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A novel sub-seabed CO_2 release experiment informing monitoring and impact assessment for geological carbon storage

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ABSTRACT

Carbon capture and storage is a mitigation strategy that can be used to aid the reduction of anthropogenic CO_2 emissions. This process aims to capture CO_2 from large point-source emitters and transport it to a long-term storage site. For much of Europe, these deep storage sites are anticipated to be sited below the sea bed on continental shelves. A key operational requirement is an understanding of best practice of monitoring for potential leakage and of the environmental impact that could result from a diffusive leak from a storage complex. Here we describe a controlled CO_2 release experiment beneath the seabed, which overcomes the limitations of laboratory simulations and natural analogues. The complex processes involved in setting up the experimental facility and ensuring its successful operation are discussed, including site selection, permissions, communications and facility construction. The experimental design and observational strategy are reviewed with respect to scientific outcomes along with lessons learnt in order to facilitate any similar future.

1. Introduction

This paper presents and discusses the controlled release of CO_2 beneath the seabed for the QICS project (Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage, http://www.qics.co.uk), which was undertaken by researchers from seven research institutes in the UK and a further seven partner organizations in Japan in 2012.

Carbon capture and storage (CCS) has been argued as presenting a technically possible, financially attractive and socially acceptable method for mitigating global CO_2 release (IEA, 2013; IPCC, 2005; The Global CCS Institute, 2014). The main benefit of this emergent technology is that release of anthropogenic CO_2 can be mitigated: emissions targets and "green" commitments can be met, while simultaneously utilizing existing energy production infrastructure and contributing to the global carbon economy (Bachu, 2008). Nevertheless, as with the inception of any new technology, it is important that the degree of risk posed by the solution is fully constrained, prior to full deployment.

In the case of CCS these risks fall into a number of categories (IPCC, 2005). One risk factor is the potential for leakage from a CCS storage facility, producing either a diffuse leak of gaseous or dissolved CO_2 from a small fracture in the reservoir seal, through to a catastrophic rupture in, for example, a transfer pipeline of supercritical or dense phase CO_2 (Blackford et al., 2009). This is especially the case for the sub-seabed storage of CO_2 in abandoned oil and gas reservoirs where the immediate impact of any leak may not be so apparent.

Research to date has made significant advances to our understanding of the dispersion of CO_2 in the marine environment,

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its chemical signature and potential to impact ecosystems, using a combination of models, natural analogue sites and laboratory manipulations (Blackford et al., 2009). However each of these approaches has limitations.

Models are able to simulate the dispersion of gas and liquid phase bubbles/droplets in the vicinity of the leakage site and calculate the resulting change in acidity (pH) and the partial pressure of CO_2 (pCO_2) (e.g. Dewar et al., 2013). Similarly, models can address large-scale dispersion of dissolved CO_2 along with its resulting changes in seawater chemistry (Phelps et al., 2014). Such models are able to inform both monitoring strategy and impact by quantifying the volume of seawater experiencing either detectable or damaging chemical changes. However, these models fail for lack of observational data by which to properly evaluate their predictions (Mori et al., 2014). Models have also been used to attempt impact studies (Blackford et al., 2009); however, models have very limited ability to represent the complexity of marine communities and the intricacy of their response to high CO_2.

Laboratory simulations have revealed a range of both chemical impacts, such as heavy metal mobilization (e.g. Ardelan et al., 2009; Cruz Payan et al., 2012) and biological impacts ranging from stimulation of species to mortality in others (Widdicombe et al., 2013 and papers in the associated special issue, e.g. Widdicombe et al., 2009). These reveal a high degree of species- and circumstance-specific responses. Other stressors acting on a population can greatly exacerbate the detrimental effect of CO_2. Laboratory experiments are also limited in that they cannot replicate true environmental complexity; ecological or behavioural responses to, for example changes in predation pressure or resource competition and escape. It also remains difficult to establish the recovery potential of communities in laboratory simulations.

The third widely used approach is the study of natural CO_2 emission sites as analogues for CCS leaks (e.g. Caramanna et al., 2011; Pearce, 2006). This approach, while having many merits, has limitations, including (1) most studied sites are long-term phenomena and thus no base-line (pre-release) data exists, (2) the release rate cannot be controlled or "turned off" to study the rapidity with which more typical local conditions are re-established, (3) many sites are within volcanic settings (Hall-Spencer et al., 2008) and therefore may be contaminated with H_2S and have atypical temperatures. Although these analogue studies are often insightful, they are of limited geographical distribution; for example the shallow, warm and clear water situations described by Caramanna et al. (2011) and Hall-Spencer et al. (2008) do not directly translate to colder deeper and turbid sites on other continental shelves. If offshore implementation of CCS in Europe is to become a more established mitigation strategy, it will almost certainly be used in colder, more turbid, shelf seas, such as the North Sea, so that more appropriate analogues, with closely similar fauna, seabed sediments, irradiance and temperatures need to be studied before the findings can be directly utilized by policy makers.

Whilst some injections of small amounts of CO_2 directly into the water column have been performed (Barry et al., 2013), the injection of significant and quantified amounts of CO_2, in a controlled way, directly into marine sediments from below would effectively mimic the final stages of a leakage from storage reservoirs. This would allow for the first time a study of the vertical movement of CO_2 through the sediments, into the water column and of the biochemical transformations and impacts that occur as the CO_2 passes through a vertically structured marine sediment ecosystem, thereby mimicking the shallowest stages of migration and emission at the seabed.

An initial scoping study developed a set of criteria for a successful experiment, namely an injection of between one and ten tonnes of CO_2, at approximately ten metres below the seafloor, continuing over a period of several weeks. The main driver for these calculations was the need for a release large enough to impose changes and detectable signals onto a natural system, but small enough to avoid a large-scale pollution event. Clearly a short-term, small-scale release of CO_2 is not a full analogue for a CCS leak. However, it does encompass many of the processes and systems that are important to understand and guide both monitoring and impact assessment within the marine environment. A release of CO_2 into a sufficient thickness of sediment to include a hetrogenous sequence and diverse geological structures provides an opportunity to assess the dispersive and retentive capacity of a range of unconsolidated sediment types. These control the phase and dynamics of CO_2 passing through the sedimentary sequence and transfer into the water column, mechanisms about which knowledge is essential, if adequate and successful monitoring systems are to be designed.

This release would permit the examination of how fine-scale hydrodynamic processes act to disperse both the detectable and harmful plumes of CO_2-enriched water. This approach would also allow a range of monitoring methods: passive and active acoustics; chemical sensors; biological and geochemical indicators. At the same time the experiment allows the assessment of ecosystem impact within the context of normal seasonal cycles and behavioural responses.

Successful completion of the experiment required a number of challenges to be overcome. The first was to develop a risk adverse and cost-efficient mechanism for injecting CO_2 into a sediment layer without creating artificial conduits for leakage. There was then a need to identify a site which was both a suitable analogue for operational CCS but sufficiently accessible to facilitate injection and numerous observations. Not least, there is a social and political dimension in that injection of a potentially harmful substance into any environment is inherently controversial (e.g. Schiermeier, 2009).

An overview of the experimental design, the processes behind the release site selection and the permissions and communication strategy that were required is outlined in this paper. Following this, the experiment site, drilling methodology, the gas release facility and its performance are described. Further, information on the initial baseline study and outline of the sampling strategy are presented, before outlining the range of findings generated. The scientific outcomes of the experiment are described in more detail in Blackford et al. (in press) and in many other papers presented in this special issue, referenced below. This manuscript, as well as providing the detailed methodology in support of these papers seeks to present, discuss and identify lessons learnt from the delivery of this complex project in order to support and facilitate future work of a similar nature.

2. Methodology

The volume of CO_2 required to detect an impact, along with the need to approach the release point from below to avoid disturbing overlying sediment layers dictated that a borehole containing the injection pipeline should be horizontally directionally-drilled from shore into a suitable coastal setting (Fig. 1). This allowed the CO_2 to be stored and control mechanism equipment to be situated on land for ease of access.

A general summary of the risk analysis procedures applied to the controlled release experiment with selected examples is presented in Table 1. In practice a generic risk assessment was developed and then applied to each prospective site as part of the site selection process. Whilst many of the individual hazard-consequence-action elements are largely common sense the collation of all risk elements based on discussions within a multi-disciplinary project team and using consultants where appropriate proved valuable.

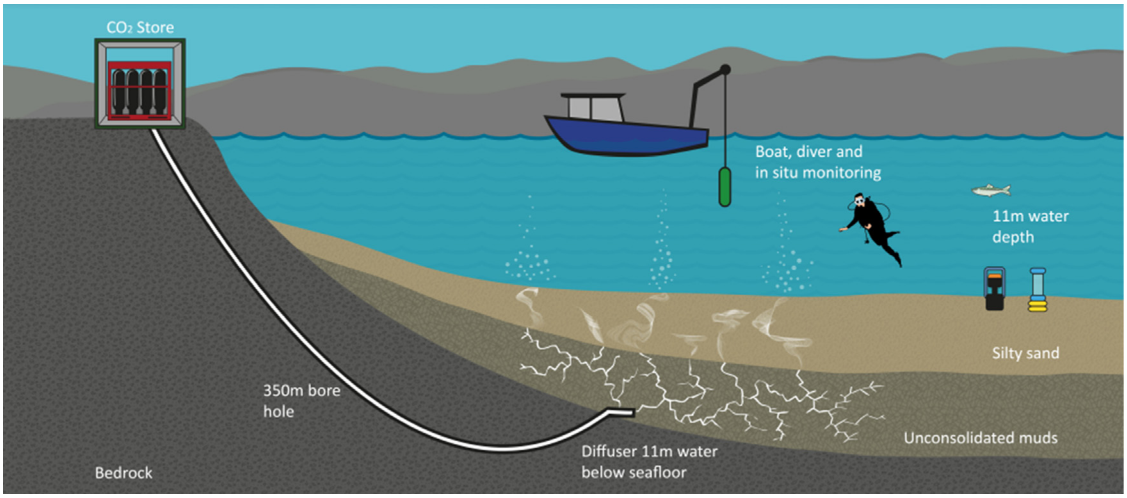

Fig. 1. Simplified schematic of the experiment, showing the on-shore location of the gas injection equipment, the borehole and associated submarine CO_2 release point.

Table 1
A general summary of the risk analysis procedures applied to the controlled release experiment with selected examples.

