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Geological storage of CO_2 in sub-seafloor basalt: the CarbonSAFE pre-feasibility study offshore Washington State and British Columbia

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Abstract

The CarbonSAFE Cascadia project team is conducting a pre-feasibility study to evaluate technical and nontechnical aspects of collecting and storing 50 MMT of CO_2 in a safe, ocean basalt reservoir offshore from Washington State and British Columbia. Sub-seafloor basalts are very common on Earth and enable CO_2 mineralization as a long-term storage mechanism, permanently sequestering the carbon in solid rock form. Our project goals include the evaluation of this reservoir as an industrial-scale CO_2 storage complex, developing potential source/transport scenarios, conducting laboratory and modeling studies to determine the potential capacity of the reservoir, and completing an assessment of economic, regulatory and project management risks. Potential scenarios include sources and transport options in the USA and in Canada. The overall project network consists of a coordination team of researchers from collaborating academic institutions, subcontractors, and external participants. Lessons learned from this study at the Cascadia Basin location may be transferrable elsewhere around the globe.

Keywords: CO_2 storage; basalt; ocean crust; feasibility

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1. Introduction

Cutting carbon dioxide (CO_2) emissions and lowering atmospheric concentrations is essential to our future and one of the greatest challenges of this century. We investigate one solution for the geologic storage of large amounts of CO_2 by injection into basalt beneath the ocean floor—the world's most common volcanic rock—where it will transform into a solid carbonate form, similar to the recent land-based demonstration projects in Iceland and Washington State [1–6]. Sub-ocean basalts possess enormous storage capacity and are distant from human activities, potentially providing a publically acceptable solution for the large-scale, permanent geological storage of CO_2 [7].

In this project, we investigate the feasibility of providing 50 million metric tons (MMT) of CO_2 to an integrated, industrial-scale Carbon Capture and Storage (CCS) operation through injection into basalt formations in the Cascadia Basin offshore from Washington State and British Columbia. The major components of this study include: (1) a compiled evaluation of industrial CO_2 sources and potential modes of transportation in the region; (2) an inventory of existing geophysical and geological data in the area and an evaluation of new data acquisition required to assess the storage potential and pre-, syn- and post-injection environmental monitoring; (3) an initial reservoir model of the potential storage complex; (4) a preliminary analysis of regulatory requirements, stakeholder and financial analysis of the offshore storage complex; and (5) a comprehensive project risk assessment analysis.

2. 2. Source and Transport Assessment

Washington (WA), Oregon (OR), British Columbia (BC), and Alberta (AB) were identified as areas having the potential to collect and transport large quantities of CO_2 from industrial and commercial emitters to the offshore storage reservoir (Fig. 1). These four regions have been estimated to generate a total of approximately 140 MMT of CO_2 annually from stationary sources. Using publically available data sources, we consider large (>100,000 MT/year) CO_2 emitters in the region. More than half of these emissions are associated with power plants, primarily fueled by natural gas (e.g., 52% of WA and 86% of OR emissions). The remainder is from other industrial sources, such as refineries, ammonia production operations, and mineral processing plants. Fig. 1 illustrates our source/transport workflow, resulting in five scenarios (three in USA and two in Canada) that are developed more comprehensively, including one carbon-negative scenario that would reduce atmospheric CO_2 levels. Although no dedicated CO_2 pipelines exist in the region, most of the large emitters and diverse set of potential sources are located near the Pacific shore, Columbia River, or existing freight rail. Offshore transportation options are common for all scenarios, using either dedicated offshore pipeline or shipping vessels. We highlight one scenario below that is representative of the region, enabling different potential transportation options.

