Potential studies

- Deploy *Field Trial* measuring equipment to measure *windfarm noise signature*.
  - Test a range of scenarios to assess impacts and potential uses for seismic acquisition

- Carry out a *4D Seismic Repeatability Field Trial* (HR 3D vs 2.5D) to evaluate if data acquisition approaches/methods can be scaled back to greater enable wind turbine placement.

North Sea Transition Authority

10. References

References

(1) ORE Catapult & NZTC (2021) CCUS & Offshore Wind Overlap Study Report *PN000452-LRT-002*. Energy Transition Alliance (ORE Catapult and OGTC/NZTC) report for The Crown Estate.

(2) Quintessa (2021) UKCS CARBON CAPTURE RISK REGISTER AND GLOBAL LESSONS LEARNED REPORT *QRS-10053A-Report*. Internal report for the Oil & Gas Authority.

(3) Oil and Gas Authority: Interactive Energy Map for the UKCS - The move to
net zero [redacted]

(4) CAA Policy and Guidelines on Wind Turbines (CAA 764) [redacted]

(5) Offshore Renewables Aviation Guidance (ORAG) Good Practice Guidelines for Offshore Renewable Energy Developments [redacted]

(6) Meet Ronnie Parr, BP's geophysicist in the North Sea – YouTube

(7) Toward one-meter resolution in 3D seismic | The Leading Edge [redacted]), Nina Lebedeva-Ivanova et al 2018

(8) Underground CO2 storage: demonstrating regulatory conformance by convergence of history-matched modeled and observed CO2 plume behavior using Sleipner time-lapse seismics - Chadwick - 2015 - Greenhouse Gases: Science and Technology - Wiley Online Library Chadwick and Noy 2015.

(9) 4D seismic monitoring of CO2 storage during injection and post-closure at the Ketzin pilot site, Stefan Lüth, 2017

(10) The quantification of pressure and saturation changes in clastic reservoirs using 4D seismic data [redacted], Omofoma

(11) 4D Seismic in the Catcher Area – Shining a new light on reservoir management in complex injectite sands. Gary Marsden, Harbour Energy, Seismic 2022 - SPE Aberdeen [redacted]

(12) P- Cable 3D Seismic/NCS Subsea NCS-SubSea - | P Cable 3D Seismic | Marine Seismic Imaging Technology

(13) "Ocean bottom cable acquisition - SEG Wiki" and "Ocean-bottom node - SEG Wiki";

(14) Ocean Bottom Nodes in Action – YouTube

(15) GEO ExPro - Ocean Bottom Seismic: Robots on the Seabed

(16) Autonomous Robotics | Autonomous underwater vehicle solution [redacted]

(17) GPR, a seabed nodal solution for seismic acquisition - Sercel – YouTube

(18) 4D DAS VSP as a tool for frequent seismic monitoring in deep water | The Leading Edge [redacted]

(19) Soundsabre vertical array (20-30m) SoundSabre Technology – YouTube [redacted]

References (cont. 1)

North Sea Transition Authority

(20) Focused and continuous ultra-light seismic monitoring: a gas storage example. Morgan et al. 2020. EAGE Conference & Exhibition [redacted]

(21) Fugro launches its new generation of uncrewed surface vessels in the Netherlands – Energy Northern Perspective Fugro Blue Essence – YouTube

(22) USVs for commercial sector | SEA-KIT

(23) L3Harris Technologies Awarded Medium Unmanned Surface Vehicle Program from US Navy | L3Harris™ Fast. Forward.

(24) ASV, Shell in unmanned seismic vessel project push - Offshore Energy [redacted] ASV, Shell in unmanned seismic vessel project pus

(25) USV for seismic operations - Brattørkaia 11, 7010 Trondheim, Norway [redacted]

(26) Ekofisk life-of-field seismic: Operations and 4D processing, Bertrand Ekofisk life-of-field seismic: Operations and 4D processing | The Leading Edge [redacted]

(27) British Geological Survey Seismology Monitoring Page [redacted]

(28) Real-time passive monitoring with a fibre-optic ocean bottom array [redacted]

(29) British Antarctic Survey [redacted]

(30) Picard, Kim et. Al... (2014). Seabed environments and shallow geology of the Leveque Shelf, Browse Basin, Western Australia

(31) Geological research methods | Explore the Seafloor [redacted]

(32) Baseline issue 18 by Sonardyne International Ltd

(33) Autonomous marine environmental monitoring: Application in decommissioned oil fields, Jones et al. 2019, Science of the Total Environment ScienceDirect

(34) Geological investigation of pockmarks in the Scanner Pockmark SCI area, JNCC 2015 Scanner Pockmark MPA | JNCC - Adviser to Government on Nature Conservation

(35) Pockmarks in the Witch Ground Basin, Central North Sea; Christoph Böttner. Geochem Geophys Geosyst, Volume: 20, Issue: 4, Pages: 1698-1719, First published: 14 March 2019, DOI: (10.1029/2018GC008068) [redacted]

(36) Using autonomous underwater gliders for geochemical exploration surveys Louise M. Russell-Cargill CSIRO PUBLISHING | The APPEA Journal

(37) Assuring the integrity of offshore carbon dioxide storage Connelly, D.P in prep. Journal: Renewable and Sustainable Energy Reviews

(38) Sub-seabed carbon dioxide storage | STEMM-CCS

(39) Strategies for Environmental Monitoring of Marine Carbon Capture and Storage STEMM-CCS_research_highlights_r.pdf

References (cont. 2)

(40) Deviations from environmental baseline: Detection of subsea CO2 release in the water column from real-time measurements at a potential offshore Carbon Dioxide Storage site. - OceanRep [redacted]

