A First-Order Assessment of CO_2 Storage Capacity in US Basalt Formations

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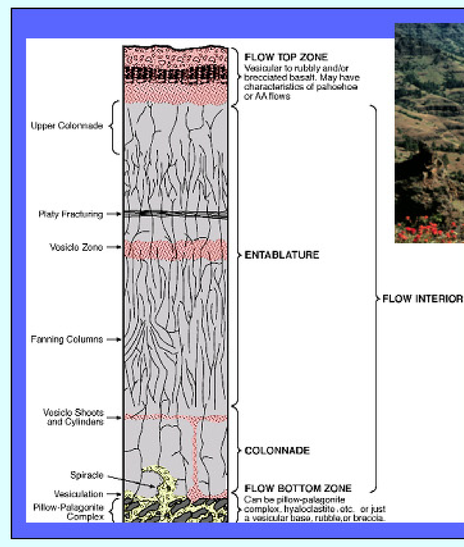
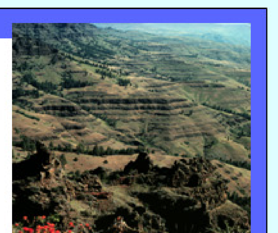
Abstract

Continental flood basalts, extruded volcanic rocks that are found in many areas of the world, show potential as geologic CO_2 storage formations. Often filled with saline formation waters, basalt flows also possess an internal structure that provides ideal host and caprock pairings within the formation, with porous, permeable layers overlain by massive, highly impermeable layers. Additionally, the geochemistry of basalt lends itself to mineralization of injected CO_2 via injectate-host rock reactions; mineralization is often considered the most stable CO_2 trapping mechanism lending to secure long-term storage. Nearly 700 large, stationary sources of anthropogenic CO_2 accounting for 1400 $MtCO_2$ of emissions per year are located within 100 miles of US basalt formations, and many of these formations are located in areas such as the Pacific Northwest and the Southeast which have few other CO_2 storage options. In addition to the often discussed deep saline sedimentary formations, unmineable coal seams, and depleted oil and gas reservoirs, these formations offer another potentially valuable CO_2 storage resource to the nation. A first-order capacity assessment of US basalts follows, comparing estimated storage capacity to that of the other major classes of geologic CO_2 storage formations, along with a discussion of the implications and importance of this potential CO_2 storage resource, particularly for those regions in which basalts are present.

Storage in Basalt Formations

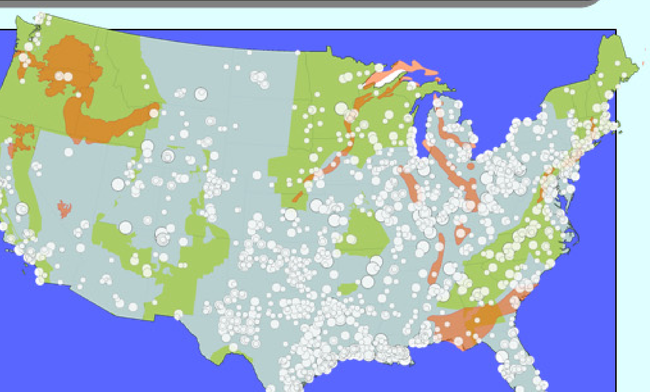




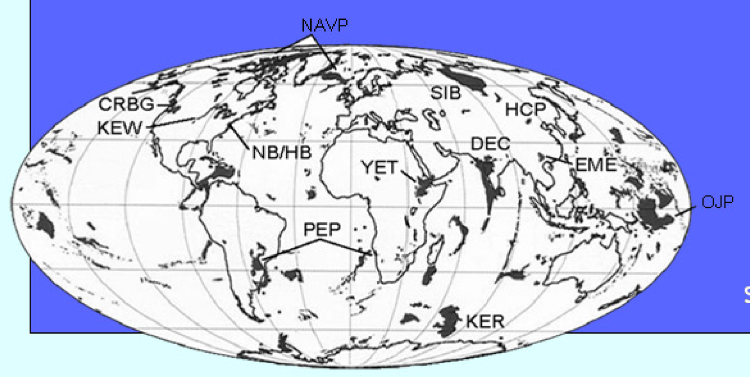
Above: Flood basalts in outcrop.
Left: Typical stratigraphy of a single flow. Porous vesicular and brecciated zones could be suitable for long-term CO_2 storage.

