The QICS project: Outcomes and implications for the development of CCS

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PML | Plymouth Marine Laboratory

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and several more….

Funders and participants

Funders

RESEARCH COUNCILS UK

NERC SCIENCE OF THE ENVIRONMENT

The Scottish Government

METI 経済産業省 Ministry of Economy, Trade and Industry

UK Participants

PML Plymouth Marine Laboratory

SAMS

National Oceanography Centre NATURAL ENVIRONMENT RESEARCH COUNCIL

BGS 1835 British Geological Survey NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF Southampton

HERIOT WATT UNIVERSITY

THE UNIVERSITY OF EDINBURGH

Japanese Participants

RITE Research Institute of Innovative Technology for the Earth

東京大学 THE UNIVERSITY OF TOKYO

CRIEPI

National Institute of Advanced Industrial Science and Technology AIST

JANUS

I²CNER KYUSHU UNIVERSITY

KANSOテクノス

Regulatory landscape

Legislation to allow sub-seabed storage has been enshrined in the London Protocol and Convention, offshore storage requirements have been produced for the NE Atlantic through OSPAR (Dixon et al., 2009; OSPAR, 2007), and much of the OSPAR regulations taken forward into the EU Directive on geological storage of CO_2 (European Union, 2009).

Regulation requires:
"**characterisation of site specific risks** to the marine environment and **collection of baseline data for monitoring**. The site operator must **consider the risk of adverse impacts** and **assess possible effects of leakage on the marine ecosystem** including human health and impacts on legitimate users of the marine environment. Site selection should consider the risk of adverse impacts on sensitive, or endangered, habitats and species and natural resources."

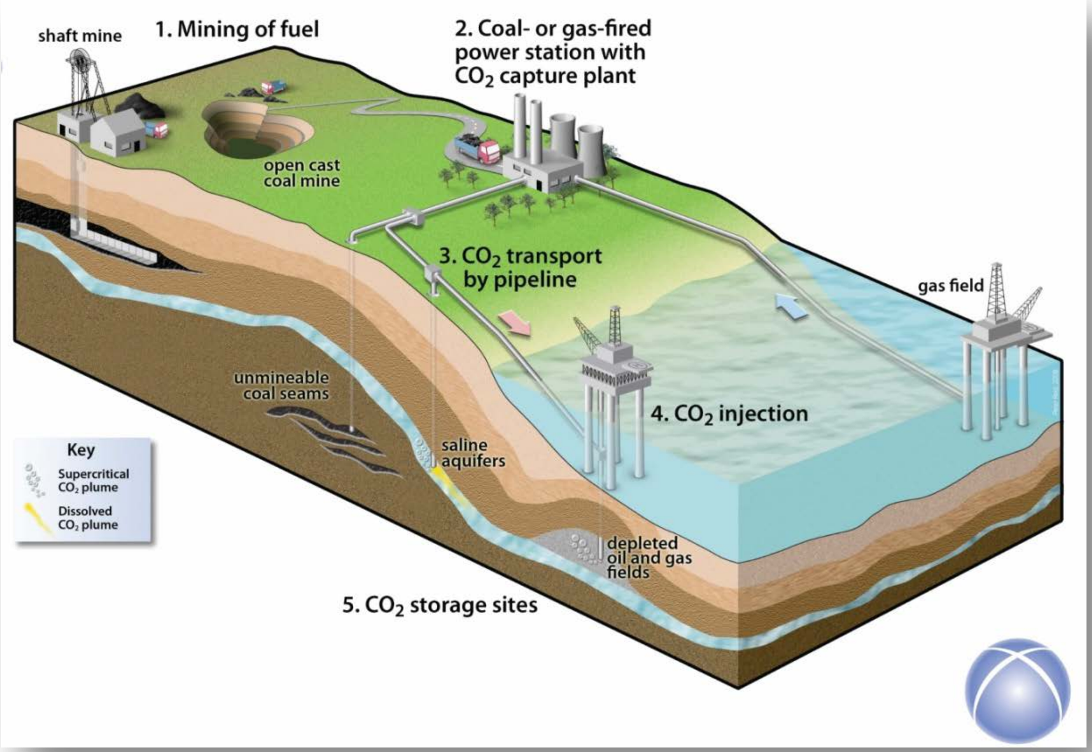
But the wording is vague:
But what constitutes "risk", "baseline data", "impacts", "monitoring"….

Research Objectives

Challenges for CCS: Primarily risk and cost reduction.

Issues across the whole CCS chain

Our focus is the marine environment : location for UK storage



Project Objectives

1. If CO_2 leaked into the living marine environment what are the likely ecological impacts, would they be significant?

2. What are the best tools, techniques and strategies for the detection and monitoring of leaks – or assurance that leakage is not happening, in the vicinity of the sea floor

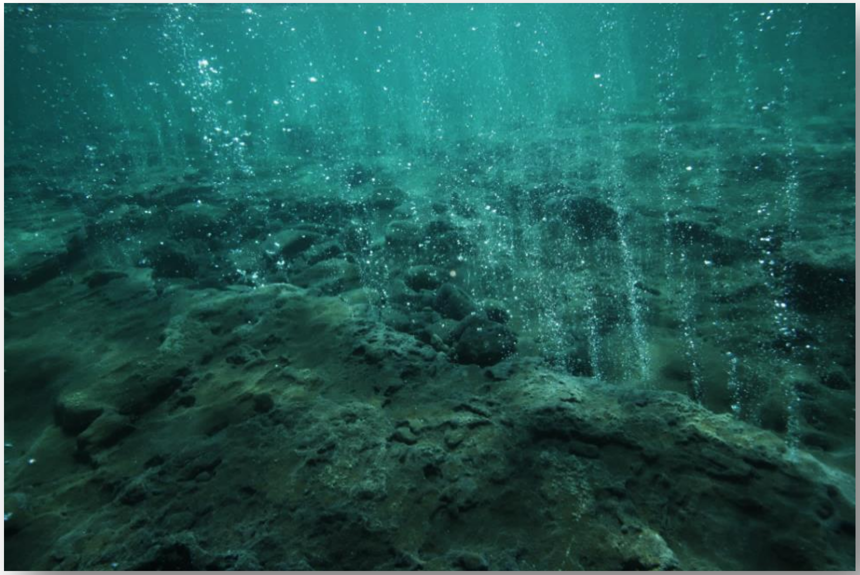
Research hypothesis and design

Initial hypothesis and questions:

- CO_2 flow will be impacted by the physical and chemical structure of the sediments.
- CO_2 dispersion will be determined by complex tidally driven mixing.
- Impacts will be moderated by CO_2 distribution and retention and by secondary chemical processes.
- Impacts will be determined by a combination of physiology, ecosystem structure and behaviour.
- Additionally we need to understand the initial stages of leakage in an environment related to UK storage sites.

Consequently we desired to recreate a "leak-like" event in the natural environment.

This requires injecting CO_2 into sediments in a way that does not produce artificial flow conduits.

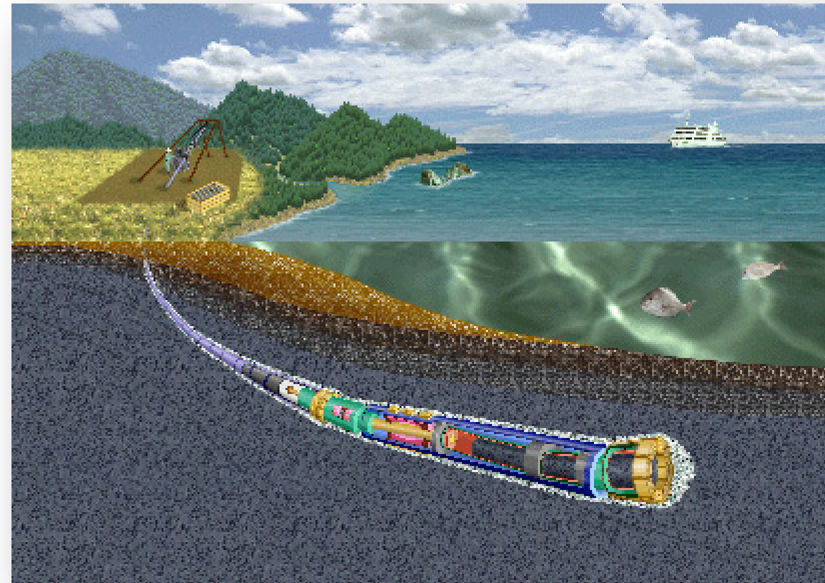


Research Challenges

Two immediate challenges:

How to inject the CO_2?

- Directional drilling at a very well understood and constrained site.
- Expensive!



Recognising that the experiment can be characterised as a deliberate pollution event how to

- get formal permission?
- and informal permission – i.e. not upset public, environmentalists and marine users?

Site identification

Site Requirements:

- Geology suitable for drilling
- Unconsolidated sediment depth > 5m
- Water column depth between 10-20m, to permit diving.
- Sediment type that is typical of UK shelf seas
- Sediment fauna that is reasonably typical, vigorous and diverse
- Currents and tidal flow to be predictable and not excessive.
- Absence of other pressure such as fishing, pollution,
- Absence of significant recreational or aquaculture use
- Reasonably close to professional scientific diving expertise
- Access to nearby land, suitable to mount drilling rig
- Permission from landowner
- Consent from local government & population.

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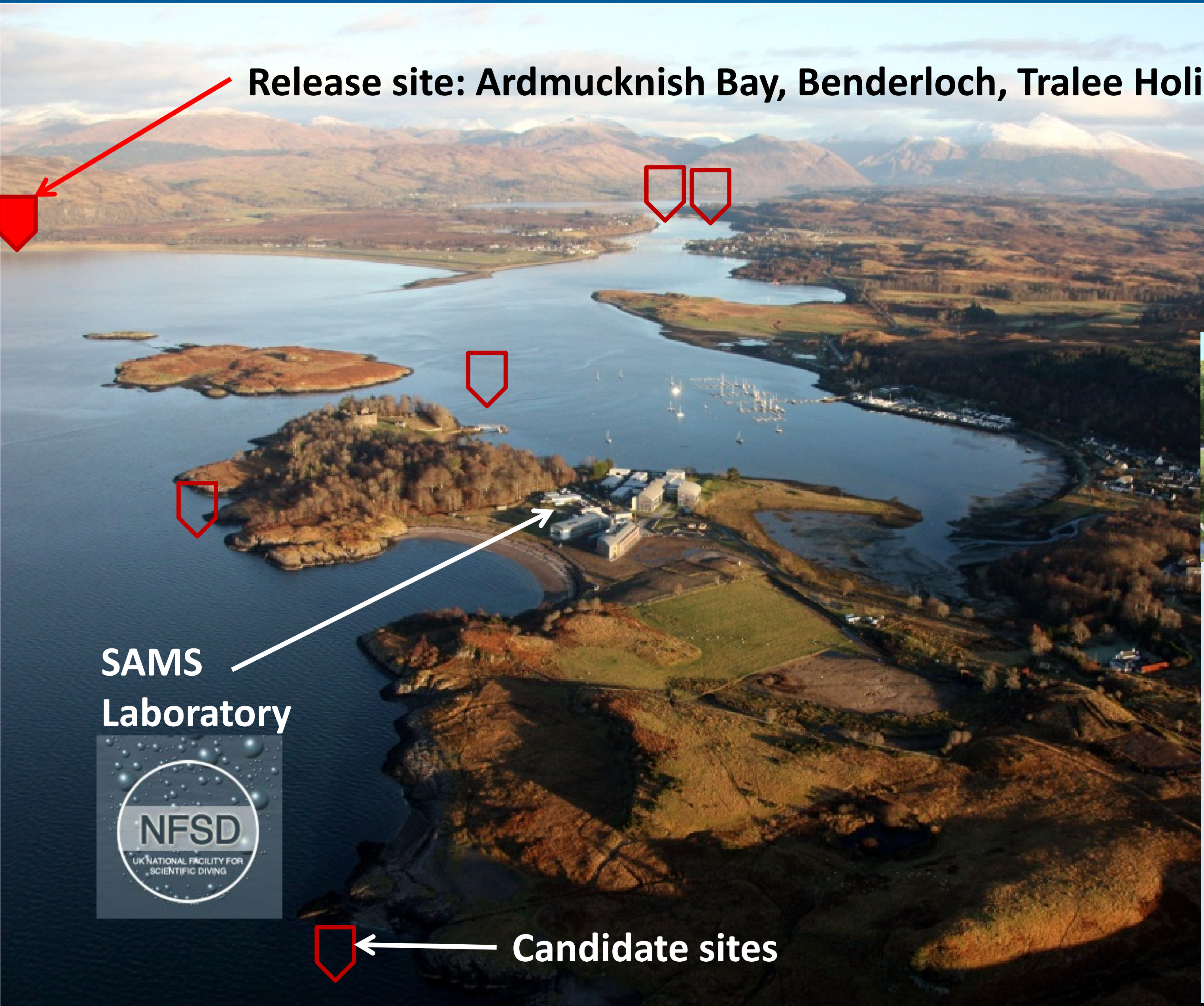
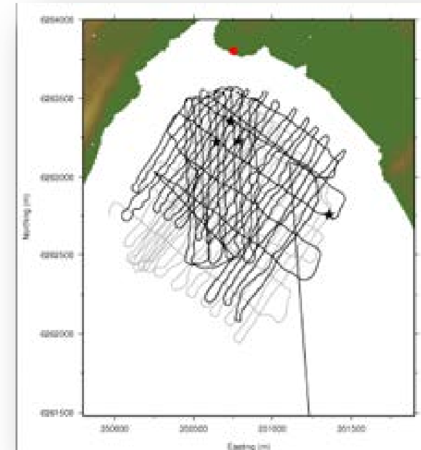
Site selection