Risk breakdown	Approach
Project phase	The risk analysis was divided into project phases based on the experimental timeline, thereby prioritising protective actions: Site selection Drilling process CO_2 release system Observational approach
Hazard/event	Every conceivable hazard was listed, for example: Inappropriate geological substrate to support drilling and bore hole No suitable affordable tenders for the drilling work Drilling fails to produce a usable borehole Sediment ecosystem is incompatible with deeper settings Gas does not percolate through the sediments or it escapes at a remote point Observations interrupted by extreme weather Land station vandalised Stakeholder objections Occurrence of unforeseen environmental impacts Diver requires medical attention
Cause	An underlying cause or causes for each hazard/event was identified: Poor site selection Mismanagement of drilling tendering process, poor costings Lack of knowledge of gas flux mechanisms in sediments Poor communication Misunderstanding of impact potential, unsuitable release strategy Poor observational planning, lack of training
Consequence	For each hazard/event, what is the consequence for the project, for example: Insufficient funds to run project as envisaged Failure of gas injection The gas flux and impact is not sufficient to be measured The experimental findings cannot be easily transferred to other settings Experimental shutdown
Measures in place	For each cause, what measures are in place to minimise the risk of occurrence or impact, for example: High resolution seismic surveys completed Biological communities characterized Literature review of gas behaviour in sediments Communication strategy planned CO_2 injection rates flexible, dosage/response impact curves understood Diving depths less than 15 m, professional divers contributing to planning
Further actions needed	What further actions are required, for example: Increased or additional site characterization Scope alternative and flexible approaches to instrument deployment Reconsideration of sampling strategy Modelling of gas flow through sediments and dispersion in water column Ensure 24 h a day on site presence
Risk category	Risks where categorised broadly in to three categories, enabling further prioritization: Green: unlikely to cause an impact, even if event occurs Orange: could be significant, but unlikely to halt the experiment Red: potential show-stoppers

In the following sections we detail the approach to site selection, site characterization, regulatory permissions and communications, drilling operations, gas supply, injection strategy and sampling strategy.

2.1. Site selection

The suitable experimental location had to meet several important criteria to ensure successful experimental set-up and accurate, repeatable monitoring of the CO_2 injection:

1. *Accessibility:* The site had to be easily accessible, both from land and by sea. On-shore, there needed to be appropriate access for large drilling machinery and delivery of sufficient volumes of CO_2, as well as space for the installation of the CO_2 injection facility. Offshore, the site required nearby berths for survey vessels to minimize transit times and permit regular repeat surveys. Water depths needed to be between 10 m and 20 m with a moderate tidal range; deep enough to allow boat access for acquisition of high quality marine geophysical surveys, but shallow enough to facilitate diver based sampling and instrument deployment. Ideally, the site would be in a sheltered location to reduce the impact of adverse weather conditions and minimize the potential for days when survey was not possible. Land owners would have to agree to permit regular access to the site for several months during the drilling and gas release phases.
2. *Sediment stratigraphy and underlying bedrock:* Offshore, the site needed to have a minimum sediment cover of ten metres through which the injected CO_2 could migrate, and a maximum of 25 m sediment thickness to ensure injected CO_2 would migrate to the seabed within the time constraints of the experiment, but sufficient overburden of sediment would impede direct release into the sea through a large crater. Ideally, the sub-surface stratigraphy would be comparatively simple; an unfaulted, flat, shallowly dipping sequence of a range of sediment types representative of North Sea Quaternary sediments but avoiding glacial strata containing boulders (diamict) that might deflect or block the positioning of the diffuser pipe. Underlying these sediments the bedrock needed to be suitable to sustain drilling with a low density of rock fractures to ensure an appropriate grouted seal. The specific offshore release site satisfying the above stratigraphic criteria had to be within a practical drilling range (maximum 400 m) of an on-shore location
3. *Faunal type and diversity:* The study location must support faunal types and faunal diversity similar to sites targeted for CCS operations since a primary research goal was to study the effect of CO_2 injection on typical marine fauna.
4. *Logistical and scientific support:* The selected site had to be near to a well-equipped marine laboratory with appropriate research equipment, laboratories, research vessels and, importantly, a scientific diving team to reduce the cost and time of transport between the experiment site and the facilities that would be used.

Initial considerations suggested that the vicinity of Oban (Scotland) offered potential locations with an underlying bedrock suitable for drilling, and a large number of small islands and bays that would provide moderately sheltered survey conditions. Further, the location of UK national scientific diving facilities and other logistical support from the nearby marine research laboratory, Scottish Association for Marine Science (SAMS), at Dunstaffnage, Oban (Fig. 2) was a vital component. Flexible diving support was mission critical given the high intensity of sampling and installation of seafloor instrumentation at very specific target areas and the requirement to react to circumstances as the experiment developed (Fig. 2).

After detailed surveys of nine local sites with over 400 km of very-high-resolution chirp seismic reflection data, together with extensive multi-beam bathymetry surveys, a preferred location was identified for the experiment, fulfilling all of the criteria listed above. The optimal study site was selected in the northern part of Ardmucknish Bay (Fig. 2), and additional seismic reflection profiles were collected to characterize the site before and during the release (see Cevatoglu et al., 2015 for more details).

2.2. Site characterization

To fully characterize the site, the dense seismic survey grid (approximately 20 m line spacing) of over 30 line kilometers of chirp profiles and 40 line kilometers of boomer profiles acquired within an area measuring 1.5 km by 1.5 km and augmented by lithological characterization using sediment grab and gravity core samples were examined. This detailed geophysical mapping exercise allowed the identification of the sites geological structure and a target area for drilling. Following site selection, a further 18 boomer lines were run to produce a high density grid (Fig. 2c) and to confirm bedrock continuity along a likely borehole trajectory between the proposed drill rig location and the target area. The final site selection was an area in which sediment likely to contain boulders, which would have been a significant drilling challenge, was absent. It also served to generate an accurate baseline of the sediment structure as an aid for detecting the migration of carbon dioxide gas within the sediment following initiation of gas release as well as subsequent geophysical investigations during the experiment examining gas migration pathways (Blackford et al., in press; Cevatoglu et al., 2015).

2.2.1. Geology

This site survey study identified three distinct seismic stratigraphic facies (SSS I through III) overlying a very high-amplitude but irregular basal reflector of multiple overlapping diffraction hyperbola (Fig. 3), representing the interface between bedrock and unconsolidated sediments.

I. Unit SSS I is characterized by chaotic reflectors, it is discontinuous, of highly variable thickness and directly and unconformably overlies the bedrock surface.
II. Unit SSS II is a thick seismo-stratigraphic facies (up to 40 m) that overlies and infills the uneven upper surface of SSS I. It extends across most of the study area and may directly overlie bedrock where SSS I is absent. SSS II is characterized by laterally continuous layered reflectors. It is unconformably overlain and includes units of SSS III. SSS II is exposed at sea bed where SSS III is absent.
III. Unit SSS III comprises a number of locally discrete, thin (up to 5 m), acoustically transparent units that unconformably overlie or are included within SSS II. The base is always unconformable truncating the layered reflectors of SSS II and where the upper surface may be exposed at the sea bed. Where units of SSS III are within SS II the upper boundary is gradational from the transparent internal fill to the layered reflectors of SSS II.

These seismo-stratigraphic facies were interpreted as representing: a layer of glacial diamict deposited on top of the regional bedrock surface (SSS I); layered, fine-grained glaciomarine sedimentation (SSS II); and a stacked sequence of incised fluvial deposits of coarser material (SSS III). This interpretation was in keeping with the glacially dominated stratigraphy observed both locally (Howe et al., 2002; Nørgaard-Pedersen et al., 2006) and regionally (Stoker et al., 2009). The whole sedimentary sequence was observed to thin towards the shoreline, with the exception of SSS I, which locally thickens on the irregular acoustic bed-rock

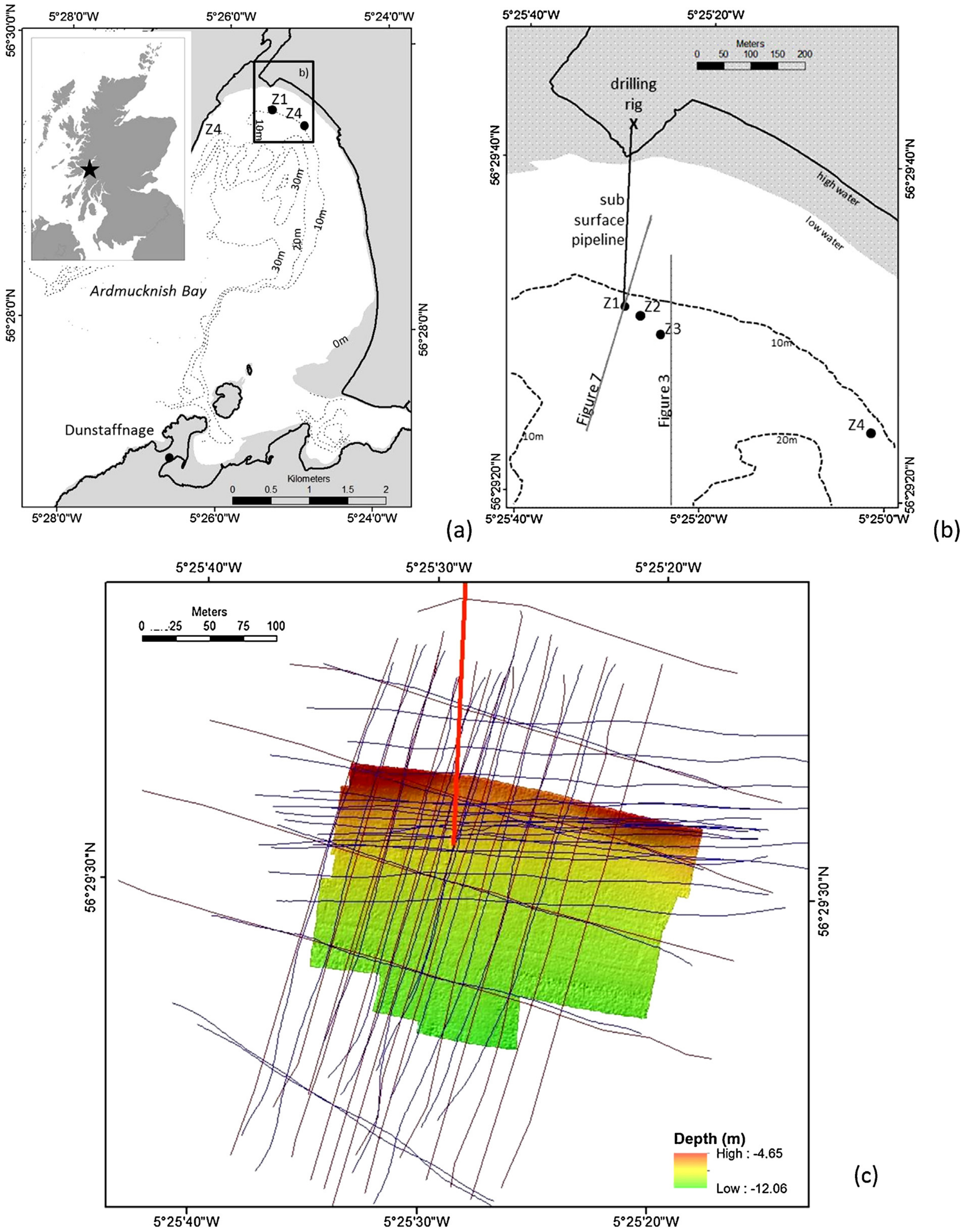

Fig. 2. QICS Experimental geometry, and pre-release geophysical data. (a) Site map of Ardmucknish Bay (on the Scottish West Coast, see inset) with water depth contours (dotted lines), positions of release epicenter (Z1) and reference (Z4) zones. (b) Close-up of experimental area at the northern end of Ardmucknish Bay, showing positions of all four sampling sites (Z1—epicenter of release, Z2–25 m distant, Z3–75 m distant and Z4—control, 450 m distant), located c. 5 km from the Scottish Association for Marine Science facility at Dunstaffnage. The position of the directionally-drilled sub-surface pipeline is indicated, which terminated at (c) 11 m depth beneath the seabed at Z1. The position of the boomer seismic reflection profiles collected pre-release and illustrated in Figs. 3 and 5 are also shown. (c) Multi-beam bathymetric image taken over the epicentre of the later release, with the colour scale indicating depth between 4 and 12 m water depth. The red line is the position of the sub-surface pipeline which was subsequently drilled. The positions of some of the boomer seismic reflection profiles taken during the site characterization (pre-release) stage of the experiment are also indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