Fig. 2 shows this representative scenario with collection from two possible source options – Shell's Puget Sound refinery and/or from Alcoa's aluminum production facility – neither of which is currently capturing CO_2 emissions. The Shell refinery, located in Anacortes, is one of the largest among all sources in WA and OR. CO_2 emissions have been relatively stable for this facility for the last 6 years, averaging 1.97 MMT/year; 73% of the site emissions are estimated to be from stationary combustion, and petroleum refining represents about 27% of the emissions. The second source in this scenario is an aluminium smelter operation, Alcoa Intalco Works, located in Ferndale. From 2011 to 2016, CO_2 emissions reported from this plant were very stable, averaging 0.41 MMT/year (0.38 MMT/year in 2016). Aluminium smelters emit diluted CO_2 emissions with concentrations from ~1 to 4%.

The transportation options for this scenario consider two alternatives – via ship and via pipeline. For pipeline, one 80 km-long line could connect the Alcoa Intalco Works facility to a pumping station located near the Shell Puget Sound refinery. An offshore pipeline with ~2.5 MMT/year capacity would be required to connect the pumping station to the injection site located ~250 km offshore. For shipping, a tanker collecting CO_2 from each source facility, with a multi-source design concept [8], would transport CO_2 to the offshore injection site. Large CO_2 carriers with capacities of 20,000 to 30,000 m^3 are viable, and volumes as large as 100,000 m^3 have been proposed for future CCS projects [9]. Different combinations of these transport options are also considered and could be expanded to include available CO_2 sources in British Columbia.

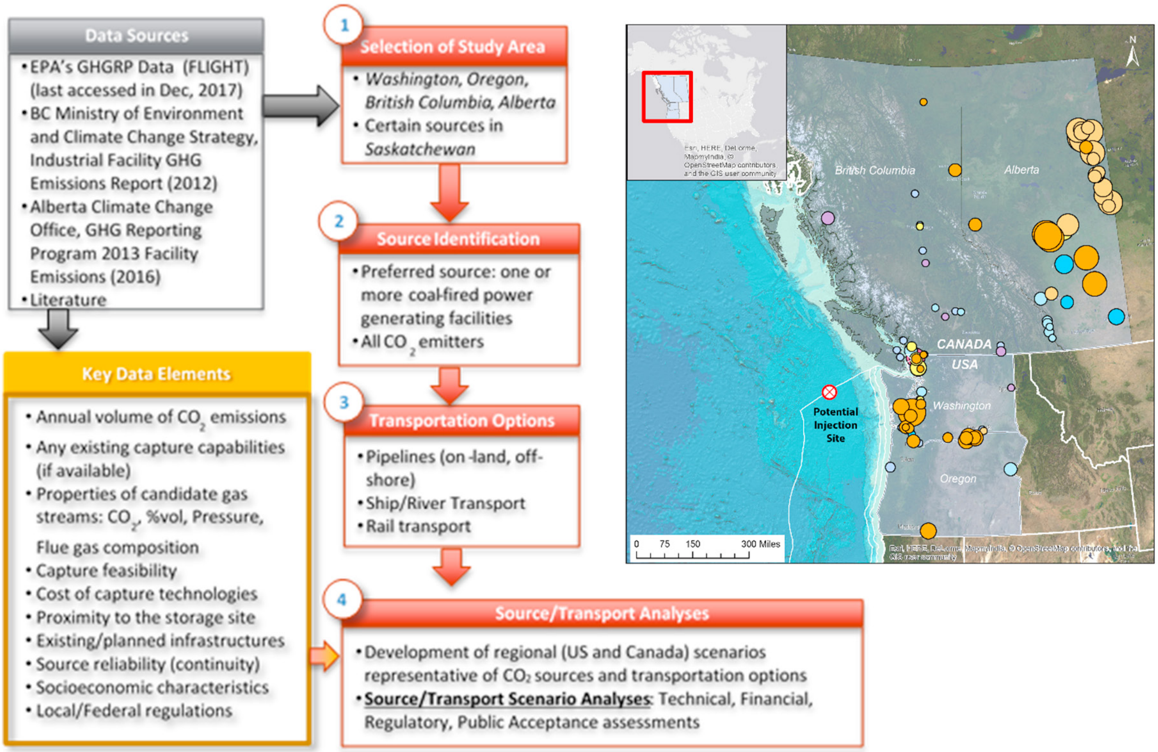

Fig. 1. CO_2 source and transportation technical, financial, public acceptance, and regulatory assessment workflow for the CarbonSAFE Cascadia project showing the study area and large (>100,000 MT/year) emitters. Color and diameter of circles indicate power (orange) and manufacturing (purple–yellow) plants and relative annual CO_2 emission volumes, respectively.

