Final Report for DoE grant # FG0204-ER63721**,** ***Direct Experiments on the ocean disposal of fossil fuel CO_2***

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Summary of Activities

Funding from DoE grant # FG0204-ER63721, *Direct Experiments on the Ocean Disposal of Fossil Fuel CO2*, supposed several postdoctoral fellows and research activities at MBARI related to ocean CO2 disposal and the biological consequences of high ocean CO2 levels on marine organisms. Postdocs supported on the project included Brad Seibel, now an associate professor at the University of Rhode Island, Jeff Drazen, now an associate professor at the University of Hawaii, and Eric Pane, who continues as a research associate at MBARI. Thus, the project contributed significantly to the professional development of young scientists. In addition, we made significant progress in several research areas. We continued several deep-sea CO2 release experiments using support from DoE and MBARI, along with several collaborators. These CO2 release studies had the goal of broadening our understanding of the effects of high ocean CO2 levels on deep sea animals in the vicinity of potential release sites for direct deep-ocean carbon dioxide sequestration. Using MBARI ships and ROVs, we performed these experiments at depths of 3000 to 3600 m, where liquid CO2 is heavier than seawater. CO2 was released into small pools (sections of PVC pipe) on the seabed, where it dissolved and drifted downstream, bathing any caged animals and sediments in a CO2-rich, low-pH plume. We assessed the survival of organisms nearby. Several publications arose from these studies (Barry et al. 2004, 2005; Carman et al. 2004; Thistle et al. 2005, 2006, 2007; Fleeger et al. 2006, 2010; Barry and Drazen 2007; Bernhard et al. 2009; Sedlacek et al. 2009; Ricketts et al. in press; Barry et al, in revision) concerning the sensitivity of animals to low pH waters. Using funds from DoE and MBARI, we designed and fabricated a hyperbaric trap-respirometer to study metabolic rates of deep-sea fishes under high CO2 conditions (Drazen et al, 2005), as well as a gas-control aquarium system to support laboratory studies of the effects of high CO2 waters on marine animals (Barry et al. 2008). This system is capable of controlling oxygen, pH, and temperature of seawater for use in studies of the physiological responses of animals under acidified conditions. We have investigated the tolerance of deep- and shallow-living crabs to high CO2 levels (Pane and Barry 2007; Pane et al. 2008), and are now working on brachiopods (Barry et al. in prep.) and a comparison of deep and shallow living sea urchins. This research program, supported in part by DoE has contributed to a number of other publications authored or co-authored by Barry (Caldeira et al. 2005; Brewer and Barry 2008; Barry et al. 2006, 2010a,b,c; National Research Council, in press; Hoffman et al. in press) as well as over 40 invited talks since 2004, including Congressional briefings and testimony at U.S. Senate Hearings on Ocean Acidification.

Through the grant period, the research emphasis shifted from studies of the effects of direct deep-sea carbon dioxide sequestration on deep-sea animals, to a broader conceptual framework of the effects of ocean acidification (whether purposeful or passive) on the physiology and survival of deep and shallow living marine animals. We feel that this has been a very productive program and are grateful to DoE for its support.