Continental flood basalts (CFBs) provide a promising opportunity for fluid injection and storage because of the porosity and permeability differences between the massive inner structure of each flow (the colonnade and entablature) and the fractured, vesicular flow top and bottom that surround it. The former, which is typically quite dense and generally lacking in primary or secondary porosity and permeability, provides an effective aquitard, preventing fluids from migrating out of the porous, permeable sedimentary interbeds, flow top and flow bottom that often serve as host formations for fluids such as water and gas. The saline formation waters often present in flood basalts provide a good analogy for potential injected fluids, and the aquifer / aquitard relationship between the flow margins and the flow interior provide encouraging evidence of the ability of these formations to accept and retain injected CO_2. Indeed, these formations have been studied as potential storage sites for injected natural gas. Because the characteristics that govern fluid storage capacity and flow in basalt aquifers (permeability and porosity) speak almost exclusively to the characteristics of the interflow zone - consisting of the flow top, any sedimentary interbedded materials, and the flow bottom of the next-youngest flow - and because these characteristics are in turn a function of the depositional (flow bottom, interbeds) and erosional (flow top) environments, there tends to be significant variability in porosity and permeability both laterally within a given flow and vertically between various flows.

Locations of Major Basalts

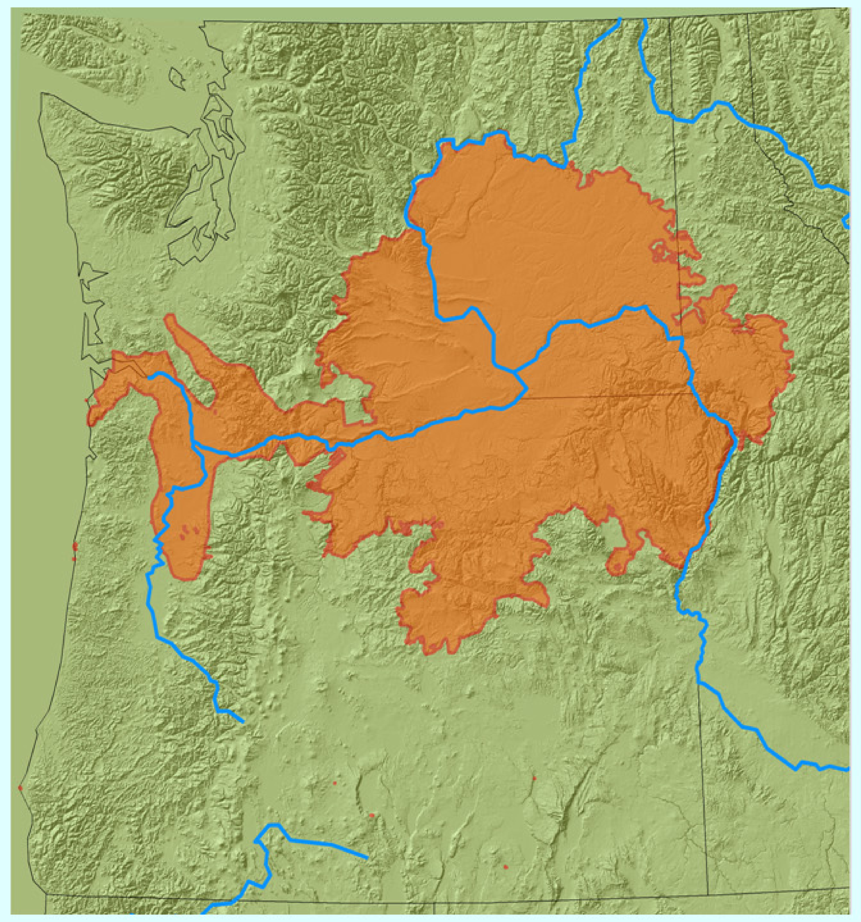


In the US, basalts (in orange) may offer storage potential in areas where there are few other candidate storage formation types (in blue). In particular, these may serve CO_2 sources (white dots) in the Pacific Northwest, the upper Midwest and the Southeastern US.



