Potential for Permanent CO_2 Sequestration in Sub-Bottom Oceanic Basalt

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Abstract

Ridge-flank basalt aquifers offer a unique scientific and technical opportunity for long-term sequestration of CO_2. We investigate the potential for injection testing on the flank of the Juan de Fuca ridge, approximately 250 km west of Seattle. The ocean crust offers three explicit advantages over other potential sequestration targets: (1) it has a potential geological capacity large enough to accommodate a major portion of ~22 billion tons/yr of fossil fuel CO_2 (6 Gt-C/yr) which is produced globally; (2) the chemical reaction of CO_2 with basalt will produce $(Ca,Mg,Fe)_2\ CO_3$ infilling minerals, permanently sequestering carbon in a chemically stable and non-toxic form; and (3) physical traps for potential CO_2 leakage below thick impermeable sediments and 2.5 km of cold ocean water. Based on laboratory and land-based field experiments, the rates of basalt dissolution and carbonate precipitation reactions are efficient. Recent studies from the Integrated Ocean Drilling Program suggest that deep basaltic aquifers on the eastern flank of the Juan de Fuca ridge offer large volumetric capacities, warm temperatures to facilitate CO_2-basalt reactions, high permeability and sufficiently closed water-rock circulation pathways, long fluid retention times, and pre-existing technological options for the injection and subsequent monitoring of CO_2. Field experiments are needed to monitor the fate of injected CO_2-fluid tracers using sealed-in, semi-permanent instruments and samplers. Such experiments will establish the in situ rates of the basalt-brine-CO_2 reactions, the relationship of CO_2 injections to subsurface biologic activity, and the potential for immobilizing CO_2 as non-toxic and stable Ca-Mg carbonate minerals in oceanic basalt.

Geochemical Sequestration Model (idealized reaction scheme)

Process 1:

CO_2 dissolution into formation fluid, carbonic acid formation,and deprotonation

$CO_2(g) = CO_2(aq)$

$CO_2(aq) + H_2O = CO_3^{2-} + 2H^+$

Process 2:

Acid Neutralization Reaction with host rocks and $CaCO_3$ precipitation

$CaAl_2Si_2O_8 + 2H^+ + 2H_2O = Ca^{2+}\ Al_2Si_2O_5(OH)_4$

$Ca^{2+} + CO_3^{2-} = CaCO_3(s)$

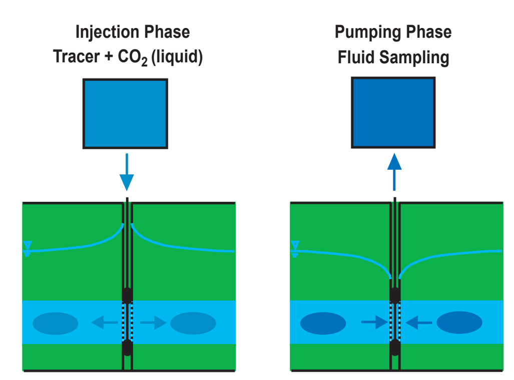
Net Mineral Trapping Reaction

$CaAl_2Si_2O_8 + CO_2 + 2H_2O = CaCO_3 + Al_2Si_2O_5(OH)_4$

Natural Analog: Magnesite filled fractures in the Samail Ophiolite, Sultanate of Oman

CO_2 injection tests on land (Palisades diabase)

