INL/CON-12-24585
PREPRINT

Sub-Seafloor Carbon Dioxide Storage Potential on the Juan de Fuca Plate, Western North America

11th International Conference on Greenhouse Gas Control Technologies

Jerry Fairley
Travis McLing
Robert Podgorney

November 2012

Sub-Seafloor Carbon Dioxide Storage Potential on the Juan de Fuca Plate, Western North America

Jerry Fairley[1,2] Travis McLing[1,3], and Robert Podgorney[1,3]

[1]Center for Advanced Energy Studies, Idaho Falls, ID, USA
[2]University of Idaho, Moscow, ID, USA
[3]Idaho National Laboratory, Idaho Falls, ID, USA

ABSTRACT

The Juan de Fuca plate, off the western coast of North America, has been suggested as a site for geological sequestration of anthropogenic carbon dioxide because of its many attractive characteristics (high permeability, large storage capacity, reactive rock types). Here we model CO_2 injection into fractured basalts comprising the upper several hundred meters of the sub-seafloor basalt reservoir, overlain with low-permeability sediments and a thick saline water column, to examine the feasibility of this reservoir for CO_2 storage. Our simulations indicate that the sub-seafloor basalts of the Juan de Fuca plate may be an excellent CO_2 storage candidate, as multiple trapping mechanisms (hydrodynamic, density inversions, and mineralization) act to keep the CO_2 isolated from terrestrial environments. Questions remain about the lateral extent and connectivity of the high permeability basalts; however, the lack of wells or boreholes and thick sediment cover maximize storage potential while minimizing potential leakage pathways. Although promising, more study is needed to determine the economic sociological viability of this option.

INTRODUCTION

Although it is likely that the stabilization of CO_2 concentrations in the atmosphere will require a variety of technical and social solutions, large-scale geologic sequestration of anthropogenic CO_2 may be the most important. In their report the Working Group III of the Intergovernmental Panel on Climate Change (IPCC 2005) states that geologic storage of anthropogenic CO_2 can make a significant contribution to stabilizing atmospheric CO_2 levels. Because many of these natural reservoirs are known to have stored fossil fuels, naturally occurring CO_2,and other fluids over geologic time frames. Research to date has largely concentrated deep saline aquifers, and depleted oil/gas reservoirs as targets for geologic storage of CO_2. In recent years, storage of CO_2 in mafic/ultramafic rocks has received increased attention (Goldberg et al., 2008; Schaef and McGrail, 2009; Smith et al., 2004). The mineralogy of rocks gives them a significant potential to rapidly mineralize CO_2 into stable secondary minerals, which increases the potential for the long-term sequestration of CO_2 through mineral trapping. Basalt is the most common rock type in the earths crust, with large occurrences suitable for sequestration occurring as large igneous provinces (LIPs) representing voluminous eruptions of mafic (iron- and magnesium-rich) magmas. The basalts minerals in these formations are rich in base cations (Ca^{2+}, Mg^{2+}, Fe^{2+}, etc) that are necessary for the conversion of CO_2 into stable secondary phases primarily carbonates. Oceanic crust or deep-sea basalt makes up the largest volume of mafic rocks on the earth. Because of the abundance of deep-sea basalt these formations represent a significant global opportunity for large-scale CO_2 sequestration.

The emplacement of these basalts basalt at volcanic ridges into seawater forms pillow lavas , which have high permeability zones at the contacts between flows. As new oceanic crust forms, older flows are carried away from the active eruptive centers, the youngest basalts are found nearest the mid-ocean ridges and get progressively older the farther from one gets from the eruptive centers. Through time, these basalts are subsequently overlain by deep-sea sediments, creating zones of high permeability within the basalts, which are sealed by an impermeable cap of sediment. Creating reservoirs of high permeability basalt that are 500-600 meters thick, which have been proposed to be a suitable target for CO_2 storage (Goldberg et al., 2008).