3. Technical Reservoir Assessment

The eastern flank of the Juan de Fuca Ridge in the Cascadia Basin has features common to oceanic ridge flanks in general: an extrusive igneous basement overlain by sediments that thicken with crustal age, and abyssal hill topography bounded by high-angle faults, forming linear structural trends that run sub-parallel to the spreading ridge [10]. Three scientific drilling expeditions and several site surveys have occurred previously in the region, making it one of the most comprehensively studied ocean crustal sites in the world [11–13]. The characteristics of the basalt crust in this region are potentially beneficial to CO_2 sequestration, because structural features may provide natural boundaries to reservoir storage compartments and the nearly continuous sedimentary cover provides a low-permeability barrier separating the permeable reservoir from the overlying ocean. Based on regional heat flow evidence, hydrothermal circulation is likely to be focused within the uppermost basalt layers and sustain lateral transport at a scale of 50 km or more [14, 15]. As illustrated in Fig. 3, data acquired from previous scientific drilling expeditions, existing borehole completions, and regional computer simulations suggest that permeability is on the order of 0.1 to 1 Darcies within the uppermost 600 m (probably mainly the uppermost 300 m) of basalt crust [16–20]. Bulk density logs have been used to infer porosity values reaching 10–20% in this interval, likely restricted to thin layers that may provide flow channels and access to potential CO_2 storage reservoirs in porous and permeable basalt [7]. Fine-grained sediments overlying the basalt allow relatively little fluid flow and should act as a physical seal above a potential injection and storage interval [21].