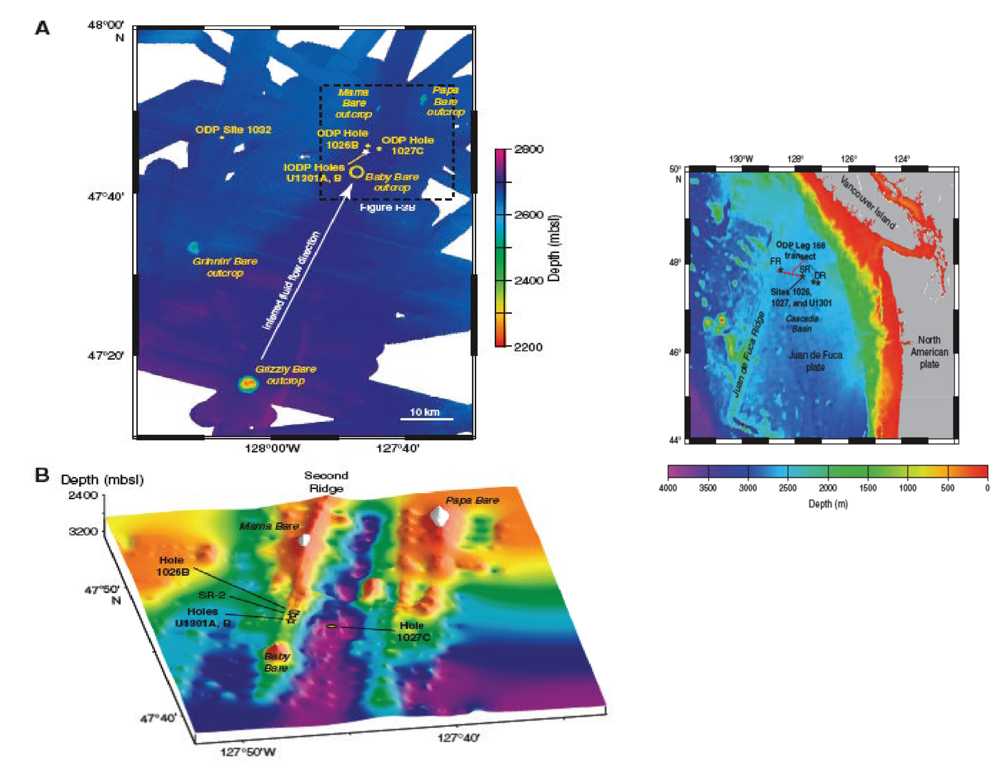
See B33A-1010 for further detail on land injection tests



Carbon dioxide injection test were conducted in a basalt formation as single well push-pull tests. A CO_2 saturated fluid (pCO_2 ~20 atm, pH ~3.5) was injected into a hydraulically isolated zone, and pumped back after an incubation time of 1 to 3 weeks. Solute concentrations were measured in the extracted water samples and used to develop breakthrough curves. Breakthrough curves of conservative tracers (e.g. chloride, δ^2H) were used to calculate recovery percentages for the injected solution and as a reference point that discounts for dilution through mixing.

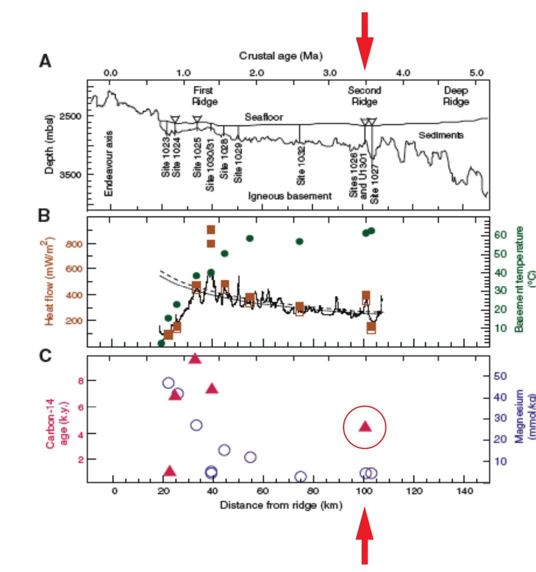
Juan de Fuca ridge flank:

Drill site locations and basement topography



Location maps of drill sites and nearby basement topography on the eastern flank of the Juan de Fuca ridge. The direction of fluid flow in the crust is inferred. Heat flow data indicate the drawdown of bottom water at Grizzly Bare, outflow at Baby Bare and a lack of thermal anomalies in between, suggesting that impermeable sediments blanket the region near existing and proposed drill sites (from Fisher et al., 2003; Shipboard Scientific Party, 2004).

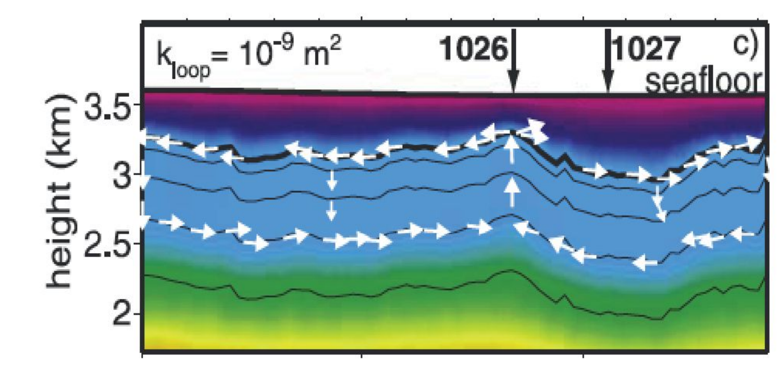
Hydrothermal flow and fluid chemistry



(A) Spatial distribution and depths of existing drill sites at basement ridges and troughs.

