Characterizing the Columbia River Basalt Group for geologic carbon sequestration using geophysical remote sensing

Introduction

Project TrapRock is a multidisciplinary research project designed to characterize the Columbia River Basalt Group (CRBG) over a region large enough to safely sequester millions of tons of carbon dioxide (CO_2). The target geologic formation is a thick sequence of flood basalts created by hundreds of episodic lava flows in the U.S. Pacific Northwest between 16.7 and 5 million years ago. The CRBG underlies much of Washington State and portions of Oregon and Idaho, with an estimated volume of 210,000 km^3 and a thickness up to 5 km in the central basin. Some ancient flows are exposed at the surface; most are buried (Figure 1). The episodic flows created a cyclical layering visible in outcrops, with massive flow interiors crowned by thinner, permeable flow tops developed during long intervals between eruptions.

Unlike in standard forms of geologic carbon sequestration—in which CO_2 injected into the pore space of depleted petroleum reservoirs or deep saline aquifers is expected to be trapped in place by impermeable rock (caprock) bounding the underground reservoir—CO_2 mixed with water in the pore space of basalt reacts with minerals in the rock matrix to precipitate solid carbonate minerals such as calcium carbonate (calcite), locking carbon into the matrix. Pioneering laboratory and field work by Pacific Northwest National Laboratory (PNNL) has led to an estimate that a region of the CRBG in south-central Washington could permanently sequester at least 40 billion tons (Gt) of CO_2 (McGrail et al., 2006; Cao et al., 2024). Upper estimates put the sequestration potential of the entire CRBG at 770 Gt, or about 20 times the world's current annual CO_2 emissions (Miller et al., 2026).

Detailed characterization of shallow, underground reservoirs usually requires drilling many wells and taking rock and water samples. This study aims to show that modern, non-invasive geophysical remote sensing anchored by a large-scale airborne EM (AEM) survey and a 3D seismic survey—and validated against logs from existing wells—can create a 'digital twin' of (part of) the CRBG with enough fidelity to realistically simulate reactive flow and carbon mineralization in the formation's permeable flow tops.

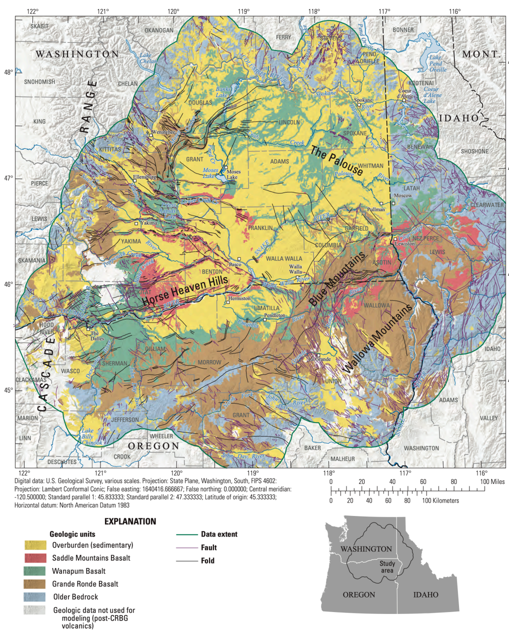

Figure 1 (ABOVE) Layers of the CRBG exposed in an outcrop along the Columbia River (Photo: Shutterstock). (RIGHT) USGS geologic map of the Pacific Northwest showing the full sequence of flood basalts making up the CRBG and their geographic extent.

Data Acquisition and Processing

In 2024 and 2025, Project TrapRock carried out several geophysical remote-sensing surveys in an approximately 60×40 km study region along the Columbia River (Figure 2). The surveys included:

- Two helicopter-borne, time-domain AEM surveys covering about 1750 km^2 of southern Washington and northern Oregon down to a depth of about 600 m. Both surveys were done with the Geotech VTEM^{TM} Plus system, which uses a 4-turn, 26-m source loop carrying a pulsed peak current of 189.7 A and records the decaying magnetic field (Z-component) induced by the source at 43 sample times ranging from 0.021 to 8.083 ms after the source current is rapidly shut off.
    - The 2024 survey covered 1535 line-km over 712 km^2 at (approximately) 2.5 m inline and 500-m crossline spacing and an average terrain clearance of 41 m.
    - The 2025 survey covered 2485 line-km over 1028 km^2 at (approximately) 2.5 m inline and 450-m crossline spacing and an average terrain clearance of 44 m.
- Absolute and gradient magnetometer surveys at a sensor height of 51 m.
- Passive and active 3D seismic surveys in a 5×5 km patch in the northwest corner of the AEM surveys in Washington (Figure 2). The seismic surveys included:
    - A passive array of 145 three-component (3C), low-frequency (2-Hz) geophones recorded ambient seismic noise from mid-August to mid-October 2025.
    - The active 3D survey used 8246 vibroseis source locations at 53.5 m spacing, shooting into an array of 2069 1C geophones at 106.7 m spacing, recording from 10–80 Hz. Estimated depth of the reflection survey is about 4 km.
- A microgravity survey with 339 stations at 250 m spacing in the seismic survey region.

The AEM data followed a standard noise-reduction workflow, including (a) half-cycle stacking, (b) system-response correction, (c) removal of parasitic noise and drift, and (d) low-pass filtering. Resistivity vs depth inversion was then applied at every 5th station recording along flight lines (i.e., at about 12.5 m intervals) to fit the sampled magnetic field decay curve with the response of a plane-layered Earth model consisting of 30 uniform, isotropic layers of varying resistivities and thicknesses, extending from the topography to a depth of about 600 m (determined from the modelling as the maximum depth of penetration of the EM response). The nonlinear inversion used the method and software described in Brodie (2015) and available from Geoscience Australia (Brodie 2026). Figure 2 shows a typical resistivity vs depth profile along a flight line in the far northwestern part of the survey.