Annotated Bibliography

- 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. Sensitivity of deep-sea animals to a high-CO2 ocean. *Marine Ecology Progress Series*, (in revision).
    - Results of deep-sea CO2 release experiment indicating that episodes of a -0.2 unit pH change can have important effects on the survival of lower invertebrates, but is less impactful for cephalopods and fishes. National Research Council Panel (J. Barry – member), (in press). Ocean Acidification: A national strategy to meet the challenges of a changing ocean. The Nat. Acad. Press, Washington, D.C.
- Barry, J.P. and Hall-Spencer, J. (in press) In *situ* perturbation experiments on ocean acidification. Chapter 2.6 in, *Best Practices for Ocean Acidification Research,* Geo-Mar.
    - Guide for methods concerning ocean acidification research
- Barry, J.P., Tyrrell, T., Hansson, L., Gattuso, J-P. (in press). Atmospheric CO2 targets for ocean acidification perturbation experiments. Chapter 2.1 in, *Best Practices for Ocean Acidification Research,* Geo-Mar.
    - Guide for methods concerning ocean acidification research
- Hofman, G.E., Barry, J.P., Edmunds, P.J., Gates, R.D., Hutchins, D.A., Klinger, T., Sewell, M.A. (in press). The effects of ocean acidification on polar, tropical and temperate marine calcifying organisms: an organism to ecosystem perspective. *Ann. Rev. of Ecol. & Systematics*
    - Literature review concerning the effects of ocean acidification on marine animals with calcium carbonate skeletal elements
- Ricketts, E.R., Kennett, J.P., Hill, T.M., and Barry J.P. (in press). Effects of CO_2 hydrate emplacement on deep-sea foraminiferal assemblages: 3600 m on the California Margin. *Mar. Micropaleontology*
    - Results of deep-sea CO2 release experiment concerning the effects on benthic foraminifera
- Fleeger, J.W., Johnson, D.S., Carman, K.R., Weisenhorn, P.B., Gabriele, A., Thistle, D., Barry, J.P. (2010). The response of nematodes to deep-sea CO2 sequestration: A quantile regression approach. Deep-Sea Res. I, 57:696-707.
    - Results of deep-sea CO2 release study on benthic nematodes.
- Bernhard, J.M., Barry, J.P., Buck, K.R., Starczak, V.R. (2009) Impact of intentionally injected carbon dioxide hydrate on deep-sea benthic foraminiferal survival. *Global Change Biology,* doi: 10.111/j.1365-2486.2008.01822.x
    - Results of deep-sea CO2 release study on benthic foraminifera
- Sedlacek, L., Thistle, D., Carman, K.R., Fleeger, J.W., Barry, J.P. (2009). Effects of carbon dioxide on deep-sea harpacticoids revisited. *Deep-Sea Res. I,* **56**: 1018-1025.
    - Results of deep-sea CO2 release study on benthic meiofauna
- Pane, E.F., Grosell, M., Barry J.P. (2008). Comparison of enzyme activities linked to acid-base regulation in a deep-sea and a sublittoral decapod crab species. *Aquatic Biology*, **4**: 23-32.
    - Laboratory comparison of deep and shallow living crab physiology during exposure to high CO2 levels.
- Barry, J.P., Lovera, C., Okuda, C., Nelson, E., Pane, E.F. (2008) A gas-controlled aquarium system for ocean acidification studies. *IEEE Xplore*, 978-4244-2126-08/08
    - Description of our gas-control CO2, O2, and temperature regulated aquarium system
- Barry, J.P. & J.C. Drazen (2007). Response of deep-sea scavengers to mild hypercapnia and the odor from a dead grenadier. *Marine Ecology Progress Series*, **350**: 193-207.
    - Results of deep-sea CO2 release study on bentho-pelagic fishes and cephalopods