The subject of this study is the Juan de Fuca plate, shown in Figure 1, located near the west coast of Vancouver Island, Oregon, and Washington. Previous studies and ocean drilling research have confirmed that the Juan de Fuca plate contains interconnected zone of high permeability and porosity up to 20% in the pillow basalts (Fisher et al., 2005), with sealed impermeable fine-grained sediments (Davis and Becker, 1998; Davis and Becker, 1997). In this study, we examined some of the technical factors that are associated with this method of disposal.

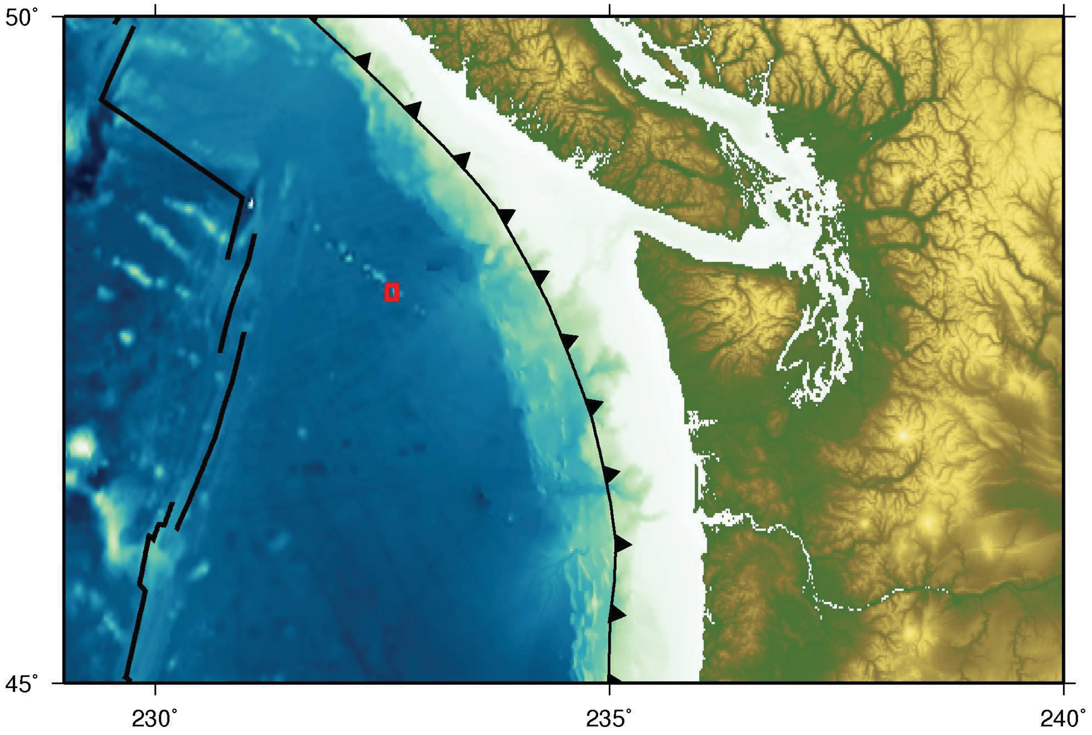

Figure 1: The area shown in the red box above indicates the location of investigations by the IODP (i.e., IODP 301 and IODP 327). The study area is a subset of the area shown here.

APPROACH

Basalts of all types present difficulties for numerical modelers because of their bimodal permeability distribution, in which the two modes vary by orders of magnitude. More specifically, basalt flow sequences can be conceptualized as comprising a very low permeability matrix that is ubiquitously perturbed with fractures that vary dramatically in both permeability and connectivity. This "strong" heterogeneity (i.e., contrasting permeability domains that differ by several orders of magnitude) is a key feature that must be accounted for in any realistic determination of the potential for geologic sequestration of carbon dioxide in basalts. In the case of the Juan de Fuca plate injection studied here, an additional feature of the potential reservoir is the thickness of low permeability sediments (the "cap") that overlies the fractured basalt.