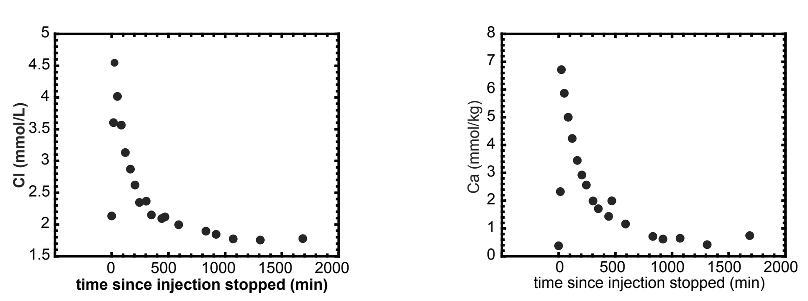
(B) Measured heat flow and basement temperatures. Near-constant 60˚C temperatures imply vigorous advection and homogenization of basement fluids.

(C) C^{14} age and Mg^{++} concentrations in recovered basement fluids. Younger ages at Sites 1026/1027 relative to the ridge indicate that fluids must recharge elsewhere. C^{14} age of basement fluids at Site 1026 is ~4300 yrs with respect to zero-age bottom water, a residence time sufficient for geochemical equilibration with altered basalt (from Elderfield et al., 1999; Shipboard Scientific Party, 2004).



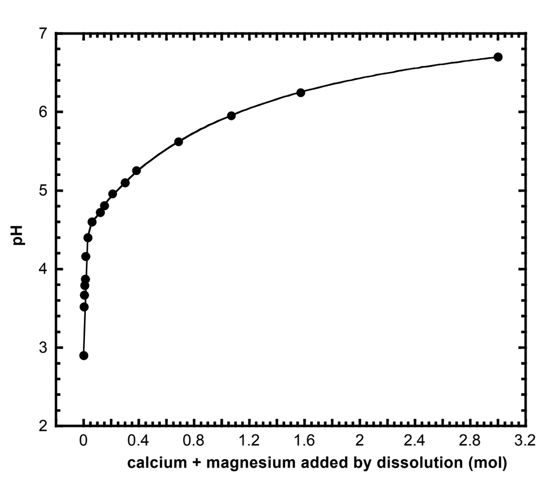
Preferred flow model in basement near Site 1026 and 1027. Channelized fluid flow with $k=10^{-9}\ m^2$ reproduces relative pressure observations at Site 1026 and 1027 (from Spinelli and Fisher, 2004). Experimental data indicate bulk $k=10^{-10}$ to $10^{-13}\ m^2$, with significant uncertainty due to scale and anisotropy effects (Shipboard Scientific Party, 2004).

Solute breakthrough curves



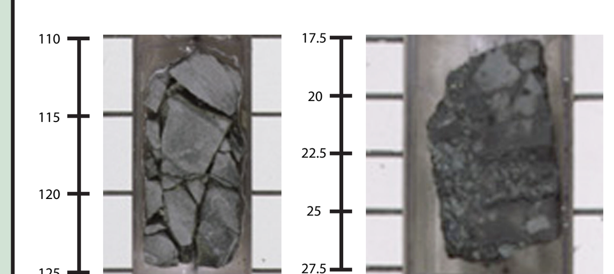
Breakthrough curves indicate chloride and major cation concentrations were reduced to background levels <1000 minutes after pumping. Similar peak arrival times and shapes for these two curves suggest similar transport properties for chloride and calcium, although the mass of recovered calcium is larger than chloride (area under curves), indicating a significant contribution of cations by rock dissolution.

Geochemical modeling



CO_2 and subsequent mineral dissolution reactions were modeled using PHREEQC. The initial fluid composition used in the model calculations is based on field measurements by Elderfield et al. (1999). The fluid was equilibrated with CO_2 (pCO_2 10 MPa, 60˚C), resulting in a pH of 3.09 and subsequently reacting with Ca-Mg silicate minerals (diopside, forsterite in 2:1 molar ratio). The change in pH due to mineral dissolution reveals that approximately 1.6 moles of Ca, Mg are required to neutralize injection conditions (pH 3 --> 6.7).