Similarly, basalts may offer CO_2 storage capacity in areas of the world with fewer other capacity resources. For example, the Deccan Basalts (DEC) could potentially provide a significant storage resource for CCS in India.

Case Study: Assessing Capacity in the Columbia River Basalts



The Columbia River Basalts Group (left), thanks to a \$400M investment by the US Department of Energy to study the CRBG for potential nuclear waste storage, is the most thoroughly characterized basalt formation in the world. This series of four CFB formations comprising over 80 members, erupted between 18 and 6 million years ago, covers over 200,000 km^2 of the Pacific Northwest, and can be more than four kilometers thick in places. Each flow consists primarily of a dense, massive inner section capped by a highly vesicular, often fractured and brecciated flow top, and often also underlain by a base of rubble, vesicular basalt, or pillow palagonite. Most flows are overlain by sedimentary interbeds including lacustrine, fluvial, and volcaniclastic (ash / tuff / lahar) sediments deposited during time intervals between flows. While the local presence and thickness of each individual flow varies laterally across the CRBG region according to the flow path and initial volume of each eruptive event, these basalts as a group extend throughout a significant portion of eastern Washington and Oregon, and western Idaho. While the shallower CRBG formations may be utilized as freshwater aquifers for drinking and irrigation, water-bearing zones at depths suitable for injection of supercritical CO_2 contain nonpotable formation waters containing high concentrations of dissolved solids.

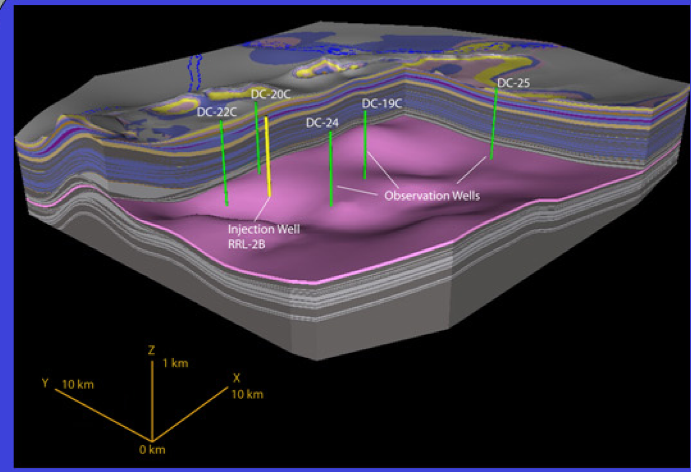
Because these formations are saturated with water, and in order to avoid the complexities associated with issues surrounding the removal of formation waters or formation overpressurization, the capacity assessment methodology presented here evaluates only the capacity available via dissolution trapping, neglecting capacity from hydrodynamic or mineral trapping. However, Columbia River basalts may have significant potential for mineral trapping due to their high iron content (10% Fe by weight, primarily as Fe^{2+}). Evidence indicates that geochemical reactions between the host rock and supercritical CO_2 can precipitate carbonates (e.g., siderite) over relatively short timeframes at typical formation temperatures and pressures, and that such mineralization of injected CO_2 may even serve to close migration pathways along the injectate front.

Also, as noted below, the CRBG flows exemplify the variability of porosity and permeability mentioned earlier, and hydraulic conductivities in these formations vary between 10^{-2} and 10^{-12} m/s, a range of ten orders of magnitude.