Although both the strong heterogeneity of the basalt pile itself and the overlying thickness of low permeability sediments should be accounted for in a realistic assessment of the potential of the Juan de Fuca basalts as a geologic repository for anthropogenic CO_2, practical difficulties do not permit a detailed representation of either type of heterogeneity. The primary reason for this is the relative inaccessibility of the site, and attendant paucity of data regarding such critical aspects of the conceptual model as the spatial distribution of permeability and its connectivity, the continuity of high permeability features over long distances, the degree of anisotropy of the basalt in the ridge-parallel versus ridge-normal directions, the variability in thickness of the sediment cover, etc. Some of these features are critical to correctly portraying the hydraulic structure of the proposed reservoir; for example, Fisher et al. (1994) and Hutnak et al. (2006) presented interesting simulations suggestive of long-range connectivity of high permeability zones that would make injection both attractive (because of the large storage volumes and high injectivity of the formation) and require caution (to plan the injections in such a way as to minimize the potential for leakage).

In the presence of such uncertainty regarding the structure of the reservoir, we opted for an approach that utilizes the available data while acknowledging the relative lack of reservoir-specific data (that is, in comparison with a land-based reservoir). In the case of the overlying sediments, a certain amount of data is available on sediment thickness, elevations of the sediment/basement contact, etc., from seismic studies reported in Davis et al. (1997). We used the reported data to develop a kriged isopach map of sediment thickness in the area of the hypothetical test injection. Kriging is a minimum error, unbiased estimator of a spatially correlated random variable (e.g., Deutsch and Journel, 1998); as such, it gives the most likely estimate of the variable (in this case, sediment thickness) at a given point. However, kriging does not provide the full range of variability that would be expected in a field situation--instead, kriging provides a smoothed representation of the underlying generating process that honors the data at known points and minimizes error of estimate at unsampled locations. We used our kriged isopach (sediment thickness) map to provide a deterministic sediment thickness overlying the fractured basalt reservoir; that is, we assumed the thickness of sediment over the basalt/sediment contact was "known" and given by the kriging estimates. Topographic contours for the top of basalt and the sea floor interpolated from the Davis et al. (1997) data are shown in Figure 2; maps and cross-sections of our inferred sediment thicknesses are shown in Figure 3.

For the heterogeneity of the fractured basalt reservoir we took a different approach. Some data were available from a series of sea floor-based well tests at site 1301 (see Fisher et al 2008, for details) and in other areas. In addition, single hole and cross hole testing reported in the Preliminary Report: Integrated Ocean Drilling Program Expedition 327 showed apparent strong anisotropy, with higher permeability parallel to the ridge and lower permeabilities normal to the ridge. To honor these observations while still including the effect of strong and spatially-correlated permeability, we used a model of spatial correlation for low volume basalt flows proposed by Pollyea and Fairley (2011) for the East Snake River Plain (Figure 4).