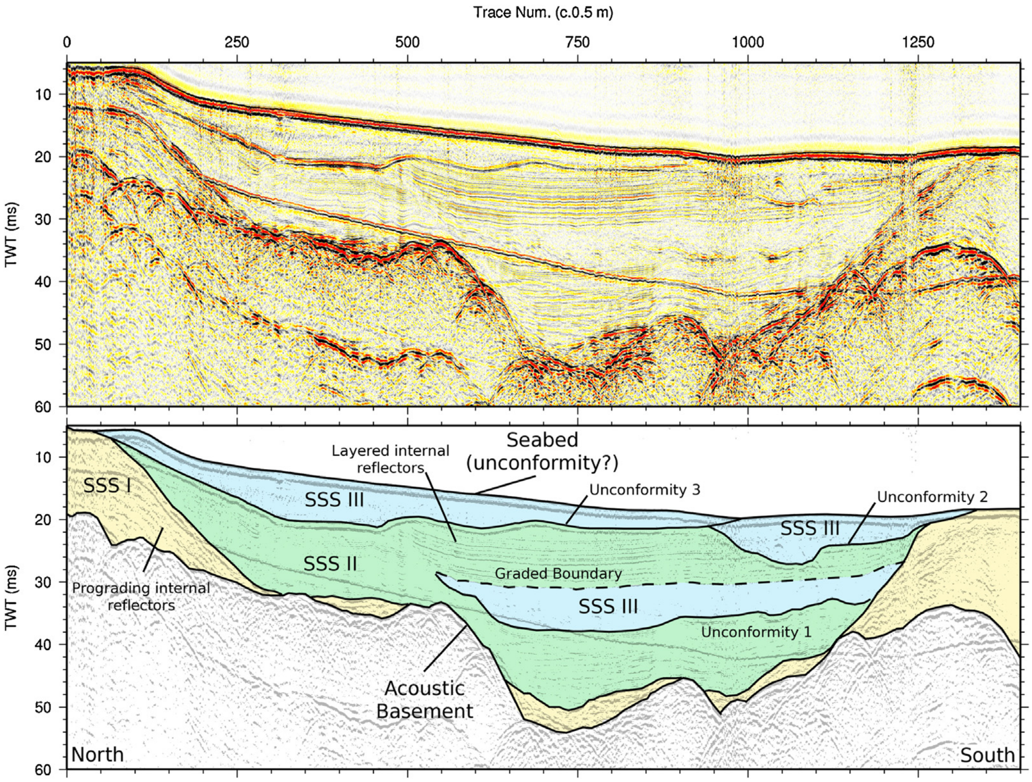

Fig. 3. Uninterpreted (top) and interpreted (bottom) seismic reflection profile within Ardmucknish Bay (position indicated in Fig. 2) illustrating the main sedimentary packages and sub-surface horizons. Refer to the main text for further explanation. The vertical axes are TWT (two way time) in milliseconds. Unconformity 3 has a major role in controlling gas migration during the release experiment (called horizon H2 by Cevatoglu et al., 2015).

topography, and a surficial SSS III unit which thickens towards the beach and demonstrates limited internal architecture in very shallow water (Cevatoglu et al., 2015). The boundary between SSS II and this surficial SSS III deposit was observed to play an important role in gas migration through the subsurface (Cevatoglu et al., 2015).

The selected access point for drilling equipment was a large flat area suitable for heavy vehicles, within 20 m of the shore. The site was secluded and surrounded by trees which reduced the impact of noise from the drilling operations on the nearby Tralee Bay Holiday Park visitors. Following site selection, a further 18 boomer seismic lines were run to produce a high density grid (Fig. 2c) close inshore and to confirm bedrock continuity along a likely borehole trajectory between the proposed drill rig location and the target area. The bedrock at the drill rig location is Dalradian Quartzite (British Geological Survey, 1991), with an unconfined compressive strength of 187 MPa, indicative of hard drilling (Long et al., 2012). This would tend to facilitate a secure and stable borehole that would not collapse during the drilling process, avoiding long delays and large cost over-runs. The quartzite continues, interrupted only by a Carboniferous quartz-dolerite dyke up to two meters wide, until the final ten meters of the required hole where the planned borehole exits this rock formation into unconsolidated sediments, interpreted to be dominantly silty, but may comprise a thin layer of diamict (till) at the bedrock surface. The bedrock exit point was targeted where the shallow seismic suggested the lag and/or diamict (SSS I) was thinnest or absent to minimise potential drilling difficulties. The only observed fault trends north-east to south-west, dipping to the south-east, and has a throw of 20–30 m. The proposed release site was provisionally selected at 11 m below the seafloor and 23 m below mean sea level

2.2.2. Hydrodynamics

The characterization of local hydrodynamics was important to ensure that vertical and horizontal water mixing was not atypical in the selected area. It was also required to optimise the sampling strategy, including the location of the control or reference site. This detailed information was also essential for modelling and tracking the plume of CO_2 enriched water generated during the experiment. Ideally, the area selected should have had an element of tidal flushing, distributing CO_2 enriched sea water to facilitate investigations into techniques for tracing CO_2 leaks over a wide area, but not so great a flushing rate that there would be no build-up of CO_2 concentrations in the area during the experiment.

Ardmucknish Bay is small, 3 km long and 3.5 km wide. It is open to the Firth of Lorn, the largest gulf on the West coast of Scotland at its south western extent and connected via a narrow (100 m) and shallow (9–13 m) channel to Loch Etive to the southeast. The circulation and mixing regime in Ardmucknish Bay is primarily driven by the semidiurnal tide with a maximum tidal range of 4.3 m. The tidal wave brings saline ($S > 34$) waters from the west during the flood phase whilst releasing pulses of brackish ($S = 21–30$) water from the adjacent strongly salinity-stratified sea loch during the ebb. This brackish low density water flows over the sill of the loch at high speed ($4.5\,\mathrm{m\,s^{-1}}$) and develops into a buoyant plume as it decelerates and propagates out into the bay at speeds of approximately $0.3\,\mathrm{m\,s^{-1}}$. This repeated buoyancy input leads to the formation of a very thin (2–5 m) surface layer resulting in a persistent, near surface salinity stratified water column, with the sea bed at the experiment site below this surface layer at all times. The dynamics of each plume and the ambient stratification are known to generate sharp fronts and nonlinear internal wave features both ahead of, and in response to the reflection of the plume from the North-westerly headland.

The nature of these dynamic processes has more recently been investigated using a Hydroid Remus Autonomous Underwater Vehicle (AUV) equipped with forward-mounted microstructure sensors (Boyd et al., 2010). The authors demonstrate that nonlinear internal wave processes lead to the downward displacement

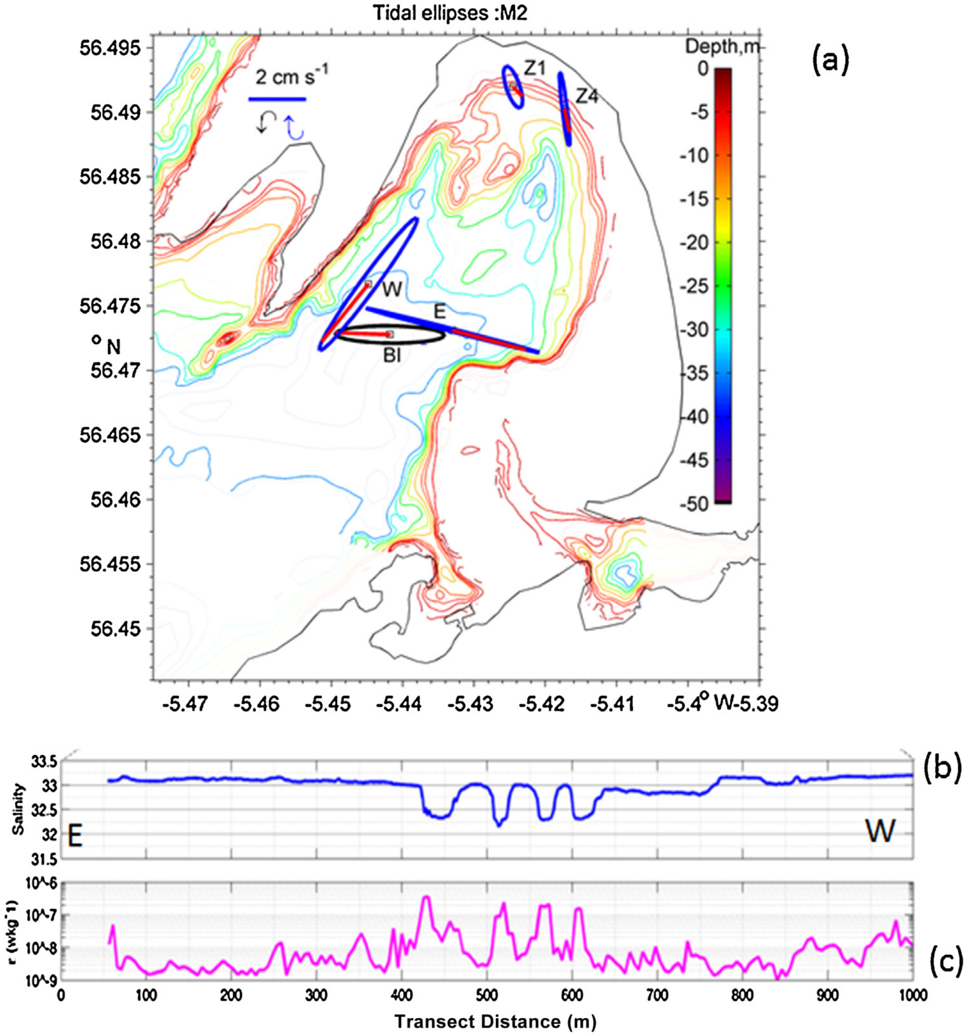

Fig. 4. (a) Tidal current ellipses of M_2 constituent from the single depth current meters deployed at a depth 10 m in May–October 2012 (site Z1 with Seaguard, sites Z4 and BI with RCM9) and from the vertically-average currents velocities form the East and West sites in February 2011 (RDI-ADCP). The latest (2012) multibeam topography (survey HI-Number 1373, courtesy of UK Hydrographic Office) is shown with every 5 m isobaths. AUV transect between E and W sites with salinity (b) and Turbulent Kinetic Energy values (c), obtained from velocity microstructure sensor at a depth of 10 m in February 2011 are shown at lower panel.

of near-surface water coinciding with a two orders of magnitude increase in the measured turbulent kinetic energy (TKE) above the background level (Boyd et al. (2010)). During the periods of intensified TKE, active mixing is shown to occur as salinity and temperature values do not return to those of the ambient fluid before the arrival of the turbulent features. These internal wave features are thought to be generated each tidal cycle and evidence supporting this hypothesis was found via a further deployment of the AUV in 2011, as shown on the lower panels of Fig. 4. Direct observations of this energetic process were obtained in the central deeper section of the bay between moorings sites E and W (Fig. 4b and c), where the effects have been limited to the upper 15 m of the water column. Surface manifestations of the processes have been observed near the CO_2 release site and thus may have an impact on the local mixing energetics. The direction of the currents within the bay confirmed that a reference site to the South and East of the release zone would not be exposed to the plume of CO_2 enriched sea water that the experiment generated.