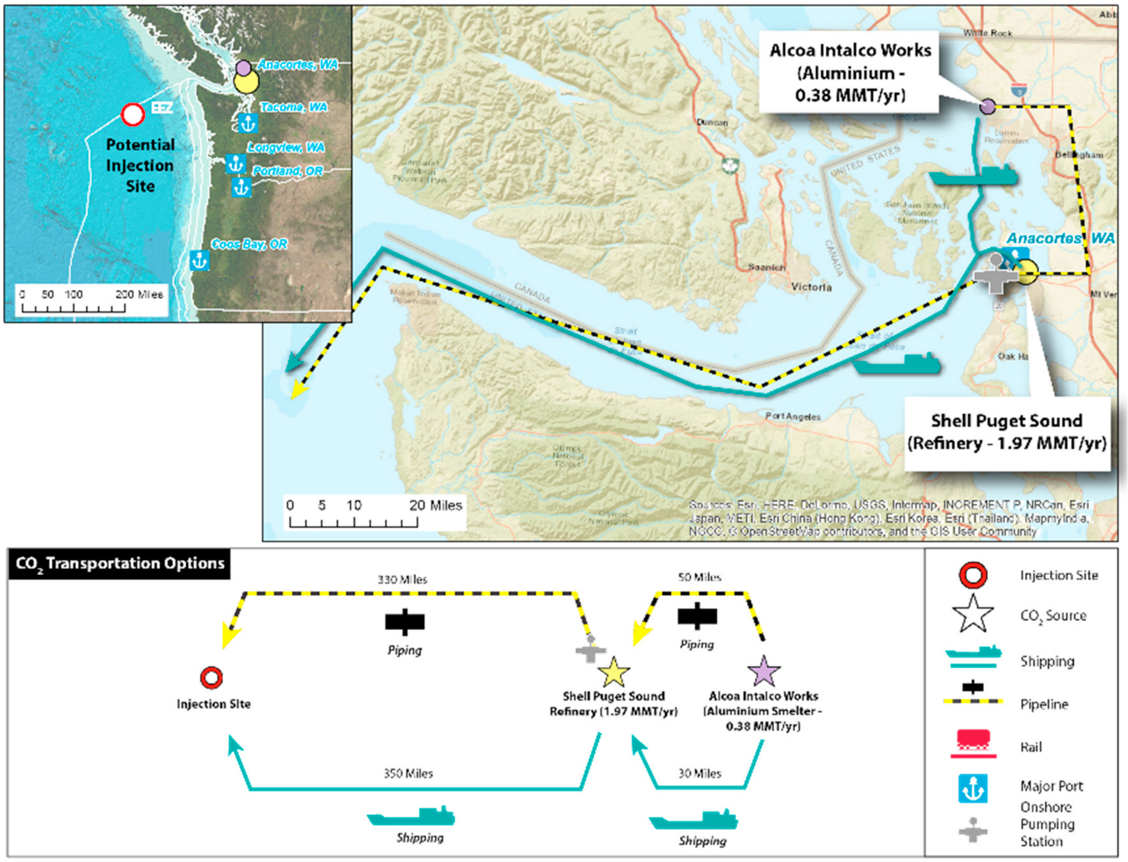

Fig. 2. Representative CO_2 source and transportation options in Washington State for the CarbonSAFE Cascadia project. Shipping and pipeline options for two source locations are shown schematically. Inset map: location of potential offshore injection site (red circle). Existing scientific research wells and nearby survey areas are shown in greater detail in Fig. 3.

This CarbonSAFE Cascadia project is based on the premise that the mineralization of CO_2 in contact with water and basalt offers advantages for safe and long-term carbon storage through both physical (stratigraphic) and chemical (mineralization) trapping mechanisms. Mineral trapping in basalt formations involves reactions of CO_2 within a closed saline reservoir system, converting Ca^{++}, Mg^{++}, Fe^{++} cations in solution into thermodynamically stable carbonate minerals [7, 23–25]. The two recent field demonstration projects in Iceland and in Washington State have indicated nearly complete mineralization of CO_2 injected into basalt formations over a two-year timeframe [2, 6].

We investigate the kinetic parameters for similar dissolution and precipitation processes for deep-sea basalt formations employing both laboratory experiments and modelling studies. Using a compositional version of the STOMP numerical simulator, we investigate hydrothermal circulation in basalt crust below the Cascadia Basin [26, 27]. Preliminary modelling results are in good agreement with field evidence, reflecting local convection and circulation occurring between distant basement outcrops in the region [20]. A geochemical model forecast for a gas-phase injection of 50 MMT supercritical CO_2 ($scCO_2$) is driven by this natural hydrothermal flow through the basalt crust and indicates the precipitation of carbonates in reservoir layers over a few decades.

In the laboratory, samples from existing drill holes in the Cascadia Basin were tested to assess various reactivity rates for basalts having different mineralogical compositions and structures. Experiments were conducted using a differential bed reactor system to measure dissolution rates at low pH and 27 ºC, simulating near-equilibrium reservoir conditions. Fig. 4 depicts the preliminary elemental extraction results for ground basalt sampled from the flow channel depth interval at this Cascadia Basin site (particle size ~60 μm, to avoid rate overestimations with fine powders) at pH 6.5. Compared with prior kinetic data from the literature, the dissolution rate of this oceanic basalt sample is faster.