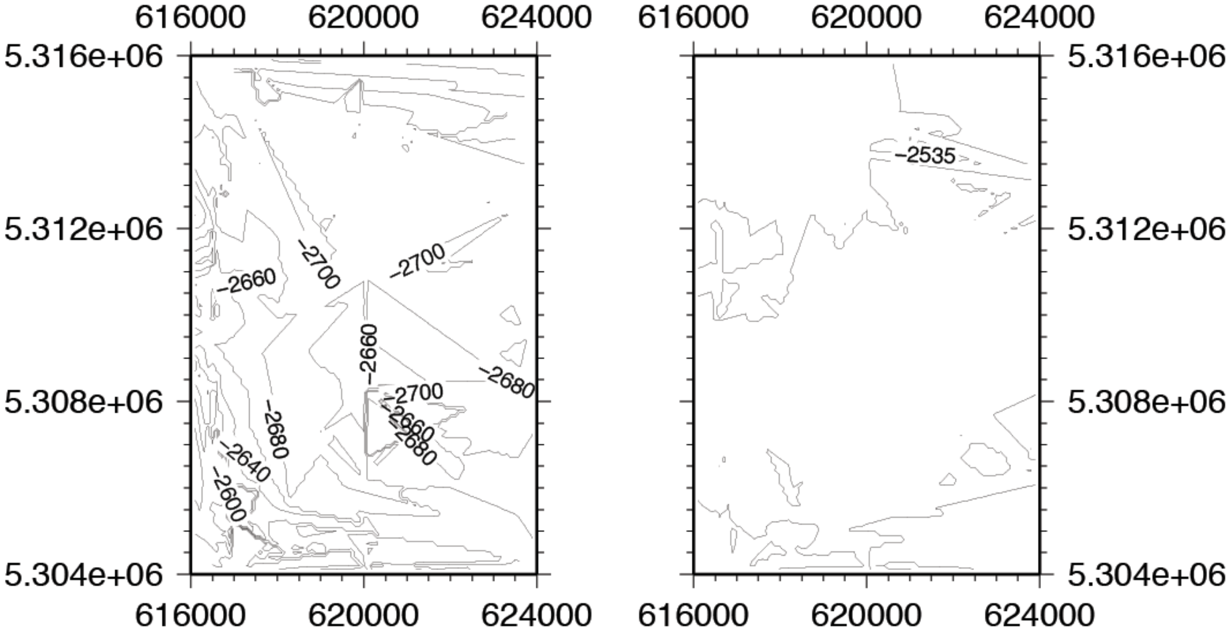

Figure 2: (Above left) Topographic contours of basalt bedrock as inferred from seismic data from Leg 168, (Above right) Bathymetric map of seafloor in the study area (contours shown in m asl). Data and bedrock picks from Davis et al. (1997).

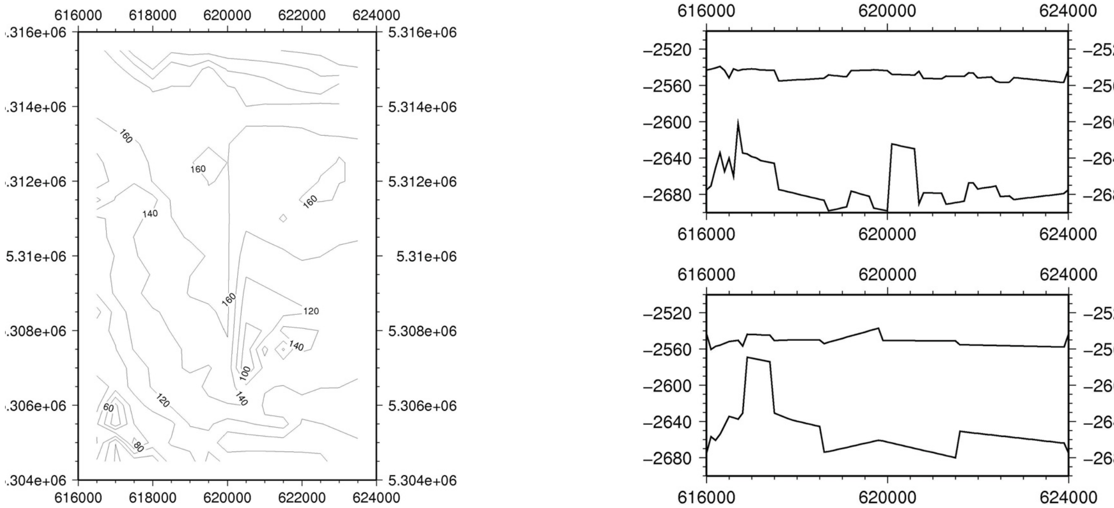

Figure 3: Maps and cross sections showing distribution of sediments in model domain. (Above left) Sediment isopach map. Isopachs were calculated by differencing the data presented in Figure 2. (Above right) Cross-sections through two portions of the model domain, showing uneven sediment coverage.