- Pane, E.F., Barry, J.P. (2007). Extracellular acid-base regulation during short-term hypercapnia is effective in a shallow-water crab, but ineffective in a deep-sea crab. *Mar. Ecol. Prog. Ser.,* **334**:1-9.
    - Laboratory study of the physiological responses of deep and shallow living crabs to ocean acidification.
- Caldeira, K, Archer, D., Barry, J.P., Bellerby, R., Brewer, P., Cao, L, Dickson, A.G., Doney, S.C., Elderfield, H., Fabry, V., Feely, R.A., Gattuso, J.P., Hoegh-Guldberg, O., Haugan, P.M., Kleypas, J.A., Langdon, C., Orr, J.C., Ridgwell, A., Sabine, C.L., Seibel, B., Turley, C., Watson, A., Zeebe, R. (2007). Comment on "Modern-age buildup of CO_2 and its effects on seawater acidity and salinity" *Geophysical Res. Letters,* **34**, L18608, doi:10.1029/2006GL027288
    - Group rebuttal to a model of expected ocean pH conditions due to human CO2 emissions.
- Thistle, D., Sedlacek, L., Carman, K.R., Fleeger, J.W., Barry, J.P. (2007). Emergence in the deep-sea: evidence from harpacticoid copepods. *Deep-Sea Research*, **54**: 1008-1014
    - Results of deep-sea CO2 release study on benthic harpacticoid copepods – the focus here was not on CO2, but on harpacticoid biology
- Thistle, D., Sedlacek, L., Carman, K.R., Fleeger, J.W., Brewer, P.G., Barry, J.P. (2007). Exposure to carbon dioxide-rich seawater is stressful for deep-sea species: an in situ, behavioral study. *Mar. Ecol. Prog. Ser.*, **340**: 9-16.
    - Results of deep-sea CO2 release study on benthic meiofauna
- Fleeger, J.W., Carman, K.R., Weisenhorn, P.B., Sofranko, H., Marshall, T., Thistle, D., and Barry, J.P. (2006). Simulated sequestration of anthropogenic carbon dioxide at a deep-sea site: effects on nematode abundance and biovolume. *Deep-Sea Research I,* 53: 1135-1147.
    - Results of deep-sea CO2 release study on benthic nematodes
- Thistle, D., Sedlacek, L., Carman, K.R., Fleeger, J.W., Brewer, P.G., Barry, J.P. (2006). Simulated sequestration of anthropogenic carbon dioxide at a deep-sea site: effects on harpacticoid-copepod species. *J. Exp. Mar. Biol. Ecol*., 330: 141-158
    - Results of deep-sea CO2 release study on benthic meiofauna
- Barry, J.P., Buck, K.R., Lovera, C., Kuhnz, L, Whaling, P.J. (2005) Utility of deep-sea CO_2 release experiments in understanding the biology of a high CO_2 ocean: Effects of hypercapnia on deep-sea meiofauna. *Journal of Geophysical Research, Oceans*, 110, C09S12.
    - Summary of several deep-sea CO2 release studies, evaluating how useful this method is and summarizing some of the results concerning benthic meiofauna.
- Drazen, J.C., Bird, L.E., Barry, J.P. 2005. Development of a hyperbaric trap-respirometer for the capture and maintenance of live deep-sea organisms. *Limnol. and Ocean. Methods,* 3, 48849
    - Methods paper describing the development of our deep-sea fish trap respirometer.
- Caldeira, K., Brewer, P.G., Chen, B., Hansen, L., Haugan, P., Iwama, T., Johnston, P., Kheshgi, H., Li, Q., Ohsumi, T., Poertner, H., Sabine, C., Shirayama, Y., Thomson, J. (authors), Barry, J.P. (contributing author) (2005). Chapter 6: Ocean Storage. In *IPCC Special Report on Carbon Dioxide Capture and Storage*, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge
    - Chapter on ocean storage of carbon dioxide for the IPCC.
- Thistle, D., Carman, K.R., Sedlacek, L., Brewer, P.G., Fleeger, J.W., Barry, J.P. (2005) Deep-ocean, sediment-dwelling animals are sensitive to sequestered carbon dioxide. *Mar. Ecol. Prog. Ser.*, 289: 1-Ricketts, E.R., Kennett, J.P., Hill, T.M., and Barry, J.P (2005). Effects of CO2 hydrate on deep-sea foraminiferal assemblages. Proceedings of the Fifth International Conference on Gas Hydrates, Trondheim, Norway, 3, (3020): 839-847.
    - Results of deep-sea CO2 release study on benthic meiofauna

- Barry, J.P., Kurt R. Buck, Chris F. Lovera, Linda Kuhnz, Patrick J. Whaling, Edward T. Peltzer, Peter Walz, and Peter G. Brewer (2004) Effects of Direct Ocean CO2 Injection on Deep-Sea Meiofauna. *Journal of Oceanography*, 60: 759-766
    - Results of deep-sea CO2 release study on benthic meiofauna
- Carman, K.R., Thistle, D., Fleeger, J., Barry, J.P. (2004) The influence of introduced CO2 on Deep-Sea metazoan meiofaunal, *Journal of Oceanography*, 60(4): 767-772
    - Results of deep-sea CO2 release study on benthic meiofauna