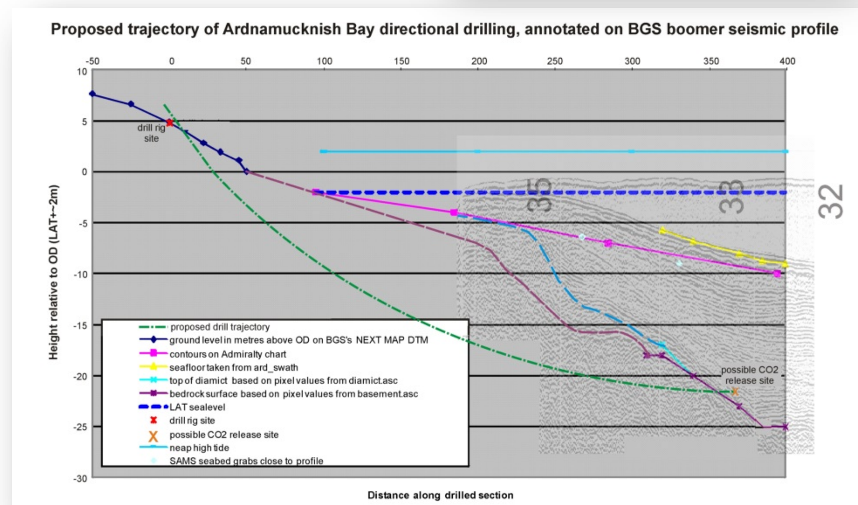


Site Characterisation involved:

Geophysical surveys

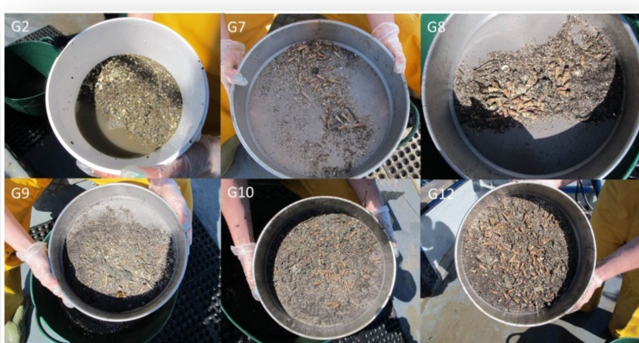
- to characterise the bed rock – required unfaulted geology to de-risk drilling, no glacial till
- characterise the sediments – ensure no gas deposits, appropriate depth of unconsolidated sediments
- required significant seismic surveys





Benthic surveys

- to characterise the sediment composition and community structure



Hydrodynamic surveys

- to characterise flow regimes

Permission and consent

Project proposal stage:

Contacted regulators (Marine Scotland and The Crown Estate), for informal support.

After project funding award: staged, local first approach

1. Identified the preferred site
2. Formal permission from regulators
3. Approached land owners and immediate users, obtained consent

1. Approached local council
2. Pro-actively engaged local newspapers
3. Pro-actively engaged local population
4. Regional media
5. National media

Ongoing

- Clearly stated project independence
- Maintained facebook page
- 24/7 presence at release site with public information including open day
- Engaged local schools
- Developed a stakeholder group

Firth of Lorne to host carbon capture project

'Argyll demonstrates that this part of the world makes important contributions to research that matters'

ARDMUCKNISH Bay, near Benderloch will host a leading research project into the safety of Carbon Capture and Storage (CCS) techniques next spring.

Dr Henrik Stahl, a scientist at the Scottish Marine Institute (SAMS) at Dunstaffnage, is leading the project which will investigate possible issues relating to carbon dioxide storage in sub-seabed reservoirs.

An information evening will be held for the public in Benderloch next month to discuss the project in more detail and answer any questions.

CCS is favoured by a growing number of governments as a clean method of reducing carbon dioxide emissions by storing it underground. While the technology for CCS is more or less in place, little research has been done into the success or safety of the technique.

Dr Stahl and his team hope to examine just how sound the theory behind CCS is by replicating in miniature what happens in the event of a leak in a marine environment.

As well as looking at how the eco-system is initially impacted, the team will study how quickly it recovers.

Dr Stahl said: 'It is critical to understand the impacts from potential carbon dioxide leaks and how best to monitor CCS sites, as little is known about what will happen to marine life around a potential leak of carbon dioxide from a CCS reservoir.

'Our project will investigate the nature and environmental impacts of carbon dioxide leaks that could develop at CCS storage sites.

"It is critical to understand the impacts of potential carbon dioxide leaks."
Dr Henrik Stahl

'We will also use the experiment to test various methods of monitoring and discovering potential carbon dioxide leaks from a CCS reservoir.

'Our work will provide important information on operational and risk assessment procedures for any future CCS installation.'

Impacts on conservation, recreational and fishery activities in the area will be 'minimal,' he added.

Professor Laurence Mee, director of SAMS, said: 'Together with visiting experts from as far as Japan, Henrik's team of scientists will be addressing some really big issues with this research and are exploring possible solutions to the climate change challenge.

'Conducting this work in Argyll once again demonstrates that this part of the world makes important contributions to research that matters.'

Residents can find out more at the Victory Hall, Benderloch at 7.30pm, Thursday, December 8.

Communications and outreach

Stakeholder Group

Included

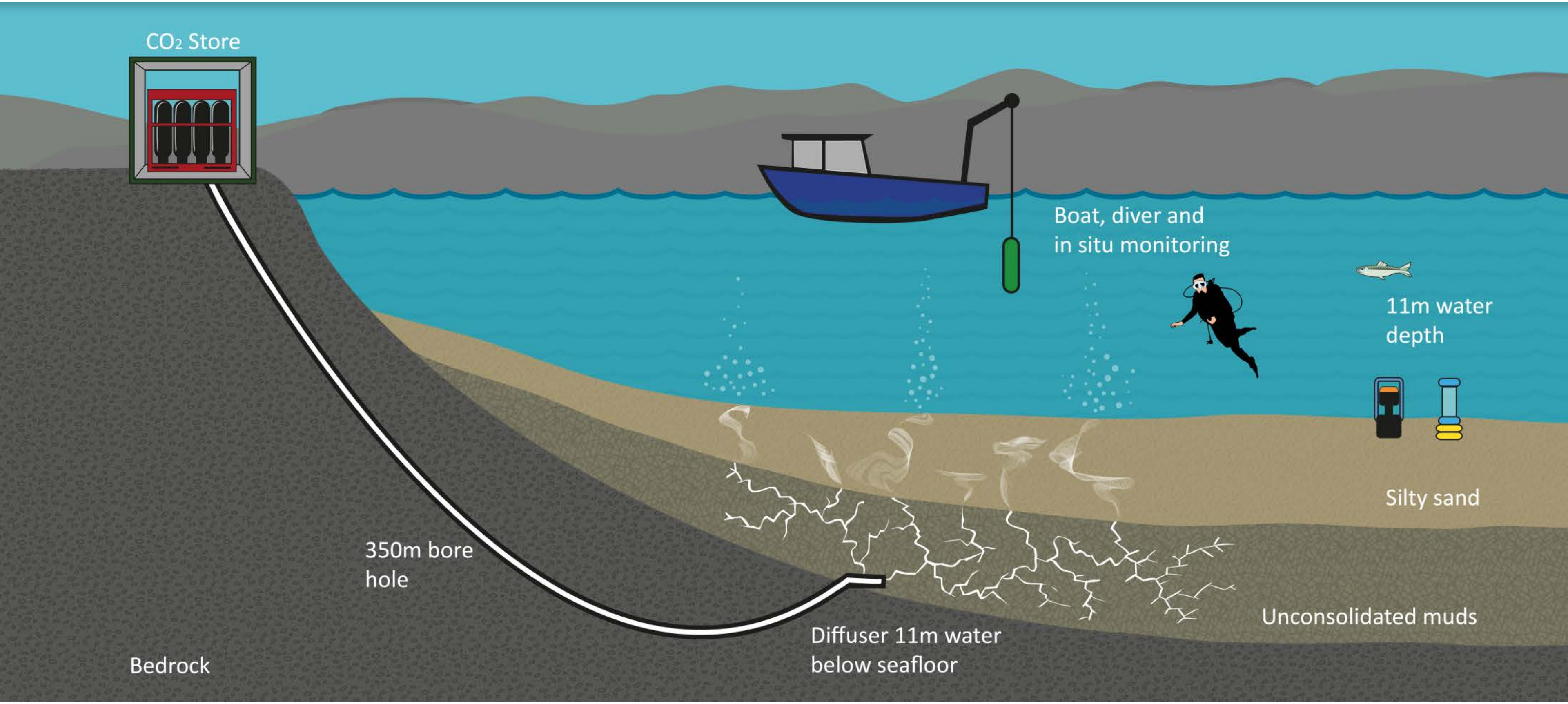
Those interested in the conduct of the experiment

Those interested in the outcomes of the experiment

Government & departments **Regulators** **Local planning authorities**
Oil & Gas companies **Power generators**
Environmental NGOs **Public**

Scottish Environment Protection Agency	EON
Marine Scotland	Scottish & Southern Energy
The Crown Estate	BP
Marine Management Organisation	Shell
Scottish Natural Heritage	Argyll and Bute Council
IUCN	Scottish Shellfish Growers Association
Wildlife & Country Link	Scottish Association of Marine Science
Greenpeace	Local community

Experimental Process



Animated procedure can be seen at www.qics.co.uk

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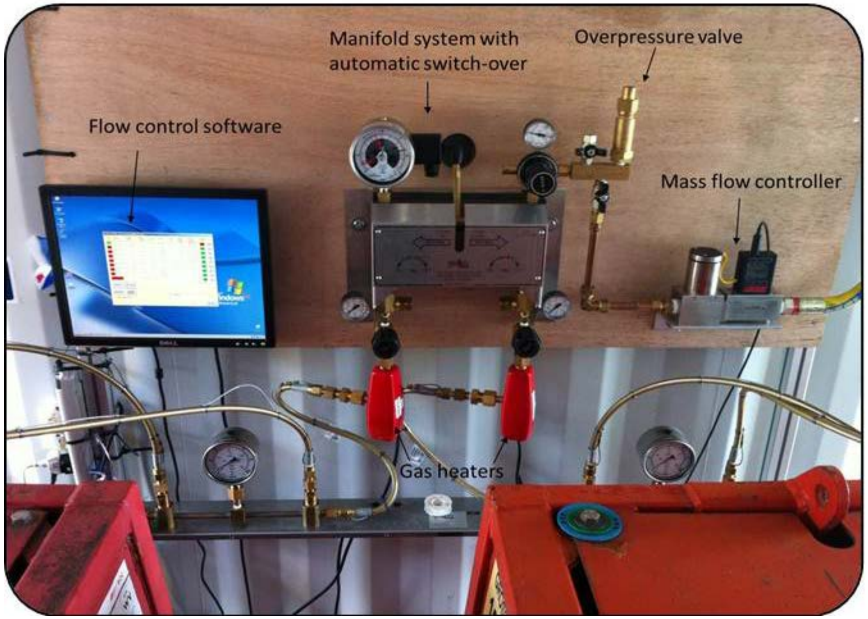
Drilling operations