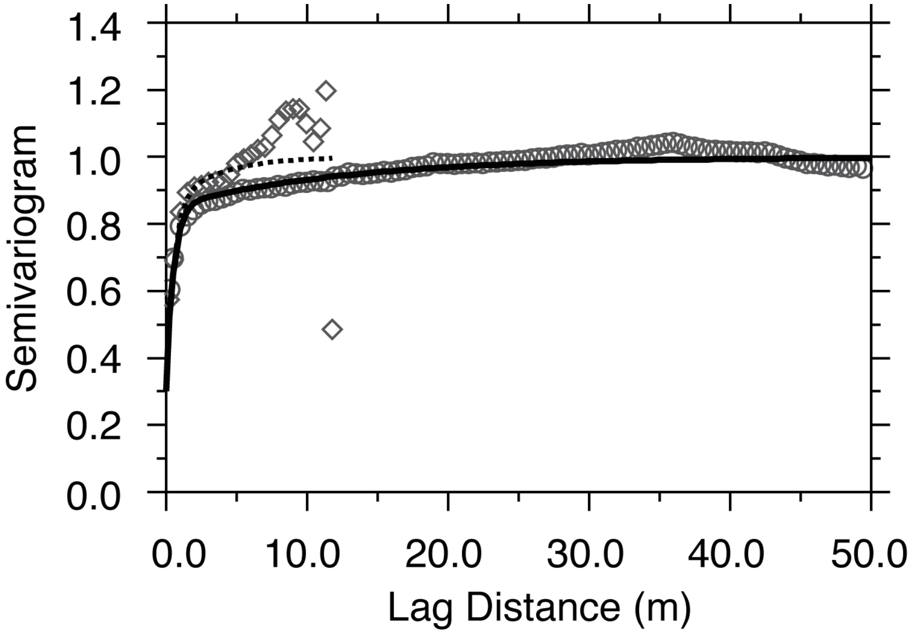

Figure 4: Two-dimensional anisotropic semivariogram of fracture distributions from data collected on cross-sectional exposures from low-volume basalt flows in the East Snake River Plain, Idaho (Pollyea and Fairley, 2011). Maximum spatial continuity is horizontal, which is modeled (solid line) as a linear combination of a nugget effect (0.3) and two exponential structures (practical range is 36.1m). The direction of minimum spatial continuity is vertical, which is modeled (dashed line) as a linear combination of a nugget effect (0.3) and two exponential structures (practical range is 9.5 m).

In addition to the horizontal/vertical anisotropy observed in the ESRP basalts, we included a 5:1 hoizontal anisotropy, with the direction of maximum continuity ridge-parallel. Using the variograms of Pollyea and Fairley (2011; Figure 4), we generated 100 equally-probable realizations of heterogeneous, low-volume basalt flows and used these realizations to populate our model grid. The property sets were truncated at the basalt-sediment contact, and the uniformly low-permeability sediment cover was used for the top layers of the model.

We modeled injections of supercritical CO_2 at a rate of 21.6kg/s using TOUGH-MP (Zhang et al., 2008). We chose an injection rate of 21.6kg/s for consistency and ease of comparison with previous work (e.g., Pollyea and Fairley, 2012); the chosen rate is about half the CO2 emission that would be expected from a moderate-sized coal-fired power plant. The models were set to run for 1 and 5-year injection periods; an example of some types of behavior observed in the individual simulations is shown in Figure 5. To better understand the overall behavior and range of uncertainty that could be expected from the system, we also examined the aggregate results (i.e., “e-type estimates”), which are displayed in Figure 6).

