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Behavioral responses of *Arctica islandica* (Bivalvia: Arcticidae) to simulated leakages of carbon dioxide from sub-sea geological storage

Shaw D. Bamber*, Stig Westerlund

International Research Institute of Stavanger, Mekjarvik 12, N-4070 Randaberg, Norway

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ABSTRACT

Sub-sea geological storage of carbon dioxide (CO_2) provides a viable option for the Carbon Capture and Storage (CCS) approach for reducing atmospheric emissions of this greenhouse gas. Although generally considered to offer a low risk of major leakage, it remains relevant to establish the possible consequences for marine organisms that live in or on sediments overlying these storage areas if such an event may occur. The present study has used a series of laboratory exposures and behavioral bioassays to establish the sensitivity of *Arctica islandica* to simulated leakages of CO_2. This long-lived bivalve mollusc is widely distributed throughout the North Sea, an area where geological storage is currently taking place and where there are plans to expand this operation significantly. A recently published model has predicted a maximum drop of 1.9 pH units in seawater at the point source of a substantial escape of CO_2 from sub-sea geological storage in this region. Valve movements of *A. islandica* exposed to reduced pH seawater were recorded continuously using Hall effect proximity sensors. Valve movement regulation is important for optimising the flow of water over the gills, which supplies food and facilitates respiration. A stepwise reduction in seawater pH showed an initial increase in both the rate and extent of valve movements in the majority of individuals tested when pH fell to 6.2 units. Exposing *A. islandica* to pH 6.2 seawater continuously for seven days resulted in a clear increase in valve movements during the first 40 h of exposure, followed by a gradual reduction in activity intensity over the subsequent five days, suggesting acclimation. The ability of both exposed and control bivalves to burrow successfully into sediment on completion of this exposure was very similar. A final exposure trial, testing whether increased valve movements initiated by reduced pH were related to foot extension during attempted burrowing, found no such association. In summary, significant changes in valve behavior did not occur until seawater pH fell to 6.2 units. The response took the form of an increase in valve activity rather than closure. The absence of foot extension coincident with increased valve movements indicates *A. islandica* were not attempting to burrow, leaving the possibility that valve movements are supporting a respiratory response to hypercapnia. In conclusion, *A. islandica* appears to be tolerant of reductions in seawater pH equivalent to those predicted for substantial losses of CO_2 through leakage from sub-sea geological storage.

1. Introduction

Release of carbon dioxide (CO_2) from human activities is now considered a significant contributor to observed changes in global climate patterns and acidification of the oceans (IPCC, 2014). Carbon Capture and Storage (CCS) provides a partial solution to this problem by gathering large volumes of CO_2 at source of production, then transporting and subsequently pumping the gas into sub-sea geological formations that act as permanent stores. Although this approach provides a means to reduce atmospheric emissions of CO_2, it also presents a risk to the environment from the potential leakage of 1000's of kg of gas through the seabed, creating significant changes in local carbonate chemistry, including acidification of overlying seawater (Phelps et al., 2015). Although generally considered to be a secure form of storage (IPCC 2005; Widdicombe et al., 2015) a number of potential sources of leakage from CCS have been identified, including undetected geological fractures, passage through abandoned wells and escapes during injection (Damen et al., 2006; IEA, 2008). Based on these risks, the need for further research to increase our understanding of the environmental implications of possible leaks has been recognized (Blackford et al., 2008; Carroll et al., 2014; IPCC, 2014; Widdicombe et al., 2015).

The North Sea is under particular scrutiny in the search for suitable CO_2 sub-sea storage sites, in part due to the number of depleted oil and gas reservoirs that exist within its boundaries that could

* Corresponding author.
E-mail addresses: shaw.bamber@iris.no (S.D. Bamber), sw@iris.no (S. Westerlund).

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function as stores. Modelling of large-scale CO_2 leakages in this region has indicated the potential for substantial acidification close to release sites, with a reduction of up to −1.92 pH units reported (Phelps et al., 2015). Rapid dilution is likely to dissipate the effect relatively close to the sediment surface (centimetres to metres) due to ocean mixing (Blackford et al., 2014), but not before close contact with marine organisms living on or within the sediment has taken place. *Arctica islandica* is widely distributed throughout the North Sea, reaching densities of tens of thousands per 100 m^2 (Witbaard and Bergman, 2003). It typically lies buried just beneath the sediment surface, with short siphons supplying the gills with seawater that provides food and a conduit for respiratory gas exchange and removal of waste products (Morton, 2011). Recent research has described exceptionally long life spans of several hundred years for individuals in some populations of *A. islandica* (Gruber et al., 2014; Ridgway and Richardson, 2011), with lifestyle and physiological traits proposed as possible explanations for this longevity (Morton, 2011; Ridgway and Richardson, 2011).

The present study has recorded patterns in valve activity and burrowing behavior in *A. islandica* as a measure of their sensitivity to increased seawater acidification following exposure to laboratory based simulations of CO_2 leakages from sub-sea CCS. Behavior is a high-level biological function and when used as a measurement endpoint can provide a sensitive and rapid indication of response to environmental change, with the results often readily interpreted within an ecological context (Briffa et al., 2012). Water flow through bivalve molluscs is controlled in part by the position and movements of their valves. Closing the valves isolates the animal from the surrounding seawater, whilst maintenance of a stable gape distance can optimize the basal water flow generated by the beating cirri on the gills. Rapid valve closure and re-opening movements change the water pressure within the bivalve, creating a force that facilitates a rapid exhalent pumping action (Robson et al., 2009). Disruption to natural patterns of valve activity will clearly affect food supply and respiratory efficiency and this could have consequences for both the fitness of the affected individuals and for the wider ecosystem through diverse means such as interspecies interactions and habitat modification.