Onshore laboratory



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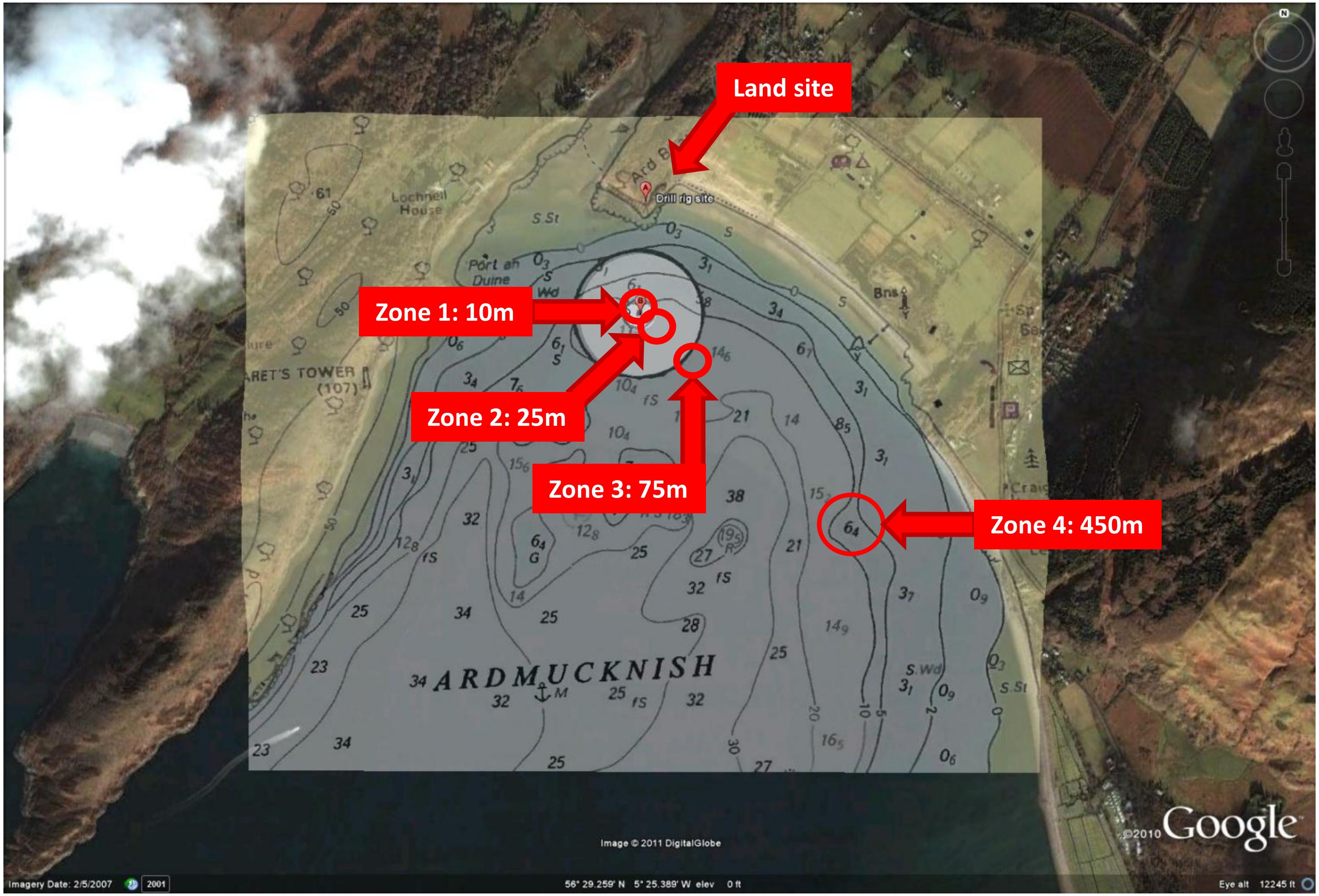
Sampling strategy



May | Pre release | Injection | Recovery | Sept

P-14 P-7 D7 D14 D35 R7 R30 R90

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Observations and sampling

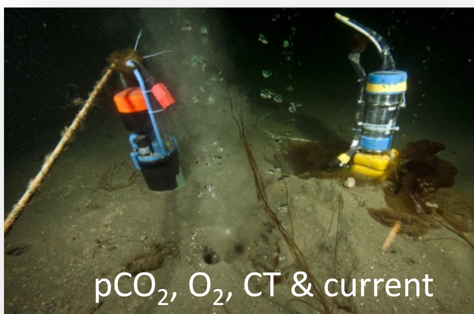
Diving surveys & sampling: >260 individual dives

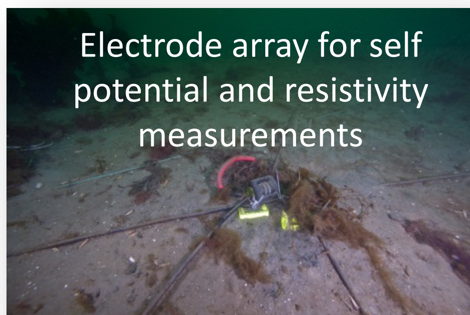

>650 individual cores collected

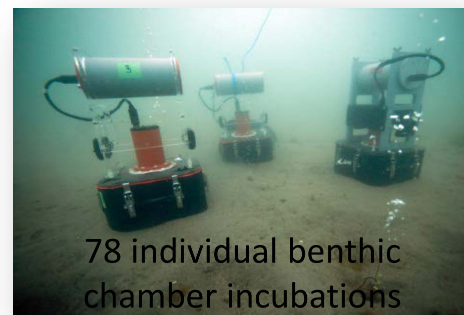

>300 water samples taken


24 mussel cages deployed

In situ sensors & measurements

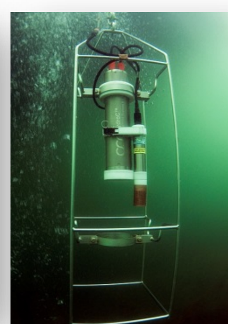

pCO_2, O_2, CT & current

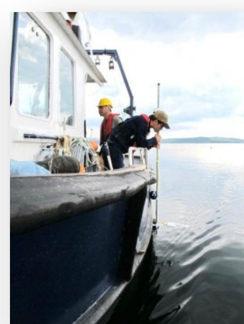

Electrode array for self potential and resistivity measurements


78 individual benthic chamber incubations

Ship-board measurements


Geophysics





Injection

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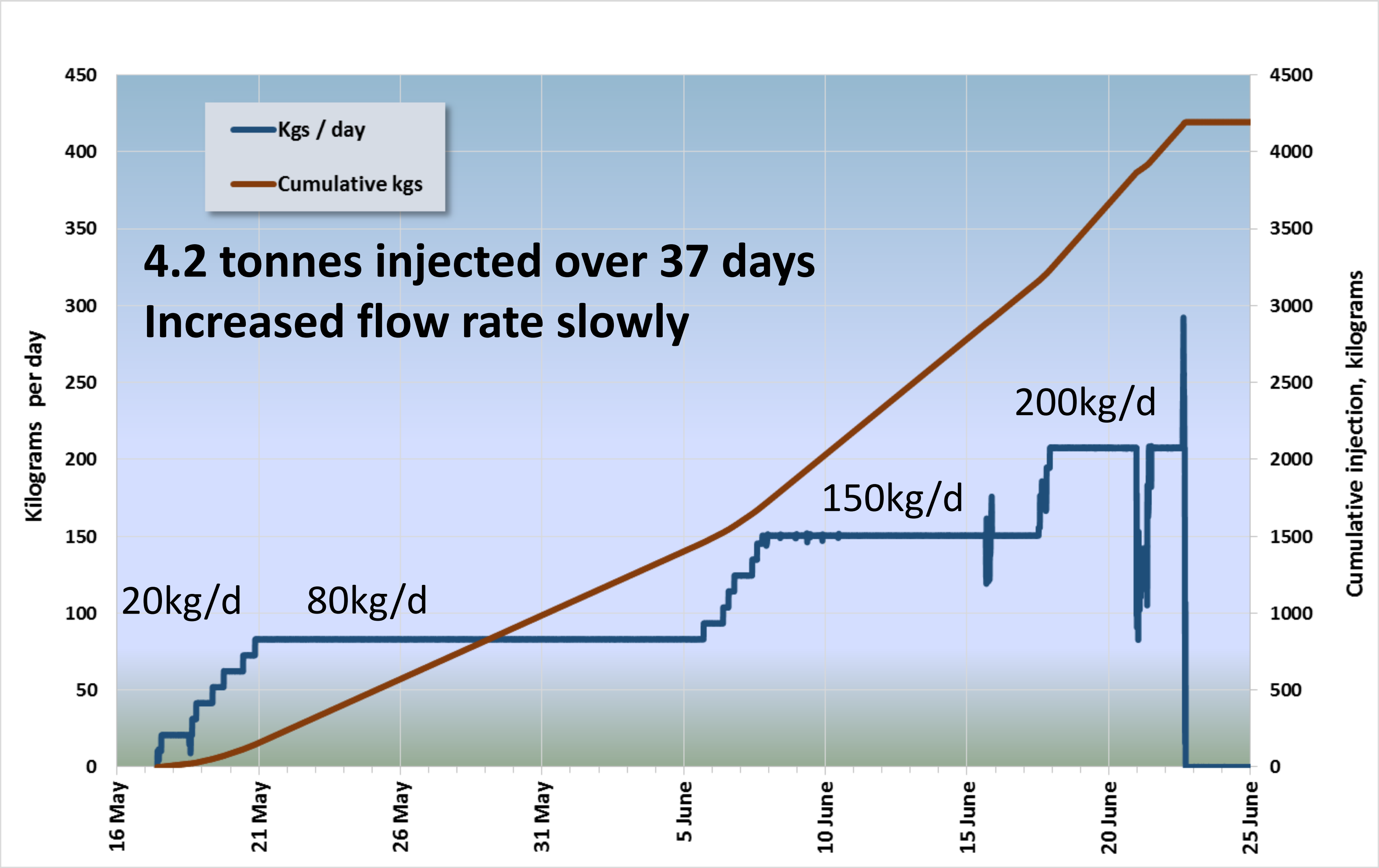

~ abandoned well bore scenario

Injection outcomes

Video clip of CO_2 gas emission at epicentre

please see www.qics.co.uk

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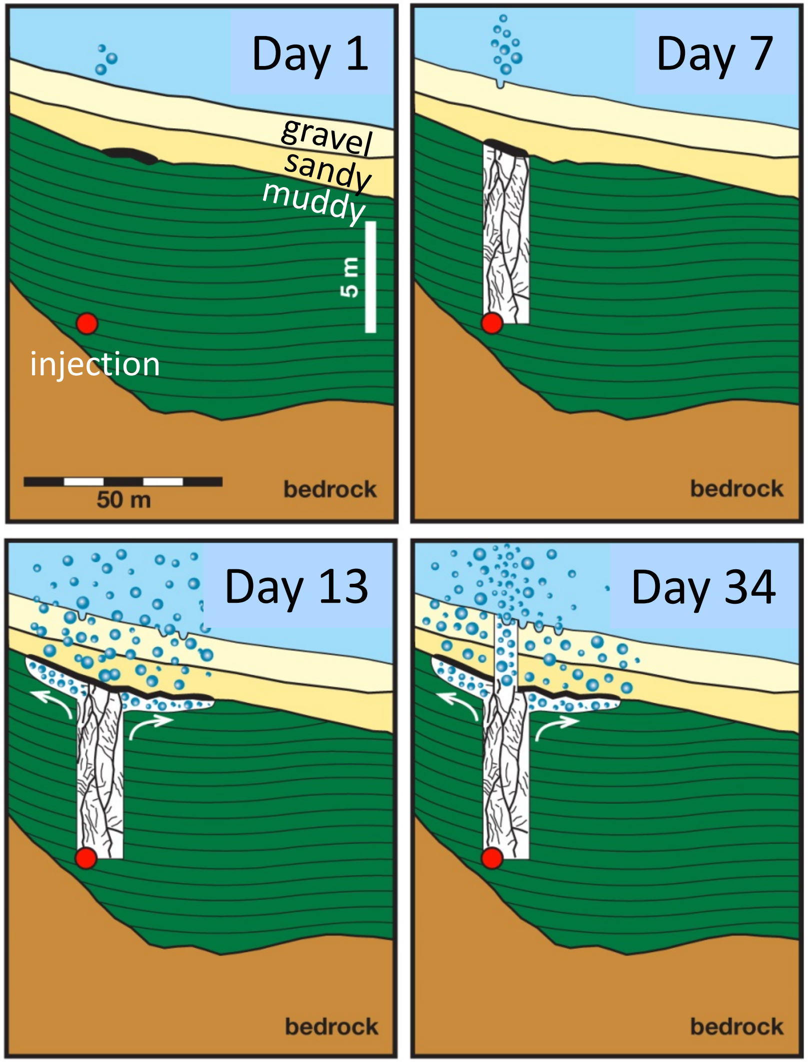
Seismic imaging of sediment gas

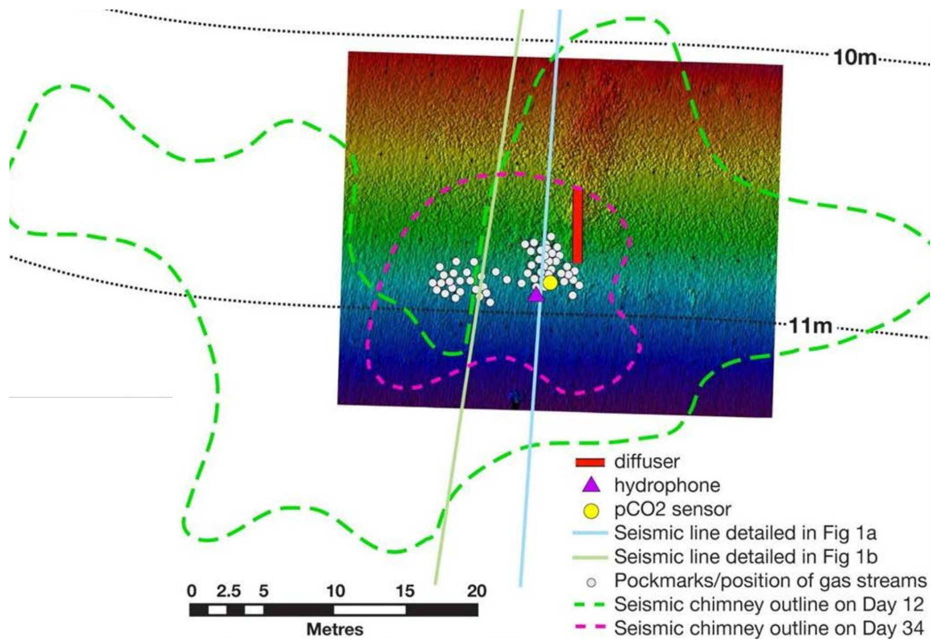


Day 1: Gas propagation via pre-existent pathways.

