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Deep-ocean, sediment-dwelling animals are sensitive to sequestered carbon dioxide

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ABSTRACT: The burning of fossil fuel is producing the greenhouse gas CO_2 at a rate that is causing global warming and threatens to change the global environment adversely. One proposed solution involves sequestering in the deep sea a substantial portion of the excess CO_2 produced. Because large areas would be affected and this environment harbors one of the world's largest reservoirs of biodiversity, the approach is controversial. In particular, deep-sea diversity is found largely in the animals that live in the sediment, but the effects of sequestered CO_2 on these organisms are not known. We therefore introduced ~60 l of liquid CO_2 onto the seafloor at 3250 m depth and sampled ~2 and ~40 m from the deposition site 30 d later. The pore water in the samples taken near the site was 0.75 pH unit more acidic (pH decreases when CO_2 concentration increases) than that in samples taken farther away. Representative infauna had been killed in significantly greater numbers in the former than in the latter location. This demonstration that sequestered CO_2 can adversely affect the deep-sea infauna brings CO_2 sequestration in the deep sea into potential conflict with the preservation of deep-sea biodiversity.

KEY WORDS: · Global warming · CO_2 sequestration · Deep sea · Benthic infauna · Harpacticoid copepods · Diversity

INTRODUCTION

Since the beginning of the industrial revolution, the concentration of CO_2 in the atmosphere has increased from 275 parts per million (ppm) to 370 ppm (Hoffert et al. 2002), and it continues to increase by ~1.5 ppm yr^{-1} (Herzog et al. 2000). Because CO_2 is a 'greenhouse' gas, the increasing concentration will exacerbate global warming. The ocean has a large capacity to absorb CO_2 and is being considered as a reservoir in which CO_2 could be sequestered (Glover & Smith 2003, Tyler 2003).

One strategy involves the collection of CO_2 before it enters the atmosphere and its injection into the deep ocean (Ormerod et al. 2002). Because large areas would be affected and the deep sea harbors one of the world's greatest reservoirs of biodiversity (Hessler & Sanders 1967, Grassle & Maciolek 1992, but see Lambshead & Boucher 2003), the approach is controversial. In particular, the bulk of metazoan biodiversity is concentrated in the invertebrate infauna (e.g. polychaete worms, bivalve mollusks, nematode worms, harpacticoid copepods; Lambshead 1993), but the ecological effects of sequestered CO_2 on these organisms are unknown (Glover & Smith 2003, Tyler 2003). Here, we present results of an experiment that examined the ecological effects of sequestered CO_2 on the infauna.

MATERIALS AND METHODS

At 3250 m depth off Monterey, CA, USA (36° 22.8' N, 122° 40.7' W), we transported CO_2 to the seabed with the remotely operated vehicle 'Tiburon' of the Monterey Bay Aquarium Research Institute and pumped approximately 20 l of liquid CO_2 into each of three

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48 cm diameter by 20 cm long plastic pipe segments ('corrals'), which had been set vertically into the seabed such that each formed a ring that extended ~10 cm into the overlying water. The liquid CO_2 was denser than seawater at this depth and formed a pool in each corral (Fig. 1). Thirty days later, we collected sediment cores (7 cm inner diameter) from an area ~2 m away from a corral (a region expected to have been exposed to CO_2-rich seawater) and from an area ~40 m away from the nearest corral, which should not have been influenced by the CO_2 additions (Fig. 2).

Because CO_2 concentration is difficult to measure at the spatial resolution we required, we used pH as a surrogate, as has been done in previous experimental work on CO_2 sequestration (Tamburri et al. 2000). Changes in CO_2 concentration change pH through the $CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$ equilibrium. We measured pH profiles in recovered cores using a Unisense® microelectrode (tip diameter = 100 µm) and an externally calibrated Knick® Portamess 913 pH meter. The microelectrode was mounted on a micromanipulator, and measurements were made at 250 µm intervals.