In order to study the depth averaged tidal dynamics, those beneath the brackish surface layer of the bay and the CO_2 release site itself, several long and short term moorings, including an AANDERA and RDI-ADCP current sensor and a CTD along with an ADCP were deployed at various sites in Ardmucknish Bay during 2011–2012, prior to the QICS experiment commencing, to gather detailed base-line data. Tidal analysis of the most energetic constituent, that of the semidiurnal tide, allows for an insight into the circulation patterns within the bay. The tidal ellipses from each mooring site show that currents are generally aligned with the bathymetric contours (Fig. 4a). Rotation direction of tidal velocity vector was found to be mostly clockwise, except at the Bay Inlet (BI) mooring, where it was anticlockwise. The tidal currents reduce in strength from the southern entrance towards the head of the Bay from 6.3 cm s^{-1} at site E to 1.6 cm s^{-1} at the release zone.

The E and W tidal ellipses shown in Fig. 4a represent currents flowing towards the Northwest and Northeast, respectively, during the flood phase and Southeast and Southwest during the Ebb phase, resulting in a tidally driven horizontal circulation within the bay. Long term residual current velocities near the CO_2 release site (Atamanchuk et al., 2014) demonstrate a westerly and southwesterly flow, which is consistent with the prevailing winds in the area during the experiment.

2.2.3. Biology and seafloor sediment characteristics

A key aim of this study was to conduct the experiment in a habitat that had relevance to those habitats that could potentially be affected by leakage from industrial applications of CCS. These habitats will predominantly be soft sediment areas in the North Sea and most of these areas will be in water depths greater than could be achieved with the current study. However, even with the constraints of needing a shallow environment, due to limitations associated with the drilling and the use of divers for sampling, it was still possible to find an environment that had general relevance to these other situations. After a series of preliminary surveys across a number of potential sites it was concluded that the sediment characteristics and biology found in Ardmucknish Bay was representative of the North East Atlantic margin and whether there were any significant differences in sediment or biology across the bay that may limit the validity of conclusions arising from the QICS project. To support this conclusion a series of more detailed measurements and observations were made before the start of the release experiment.

The initial stage of habitat characterization was to determine if the sediments across Ardmucknish Bay were of uniform type in terms of physical structure and carbon content. For this a total of 24 cores were collected across the site from the four zones outlined in Fig. 2. They were cut into 2 cm slices and then analysed for porosity, organic carbon content (C_{org}%) and grain size. Analysis of the data shows that the sediments had a uniform grain size and porosity across the four zones (Fig. 5). The organic carbon content was analyzed in zones one and four and, although more variable, there were no large differences between the two zones.

It was clear from this work that the basic properties of the sediment were uniform across the experiment area, allowing a valid comparison to be made between the different experiment zones during and after the CO_2 release phase.

The structure and diversity of the macro-infaunal communities found in Ardmucknish Bay are detailed by Widdicombe et al. (2014). In summary, all four experimental zones were considered typical of NE Atlantic shallow, coastal fine sand sediments. The fauna were numerically dominated by several species of annelids (*Exogone hebes, Prionospio fallax, Chaetozone christei, Tharyx killariensis, Euclymene oerstedii*), a bivalve mollusc (*Thyasira flexuosa*) and a crustacean (*Tanaopsis graciloides*). Mean diversity and abundance were similar across all zones. The total number of taxa found within each zone was highest in Zones 1 and 4 (60 and 63 taxa, respectively), and slightly lower in Zones 2 and 3 (51 and 47 taxa, respectively). PERMANOVA analysis on 4th root transformed species abundance data showed that there was a small yet significant difference in community structure before injection commenced between the zones (Pseudo $F = 2.5077$, $P(\text{perm}) = 0.001$), with significant pairwise difference seen between all zones except between Zones 1 and 2 (Table 2).

However, the variability between the five replicate community samples taken from within each of the zones was high with average Bray–Curtis similarity ranging from as low as 42.3% at Zone 2 up to 60.56% at Zone 3. Measurements of community variability between zones was only slightly lower than the variability seen within zones, with average Bray–Curtis similarity ranging from 35.05% between Zone 1 and Zone 4, to 45.81% between Zone 1 and Zone 4. Shallow sediments are inherently patchy over very small scales (Kendall and Widdicombe, 1999) so much of the variability observed between cores, both within and between sites could largely be due to the relatively small core size (10 cm diameter, 0.008 m^2) used to collect macrofaunal samples. In a study conducted in sediment similar to that sampled in the current study (fine sand), also using a 0.008 m^2 diver operated core in similar water depths (10–12 m), Kendall and Widdicombe (1999) found similar numbers of species (21.45 ± 1.1) and slightly higher numbers of individuals (78.82 ± 6.31) per core. The slightly higher levels of abundance may be due differences in the timing of sampling between the two studies.

In addition, Kendall and Widdicombe (1999) found that in an area of sediment that was considered to be a homogeneous area of fine sand, average levels of dissimilarity between samples taken only 50 cm apart was around 59% and for samples taken around 500 m apart average similarity was reduced to 49%. All of which indicates that the zones selected for the QICS study are not atypical in terms of the macrofaunal diversity, abundance and community structure expected for, fine sand sediments in the UK. For a more comprehensive description of the macrofaunal community response to the QICS experiment see Widdicombe et al. (2014).

2.3. Permissions and public consultation

With sufficient geological, hydrodynamic, biological and biogeochemical information having been gathered to assure ourselves that Ardmucknish Bay was a suitable location for the release experiment, we proceeded to pinpoint an optimal target for the drillers and identify the requirements of the gas diffusion and release equipment. At this point we initiated the process of gathering the relevant permissions needed to proceed with the experiment.

At the project proposal stage, prior to site selection the bodies with formal regulatory roles were approached for an informal indication that the experimental procedure would meet with their approval. This afforded an opportunity to identify any initial concerns from these parties. For this experiment the regulatory bodies were Marine Scotland and the Crown Estates, the later control activities associated with the seafloor in the UK. Clearly each country would have its unique regulatory structure.

Having identified the most favourable drilling location, the first priority was to contact the local landowner, Lochnell Estates, and the land leaseholder, Tralee Bay Holiday Park, to discuss the envisaged experiment and the associated requirements. Both parties kindly granted consent in principle for the experiment to proceed. Following this initial step, permission was sought and obtained from the two relevant regulators, Marine Scotland and the Crown Estates, for the drilling under- and into the seabed, deployment of instrumentation and marker buoys and for taking sediment samples. Scottish National Heritage, the Scottish Environmental Protection Agency and Argyll and Bute Council were also informed of the proposed activities. With no objections from the landowner and the leaseholder, support of the Scottish Government and the vast majority of the local community, all relevant permissions were granted before drilling was scheduled to commence.

A consultation with members of the local community quickly ascertained that the experimental area under active consideration was of no interest to local commercial fishers and/or aquaculturists, although this exercise revealed that a nearby jetty was under frequent use for launching small boats to transport divers to sites in the bay and by leisure fishers.

Public acceptance was greatly aided by the strong links that SAMS has with the local population. Whilst local people did not necessarily support CCS as a “good thing”, the majority were convinced by the unbiased attitude of the researchers and the need to conduct this research, once its aims were described to them. Public events before, during and after the CO_2 release phase were well attended with scientists being regularly approached by curious members of the public while the drilling and release experiment was underway, with such approaches encouraged by prior agreement with the landowners (Mabon et al., 2014a,b).

In order to address the project’s objectives of providing information of direct use to a wide range of stakeholders, and build on the discussions held in the initial stages of the project a stakeholder group was initiated which included representatives of a diverse range of interested parties, from local industry representatives such as commercial shellfish growers, through the bodies that would be approached for planning consent for CCS to other interested parties such as Natural England, the International Energy Agency Greenhouse Gas R&D Programme, NGO’s and industrial bodies with

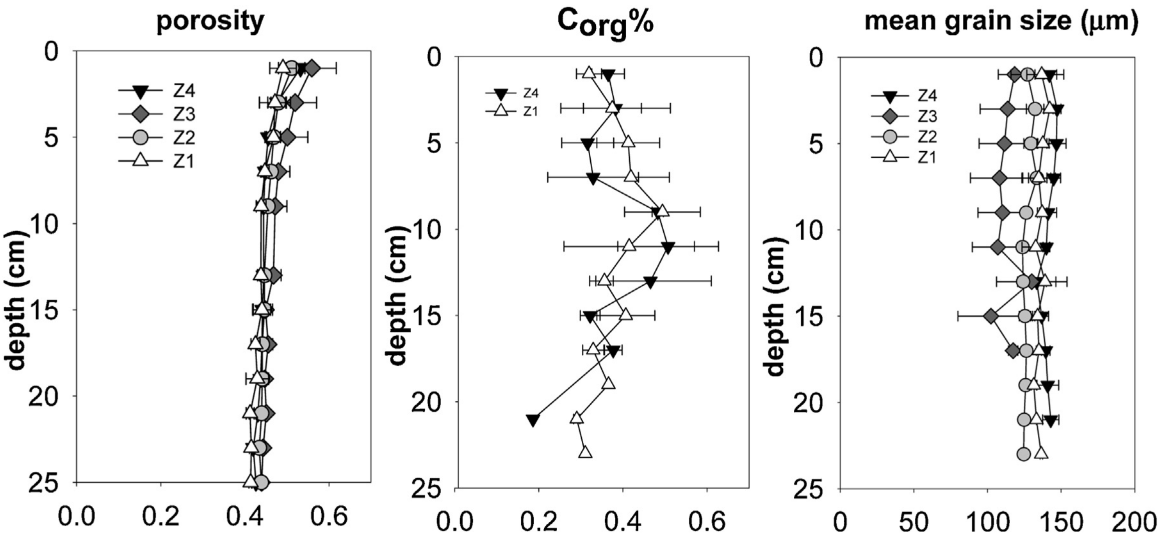

Fig. 5. Porosity, organic carbon content (C_{org}%) and mean grain size of the upper 25 cm of the sediments in the experiment Zones 1 to 4. The horizontal bars are the variation of the parameters during the experiment at each site.

Table 2
Fauna information showing most dominant species and groups.

		Zone 1	Zone 2	Zone 3	Zone 4
Number of species (per core)		25.8 (±2.7)	20.8 (±5.1)	22.0 (±3.5)	24.0 (±2.0)
Total number of species (5 cores)		60	51	47	63
Number of individuals (per core)		54.4 (±10.9)	44.0 (±11.1)	47.6 (±7.9)	46.0 (±11.2)
Average similarity within site		49.13%	42.30%	60.56%	43.08%
Pairwise similarity	Pairwise dissimilarity	Zone 1	Zone 2	Zone 3	Zone 4
Zone 1			54.19	56.59	64.95
Zone 2		45.81		56.11	61.78
Zone 3		43.41	43.89		59.15
Zone 4		35.05	38.22	40.85	

an interest in CCS such as oil and power companies. A full list of stakeholders is on the QICS web page (http://www.qics.co.uk). The stakeholder forum allowed the project scientists to refine objectives and dissemination on the basis of direct feedback, but also encouraged discussion between groups with diverse attitudes to CCS.