Day 7: Clear chimney in muddy sediments, only.

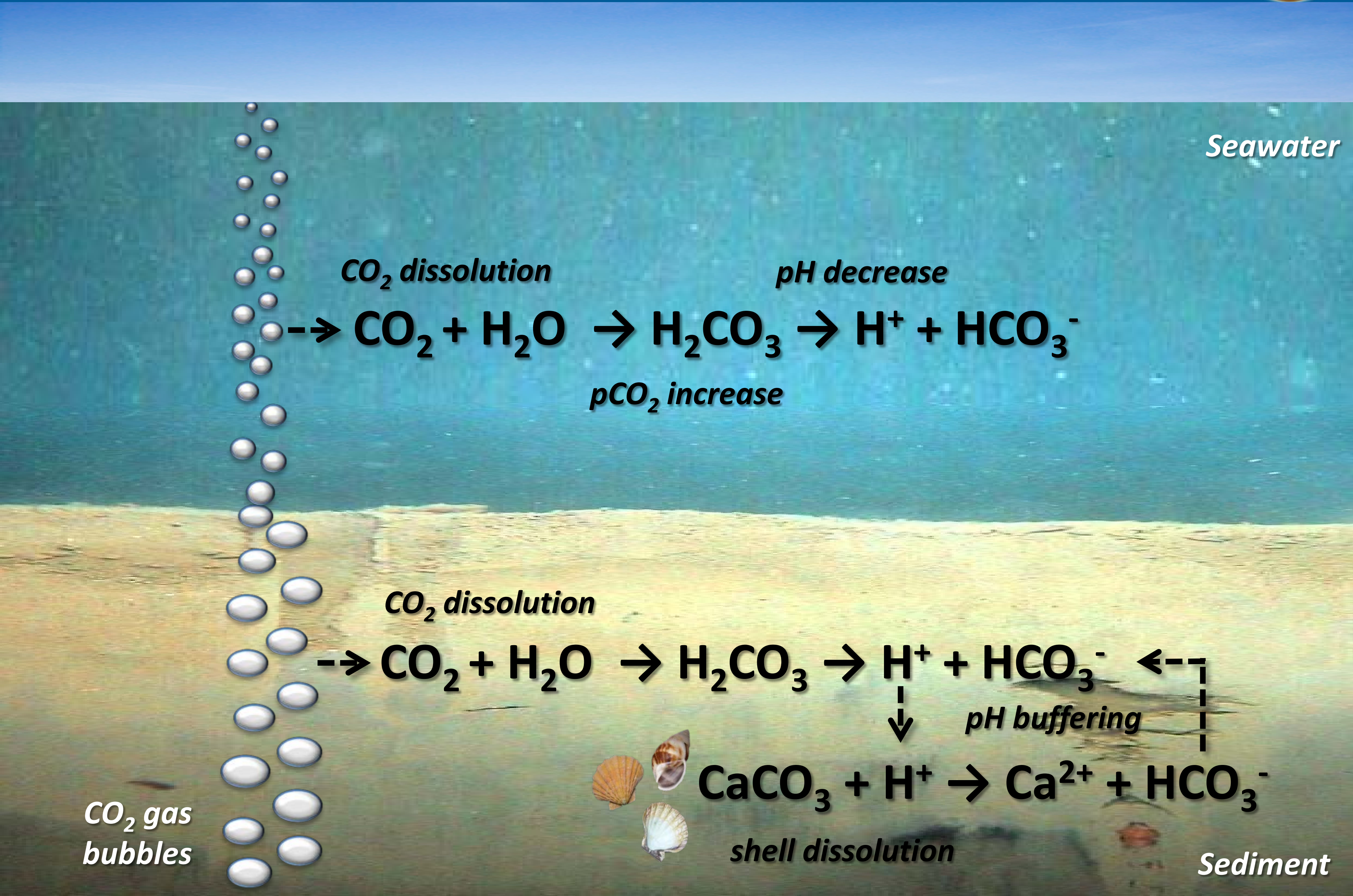
Day 13: Area of reflectivity increased.

Day 34: Narrower chimney from diffuser to surface. Vigorous venting into water column



Seismic reflectance can "see" gas above a threshold. Flow mechanisms are complex
Flow became more focussed as chimneys developed through the sediment structure

Gas flow model & chemistry



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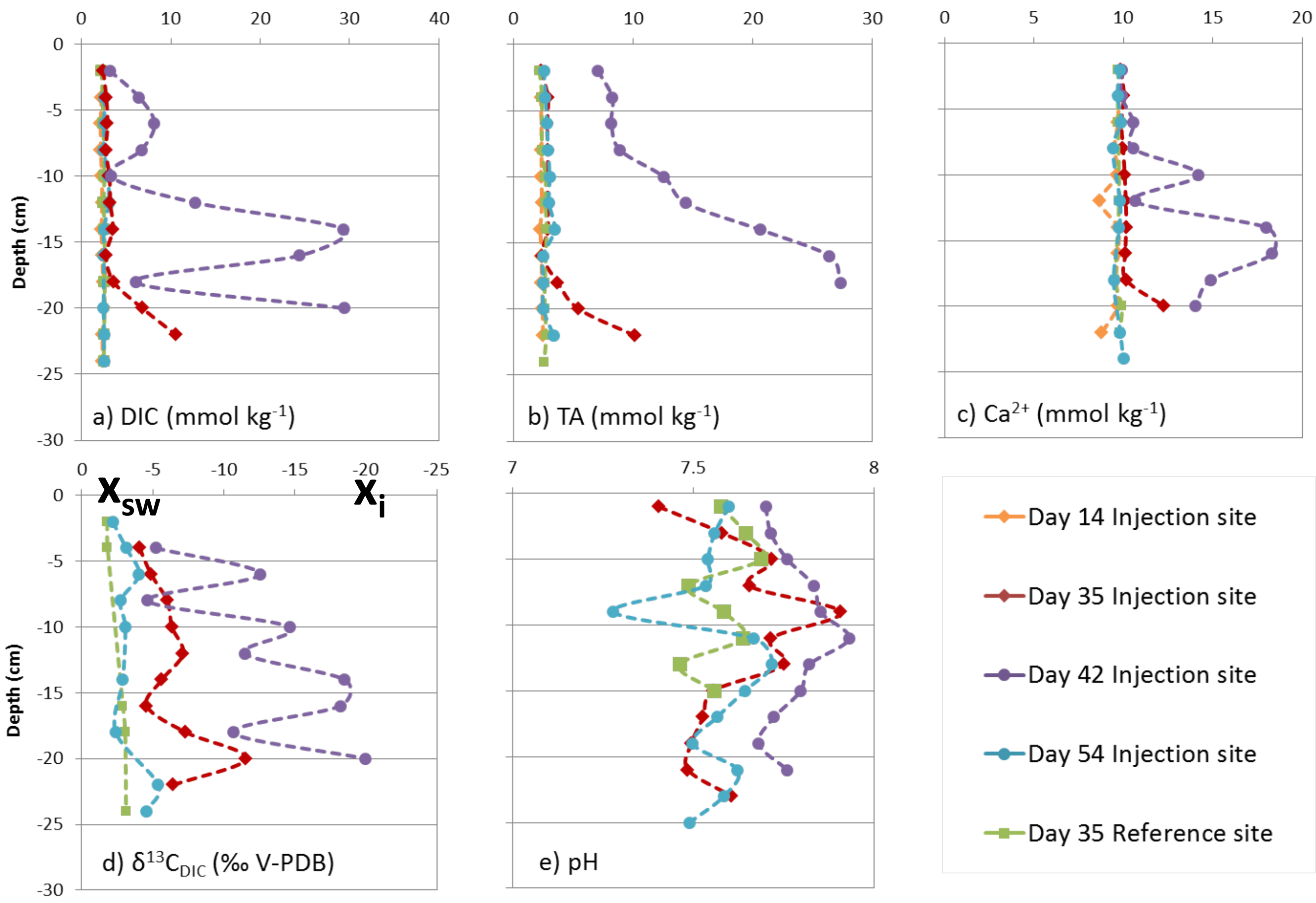
Sediment chemistry

Top 25 cm of sediment……..



- Strong evidence for buffering
- Change in pH is limited, even reversed
- Carbon isotopic composition is a clear indicator of source ($x_{sw} \approx 2$ / $x_i \approx 20$)

Sediment chemistry

Some evidence for mobilisation of heavy metals, but not to the extent of exceeding environmental impact thresholds

Table 6
Concentrations of metals in sediments collected from Zone 1 on D13/D14, D42/D43 and D53/D54. Data are given as the average (±standard deviation) of all samples collected from the upper 18 cm of each core. Data for North Sea sediments are from Stevenson (2001), sediment quality guideline values are from Long et al. (1995), and metal concentrations in North Sea drill cuttings are from Breuer et al. (2004). LOD = limit of detection, bd = below detection limit, nd = not determined.

	As (ppm)	Ba (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Ni (ppm)	Pb (ppm)	V (ppm)	Zn (ppm)
Zone 1 D13/D14	bd (LOD = 2)	668 (13)	5 (±0)	11 (±3)	2 (±1)	bd (LOD = 2)	16 (±1)	45 (±3)	39 (± 3)
Zone 1 D42/D43	bd (LOD = 2)	674 (15)	5 (±0)	14 (±7)	3 (±1)	bd (LOD = 2)	16 (±1)	46 (±3)	37 (± 2)
Zone 1 D53/D54	bd (LOD = 2)	660 (19)	5 (±0)	12 (±4)	1 (±1)	bd (LOD = 2)	15 (±1)	44 (±2)	41 (± 2)
North Sea *muddy sediments*	nd	442	9	73	13	32	23	34	82
North Sea *sandy sediments*	nd	335	5	34	3	13	14	19	25
Guideline values									
Rarely associated with effects	<8.2	nd	nd	<81	<34	<20.9	<46.7	nd	<150
Occasionally associated with effects	8.2–70	nd	nd	81–370	34–270	20.9–51.6	46.7–218	nd	150–410
Frequently associated with effect	>70	nd	nd	>370	>270	>51.6	>218	nd	>410
North Sea drill cuttings	nd	22600	nd	426	374	137	4790	523	2510