IODP drill site details and proposed CO_2/tracer injection tests



Core samples from ODP Holes 1027C and 1026B, 624.4 and 268.6 meters below seafloor. Scales are given in centimeters. Conservative tracer injections are planned near these sites, and CO_2 injection tests are proposed 18-24 months later. Monitoring will occur at nearby (existing) holes offset by 200-2000m in orthogonal directions.

Critical Questions:

- What is the potential capacity and retention time for CO_2 in the ocean crust?
- What is the rate of basalt-CO_2 neutralization and $CaCO_3$ precipitation in this environment?
- How does lateral permeability change after CO_2 injection and $CaCO_3$ precipitation?
- Where do CO_2 hydrates form?
- What is the response of subsurface microrganisms to stimulated biogeochemical processes after injection of CO_2?
- Which conservative tracers will be most effective (e.g. Xe, SF_6, etc.) in this environment?

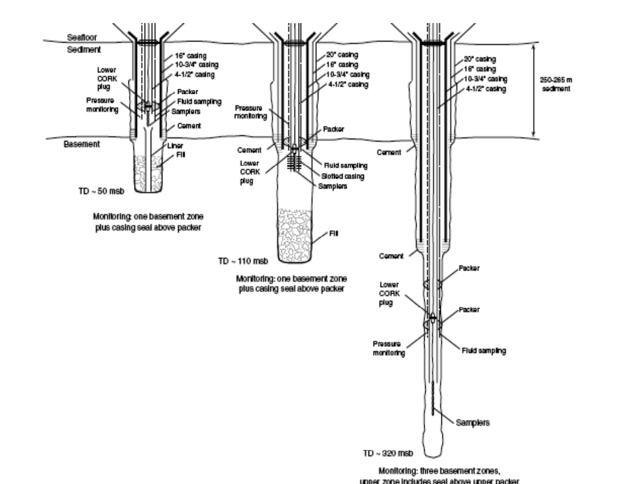
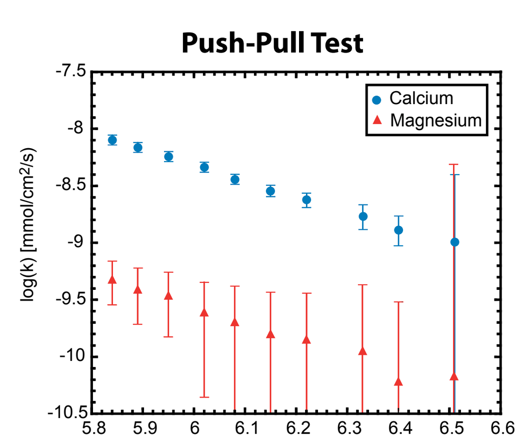
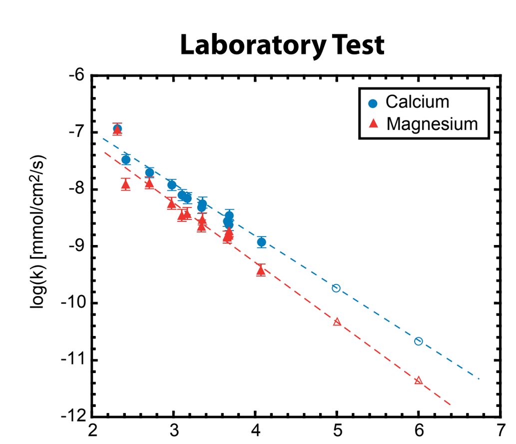


Illustration of completions in IODP Holes 1026B, U1302A, and U1301B (Shipboard Scientific Party, 2004). Instrumented borehole packer systems will be used to monitor pressure, fluid conductivity, and sample fluids.

Acid neutralization and cation release rates





In situ rate constants for the bulk rock dissolution were computed using the mass transfer from the push-pull test, the residence time of the injected fluid in the injection interval, and the reactive surface area of the test interval. The ion release rates decrease with increasing pH, which is confirmed by laboratory experiments on crushed bulk rock samples. Based on the experimental results, and applying an average bulk rock dissolution rate of 0.138 $mol/m^2/hour$, a 1000 m^3 volume of CO_2 saturated water at PCO_2 = 8 bar would be neutralized approximately 19 hours after injection. The release rates are anticipated to be even faster in oceanic basalt.

References cited

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