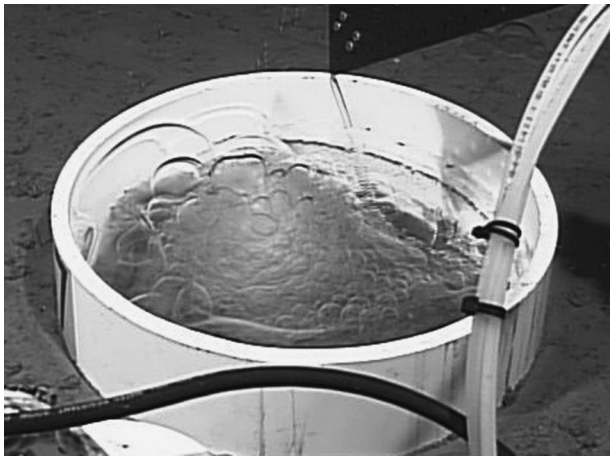

Fig. 1. The remotely operated vehicle 'Tiburon' filling a PVC corral (diameter = 48 cm) with liquid CO_2 at 3250 m depth off Monterey, CA, USA

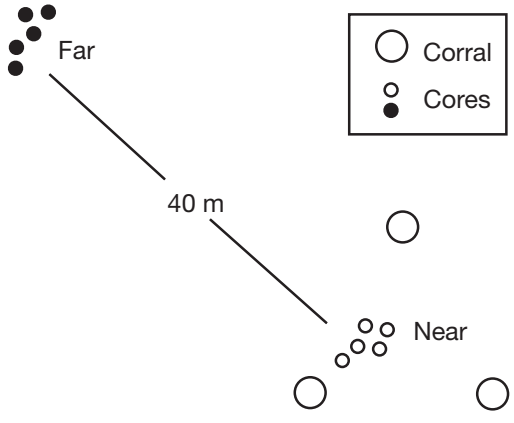

Fig. 2. Sketch (not to scale) of the sampling site, showing the relative positions of the corrals filled with CO_2, the locations cored 30 d later near the corrals in an area exposed to CO_2-rich seawater, and the locations cored far from the corrals in an area not exposed to CO_2-rich seawater. Corrals were separated by ~10 m

To test for effects on the infaunal invertebrates, we chose harpacticoid copepods as a representative taxon. These miniature crustaceans (body length <1 mm, dry weight <5 µg) are ubiquitous and abundant in sediment, and one can assess the condition of their internal organs by inspection through their transparent body walls.

So as to be able to determine whether individuals in our necessarily preserved samples had been dead or alive at the time of collection, we did a preliminary study. Two lots of 100 laboratory-cultured adults of the shallow-water harpacticoid copepod species *Amphiascoides atopus* Lotufo and Fleeger were killed by freezing because logistic limitations precluded their exposure to high concentrations of CO_2. One lot was exposed at our study site for 1 d and the second for 30 d before the specimens were preserved in formaldehyde. An investigator who did not know the origin of the specimen then examined each adult harpacticoid in lateral view under a compound microscope and scored the condition of its internal organs. From the results, we devised a 2-state criterion based on striated-muscle appearance by which specimens alive or very recently dead when collected could be reliably distinguished from specimens that had been dead for many days. This approach assumed that the striated muscles of specimens of *A. atopus* and the deep-sea species at our site were in similar condition when preserved alive. We made this assumption because, in previous work, we have examined many specimens from both shallow water and the deep sea that had been preserved alive and have found that their striated muscles were in comparable condition.

RESULTS

When we returned after 30 d, no CO_2 was visible in the corrals or on the seabed adjacent to them. (Liquid CO_2 could be seen because its refractive index differs from that of seawater, Fig. 1.) The pH profiles revealed that, on average, the pore water of cores taken near a corral was ~0.75 pH unit more acidic than that of cores taken far from corrals and that the profiles from the 2 groups of cores did not overlap (Fig. 3).

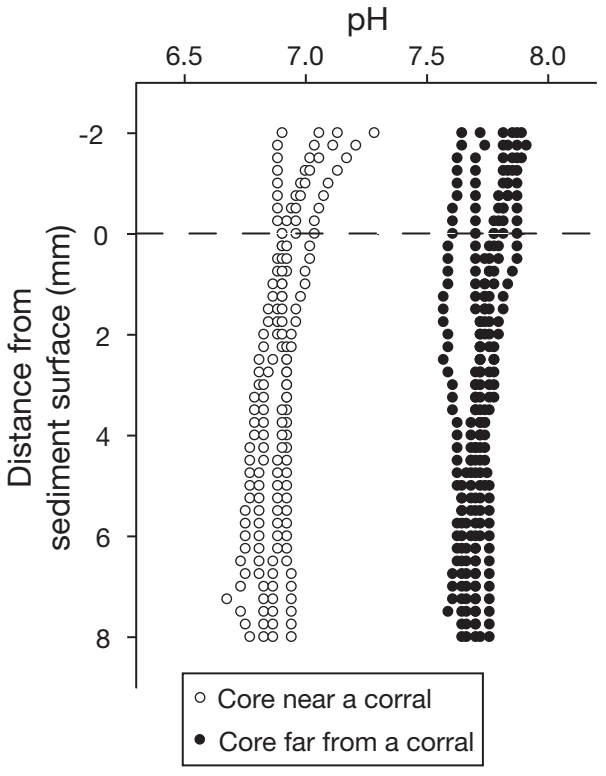

Fig. 3. Profiles of pH from 2 mm above the sediment surface to 8 mm below showing that the pH in the cores from near (~2 m) the corrals was lower than that in those taken far (~40 m) from the corrals