Lichtschlag et al, IJGGC

Sea floor flux, bubble acoustics

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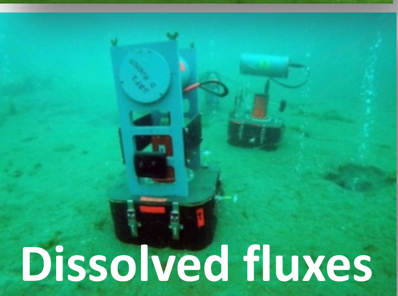
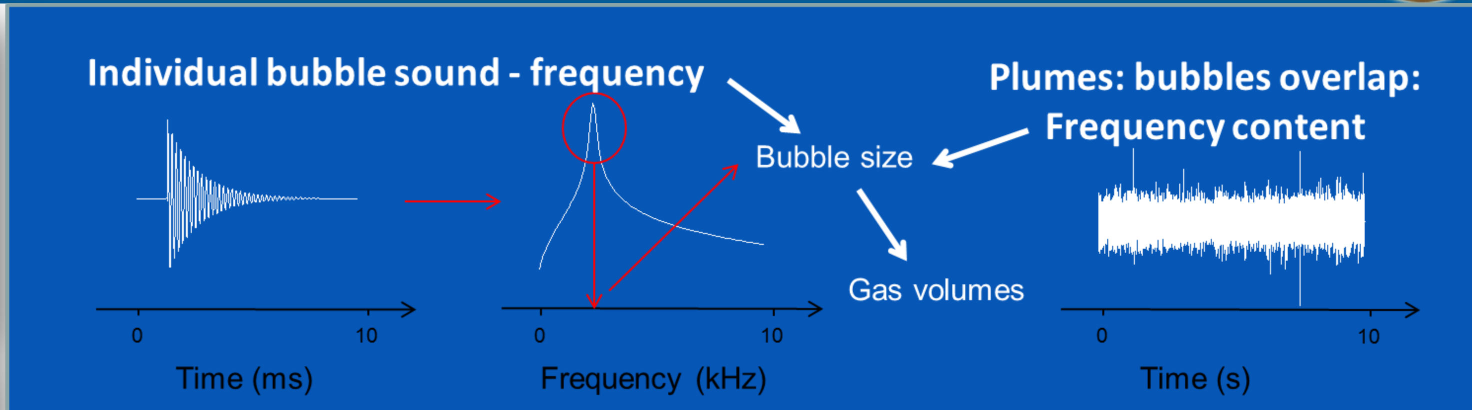
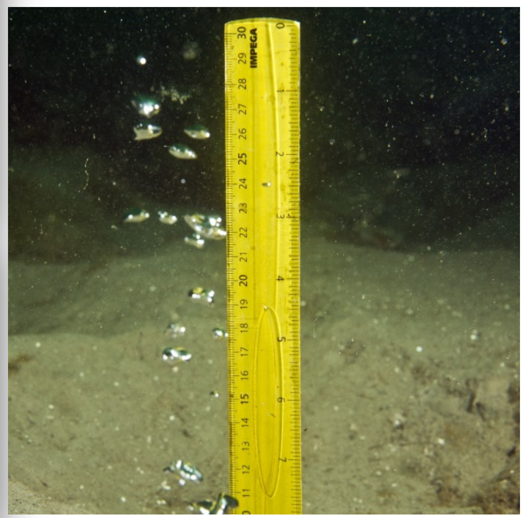
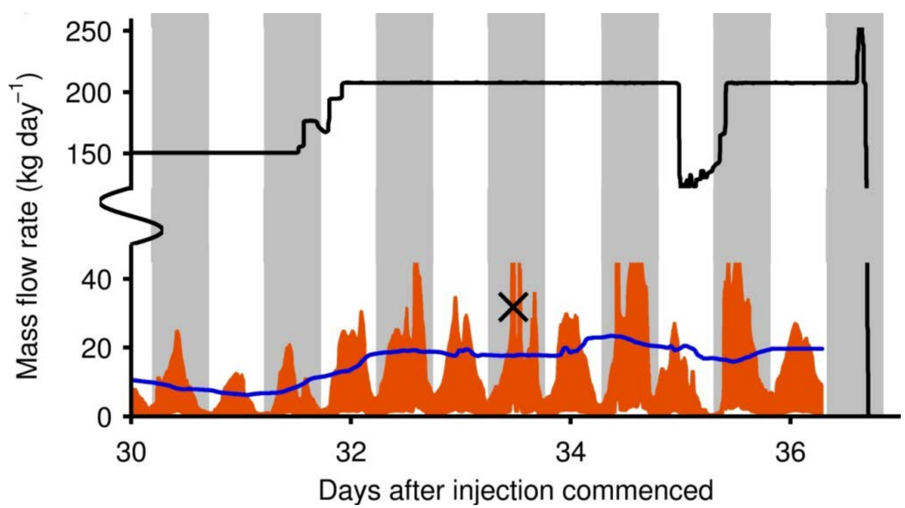




[1] T. G. Leighton and P. R. White. Proceedings of the Royal Society A., vol 468, pp 485-510 (2011)





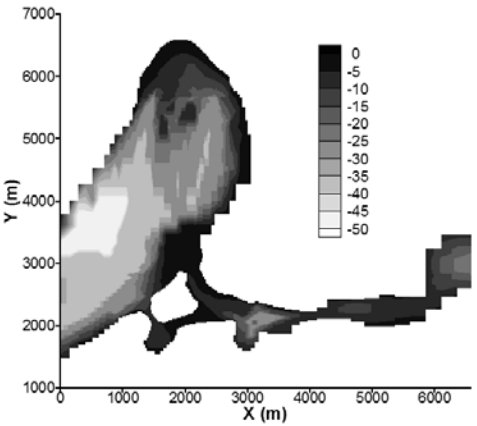
- Measurements showed no dissolved fluxes across the seabed*
- Acoustic detection and quantification – proof of concept
- Gas flow was heavily influenced by the tidal state.
- 8-15% of injected CO_2 was emitted at the sea floor in bubble form

Quantification using models

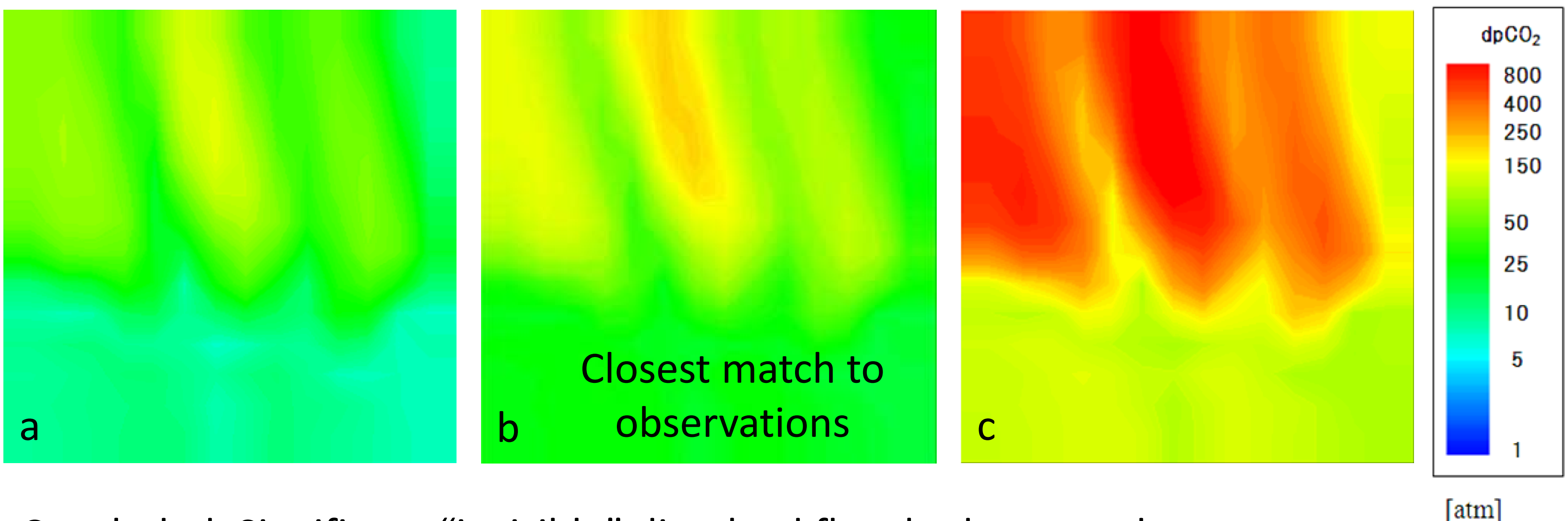
Mori, Sato et al, IJGGC

Modelled scenarios of sea floor flux in Ardmucknish Bay

Can observed pCO2 be explained by only gas bubble flow?

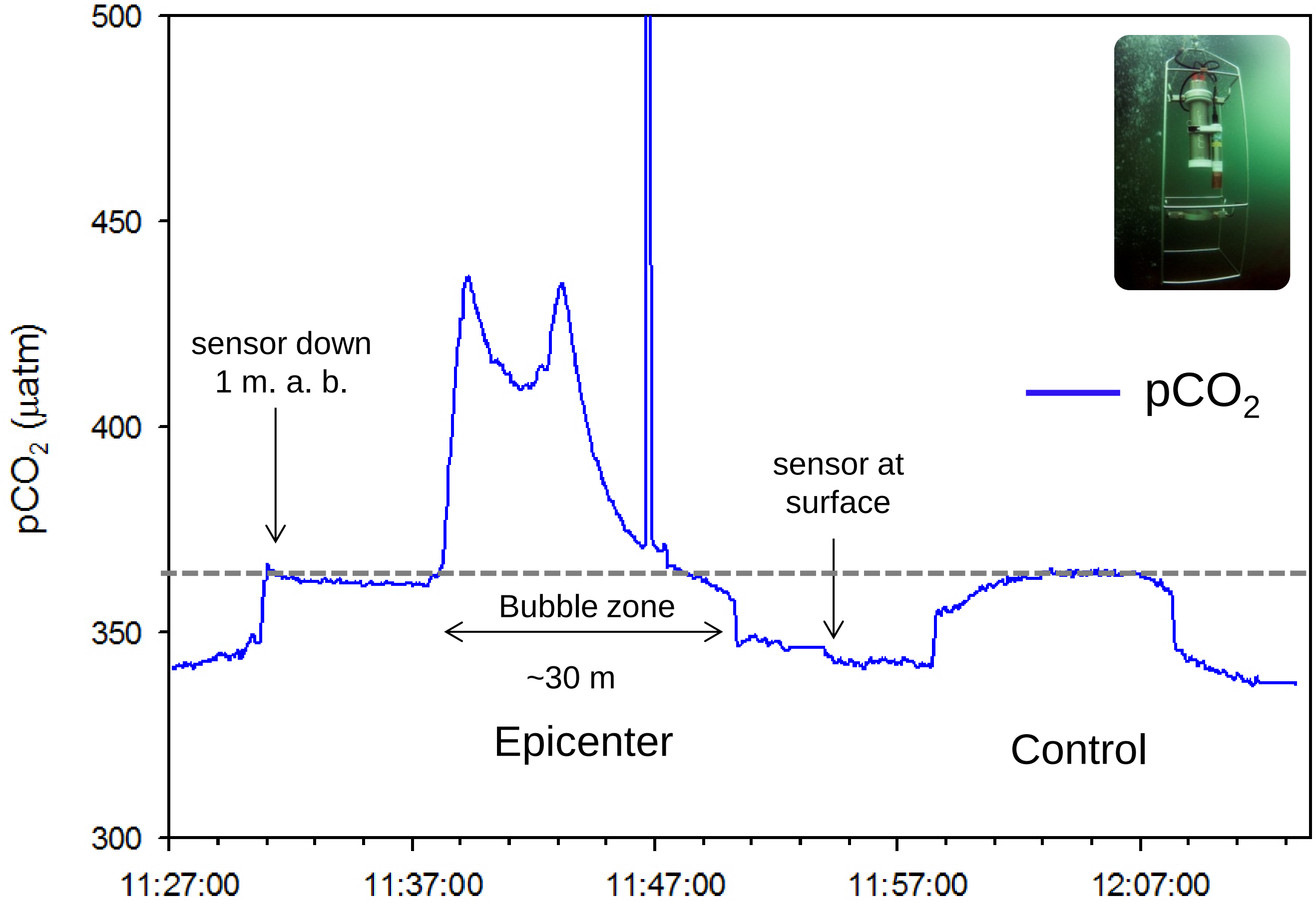


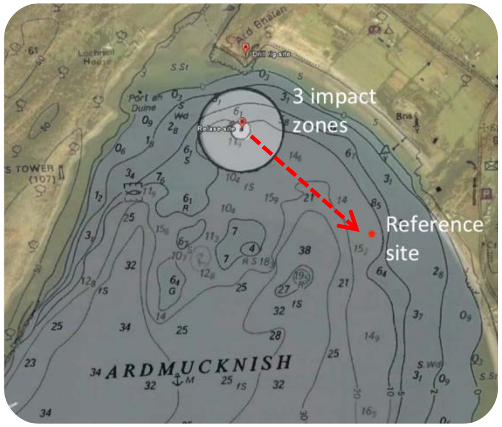
Case	Gas %	Dissolved %	Remaining %
A	8	17	75
B	8	42	50
C	8	67	25

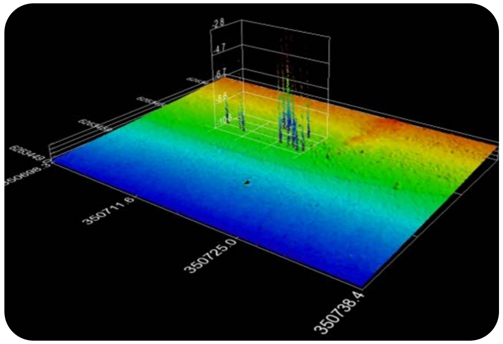


Concluded: Significant "invisible" dissolved flow had occurred.

How far did the CO_2 plume spread?