Capacity Calculation

In order to demonstrate the use of this methodology with high-resolution data, we have chosen to evaluate potential capacity within the Sentinel Bluffs Member of the Grand Ronde Basalt, focusing on the top of the Cohassett and McCoy Flows for a discussion of transmissivity. Comprising more than 150,000 km^3, the Grand Ronde is the most voluminous of the four CRBG major basalt formations. The Sentinel Bluffs Member is the youngest and best-exposed Grand Ronde member, and accounts for over 10,000 km^3 of the total volume. Calculated volumetric data for each of the five compositional types within the Sentinel Bluffs Member are available (Reidel 2005), and it is for these five types that we will evaluate storage capacity.

Based on methodology set forth in Dahowski, *et al.* (2005), we have used the specific sequestration volume tools developed by Brennan and Burruss (2003) to estimate the volume of CO_2 that could potentially be stored solely via dissolution trapping (i.e., assuming S_w=1.0). However, because of the large amount of data available on the CRBG flows examined here, actual measured salinities were used to calculate solubility. The capacity calculations shown at right assume that, of the volume of rock for each compositional type, 10% of the formation exists as flow top (target storage interval) with an assumed flow-top porosity of 10%.



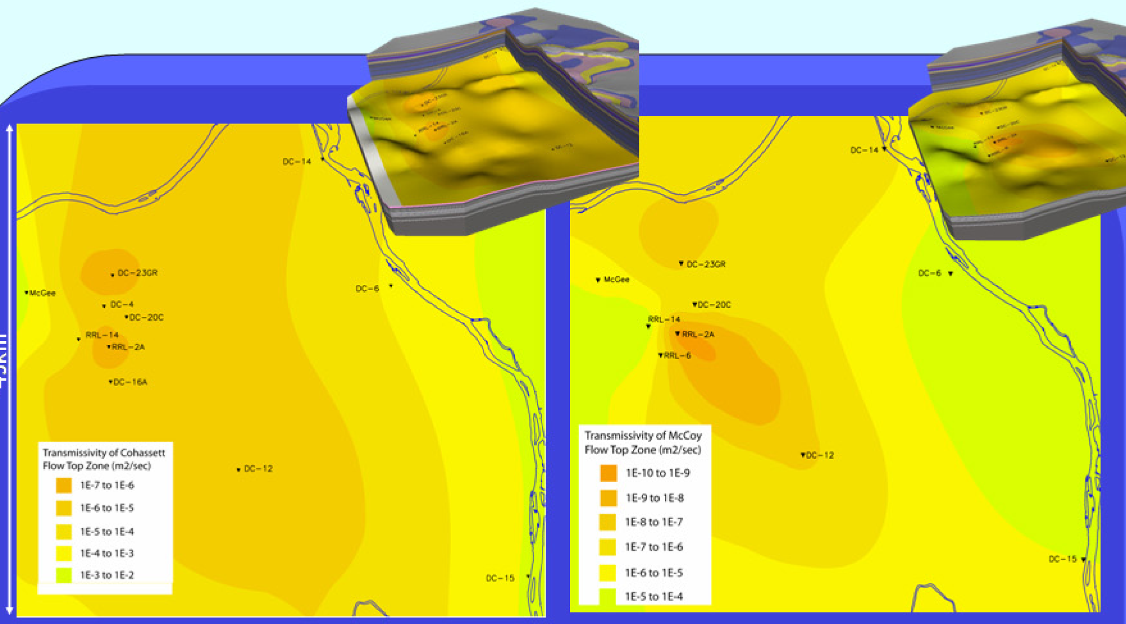
Left: Map showing the intervals of interest in this paper. The pink layer shown in the cutaway is the top of the Cohassett Flow, which includes portions of all composition types below, except McCoy Canyon.