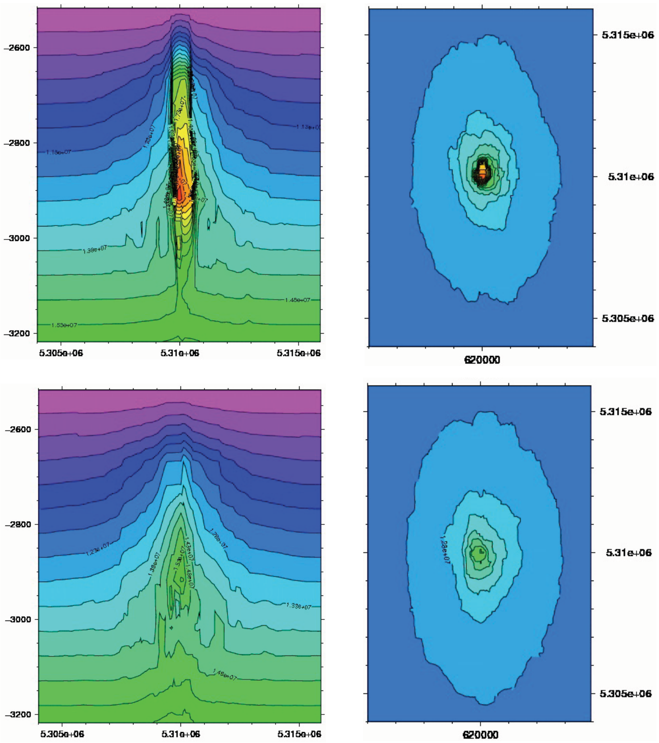

Figure 5: Cross-sections (left images) and map-view (right images) through the injection point for two representative simulations (top and bottom, respectively), after 1 year of injection. These simulations were chosen to illustrate the range of responses that may be encountered, depending on the local heterogeneity in the vicinity of the injection point.

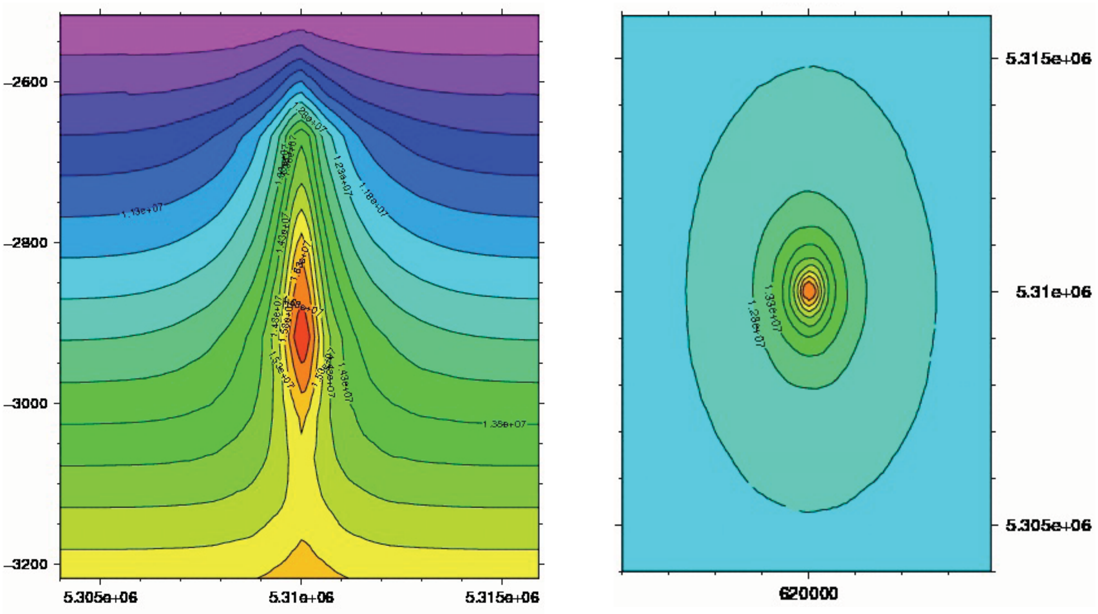

Figure 6: E-type estimates of pressure from the 74 simulations that ran to 1 year of injection time. An e-type estimate is the block-by-block mean, calculated from a series of Monte Carlo simulations, and thus represents a smoothed (averaged) representation of the heterogeneous cases.

The figure on the left is a vertical cross-section; to the right is a map-view. Note the alignment on the map view with the axes of anisotropy.