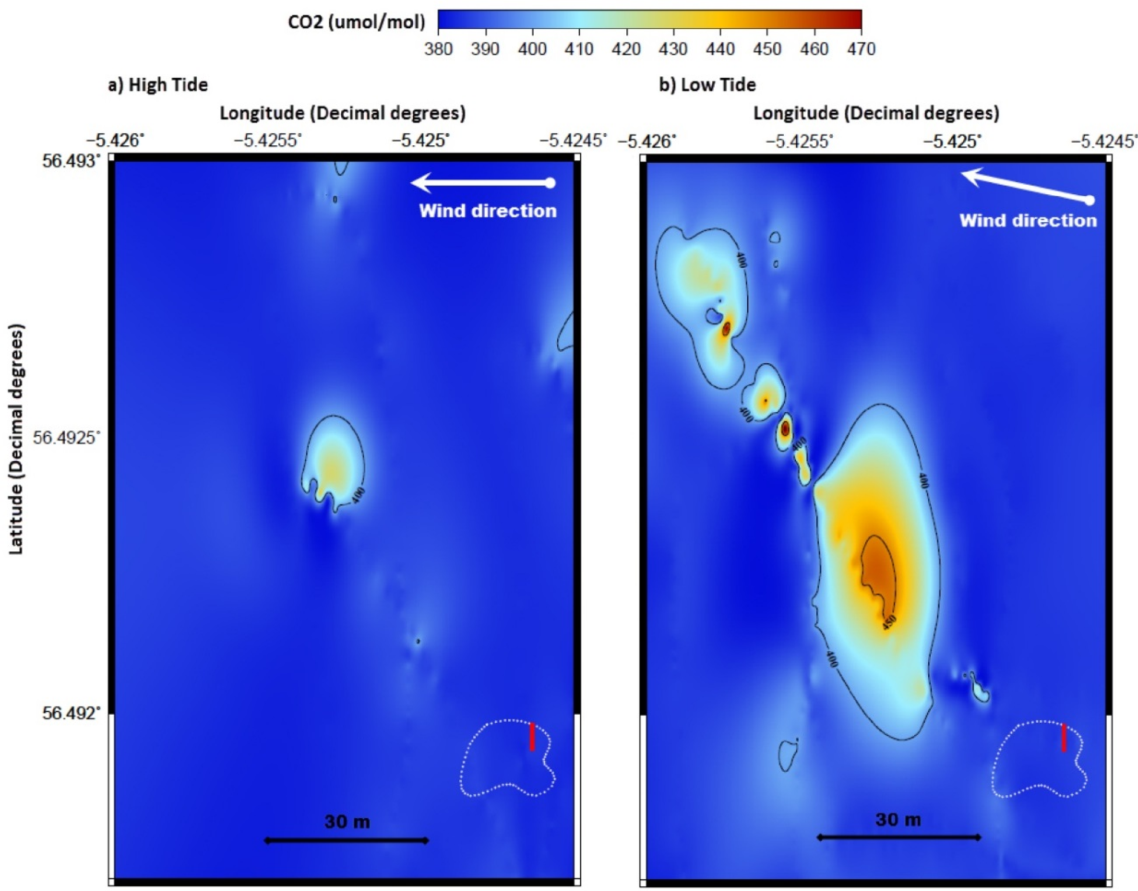






Elevated CO_2 concentrations in bottom water <u>confined to release epicentre</u>

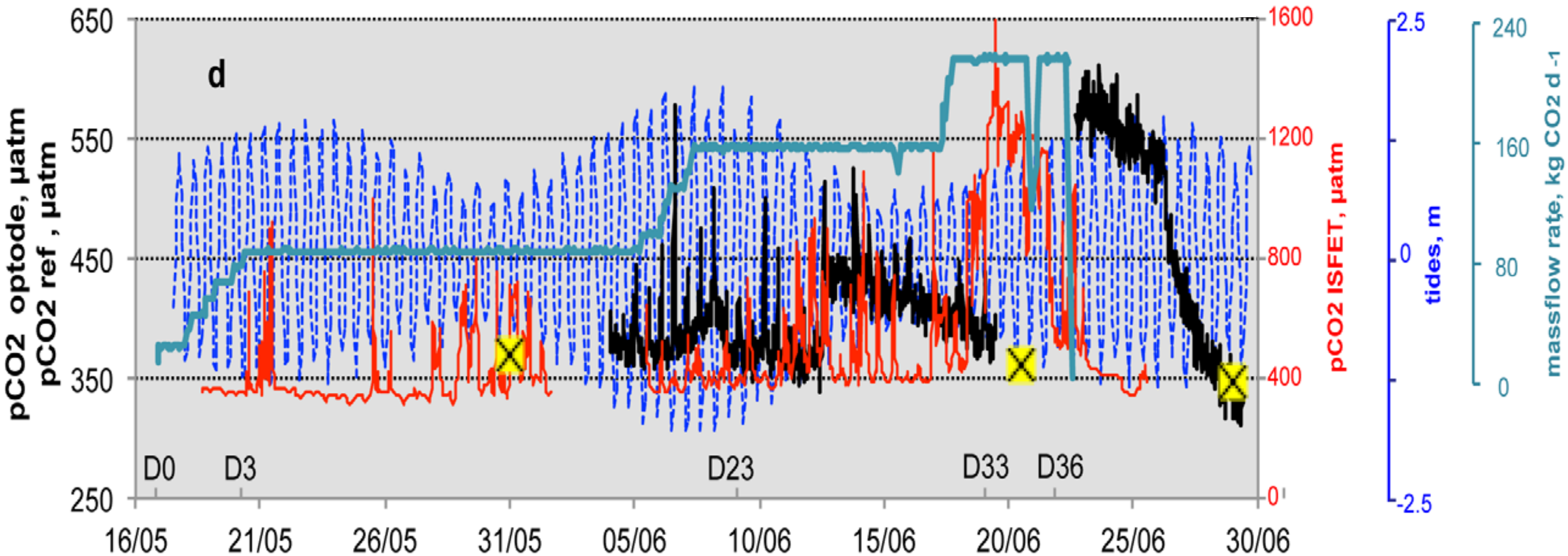
How high did the CO_2 plume reach in the water column?

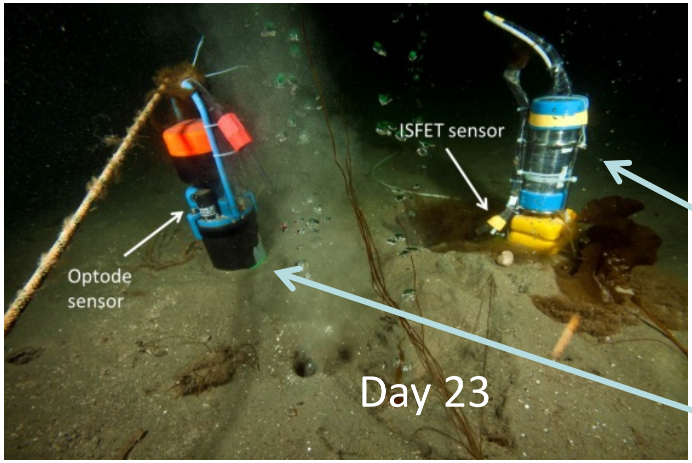


- CO_2 bubbles visible all the way to surface during low tide
- Elevated concentrations of CO_2 ~50cm above sea-surface

Water column dispersion

Small scale heterogeneity in observed pCO_2





Measuring CO_2 via pH/pCO_2 can be very dependent on sensor positioning:

ISFET sensor ~ 3cm from seabed

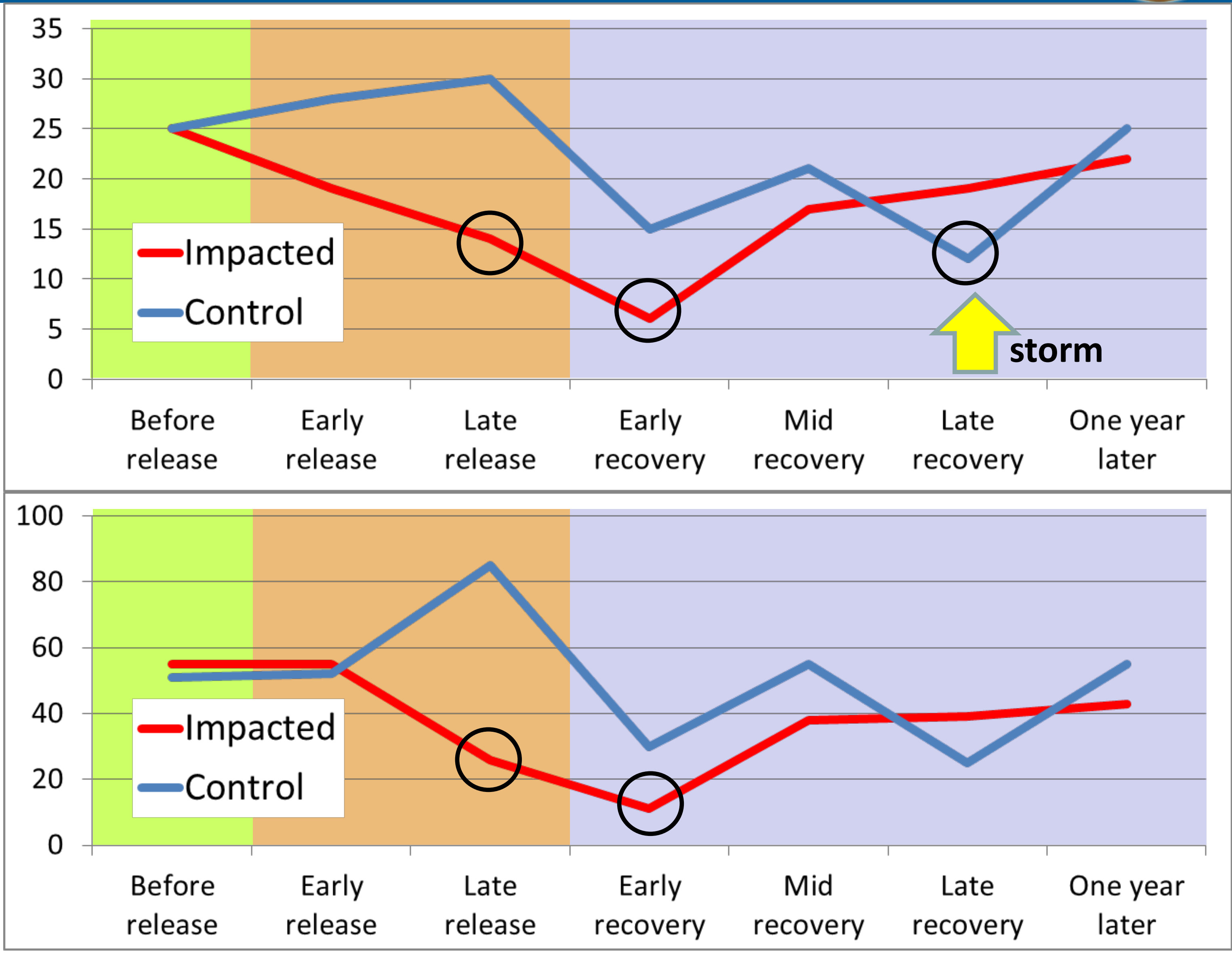
1 meter apart

Optode sensor ~25cm from seabed

Biological impacts - macrofauna

Number of Species - Biodiversity

Number of Individuals – Mortality / Emigration



Impacts only at the release site, recovery within ~3 weeks

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Biological impacts, mega and micro fauna.

Megafauna

- No evidence for impacts to the molecular ecophysiology of ion or CO_2 regulation in tissues of surface-dwelling bivalves in the vicinity of a sub-seabed CO_2 release
  Mytilus edulis, Pecten maximus
- No discernible abnormal behaviour was observed for megafauna, in any of the zones investigated, during or after the CO_2 release. Virgularia mirabilis (Cnidaria), Turritellacommunis (Mollusca), Asterias rubens (Echinodermata), Pagurus bernhardus (Crustacea), Liocarcinus depu-rator (Crustacea), and Gadus morhua (Osteichthyes).

Microbes

- A temporary impact on both the abundance and activity of specific microbial groups at the epi centre and 25m distant. Seasonality was the major factor with only minor affects from CO_2. This included a small increase in ammonia oxidation linked to an increase in ammonia availability as a result of mineral dissolution.

Proviso

Small short term leak with significant sediment buffering

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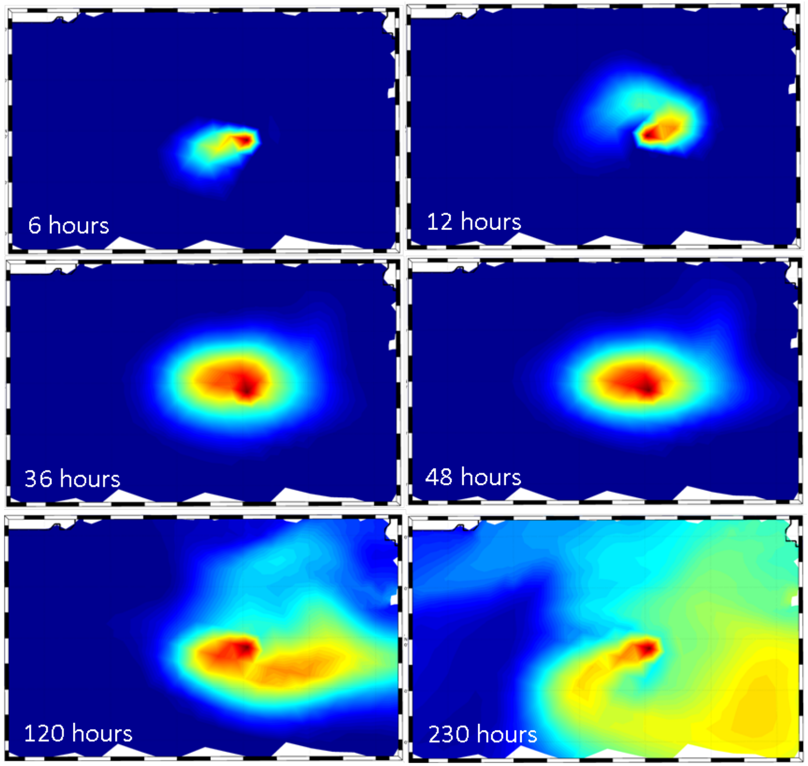
Dispersion and upscaling

Observations + modelling exercises looking at leaks from 0.0001 to 10000 tonnes / day

- Impacted area scales with flux, order of magnitude variability for leaks of the same magnitude.
- Impacted area is restricted.
- Strong tidal mixing ensures rapid dispersion and mitigates extreme impacts.
- Large difference between spring and neap tides, complex and dynamic footprints.
- Chemical recovery in the water column once leakage has stopped is rapid. Hours to few weeks.