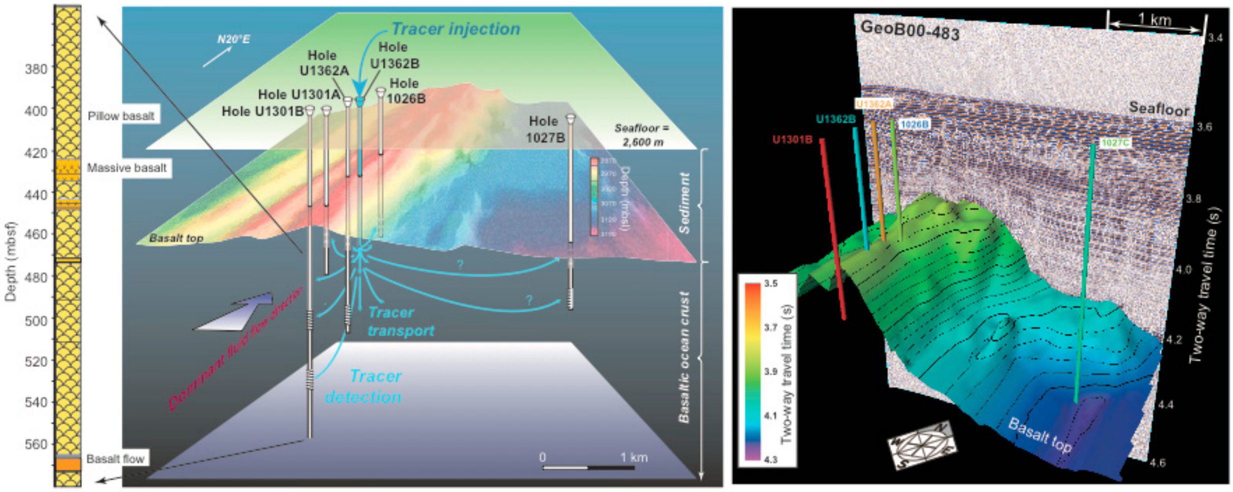

Fig. 3. The proposed storage reservoir is located in permeable pillow lavas, fractured and massive flows along a buried basement ridge in the Cascadia Basin (left, colored surface; modified from [22]). Several well completions penetrate these basalt layers, illustrated over a 200-m depth interval (left, lithology column). Tracer injections tests indicate focused northward flow in basement that is sealed by impermeable fine-grained sediments to the seafloor (left, green surface). A seismic image of the basement-sediment contact shows well locations on the basement ridge with an exaggerated vertical scale (right; colored surface).

Our laboratory results also show that the flow channel basalt appears to be much more reactive than massive basalt, reaching Ca, Mg, and Fe extraction efficiencies (total cation efficiency) of ~11–12% over a two-hour reaction window, even though these samples have similar compositions with respect to Ca, Mg, and Si. The massive basalt has slightly higher Fe content than flow channel samples. Additional laboratory measurements in oceanic basalts from the Cascadia Basin and other locations are underway.

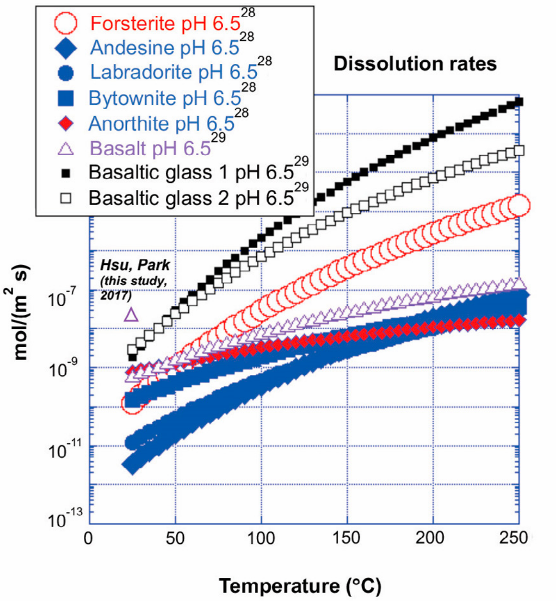

Fig. 4. Dissolution rates of basaltic rocks based on Ca release rates. Measured dissolution rates of basalt indicate that flow channels are much more reactive than the massive basalts, with Ca ion extraction efficiencies reaching ~11-12% at low pH. Compared with kinetic data in basalts from the literature, preliminary tests indicate more rapid dissolution than in shallow ocean basalts. Data from the literature for minerals [28, 29] and from this study (Hsu, Park) are annotated in the figure.