2.4. *Drilling operations*

The well design called for the majority of the drilling to go through the local bedrock, only drilling into the unconsolidated sediment for the bottom 10 m of the well, to reduce the likelihood of borehole collapse or sediment fracture to the lowest possible levels. The horizontal directional drilling (HDD) operations were conducted using an HDD rotary drilling rig, employing a tubular steel drill string (Fig. 6a), with a 16.5 cm diameter tri-cone bit with tungsten carbide stud inserts to cope with the hard bedrock (Fig. 6d and e), while optimizing the rate of penetration. The well was drilled with an initial angle of 16° to horizontal. However, the final well trajectory formed a gentle curve (Fig. 7). The location of the drill bit in three dimensions was calculated using an electromagnetic wire coil positioned on the seafloor by divers which could be energised to determine the bit location by producing a temporary magnetic field within a precisely located set of points. Magnetic direction finding sensors in the navigation package, placed 10 m behind the drill bit sensed the location of this magnetic field to within four decimal places. Drilling adjustments were then made to keep the hole in the correct trajectory. Connections between the ~9 m drill pipe sections were made-up using KopR-Cote lubricant grease in order to prevent the screw joints between the drill pipe sections seizing under high torque loading.

Drilling fluid, primarily composed of fresh water and bentonite and suitable for drilling water wells for domestic supply, was circulated through the well while drilling and recycled through two "shale shakers" – mechanical sieves – to remove all but the finest clay sized particles from the fluid.

On reaching the unconsolidated sediment, slight losses of drilling fluid to the formation were observed over the final six metres of the well bore, with an observed maximum mud loss to the unconsolidated formation of 2.3 m^3 (Long et al., 2012). When the target position was reached the drill bit was initially washed out of the hole, pumping drilling fluid while the bit was pulled back out of the hole to remove as many drilled solids as possible.

A mesh diffuser, five metres in length, composed of 316 grade stainless steel made from wedge wire mesh and with an effective mesh opening size of 0.5 mm and a 28 mm internal diameter was welded to 316 grade stainless steel tubing (Fig. 6b–d). This was used to ensure that there was an even spread of very small gas bubbles released into the sediment during the experiment. The diffuser was pushed into the well by using the pressure of drilling fluid against the black rubber packers mounted on the pipe (Fig. 6b) and then pushed a further six metres into undrilled sediment at the end of the well, located 11 m below the sediment water interface, which is 12 m below mean sea level. The spear assembly at the tip of the mesh diffuser (Fig. 6c) ensured that subsequent operations would not dislodge the mesh from the sediment. To ensure CO_2 did not migrate back up the hole, a cement pipe was used to seal the well 100 m from the end and to hold the stainless steel injection pipe permanently in place. The site was returned to its original

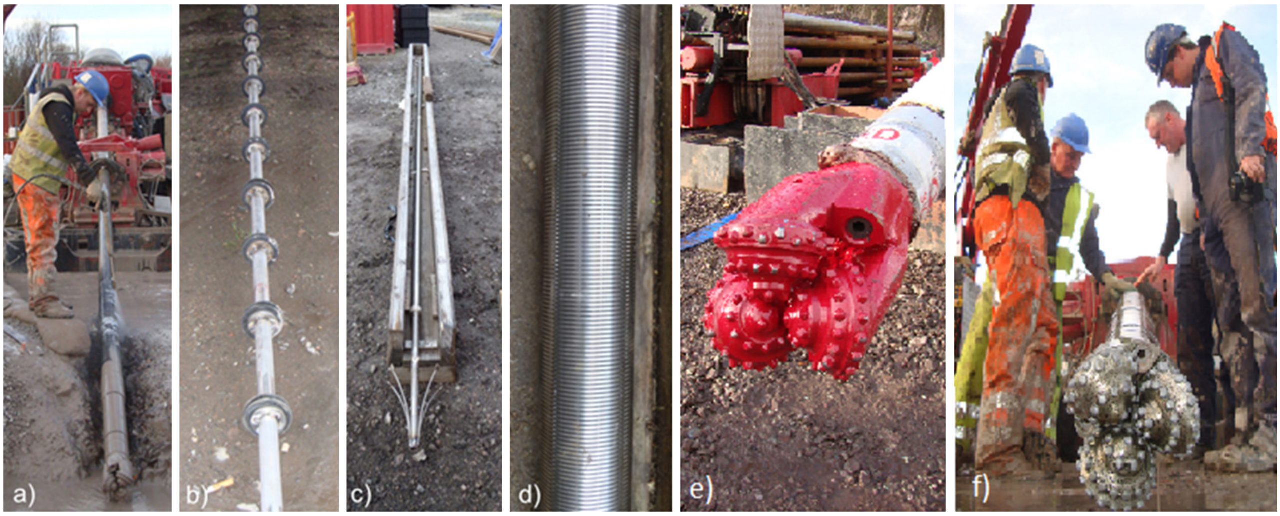

Fig. 6. Drilling images (a) directional drill rig and drill bit, (b) 5 cm diameter stainless steel pipe line with flanges, (c) 5 m gas dispersion screen with sediment anchor, (d) close up of screen with 0.5 mm wide and 5 mm long slits constructed from wedge wire mesh. (e) the 16.5 cm tri-cone bit prior to use, (f) the bit after use showing clear signs of wear, but still functional with no missing insets.

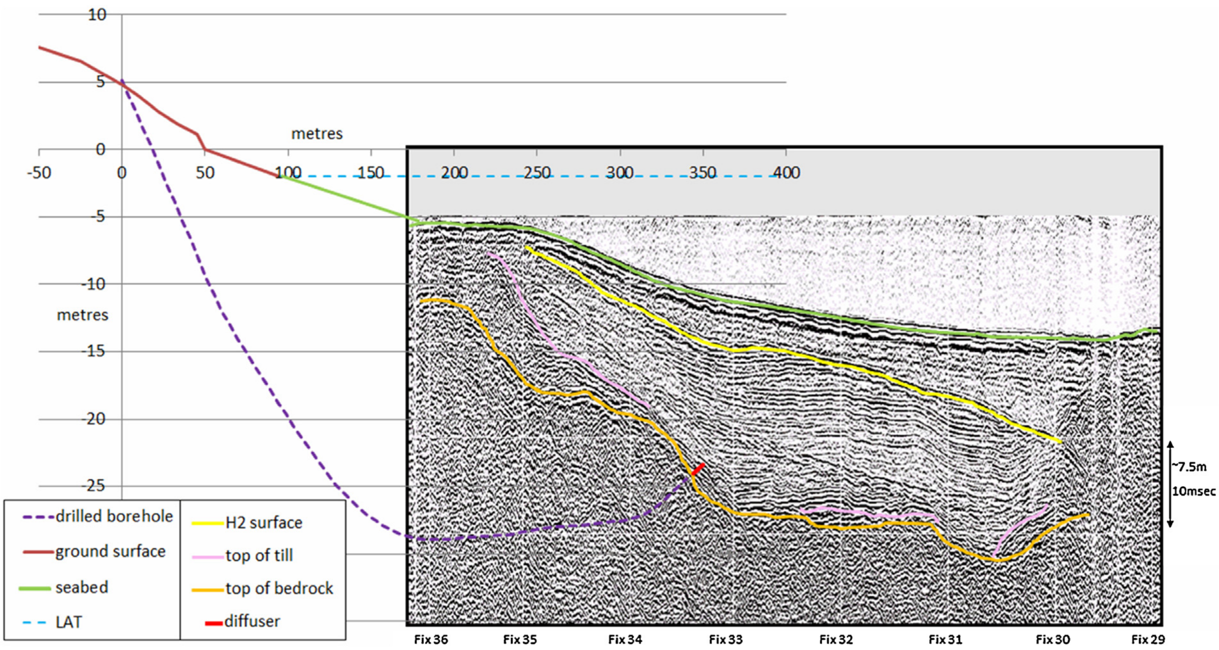

Fig. 7. Borehole trajectory and land surface superimposed on pre-release boomer seismic reflection profile. The major lithological units as well as the track of the borehole (purple line) are indicated, with the diffuser at the end of the borehole shown by the short red line. The experiment was designed so that the diffuser was positioned to come out of bedrock, at the base of the sediments, 11 m beneath the seabed. The position of the seismic reflection profile and strike of the borehole are shown in Fig. 2. The pink line indicates the interface between SSS I and SSS II as discussed in Section 2.2.1, with the yellow line indicating the horizon (H2 of Cevatoglu et al., 2015) between SSS II and SSS III. LAT is the lowest astronomical tide. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

state, leaving only a man-hole cover overlying the hole in which the injection pipe protruded from the borehole.

2.5. Gas injection system

On site, CO_2 was stored Manifolded Cylinder Pallets (MCP's), with 15 standard 80 kg gas cylinders placed in a frame, all manifolded down to a single gas outlet point. Four MCP's could be held securely at the injection site (Fig. 8a). The MCP's were connected to an automatic manifold with two MCPs supplying gas for the experiment at any time and two MCP's on standby. When the supply pressure of the gas reduced to a threshold, the manifold automatically switched to the full MCP's and injection would continue uninterrupted, the empty MCP's were then replaced. Heaters were installed to prevent freezing of the manifold as the pressure was stepped down from cylinder pressure to injection pressure. MCP's were housed in a secure 20 ft (6 m) container with doors at each end, allowing access for regular and easy exchange of the 2600 kg MCP's using a Rough Terrain telehandler forklift (Fig. 8b), as well as ensuring adequate ventilation in the event of a leak from the MCP's. The container was fitted with a CO_2 alarm which could be heard in the vicinity of the container.