Monitoring techniques, pros and cons

Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage

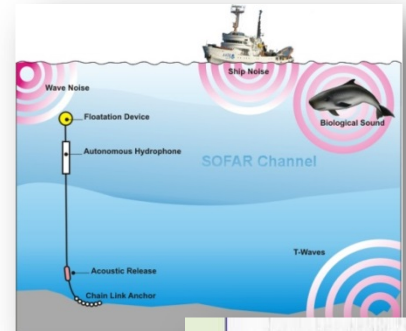
No single monitoring technique is sufficient:
Trade off between detection range / survey resolution / power consumption / deployment time / areal coverage

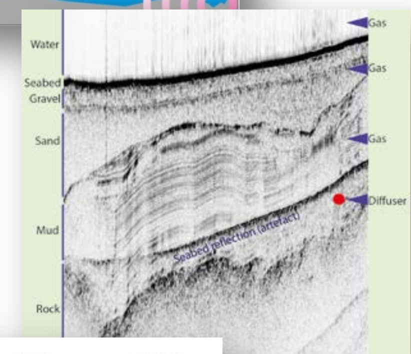
Passive acoustics: Listening for bubbles (if they exist)
Low power, needs high resolution
Detection and quantification
Shelf seas are acoustically complex

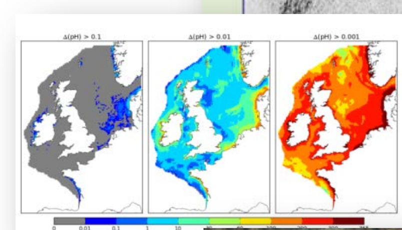
Active acoustics: Detecting gas plumes in sediments and water
Power hungry, require less resolution
Detection
Requires initial characterisation of area

Geochemistry: Sensors for pH and pCO_2 in water column
Low power
Detection, confirmation, quantification
Requires detailed characterisation baseline

Biological indicators: Video or direct sampling
Detection, mainly impact assessment
Requires detailed baseline and control, not automated

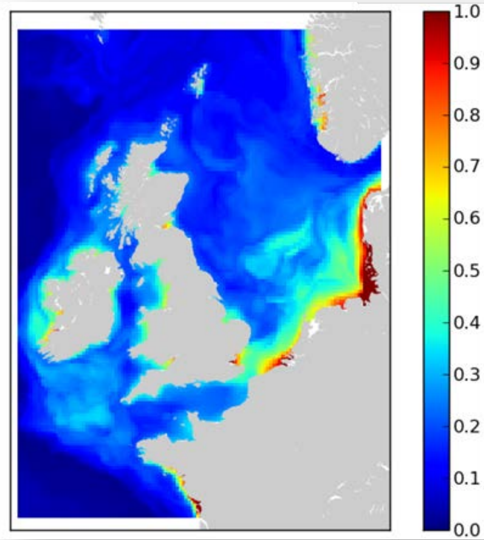




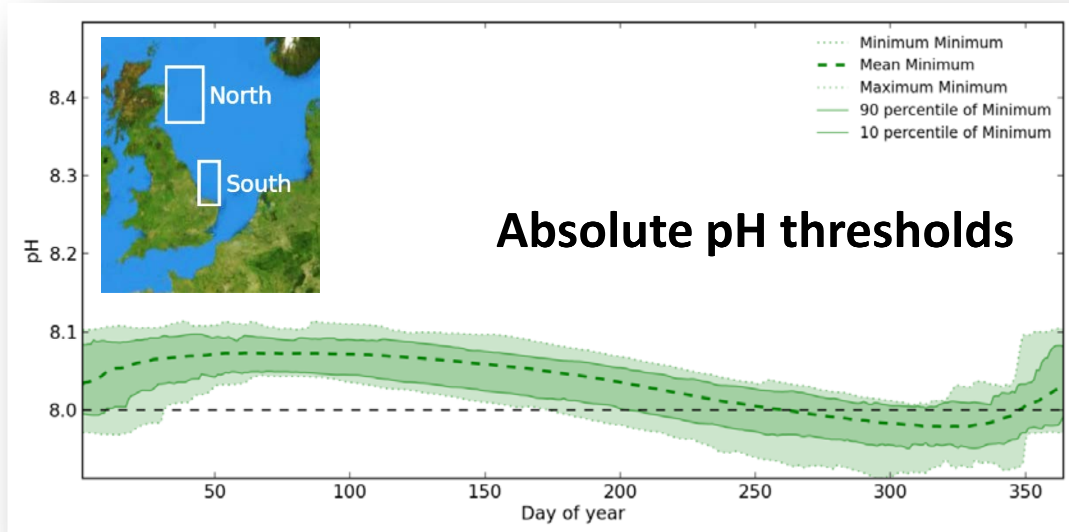


Modelling baselines

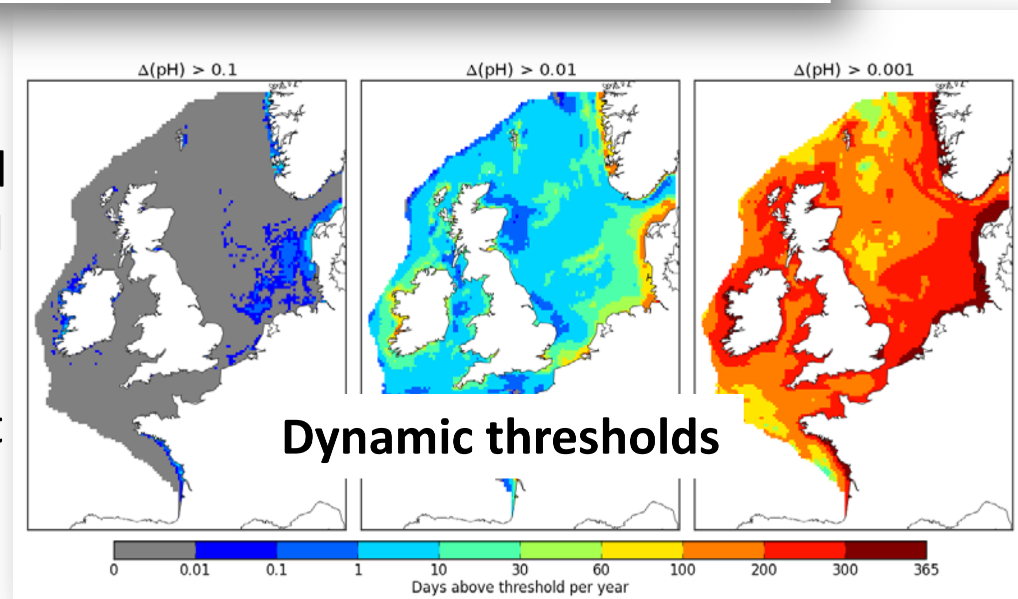
Insufficient observations: Using models to define biochemical baselines



Annual pH range, modelled



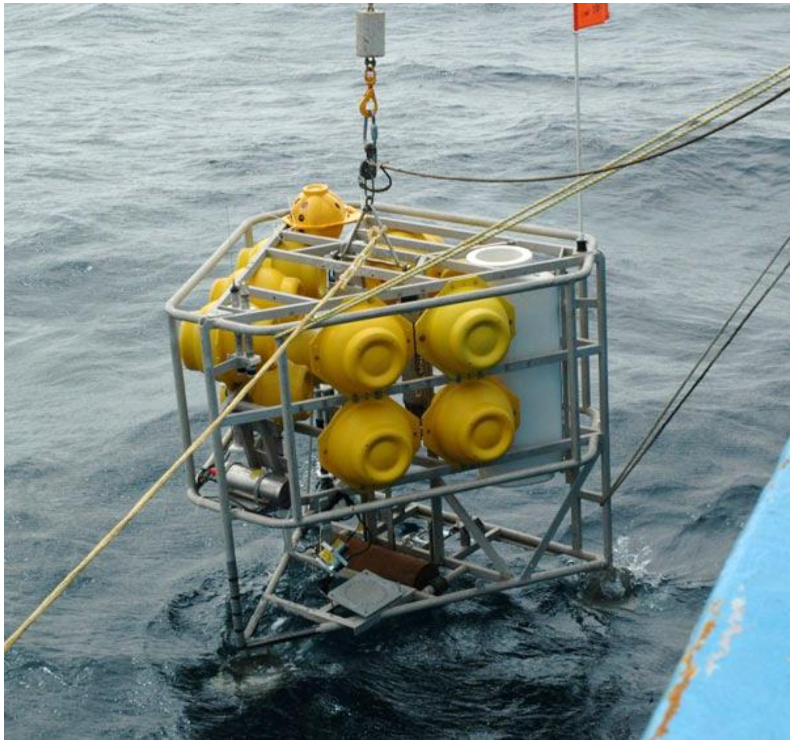
- pH chemistry is highly variable
- Requires baseline quantification and identification of absolute (fixed) and dynamic (rate of change) thresholds.
- Biochemical monitoring may benefit from co-measuring O_2, Nutrients and temperature to identify natural variability.

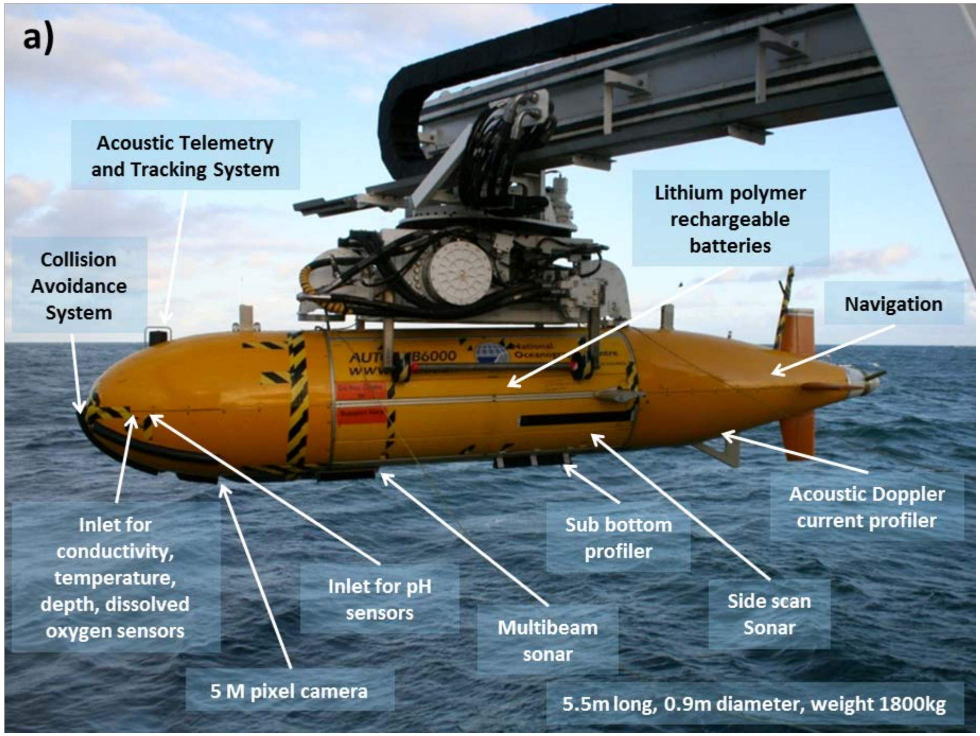


Monitoring platforms

Benthic landers:
For specific at risk locations
Deployment and data retrieval challenging
Vulnerable to trawling

Autonomous underway vehicles:
Cover large areas, 1-6 month deployment.
Data retrieval challenging





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Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage

Monitoring and baselines - approach

Monitoring strategy

1. Detect anomalies:

- Wide area surveys on AUVs / Site specific landers near "high-risk" sites
- pH / pCO_2 / bubble acoustics / active acoustics

2. Confirmation and attribution:

- Targeted sampling
- CO_2 assays, isotopic composition, tracers

3. Quantify leakage:

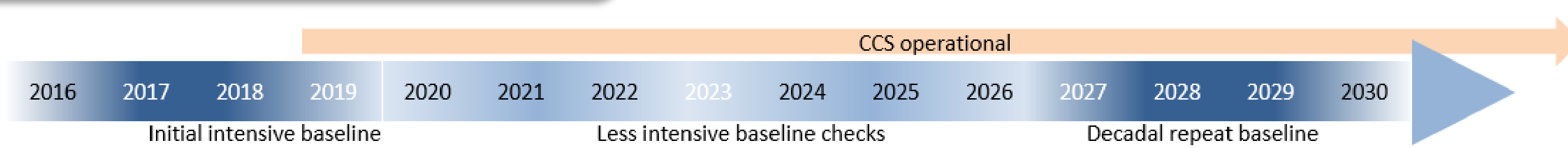
- Targeted sampling
- Bubble acoustics, benthic chambers

4. Assess impact:

- Targeted sampling
- Biological and biochemical surveys

Baseline strategy

Sampling frequency	Duration	Measurement
Hourly	Few days during main growing season	Carbonate chemistry Oxygen, Temperature Pressure, Salinity
Weekly	During main growing season preferably whole year	Carbonate chemistry Oxygen, Temperature Pressure, Salinity
Monthly	18 month period encompassing two summers	Acoustics Biological coring
Occasional	One or two surveys with a repeat after a few years	Geophysics Imaging



Summary

- Leaks can be detected but the target may be relatively small, dynamic and complex.
- There are no absolute indicators of leakage.
- Multiple monitoring methodologies in a staged approach are recommended.
- Comprehensive baseline data will be required.
- The impact of a small CO_2 leak is minimal and recovery rapid.
- Larger leaks could have more severe but still relatively local impacts.
- Quantification of leakage will be challenging.
- The emerging understanding synthesising footprint, impact and recovery implies that, augmented by thorough monitoring and baseline activities, impacts of CCS leakage should not be seen as an impediment to the development of full scale CCS.