(41) Time-lapse imaging of CO2 migration within near-surface sediments during a controlled sub-seabed release experiment | Elsevier Enhanced Reader Ben Roche et al. [redacted] International Journal of Greenhouse Gas Control 2021

(42) International Journal of Greenhouse Gas Control | Special Issue on Monitoring, Measurement and Verification for Offshore CCS: Outcomes of the STEMM-CCS project | [redacted]

(43) Geochemistry of Geologic CO_2 Sequestration, Ed. de Paolo, Reviews in Mineralogy and Geochemistry Vol 77

(40) Recent advances in well based monitoring of CO_2 sequestration, Friefeld et al. 2008

(44) Silicon Microgravity | SMG | Reservoir [redacted]

(45) Monitoring CO_2 injection for carbon capture and storage using time-lapse 3D VSPs | The Leading Edge [redacted]

(46) Using a Walk-away DAS Time-lapse VSP for CO₂ Plume Monitoring at the Quest CCS Project | Apr. 2017 | CSEG RECORDER

(47) Downhole Pressure Measurement Gauges - Reservoir Testing | Schlumberger [redacted]

(48) Operational Demonstration of Distributed Pressure Sensing Ekechukwu, G.K., Sharma, J. Well-scale demonstration of distributed pressure sensing using fiber-optic DAS and DTS. *Sci Rep* 11, 12505 (2021). [redacted]

(49)Using a Walk-away DAS Time-lapse VSP for CO₂ Plume Monitoring at the Quest CCS Project | Apr. 2017 | CSEG RECORDER

(50) While 2020 Expanded abstracts, reproduced in Seismic applications of Downhole DAS, Lellouch et al. *Sensors* **2021**, *21*(9), 2897; [redacted]

(51) Carina Subsea 4D - ultra HD subsea in-well seismic data acquisition | Silixa Ltd

(52) Marine Monitoring for CCS using Cost Effective Autonomy, Kim Swords, Sonardyne 2017

(53) GEOSEA SEAFLOOR GEODESY NETWORK Seafloor Geodesy - GEOMAR - Helmholtz-Zentrum für Ozeanforschung Kiel4

(54) Enhanced Oil Recovery as secondary revenue stream in a gas storage facility: Understanding and monitoring the Humbly Grove Field, Hampshire, UK< A Satterley et al. First Break, Vol 38, Sep 2020 DOI: 10.3997/1365-2397.fb2020069

(55) Carbon capture and storage - CCS - at In-Salah - TRE ALTAMIRA [redacted]

(56) Wiehle, 2019 Automatic bathymetry retrieval from SAR images | SpringerLink

References (cont. 3)

(57) GRAVIMETRY AND SEAFLOOR DEFORMATION SURVEY TECHNOLOGY | MONVIRO; ;

OCTIO GRAVITUDE'S TECHNOLOGY FOR GRAVIMETRY AND SEAFLOOR SUBSIDENCE MONITORING - YOUTUBE

(58) Ormen Lange Gravity survey [redacted]

(59) Equinor/ IEAGHG FUNDS RESEARCH INTO THE DEVELOPMENT AND DEPLOYMENT OF CARBON CAPTURE AND STORAGE (CCS) TECHNOLOGIES [redacted]

(60) The Use of GNSS GPS Technology for Offshore Oil and Gas Platform Subsidence Monitoring [redacted]

(61) Introduction to CSEM | Earthdoc

(62) Strategies for Environmental Monitoring of Marine Carbon Capture and Storage STEMM-CCS_research_highlights_r.pdf

(63) Introduction-to-CSEM_First-Break-November-2020.pdf [redacted]

(64) Multiphysics Towed CSEM Streamer Data with Seafloor CSEM/MT Nodes - Ocean Floor Geophysics

11. Appendix

Acronyms Used in this Report

North Sea Transition Authority

AA- Appropriate Assessment
AVO – Amplitude Versus Offset, AI – Acoustic Impedance
AUV- Autonomous Underwater Vehicle
BEIS – Department for Business, Energy and Industrial Strategy
CCS – Carbon Capture and Storage
CSEM - Controlled Source Electro-Magnetic
CES – Crown Estate Scotland
CO_2 – Carbon Dioxide
CCUS – Carbon Capture Usage and Storage
CSEM - Controlled source Electromagnetics
DAS – Distributed Acoustic Sensing
DTS/ DSS – Distributed Temperature/ Strain Sensing
EM – Electro Magnetic
EU - European Union
FOAK – First of a kind
GPS - Global Positioning system
HR – High Resolution
Hz – Hertz measure of frequency
InSar - Interferometric Synthetic Aperture Radar
JNCC – Joint Nature Conservation Committee
MBES - Multi Beam Echo Sounder
MMV – Measurement, Monitoring and Verification
NM - Nautical Mile
NSTA – North Sea Transition Authority
OBC - Ocean Bottom Cable,
OBN – Ocean Bottom Node
O&G - Oil and Gas
OGA - Oil and Gas Authority – now known as the NSTA
OPRED - Offshore Petroleum Regulator for Environment & Decommissioning
OGTC/NZTC- Oil and Gas/ Net Zero Technology Centre
OREC – Offshore Renewable Energy Catapult
PRM- Permanent Reservoir Monitoring
ROV – Remotely Operated Vehicle
RST – Repeat Saturation tool
SAC - Special Area of Conservation
SIMOPS – Simultaneous Operations
SNS – Southern North Sea
SSS – Side Scan Sonar
SUV Surface Unmanned Vessel
TCE – The Crown Estate
UKCS – United Kingdom Continental Shelf
VSP – Vertical Seismic Profile
2D/3D/4D – 2/3/4 Dimensional (aka time lapse 3D) Seismic
2.5D – 2.5 Dimensional Seismic
3C – 3 Components
4C - 4 Components (3 geophones + hydrophone)