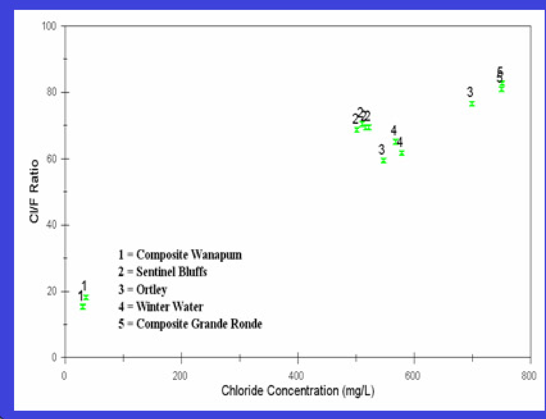
Below: Volumes and calculated potential storage capacity for the 5 Sentinel Bluffs Member compositional types and the entire Sentinel Bluffs Member.

Because of the excellent data availability for the CRBG, we were able to calculate capacities based on actual salinities, which resulted in capacities nearly double those based on 4m formation water salinity assumptions. This illustrates the impact that salinity has on capacity estimates, and suggests the need for more accurate, formation-scale data in capacity analysis.

Sentinel Bluffs Member Flows	Volume (km^3)	Capacity ($ktCO_2$)
Museum	2,349	1,200
Spokane Falls	777	400
Stember Creek	1,192	600
Spokane and Airway Heights	1,543	800
McCoy Canyon	4,278	2,100
TOTAL Sentinel Bluffs Member	**10,139**	**5,100**

note: capacities calculated using actual salinities rather than 4m assumption used in other capacity calculations





Top, left and right: Transmissivity maps (m^2/sec) for the tops of the McCoy and Cohassett Flows, Sentinel Bluffs Member, Grand Ronde Basalt. Triangles indicate sampling wells.

Bottom: Geochemical crossplot for Wanapum and Grand Ronde Basalt Formations (composites), and three members of the Grand Ronde. Separation of points indicates relative isolation between stratigraphic units.

Other Storage Considerations

In order for a formation or a particular flow to be considered as a viable option for long-term CO_2 storage, it must meet requirements for permanency and satisfy cost constraints. One of the primary drivers of storage cost (see Dahowski, *et al.*, 2005) is the ability of rock in the storage interval to transmit injectate away from the wellbore and into the target formation. An interval that allows CO_2 to flow quickly away from the injection well will require fewer injection wells per volume of injectate than an interval in which fluid flow is less rapid. The top maps (left) show transmissivity in the flow tops of the McCoy and the Cohassett Flows on the Hanford Site in Washington State (note difference in scales). As these maps show, the transmissivity - or the area around the wellbore affected per unit time - can vary by five or six orders of magnitude over a distance of 25km or less.

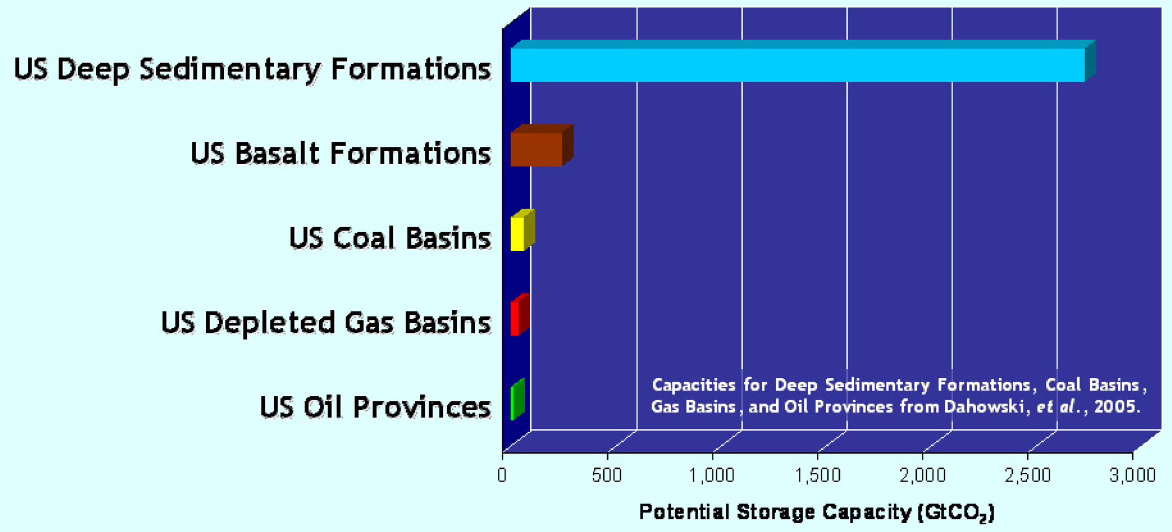
Addressing the permanence question involves, in part, an evaluation of the isolation of the storage interval relative to overlying formations. The crossplot at left shows geochemical indicators for several Grand Ronde Basalt members, as well as composites for the Grand Ronde and Wanapum Basalt Formations. Note that the signature for the Sentinel Bluffs Member (2) is markedly different from the composite (1) of the Wanapum Basalt that directly overlies it. Similarly, the Sentinel Bluffs Member appears to be relatively well isolated from the Winter Water (4) and Ortley (3) Members, both of which it overlies.