Outputs

www.qics.co.uk

nature climate change

Detection and impacts of leakage from sub-seafloor deep geological carbon dioxide storage

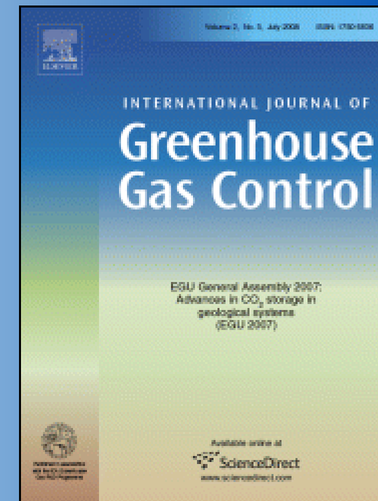
Jerry Blackford, Henrik Stahl, Jonathan M. Bull *et al.*†

http://dx.doi.org/10.1038/nclimate2381

Special issue

~20 research papers

~Feb 2015



Key findings

Video

Factsheets

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Outputs

1 **A novel sub-seabed CO_2 release experiment informing monitoring and impact assessment for geological carbon storage.**
Peter Taylor, Henrik Stahl, Mark E. Vardy, Jonathan M. Bull, Maxine Akhurst, Chris Hauton, Rachel H. James, Anna Lichtschlag, Dave Long, Dmitry Aleynik, Matthew Toberman, Mark Naylor, Douglas Connelly, Dave Smith, Martin D.J. Sayer, Steve Widdicombe, Ian C. Wright, Jerry Blackford. Doi:10.1016/j.ijggc.2014.09.007

2 **Marine baseline and monitoring strategies for Carbon Dioxide Capture and Storage (CCS)** .
Jerry Blackford, Jonathan M. Bull, Melis Cevatoglu, Douglas Connelly, Chris Hauton, Rachael H. James, Anna Lichtschlag, Henrik Stahl, Steve Widdicombe, Ian C. Wright. Doi:10.1016/j.ijggc.2014.10.004

3 **Modelling Large-Scale CO_2 Leakages in the North Sea.**
Phelps, J.J.C, Blackford, J.C., Holt, J.T., Polton, J.A. Doi:10.1016/j.ijggc.2014.10.013

4 **Dynamics of rising CO_2 bubble plumes in the QICS field experiment. Part 2 – Modelling.**
Dewar M., Sellami N., Chen B. Doi:10.1016/j.ijggc.2014.11.003

5 **Effect of a controlled sub-seabed release of CO_2 on the biogeochemistry of shallow marine sediments, their pore waters, and the overlying water column**
Lichtschlag A., James R.H. Stahl H., Connelly D. Doi:10.1016/j.ijggc.2014.10.008

6 **No evidence for impacts to the molecular ecophysiology of ion or CO_2 regulation in tissues of selected surface-dwelling bivalves in the vicinity of a sub-seabed CO_2 release.**
Pratt N., Ciotti B.J., Morgan E.A., Taylor P., Stahl H., Hauton C., Doi:10.1016/j.ijggc.2014.10.001

7 **Optical assessment of impact and recovery of sedimentary pH profiles in ocean acidification and carbon capture and storage research.**
Queirós A.M., Taylor P., Cowles A., Reynolds A., Widdicombe S., Stahl H. Doi:10.1016/j.ijggc.2014.10.018

8 **Impact and recovery of pH in marine sediments subject to a temporary carbon dioxide leak.**
Taylor, Peter, Lichtschlag, Anna, Toberman, Matthew, Sayer, Martin D.J., Reynolds, Andy, Sato, Toru and Stahl, Henrik Doi:10.1016/j.ijggc.2014.09.006.

9 **Detection of CO_2 leakage from a simulated sub-seabed storage site using three different types of pCO_2 sensors.**
Dariia Atamanchuk, Anders Tengberg, Dmitry Aleynik, Peer Fietzek, Kiminori Shitashima, Anna Lichtschlag, Per O.J. Hall, Henrik Stahl. Doi:10.1016/j.ijggc.2014.10.021

10 **Response of the ammonia oxidation activity of microorganisms in surface sediment to a controlled sub-seabed release of CO_2.**
Yuji Watanabe, Karen Tait, Simon Gregory, Masatoshi Hayashi, Akifumi Shimamoto, Peter Taylor, Henrik Stahl, Kay Green, Ikuo Yoshinaga, Yuichi Suwa, Jun Kita. Doi:10.1016/j.ijggc.2014.11.013

11 **Local perceptions of the QICS experimental offshore CO_2 release: Results from social science research.**
Leslie Mabon, Simon Shackley, Jerry C. Blackford, Henrik Stahl, Anuschka Miller. Doi:10.1016/j.ijggc.2014.10.022

12 **Benthic megafauna and CO_2 bubble dynamics observed by underwater photography during a controlled sub-seabed release of CO_2.**
Jun Kita, Henrik Stahl, Masatoshi Hayashi, Tammy Green, Yuji Watanabe, Stephen Widdicombe. Doi:10.1016/j.ijggc.2014.11.012

13 **Rapid response of the active microbial community to CO_2 exposure from a controlled sub-seabed CO_2 leak in Ardmucknish Bay (Oban, Scotland).**
Karen Tait , Henrik Stahl, Pete Taylor, Stephen Widdicombe. Doi:10.1016/j.ijggc.2014.11.021

14 **Numerical study of the fate of CO_2 purposefully injected into the sediment and seeping from seafloor in Ardmucknish Bay.**
Chiaki Mori, Toru Sato, Yuki Kano, Hiroyuki Oyama, Dmitry Aleynik, Daisuke Tsumune, Yoshiaki Maeda. Doi:10.1016/j.ijggc.2014.11.023

15 **Phosphorus behavior in sediments during a sub-seabed CO_2 controlled release experiment.**
Ayumi Tsukasaki, Masahiro Suzumura, Anna Lichtschlag, Henrik Stahl, Rachael H. James. doi:10.1016/j.ijggc.2014.12.023

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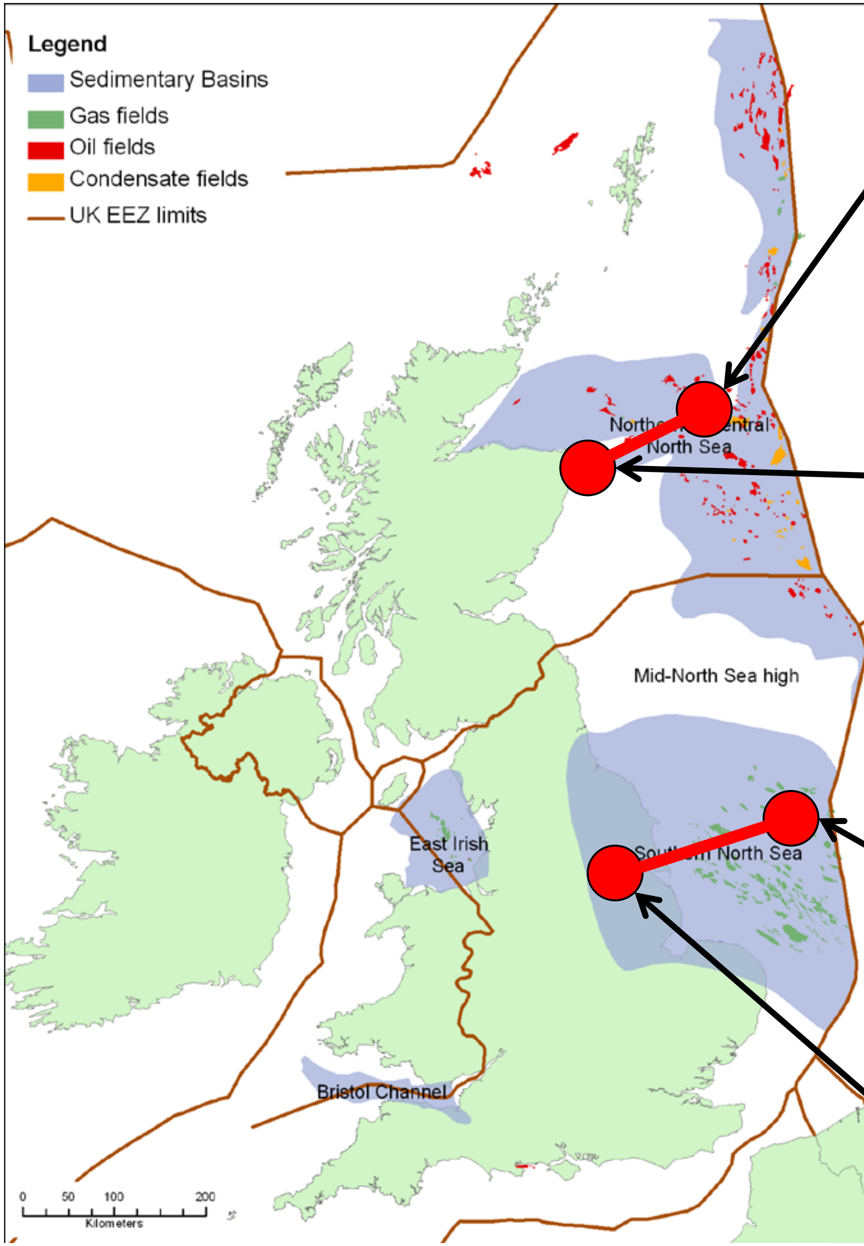
Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage

CCS in the UK



UK CCS competition
Two applicants for funding

Peterhead-Goldeneye
(Shell)
Gas fired
Depleted gas reservoir
10 MT

White Rose
(Alstrom, Drax, BOC, National Grid)
Coal fired
Saline aquifer
2MT/A

What next?

Project demonstrates scientific and operational relevance of multi-disciplinary real-world manipulations.

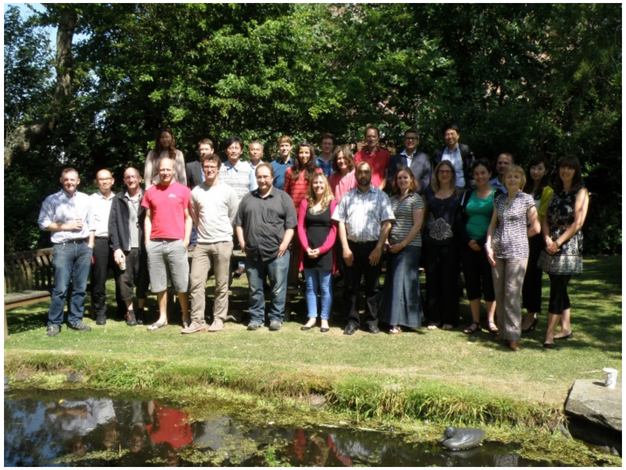
What next?

Feeding into monitoring system design

Re run the experiment, longer duration

- Testing of (pre-)operational monitoring tools and strategies
- Collaboration with SMEs / Tech developers / Industry
- Test the utility of the recommend baseline
- Test tracers as aids for attribution and quantification.
- Improved dispersion models
- Full quantification of CO_2 flows
- Understand carbonate buffering potential
- Investigate sediment saturation capacity and bubble flow
- Investigate longer-term biological impacts

Thank you



Jerry Blackford, jcb@pml.ac.uk