A mass flow controller monitored gas pressure at the injection manifold, as well as controlling the rate of flow of gas in standard litres per minute. The system logged the temperature, pressure and rate of gas injection every 12 s. The outlet of the mass flow controller

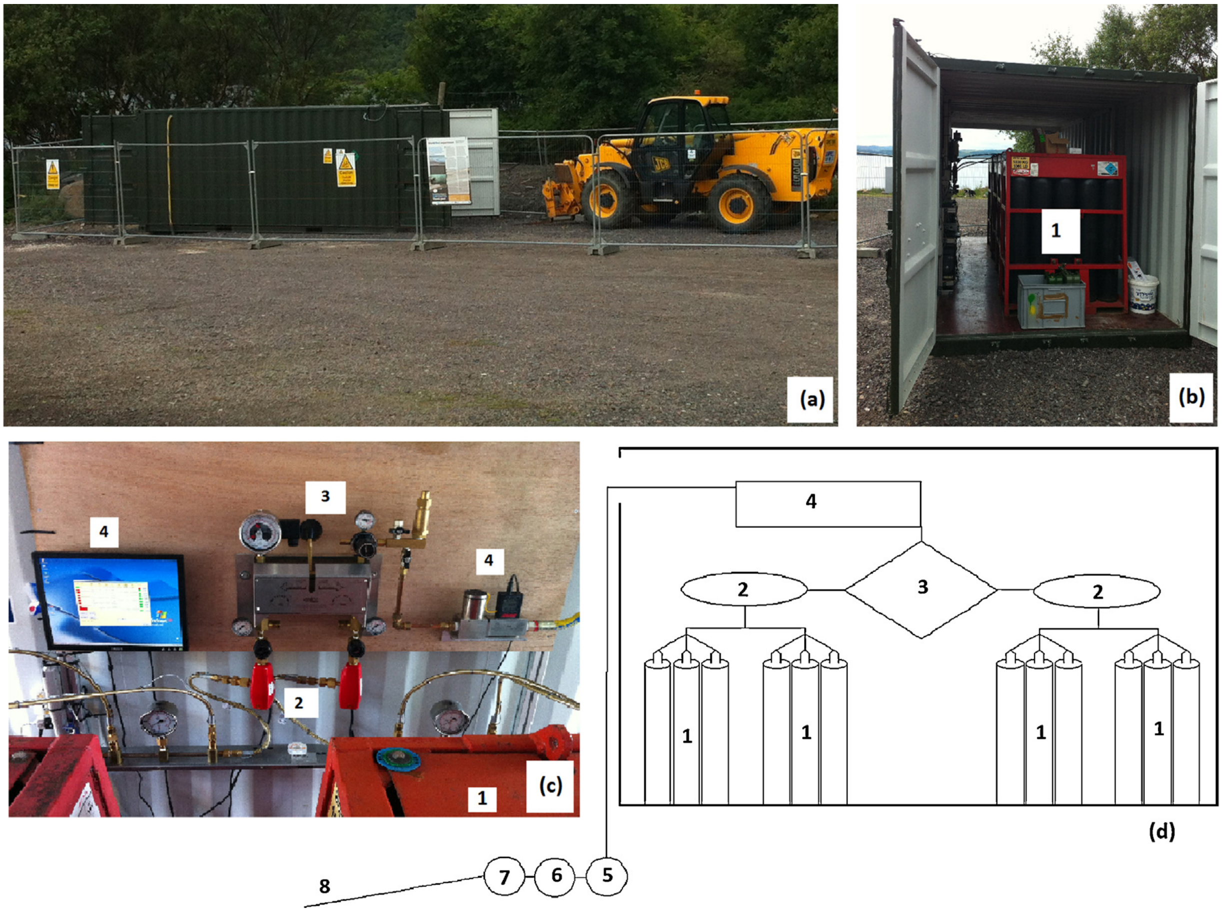

Fig. 8. (a) 20 ft (6 m) Tunnel container with doors open, waiting for gas change with telehandler forklift. (b) inside of tunnel container showing MCP's in use. (c) manifold, heaters and computerised mass flow controller and logger. (d) simplified schematic of the gas injection system. (1) represents Manifolded Cylinder Pallets (MCP), (2) heaters to stop gas freezing at high injection rates, (3) is an automatic manifold, drawing gas from two MCPs, swapping to two full MCPs when the active two are empty, (4) is a computer controlled mass flow meter and controller, logging gas flow rate, pressure and temperature every 12 s, (5) is a one-way check valve, (6) is a shut-off valve, (7) is a pressure gauge, before the gas enters the borehole (h). The photograph to the left of the schematic, shows the MCP's, heaters, manifold and flow controller.

was attached to an armoured flexible gas hose which passed out of the container and into the manhole. Inside the manhole a pressure gauge, a check valve and a shut off valve were installed at the top of the injection pipe. The check valve was installed in case of an interruption of gas flow into the well to stop the hydrostatic pressure of the sea water forcing gas back up the injection pipe should there be a sudden reduction in gas pressure The pressure gauge was installed so that a comprehensive leak test could be carried out on the equipment prior to operation. A simplified schematic of the gas injection system is shown in Fig. 8d, (detailed schematic available on request from lead author).

2.6. Gas release strategy

The primary risk in the design of the injection strategy was causing overpressure in the sediment, which would produce fracture-like pathways to the seabed. This was highly undesirable since the principle project aim was to explore natural pathways of leaking CO_2, and to measure the geochemical and biological changes within the sediment as a consequence of this and to monitor the fate of CO_2 as it migrated through the sediment. Conservative criteria to ensure that the sediment would be unlikely to be mobilized in a single large catastrophic gas venting event was that the overpressure at the bottom of the well should not exceed the weight of the sediment.

Conversely, sufficient CO_2 needed to be injected to induce a potentially measurable impact on the environment. The question of how much CO_2 was needed was non-trivial and could be broken down into a more refined series of questions involving: the mass balance, fluid pathways and rates of migration and whether the pathways to the seabed would be diffuse or localized? Can the CO_2 rise buoyantly through the sediment? How much CO_2 would dissolve in the sediment pore water and how much would remain in the gaseous phase?

During the design, our key uncertainty was the projected sub-surface volume distribution. If the injected CO_2 spread out symmetrically into a plume which buoyantly rises, a large volume of pore space would need to be filled before the CO_2 could reach the seabed. However, if the CO_2 were to rise up a narrow chimney—less pore space would need to be filled before the CO_2 would break through. A first-order estimate of the time to breakthrough could then be made using the injection rate. The uncertainty in such volume distribution and flow pathways led to an uncertainty in breakthrough time from days to months for this system. In practice, CO_2 emerged from the seabed in bubble form within hours of injection commencing, indicating relatively direct pathways (Cevatoglu et al., 2015).

Prior to the start of injection, the design of an injection strategy is often informed by performing a well test which then allowed the operator to determine likely achievable flow rates given some pressure differential at the well. This is where the injectivity and permeability of a target formation is constrained by performing either injection or extraction tests. In our case it was not practical to do this as it would have perturbed the site, perhaps initiating

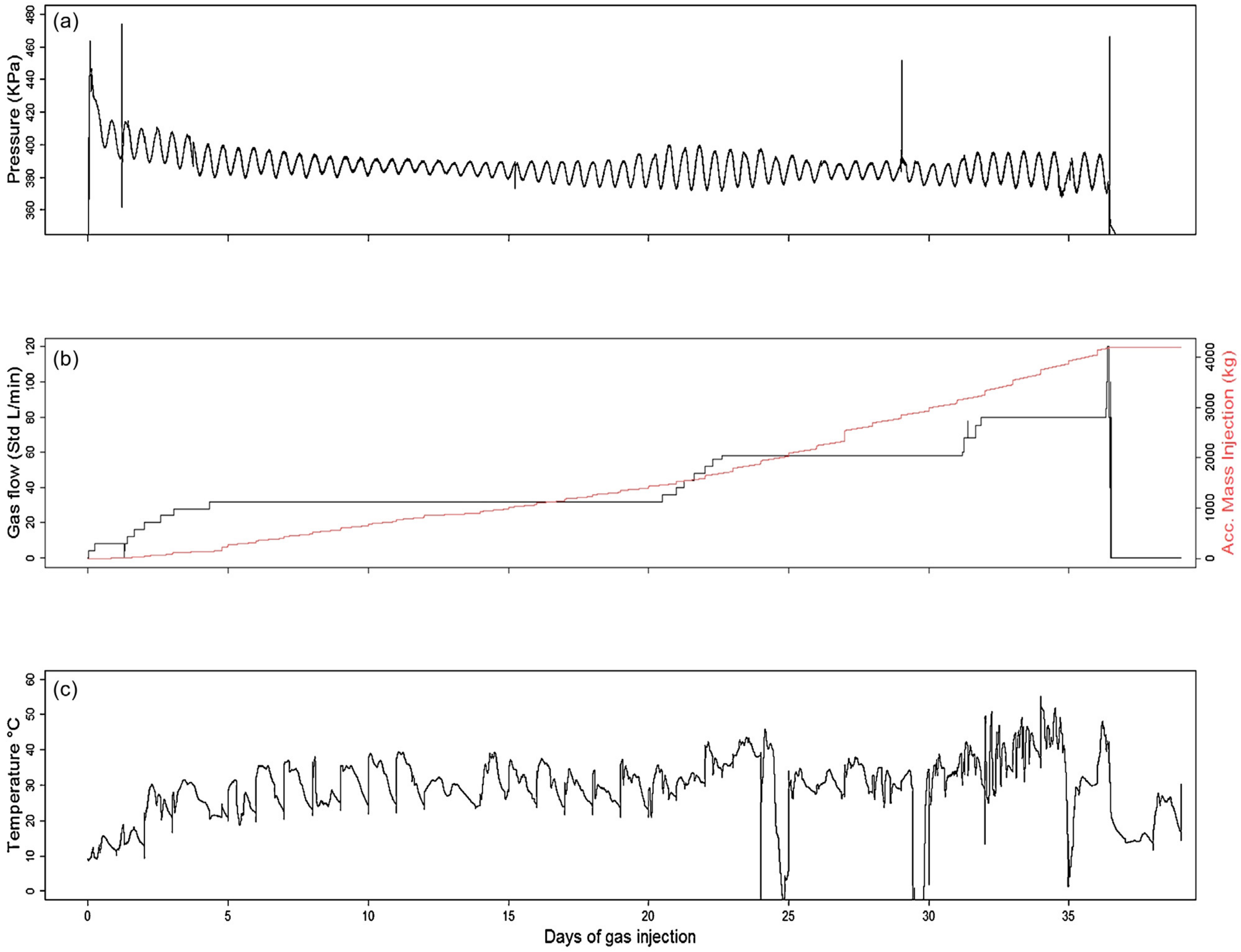

Fig. 9. Gas injection parameters: (a), injection pressure in kPa, (b) litres of gas per minute at standard pressure and temperature (100 kPa, 0 °C) in black, with the cumulative gas injected during the experiment in kilograms in red, (c) temperature of the gas at the manifold. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fractures in the sediment. At this stage, the CO_2 injection pressure was observed to oscillate in phase with tidal cycles.

In this project, the strategy was to start injecting at a low flow-rate and monitor the pressure at the well-head which gives a hydrostatically corrected indication of the pressure at the injection point. The initial flow rate of 4 L min^{-1} (at standard conditions) pressurised the system to a peak wellhead pressure of 461 kPa which rapidly decreased back to ~413 kPa. This pressure and flow rate was held for 4 h to saturate the sediments with CO_2 in order to increase the relative permeability of the CO_2 gas phase (Fig. 9). Within 3 h, streams of bubbles were observed exiting the seabed, which were shown to be CO_2 (Fig. 10). Since a measurable impact was required, gas flow rate was gradually stepped up to 32 L min^{-1} over 167 h. Over this period the average pressure stabilised at ~441 kPa despite the increase in flow rate. This was a positive indication as to the performance of the injection system. These rates were based on modelling of plumes of CO_2 in sea water (Dewar et al., 2013, 2014), which generated a guide to the flow rates of gas that would produce a significant, but not catastrophic, signal at the seafloor as well as being constrained by gas injection pressures.

In response to feedback from the remote and direct observations at day 20, the injection rate was further increased in a series of increments, reaching 80 L min^{-1} on day 32. When the injection rate reached 80 L min^{-1} there was an increase in the well-head pressure which was interpreted as the maximum flow rate deliverable to the experiment without a detrimental effect on the structural and geotechnical integrity of the sediments. The changes in flow rate were initiated to increase the rate of change in sediment chemistry and to test the responsiveness of the system to change. After 37 days, the injection was terminated as planned, with a total of 4200 kg of CO_2 released into the sediments during this period. Occasionally, undesirable fluctuations in gas injection temperature were caused as gas expanded and cooled in the manifold and the thermostat controlled gas heaters failed to respond quickly enough. In future a computer controlled system with a temperature feed-back loop to the heaters would be preferable.