A long-term comprehensive monitoring strategy for CO_2 stored in the subsurface is required to verify model predictions, address potential leakage risks, and comply with policy requirements. Methods for direct observation of the fate of CO_2 in the reservoir using geophysical methods, as used elsewhere, as well as with reactive and nonreactive tracers may be deployed in the Cascadia Basin. A unique opportunity at this site is the nearby NEPTUNE cabled array node in the Cascadia Basin, which actively transmits real-time data to shore primarily for research, real-time hazard monitoring, and for information-driven policy decisions. This subsea cabled array is operated by Ocean Networks Canada, offering very high reliability for power delivery and data communication to connected observation nodes. Existing instrumentation and data have been used to establish baseline information (such as seismicity and reservoir hydrology) in the region. Our long-term goals include use of the NEPTUNE cabled array with new and existing instrumentation to monitor properties above and below the ocean floor, for example: injection pressure changes, reservoir pore water and rock matrix chemistry, natural seismicity and any potential seismic hazards associated with injection, pipeline and well head corrosion, and potential CO_2 leakage from the storage reservoir.

4. Non-technical Project Assessment

This project addresses several nontechnical challenges associated with the safe and permanent storage of 50 MMT of CO_2 in the Cascadia Basin. Many issues have been studied in similar projects, such as the operational, financial, and environmental risks associated with CCS in general. However, the location of this particular injection site offshore, and potentially within U.S. federal or Canadian waters, presents specific challenges. For example, key laws and regulations governing CCS activities in this situation have been discussed with the relevant government agencies responsible for their enforcement in the U.S. and Canada. Consequently, there are number of gaps in the legal/regulatory regime, particularly due to the fact that no specific laws/regulations currently exist with respect to CO_2 storage below the seabed in these waters.

Although offshore CO_2 storage in basalt reservoirs offer critical advantages with respect to storage security and reduced concerns about land access, property, and human inconvenience, it is equally important to consider all potential stakeholders (i.e., commercial and recreational fisherman, recreational boaters, military purposes) and other strategic uses of the ocean. In general, many communities near Puget Sound use this vital resource actively, whether for recreation, commuting, or making a living. As an example, the Shell Puget Sound refinery in Anacortes and the Alcoa plant in Ferndale have dock facilities situated near to nature and wildlife reserve areas, other parks, farmlands, residential, and forest areas. The potential impacts of this project on the communities close to CO_2 sources and transport lines must be carefully considered with respect to impacts from the mixed-use of surrounding land and ocean areas.

Several external economic factors relevant to long-term CO_2 storage, including source reliability and transportation costs, governmental incentives, and market factors, as well as operating costs and risks are considered in this project. Prior studies typically indicate higher costs associated with offshore storage options than those onshore for CCS [30]. In this project, we assess the relative costs of offshore storage and transport components [31] for selected source/transport scenarios, and in particular, the comparison of shipping and pipeline transportation costs. CO_2 capture costs, which dominate the overall cost of any operating CCS project, are not considered.

5. Summary

Our primary goal is to conduct a pre-feasibility assessment for an industrial-scale CO_2 storage project in a subsea basalt reservoir in the Cascadia Basin, offshore of WA and BC. Basalts are very common on Earth and the lessons learned from this study may be transferrable elsewhere. In the pre-feasibility phase of this work, the CarbonSAFE Cascadia project has:

- Identified potential industry-sourced CO_2 streams in the U.S. and Canada, and evaluated five potential source/transport scenarios to reliably provide 50 MMT of CO_2 to the offshore reservoir;
- Compiled a comprehensive inventory of existing petrophysical, hydrological, and regional data in the vicinity of the offshore reservoir;
- Conducted laboratory analysis and injection modeling studies to measure mineralization rates in ocean basalt;
- Modeled the potential capacity of this offshore reservoir for CO_2 mineralization and long-term storage;

- Reviewed the framework for offshore storage regulations in US and Canada;
- Evaluated project risks, cost variables and potential economic incentives to implement this offshore CCS project.

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