Several recent studies have reported effects of leakage from sub-sea CO_2 storage on various aspects of physiology and behavior in several bivalve species (Basallote et al., 2012; Dolores Basallote et al., 2015; Jakubowska and Normant-Saremba, 2015; Pratt et al., 2015; Rodriguez-Romero et al., 2014). However, to the best of the authors' knowledge, the sensitivity of the long-lived *Arctica islandica* to reduced seawater pH, at levels simulating CO_2 storage leakage scenarios, has not previously been investigated.

The objective of the research presented here was to use behavioral responses of *A. islandica* to establish its degree of sensitivity to simulated leakages of CO_2 from sub-sea storage reservoirs and from these findings ascertain whether the longevity of this bivalve affects its susceptibility to reduced pH seawater. Greater knowledge of the degree of potential impacts resulting from leakages will inform the current discussion on environmental safety of sub-sea geological CCS and will assist in interpreting data from monitoring activities, by calibrating chemical measurements from the field against biological response thresholds established in the laboratory.

2. Materials and methods

2.1. Collection and maintenance of animals

Two separate field collections of *A. islandica* were made from a site close to the entrance of Lysefjord in south west Norway, 55 km from the laboratory. Individuals were gathered by SCUBA diver from between 9 and 16 m water depth. In March 2013 40 *A. islandica* (77–90 mm shell length) were collected. The water temperature at collection depth was between 4 and 5 °C. The bivalves were immediately transported to the laboratory in seawater and transferred to a 144 l covered tank where they were held for 16 days prior to the start of the first experiment (Section 2.4). The tank was supplied with a constant flow of filtered seawater at 2 l/min pumped up from a depth of 75 m from the fjord adjacent to the laboratory (Byfjord, Randaberg). The ambient seawater temperature fed into the holding tank was 7 °C. In July 2013, a further 25 *A. islandica* (82–93 mm shell length) were collected, transported to the laboratory and transferred to a 144 l tank where they were held for 3 days prior to the start of the second exposure experiment (Section 2.5) and 14 days prior to the third experiment (Section 2.7). The water temperature at collection depth was 8 °C. The ambient temperature of filtered seawater fed into the holding tank varied between 8.5 and 10 °C over the course of the exposure experiment. The animals were not fed during the initial holding or experimental periods but were periodically provided with concentrated algae solution (Instant Algae, 1800 diet) on completion of the experimental treatments, until their eventual return to the fjord.

2.2. Measurement of valve movements

Movement between valves of individual *A. islandica* was continuously recorded throughout the exposure experiments using Hall effect proximity sensors. These sensors respond to magnetic field strength, with their output voltage changing in relation to distance from a magnetic source. A small neodymium magnet provided the magnetic field and was attached alongside the top left edge of the valve hinge on each individual using cyanoacrylate glue. Each bivalve was supported within a frame that ensured its orientation was close to its natural state in the field, with the siphons uppermost. This was achieved by attaching a support block to the side of the right valve using cyanoacrylate glue, which was in turn secured to a vertical support post using a stainless steel bolt (Fig. 1).

The Hall effect sensor (Farnell 179-1388) was prepared for underwater use (white tube in Fig. 1) and fixed within an adjustable

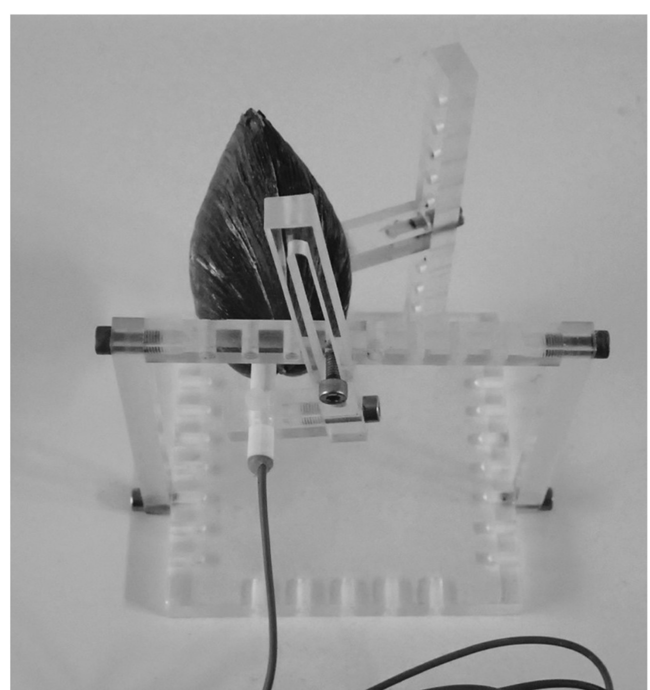

Fig. 1. *Arctica islandica* and Hall effect proximity sensor set within support frame.