2.7. Experimental remit, and observational strategy

The experiment was planned with a before–after-control–impact (BACI) design strategy, with four experiment zones chosen (Fig. 2). A 10 m radius around the release epicenter was designated Zone 1, with Zone 2 being 25 m away from this, Zone 3 a distance of 75 m away and a reference zone which could not be affected by the gas release some 450 m distant SE of the release epicenter (Atamanchuk et al., 2014; Lichtschlag et al., 2014).

In the two weeks immediately prior to the initiation of gas release 15 sediment cores, with a diameter of 10 cm, were taken by divers from each of the four experiment zones, for subsequent base-line analysis for sediment pore water chemistry, nutrient cycling, examination of in-fauna and for sub-sampling for later

Fig. 10. In situ image of the release zone, showing bubble streams of CO_2 gas leaving the sea bed, pock marks can be seen at the base of the bubble streams caused by mechanical disturbance to the sediment. Photograph also shows various sensors deployed for monitoring, to the right is an Aanderaa Seaguard current meter equipped with a pCO_2 optode and a CTD to the left. The cable running across the seafloor is an Online pCO_2/pH ISFET electrode sensor. The results from these sensors is discussed in detail in Atamanchuk et al. (2014).

examination of the microbial community. Cages containing megafauna of commercial interest (king scallops *Pecten maximus* and common mussels *Mytilus edulis*) were deployed for later collection during the release phase. Instruments comprised ADCPs, Hydrophones, spear sensors for measuring sediment pH and pCO_2 at up to 1 m depth in the sediment, cameras taking time lapse photographs to determine movement of fauna, a transect profiling lander, pCO_2 optodes and recording CTDs, pCO_2/pH ISFET sensors, sampling grids and baskets containing pCO_2 and pH optode recorders. In addition, benthic chambers were deployed to measure biogeochemical fluxes and diffuse gradient in thin film (DGT) probes were used to determine metal mobility within sediment pore waters. During this period repeated CTD casts from throughout the bay were taken, extensive Chirp seismic surveys were completed as was a multi-beam survey and water sampling.

Immediately after the release commenced, it was discovered that the gas was bubbling out of the seafloor some ten metres distant from the expected location, some lateral offset having been introduced to the gas flow by the sub-seabed geological structures. As a result the location of Zones 1, 2 and 3 were moved to compensate. This was not an issue for the experiment design as it had already been ascertained that the experiment area in Ardmucknish Bay was sufficiently homogenous with respect to the required parameters, as described in Section 2.2. Multi-beam and chirp surveys were regularly completed during the first week of release, carried out on an almost daily basis.

During the first week of CO_2 release the sampling campaign was repeated, with a further 15 sediment cores from each zone taken by divers spanning four dives in a 48 h period. Incubation chambers were again deployed, as were DGT probes, cages of fauna were collected from the pre-positioned frames and an AUV was deployed on several occasions. Sampling was also conducted during the second week of release, as well as the final week of release. Immediately on cessation of release a fourth sampling week was completed, with a fifth sampling week occurring three weeks after the cessation of gas release. A seventh sampling week took place in September, three months after the cessation of CO_2 release, with a final sampling week, of more limited scope, occurring 1 year after the initiation of CO_2 release. In total, over 200 individual dives collected over 650 sediment cores and 300 water samples, took over 500 images and laid 1600 m of underwater cable, in addition to deploying and recovering the equipment outlined in this section.

3. Discussion

3.1. Experiment outcomes

As shown in Fig. 8, gas bubbles were seen escaping the seabed during the QICS experiment, proving within hours of the release commencing that the CO_2 was being released into the sediment as planned and that gas was not migrating back up the annulus of the borehole, or one of the other worst case scenarios. However, empirical evidence collected by divers and using hydrophones suggested that only 15% of the injected CO_2 bubbled from the seafloor during the QICS experiment (Berges et al., 2014; Blackford et al., in press) with the rest of the CO_2 remaining within the sediment during the gas release phase (Cevatoglu et al., 2015). The released gas that reached the water column was detected over a small area around the release zone (Atamanchuk et al., 2014). During the release phase, CO_2 enriched pore waters were observed close to the sediment–water interface (Lichtschlag et al., 2014) and the pH of the sediment surface was significantly different to the reference zone 450 m distant (Taylor et al., 2015), with in situ pH and pCO_2 sensors in the sub-seabed also monitoring the movement of CO_2 (Shitashima et al., 2015). In addition, the observed plume of CO_2 enriched sea water was mapped, as was the CO_2 concentrations in the atmosphere in the release zone (Maeda et al., 2014).

Given that this could be characterized as a deliberate pollution event in an environment famed for its natural beauty, the local public supported the experiment and its aims, were well informed and interested in the experiment (Mabon et al., 2014a,b).

4200 kg of CO_2 gas was released into the sub-seabed sediments for a period of 37 days (Blackford et al., in press). During this time the gas could be tracked by geophysical techniques (Cevatoglu et al., 2015) and was observed bubbling from the seabed both directly by divers and remotely by hydrophones (Berges et al., 2014; Blackford et al., in press). Further, the progress of the CO_2 as it dissolved in sea water (Dewar et al., 2014; Sellami et al., 2014) was detected using several techniques (Atamanchuk et al., 2014) and mapped in both the sea water and the atmosphere (Maeda et al., 2014). The presence of injected CO_2 within the sediment was confirmed by Lichtschlag et al. (2014), while its impact on the pH and pCO_2 of the seabed sediment was directly measured (Queiros et al., 2015; Shitashima et al., 2015; Taylor et al., 2015).

Further, the effect that the CO_2 had on the microbial community and infauna in the sub-seabed as well as megafauna within the water column was quantified (Kita et al., 2014; Pratt et al., 2014; Tait et al., 2015; Widdicombe et al., 2014), consequently nutrient cycles were also investigated (Tsukasaki et al., 2014; Watanabe et al., 2014). Numerical modelling was carried out based on empirical data collected during the experiment (Dewar et al., 2014; Mori et al., 2014) and future best practices for monitoring for a leak from a CCS facility were posited (Blackford et al., 2015).

The recovery of the release zone was monitored for up to one year after the release phase was terminated (Tait et al., 2015; Widdicombe et al., 2014).

3.2. Experimental limitations

The data on the geology of Ardmucknish Bay was mostly inferred from remote sensing, such as chirp and boomer seismic surveys and by direct sampling from a number of cores taken for analysis, although these were confined to the top 20–30 cm of sediment. It was attempted to take longer cores, with a gravity corer, but this was limited by areas of larger boulders within the sediment away from the release site. The release site was expressly chosen due to the small number of larger boulders in the sediment in that area. However, collecting long (>4 m) cores close to the release site of the experiment may have generated a weak point, or conduit, which would allow preferential gas migration, in direct contradiction to the experiment requirement for a diffusive release. Extensive coring by gravity core was therefore limited in the area immediately surrounding the release zone. This in turn limited the available information on geotechnical strength of the sediment into which the CO_2 was to be released, indicating a precautionary approach to maximizing the gas release rate during the experiment. It is possible that more accurate geotechnical information on the sediments in the area could have allowed greater release rates of CO_2 during the experiment.

The base-line study prior to the experimental release was carried out fully, but over a limited time period. Ideally a longer, more intensive base-line study should be carried out, to allow better differentiation between observed impacts and natural variation in Ardmucknish Bay. Potentially this should be at high spatial resolution for a full year prior to the experiment to better understand variations in key parameters and even response to extreme events, such as a storm. Additionally, better quantification of the different phases of CO_2, dissolved, gaseous and even solid phase precipitation within the sediment would be encouraged. Ultimately, 85% of the injected CO_2 was not traced (Blackford et al., in press), however, as pointed out above, this is ultimately a difficult decision to make as it would involve deep coring, thus providing an easy conduit for gas escape and potentially negating several other aspects of the experiment. Ultimately, deep cores should be taken from an area near-by the release site, but with very similar geology to better inform modellers and geologists of the sediment.

The experiment was specifically designed to provide a concentrated and small impact to the natural environment, given that a more massive release would have a more wide ranging impact and the increased likelihood of opposition to such a move. As a result the impact area was concentrated, with a small footprint. This was exactly as dictated by the experiment design, but made coordinating deployment of sensors on the seafloor with diver movements and AUV surveys complex and time consuming, as a great deal of effort was focused on one small area.

The duration of the gas release was not long enough. The experiment had planned to release gas for 30 days. In the event, it was decided to use all stocks of CO_2 on site rather than terminate on day 30, extending the gas release to 37 days. Analysis of samples taken around this point and discussed in detail elsewhere in this special issue (e.g. Lichtschlag et al., 2014) indicate that a longer gas release phase would have resulted in a larger impact being observed as a plume of CO_2 enriched pore water was reaching the sediment water interface in the days immediately prior the gas release being stopped. However, to facilitate monitoring, tracers could be used in the injected gas, to further allow the accurate quantification of the gas and whether or not there are measurable fluxes from the sea bed.

Ultimately, the experiment should be carried out in situ proximal to a site that will use CCS as an industrial application, for example in the North Sea. This would ensure that the conditions of the experiment exactly match the geology, biology and hydrodynamics in the area surrounding the CCS facility and would “ground truth” the findings of this experiment as accurately as possible, however such an experiment was out with the resources of the QICS project.

4. Conclusions

The sub-seabed CO_2 release experiment in Ardmucknish Bay was successful. The migration of the gas could be imaged in the sub-surface, and detected in surface sediments, within the water column and in the atmosphere. Key factors which were important to the success of the experiment include:

- Initial detailed geophysical surveying to choose an appropriate site was crucial to the success of the experiment.
- The significant effort made in informing and interacting with the local population was essential. The project was successful in ensuring that local people both understood the rationale for the work and felt empowered to approach the project personnel should any issues arise. The experiment proceeded with the support from an interested public and follow up public meetings discussing the experiment were well attended.
- Drilling activities were significant and noisy and the project deliberately undertook drilling activities during the winter months to minimize any impact on tourist activities in the region.
- A constant and reliable gas supply was required; gas deliveries had to be carefully planned in advance of the release phase.
- Good site selection assured that access to the experiment site was possible throughout the experiment, with only two day’s sampling being delayed by 24 h, due to inclement weather.
- The sampling strategy was extensive and involved over 200 individual dives and 12 weeks of boat time. There was, however, a compromise in the resolution of data gathered and the cost of collecting and analyzing these samples. In retrospect, the most rapid changes in many observed parameters occurred immediately after the gas release commenced and upon its cessation. More sampling dates around these points would have been beneficial.
- From the data acquired during this experiment, a longer release phase is indicated in any subsequent experiment.

The release rate of gas was only slowly increased due to concerns about fracturing the sediment and generating a direct conduit through the sediment to the overlying water. In future geotechnical information on sediment strength would better inform this decision making process.

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References

Ardelan, M.V., Steinnes, E., Lierhagen, S., Linde, S.O., 2009. Effects of experimental CO_2 leakage on solubility and transport of seven trace metals in seawater and sediment. Sci. Total Environ. 407, 6255–6266.