RESULTS AND CONCLUSIONS

The simulations showed remarkable pressure buildup after only one year of injection (Figure 5). At the end of the first year of injection, 74% of the simulations ran to term while the remaining 26% halted execution due to near-borehole pressure buildup. By five years of injection, 98% of the simulations halted execution due to excessive pressure. In none of the simulations did carbon dioxide escape the low permeability sediments at or before 1 year of simulation time; for longer runs, gas buoyancy and mechanical disruption of the overlying sediments (indirectly tested in this study) are serious concerns for maintaining reservoir integrity. The actual potential for CO_2 to escape the sediment is highly dependent on permeability distribution local to the injection point; for example, injection into a fracture zone that concentrates pressure build-up beneath the sediments (Figure 5, top) is more likely to lead to escape than a more diffuse pressure profile (Figure 5, bottom). However, only two of the five-year simulations showed apparent leakage that lowered pressures within the reservoir sufficiently to allow the simulations to continue for the full five-year period. The implication is that the simulations showed 98% containment of the CO_2, but this was a very small sample (N=100) and the results are probably heavily dependent on the distribution of permeability in the reservoir.

The simulations demonstrated relatively small perturbations to the subsurface temperature and gas saturation (results not shown), in contrast to the pressures observed. This problem has also been noted in the context of supercritical carbon dioxide injections in sedimentary basins and depleted petroleum reservoirs. The question of pressure management in CO_2 sequestration reservoirs has long been a topic of discussion.

The need for pressure management suggests that "actively managed" CO_2 storage strategies, such as those suggested for saline petroleum reservoirs (Buscheck et al., 2010), could be applied so as to sequester carbon dioxide and co-produce relatively high enthalpy fluids for electrical power generation, given the low rejection temperatures at the sea floor. If practical, this could improve the economics of submarine carbon sequestration proposals.

REFERENCES CITED

Buscheck, T.A., et al., 2010. Energy Procedia 4:4283-4290.

Davis, E.E., Fisher, A.T., Firth, J.V., et al., 1997. Proc. ODP Init. Repts., 168: College Station, TX. DOI:10.2973/odp.proc.ir.168.1997.

Davis, E., and Becker, K., 1998. Borehole observatories record driving forces for hydrothermal circulation in young oceanic crust. *Eos,* 79:369, 377–378.

C.V. Deutsch and A.G. Journel, 1998, *GSLIB: Geostatistical Software Library and User's Guide, Second Edition*, Oxford University Press, 369 page

Fisher, A.T., Urabe, T., Klaus A., and the IODP Expedition 301 Scientific Party (2005a), Proceedings of the Integrated Ocean Drilling Program, vol. 301, doi:10.2204/iodp. proc.301, Ocean Drill. Program, College Station, Tex.

Fisher, A. T., Becker, K., Davis, E. E., Borehole-to-borehole hydrologic response across 2.4 km in the upper oceanic crust: implications for crustal scale properties, *J. Geophys. Res.*, 113, doi:10.1029/2007JB005447, 2008.

Goldberg, D.S., Takahashi, T., Slagle, A.L., 2008. Proc. Nat. Acad. Sci. 105(29):9920-9925.

Hutnak, M., Fisher, A.T., et al., 2006. Geochem. Geophys. Geosystems 7(7):1525-2027: DOI:10.1029/2006GC001242.

Working Group III of the Intergovernmental Panel on Climate Change (2005) IPCC Special Report on Carbon Dioxide Capture and Storage, eds Metz B, Davidson O, de Coninck HC, Loos M, Meyer LA (Cambridge Univ Press, New York)

Pollyea, R.M., Fairley, J.P.,2011. Geology 39(7):623-626. DOI:10.1130/G32078.1

Pollyea, R.M., Fairley, J.P., 2012. Hydrogeology Journal 20:689-699. DOI:10.1007/s10040-012-0847-1.

Schaef H.T., andMcGrail, B.P., 2009. "Dissolution of Columbia River Basalt Under Mildly Acidic Conditions as a Function of Temperature: Experimental Results Relevant to the Geological Sequestration of Carbon Dioxide." Applied Geochemistry 24(5):980-987.

Smith, R.W., T.L., McLing, W. Barrash, and W.P. Clement. 2004. “Geologic Sequestration of CO2: A Uniform Strategy for Assessing Mineralization Trapping Potential Across Rock Types.” Proceeding of the Third Annual Conference on Carbon Capture and Sequestration, Alexandria, VA, May 4, 2004.

Zhang, K., Wu, Y.-S., Pruess, K., 2008. LBNL-315E.