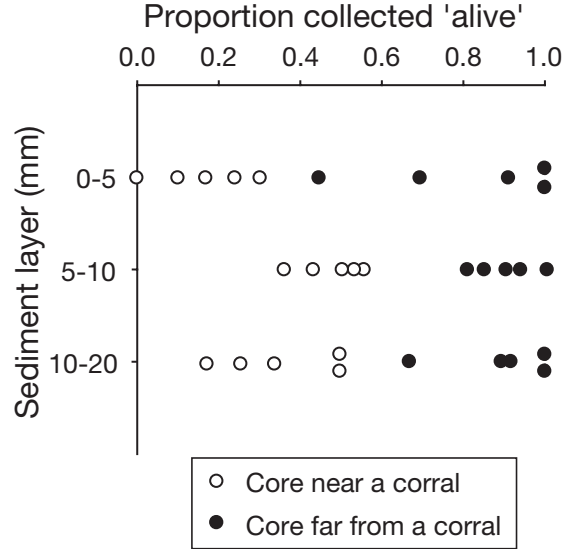

Fig. 4. Average proportion of adult harpacticoids that were 'alive' at the time of collection in samples from 3 sediment horizons, showing that a lower proportion were 'alive' at the time of collection in samples taken near (~2 m) the corrals than in samples taken far (~40 m) from the corrals. When 2 corrals had the same value, their points were plotted one above the other. Our definition of 'alive' is given in the text

For each of 3 sediment layers, the proportion of the individuals scored by our 2-state criterion as 'alive' when collected was significantly lower in the samples taken near the corrals than in samples taken far from the corrals (Fig. 4, $p < 0.003$, 2-tailed test, resampling statistics, Simon 1999).

DISCUSSION

Although the lack of a vertical gradient in our pore-water pH profiles revealed that some mixing had occurred during recovery and handling, the pore water was consistently more acidic in the cores taken near the corrals than in those taken farther away. The difference was far greater than reported natural variability (~0.1 pH unit, Ormerod et al. 2002) or the variability among profiles from the cores collected far from the corrals (Fig. 3). We infer that CO_2 dissolved into the near-bottom water and that CO_2-rich seawater flowed out of the corrals and across the surrounding seabed. Near the corrals, it reduced the pH of the pore waters. We infer that, 40 m from its source, it was much diluted and that, if it affected the pH of the pore water, the effect was much less than that near the source. Whatever the mechanism, we succeeded in subjecting infaunal organisms to different CO_2 concentrations.

Although relatively little is known about the effects of elevated CO_2 concentrations or reduced pH on them, deep-sea animals are adapted to stable CO_2 concentrations and pH and have much less buffering capacity than do shallow-water species. Even slight changes in pH are thought to have important influences on metabolic activities (Seibel & Walsh 2003), and acidification has been shown to extirpate an invertebrate population in a lake (France & Collins 1993). Our results suggest that exposure to CO_2-rich seawater resulted in the deaths of many harpacticoids and presumably other infauna. Because the intensity of exposure to CO_2-rich seawater was unlikely to have been constant during the 30 d between injection and sampling, we do not know the dose and duration that caused the deaths.

From the same experiment we describe here, Carman et al. (2004) showed that exposure to CO_2-rich seawater did not influence total abundances or vertical distributions of benthic invertebrate taxa. Only by closer examination of harpacticoid condition were we able to detect an effect of CO_2 exposure.

Determination of the environmental effects of CO_2 sequestration on infaunal species will require both a quantitative understanding of how death and illness relate to exposure to CO_2-rich seawater and knowledge of the spatial extent of the effects. In particular, if the areas in which mortality approaches 100% are

similar in size to the geographic ranges of deep-sea infaunal species, sequestration could result in species extinctions and the reduction of deep-sea biodiversity. This scenario is plausible because many deep-sea species appear to have small geographic ranges (Grassle & Maciolek 1992).

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