Atamanchuk, D., Tengberg, A., Aleynik, D., Fietzek, P., Shitiashima, K., Lichtschlag, A., Hall, P.O.J., Stahl, H., 2015. Detection of CO_2 leakage from a simulated sub-seabed storage site using three different types of pCO_2 sensors. Int. J. Greenhouse Gas Control 38, 121–134.

Bachu, S., 2008. CO_2 storage in geological media: role, means, status and barriers to deployment. Prog. Energy Combust. Sci. 34, 254–273.

Barry, J.P., Buck, K.R., Lovera, C., Brewer, P.G., Seibel, B.A., Drazen, J.C., Tamburri, M.N., Whaling, P.J., Kuhnz, L., Pane, E.F., 2013. The response of abyssal organisms to low pH conditions during a series of CO_2-release experiments simulating deep-sea carbon. Deep Sea Res., II—Top. Stud. Oceanogr. 92, 249–260.

Berges, B.J. P., Leighton, T.G., White, P.R., 2015. Passive accoustic quantification of gas fluxes during controlled gas release experiments. Int. J. Greenhouse Gas Control 38, 64–79.

Blackford, J., Bull, J.M., Cevatoglu, M., Connelly, D., Haughton, C., James, R.H., Lichtschlag, A., Stahl, H., Widdicombe, S., Wright, I.C., 2015. Marine baseline and monitoring strategies for carbon dioxide capture and storage (CCS). Int. J. Greenhouse Gas Control 38, 221–229.

Blackford, J., Jones, N., Proctor, R., Holt, J., Widdicombe, S., Lowe, D., Rees, A., 2009. An initial assessment of the potential environmental impact of CO_2 escape from marine carbon capture and storage systems. Proc. Inst. Mech. Eng., A: J. Power Energy 223, 269–280.

Blackford, J., Stahl, H., Bull, J.M., Berges, B.J.P., Cevatoglu, M., Lichtschlag, A., Connelly, D., James, R.H., Kita, J., Long, D., Naylor, M., Shitashima, K., Smith, D., Taylor, P., Wright, I., Akhurst, M., Chen, B., Gernon, T.G., Haughton, C., Hayashi, M., Kaieda, H., Leighton, T.G., Sato, T., Sayer, M.D.J., Suzamura, M., Tait, K., Vardy, M.E., White, P.R., Widdicombe, S., 2014. Detection and impacts of leakage from subseafloor carbon dioxide storage. Nat. Clim. Change, http://dx.doi.org/10.1038/nclimate2381, in press.

Boyd, T., Inall, M., Dumont, E., Griffiths, C., 2010. AUV observations of mixing in the tidal outflow from a Scottish sea loch. In: Autonomous Underwater Vehicles (AUV), 2010 IEEE/OES, 1–3 Sept. 2010, pp. 1–9.

British Geological Survey, 1991. Connel Solid Geology 1:50,000 Map Series. British Geological Survey.

Caramanna, G., Voltattorni, N., Maroto-Valer, M.M., 2011. Is Panarea Island (Italy) a valid and cost-effective natural laboratory for the development of detection and monitoring techniques for submarine CO_2 seepage? Greenhouse Gases—Sci. Technol. 1, 200–210.

Cevatoglu, M., Bull, M.J., Vardy, M.E., Gernon, T.G., Wright, I.C., Long, D., 2015. Gas migration pathways, controlling mechanisms and changes in sediment physical properties observed in a controlled sub-seabed CO_2 release experiment. Int. J. Greenhouse Gas Control 38, 26–43.

Cruz Payan, M., Verbinnen, B., Galan, B., Coz, A., Vandecasteele, C., Viguri, J.R., 2012. Potential influence of CO_2 release from a carbon capture storage site on release of trace metals from marine sediment. Environ. Pollut. 162, 29–39.

Dewar, M., Sellami, N., Stahl, H., Chen, B., 2015. Dynamics of rising CO_2 bubble plimes in the QICS field experiment. Part 2—Modelling. Int. J. Greenhouse Gas Control. 38, 52–63.

Dewar, M., Wei, W., Mcneil, D., Chen, B., 2013. Small-scale modelling of the physiochemical impacts of CO_2 leaked from sub-seabed reservoirs or pipelines within the North Sea and surrounding waters. Mar. Pollut. Bull. 73, 504–515.

Hall-Spencer, J.M., Rodolfo-Metalpa, R., Martin, S., Ransome, E., Fine, M., Turner, S.M., Rowley, S.J., Tedesco, D., Buia, M.-C., 2008. Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. Nature 454, 96–99.

Howe, J.A., Shimmield, T., Austin, W.E.N., Longva, O., 2002. Post-glacial depositional environments in a mid-high latitude glacially-overdeepened sea loch, inner Loch Etive, western Scotland. Mar. Geol. 185, 417–433.

IEA, 2013. In: International Energy Agency (Ed.), International Energy Agency: World Energy Investment Outlook. International Energy Agency (IEA Publications).

IPCC, 2005. Carbon Dioxide Capture and Storage. Cambridge University Press, Cambridge, England.

Kendall, M., Widdicombe, S., 1999. Small scale patterns in the structure of macrofaunnal assemblages of shallow soft sediments. J. Exp. Mar. Biol. Ecol. 237, 127–140.

Kita, J., Stahl, H., Hyashi, M., Green, T., Watanabe, Y., Widdicombe, S., 2015. Benthic megafauna and CO_2 bubble dynamics observed by underwater photography during a controlled sub-seabed release of CO_2. Int. J. Greenhouse Gas Control 38, 202–209.

Lichtschlag, A., James, R.H., Stahl, H., Connelly, D., 2015. Effect of a controlled sub-seabed release of CO2 on the biogeochemistry of shallow marine sediments, their pore waters, and the overlying water column. Int. J. Greenhouse Gas Control 38, 80–92.

Long, D., Smith, D.J., Tulloch, G.J., 2012. Report on drilling operations at Ardmucknish Bay for the QICS Project. In: British Geological Survey, Internal Report.

Mabon, L., Shackley, S., Blackford, J., Stahl, H., Miller, A., 2015. Local perceptions of the QICS experimental offshore CO_2 release: results from social science research. Int. J. Greenhouse Gas Control 38, 18–25.

Mabon, L., Shackley, S., Bower-Bir, N., 2014. Perceptions of sub-seabed carbon dioxide storage in Scotland and implications for policy: a qualitative study. Mar. Policy 45, 9–15.

Maeda, Y., Shitashima, K., Sakamoto, A., 2015. Mapping observation of leaked CO_2 in the overlying water column and into the atmosphere during a sub-seabed CO_2 release experiment. Int. J. Greenhouse Gas Control 38, 143–152.

Mori, C., Sato, T., Kano, Y., Oyama, H., Aleynik, D., Tsumune, D., Maeda, Y., 2015. Numerical study of the fate of CO_2 purposefully injected into the sediment and seeping from seafloor in Ardmucknish Bay. Int. J. Greenhouse Gas Control 38, 153–161.

Nørgaard-Pedersen, N., Austin, W.E.N., Howe, J.A., Shimmield, T., 2006. The Holocene record of Loch Etive, western Scotland: influence of catchment and relative sea level changes. Mar. Geol. 228, 55–71.

Pearce, J.M., 2006. What can we learn from natural analogues? In: Lombardi, S., Altunina, L.K., Beaubien, S.E. (Eds.), Advances in the Geological Storage of Carbon Dioxide. Springer, The Netherlands.

Phelps, J., Blackford, J., Holt, J., Polton, J., 2015. Modelling large-scale CO_2 leakages in the North Sea. Int. J. Greenhouse Gas Control 38, 210–220.

Pratt, N., Morgan, E., Taylor, P., Stahl, H., C., H., 2015. No evidence for impacts to the molecular ecophysiology of ion or CO_2 regulation in tissues ofselected surface-dewlling bivalves in the vicinity of a sub-seabed CO_2 release. Int. J. Greenhouse Gas Control 38, 193–201.

Queiros, A.M., Taylor, P., Cowles, A., Reynolds, A., Stahl, H., Widdicombe, S., 2015. Optical assessment of impact and recovery of sedimentary pH profiles in ocean acidification and carbon capture and storage research. Int. J. Greenhouse Gas Control 38, 110–120.

Schiermeier, Q., 2009. Ocean fertilization experiment draws fire. Nature, http://dx.doi.org/10.1038/news.2009.13

Sellami, N., Dewar, M., Stahl, H., Blackford, J., Chen, B., 2015. Dynamics of rising CO_2 bubbles from the QICS project in Ardmucknish bay, Part 2—Experimental data analysis. Int. J. Greenhouse Gas Control 38, 44–51.

Shitashima, K., Maeda, Y., Sakamoto, A., 2015. Detection and monitoring of leaked CO_2 through sediment, water column and atmosphere in a sub-seabed CCS experiment. Article Int. J. Greenhouse Gas Control 38, 135–142.

Stoker, M.S., Bradwell, T., Howe, J.A., Wilkinson, I.P., Mcintyre, K., 2009. Lateglacial ice-cap dynamics in NW Scotland: evidence from the fjords of the Summer Isles region. Quat. Sci. Rev. 28, 3161–3184.

Tait, K., Stahl, H., Taylor, P., Widdicombe, S., 2015. Rapid response of the active microbial community to CO_2 exposure from a controlled sub-seabed CO_2 leak in Ardmucknish Bay (Oban, Scotland). Int. J. Greenhouse Gas Control 38, 171–181.

Taylor, P., Lichtschlag, A., Toberman, M., Sayer, M.D.J., Reynolds, A., Sato, T., Stahl, H., 2015. Impact and recovery of pH in marine sediments subject to a temporary carbon dioxide leak. Int. J. Greenhouse Gas Control 38, 93–101.

The Global CCS Institute, 2014. The Global Status of CCS: 2014. The Global CCS Institute, Canberra, Australia.

Tsukasaki, A., Suzamura, M., Lichtschlag, A., Stahl, H., James, R., 2015. Phosphorous behaviour in sediments during a controlled sub-seabed CO_2 release experiment. Int. J. Greenhouse Gas Control 38, 102–109.

Watanabe, Y., Tait, K., Gregory, S., Hyashi, M., Shimamoto, A., Taylor, P., Stahl, H., Green, K., Yoshinaga, I., Suwa, Y., Kita, J., 2015. Response of the ammonia oxidation activity of microorganisms in surface sediment to a controlled sub-seabed release of CO_2. Int. J. Greenhouse Gas Control 38, 162–170.

Widdicombe, S., Blackford, J.C., Spicer, J.I., 2013. Assessing the environmental consequences of CO_2 leakage from geological CCS: generating evidence to support environmental risk assessment. Mar. Pollut. Bull. 73, 399–401.

Widdicombe, S., Dashfield, S.L., Mcneill, C.L., Needham, H.R., Beesley, A., Mcevoy, A., Oxnevad, S., Clarke, K.R., Berge, J.A., 2009. Effects of CO_2 induced seawater acidification on infaunal diversity and sediment nutrient fluxes. Mar. Ecol. Prog. Ser. 379, 59–75.

Widdicombe, S., Mcneill, C.L., Stahl, H., Taylor, P., Queiros, A.M., Nunes, J., Tait, K., 2015. Impact of sub-seabed CO_2 leakage on macrobenthic community structure and diversity. Int. J. Greenhouse Gas Control 38, 182–192.