Application to US Basalts

Though there is a significantly smaller amount of data available for other US CFBs, in order to begin the dialogue on basalt-based CO_2 storage in other areas of the country, the methodology used here to calculate potential storage capacity in the Columbia River Basalt Group and several selected intervals was also applied to other major US CFBs. Again, these calculations assume porosities of 10%, S_w=1.0, and a flow-top fraction of 10%. However, in the absence of salinity data for all formations evaluated here, the Brennan and Burruss salinity assumption (4m NaCl) was used. Estimated volumes and calculated capacities are shown in the table below. Note that, using true salinities for the total CRBG would result in a capacity of ~100$GtCO_2$.

US Basalt Formations	Volume (km^3)	Capacity ($GtCO_2$)
East Continental Rift Basalts	9,000	2
Keweenawan Basalts	348,000	76
Newark Basin / Hartford Basin	3,000	1
Northern California volcanic-rock aquifers	8,000	2
Southeast Rift Zone	378,000	83
Southern Nevada volcanic-rock aquifers	3,000	1
Columbia River Basalt Group	234,000	51
Snake River Plain	111,000	24
TOTAL US Basalts	**1,094,000**	**241**

The chart below shows the total capacity of US basalts calculated here relative to previously calculated total potential capacities for other major US formation types.



Conclusions

The relatively large amount of potential storage volume in continental flood basalts, along with their fortuitous geographic distribution, make this an important formation type for possible CO_2 storage, particularly in the Pacific Northwest and the Southeastern US. Further, because of the unique capacity for relatively permanent incorporation of injected CO_2 into carbonates via mineralization, basalts may offer some of the safest options for the long-term isolation of CO_2 from the atmosphere. However, the large degree of variation between interflow aquifers and the heterogeneous areal distribution of individual group members and flows in the CRBG and other US flood basalts imply that suitability for CO_2 injection, and the long term fate of injectate, will be highly site-specific, even within a single zone such as the Cohassett flow top. While the movement of injected CO_2 and formation waters within CFBs can be analogous to behavior in better-understood formations such as water-saturated sandstones, such analogies can only provide a limited understanding of CFBs as CO_2 storage reservoirs. Data availability for basalt formations is very limited when compared to sedimentary aquifers, especially in the midcontinent. More accurate, higher-resolution data on potential storage intervals within candidate formations would allow for the application of a more elegant approach to assess potential storage volumes. For example, modifying the assumption of 4m salinity used for the US basalts capacity analysis to account for lower salinities in the Columbia River Basalt Group results in a near-twofold increase in potential storage capacity. This type of data will continue to increase the resolution and accuracy of these capacity assessments as they become available for incorporation into existing methodologies. Additional reservoir characterization is required in order to understand the capabilities of these formations to serve future CO_2 storage needs.

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