At the time of writing, the large seismic dataset (about 10 TB of raw recordings) is following a standard processing workflow expected to produce a 3D seismic-reflection depth image by September. Tomographic analysis of traveltimes between source and receiver locations yielded a 3D volume of seismic compressional wave velocity from the surface down to a depth of 600 m in the area covered by the survey. Figure 3 compares the seismic velocity and electrical resistivity images on the same grid.

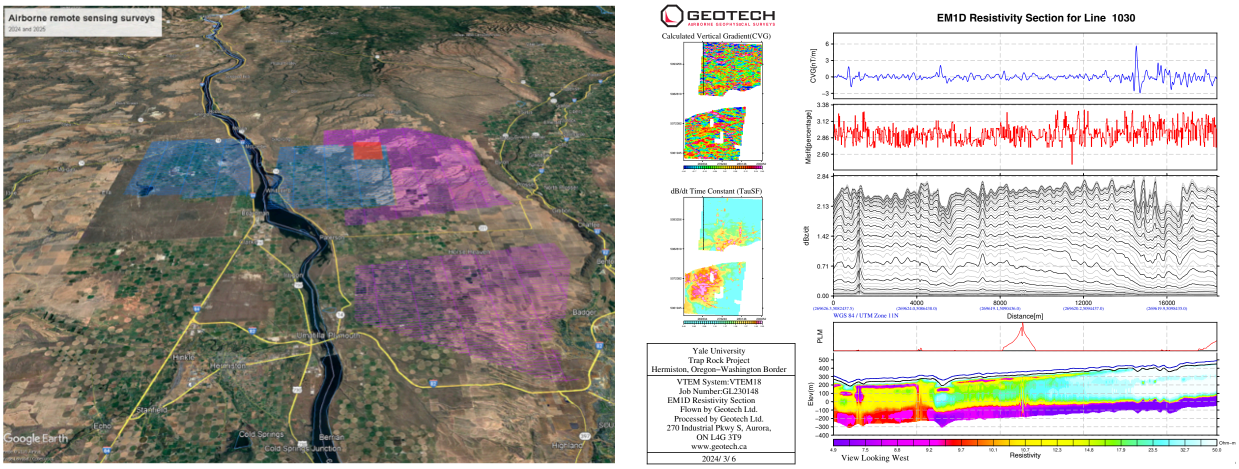

Figure 2 *(LEFT) Google Earth view looking west (north to the right) over the survey region along the Columbia River in southern Washington and northern Oregon. 2024 AEM survey flight lines are in blue; 2025 survey lines are in purple. Seismic survey area is outlined in red. (RIGHT) Standard panel of data measured along flight lines by the VTEM^{TM} Plus system, along with the color-coded profile of electrical resistivity vs depth produced by 1D inversion at every 5th measurement station along the line.*

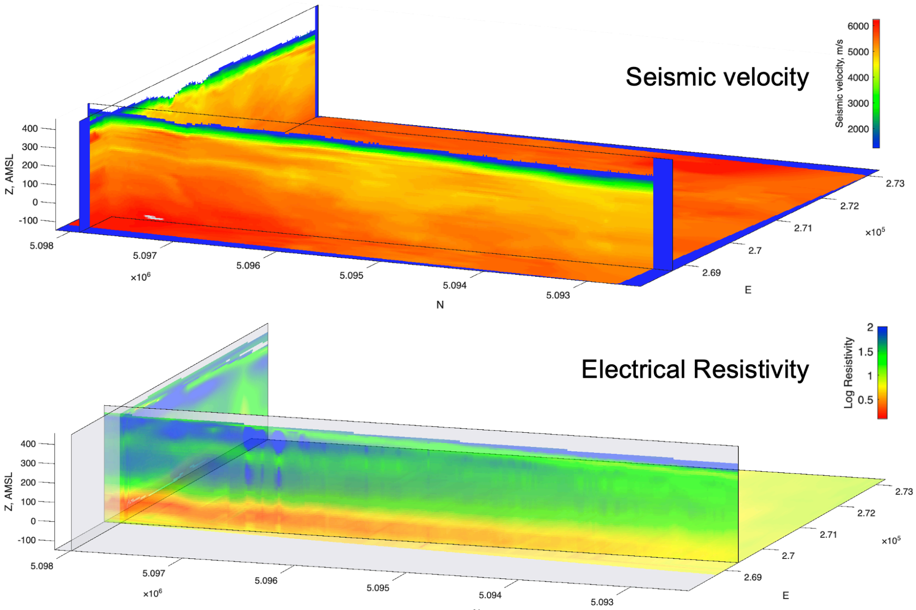

Figure 3 *Seismic compressional wave velocity (TOP) and electrical resistivity (BOTTOM) from the surface to a depth of about 600 m in the region below the seismic survey.*

Conclusion: Building a Digital Twin of the CRBG

Figure 4 shows a 3D rendering of an initial step in building a digital twin of the upper portion of the CRBG in the northwestern corner of the survey region. The goal is a digital representation of the subsurface in a computer model detailed and accurate enough to support realistic simulations of reactive flow and mineralization when CO_2 is injected into permeable flow tops in the basalt layering. This initial model, which was built in the reservoir modelling software Petrel™ using the inverted AEM resistivities, contains about 16 million cells, each 50×50 m horizontally and about 12 m thick in depth. To obtain that level of detail, the 1D inversion results were 'upscaled'—i.e., analyzed statistically, interpolated, and extrapolated horizontally and in depth—using sequential Gaussian simulation, a geostatistical technique used in simulating flow in heterogeneous petroleum reservoirs.

This initial model will be merged with the 3D seismic reflection image and well logs from nearby wells (Figure 4) to include additional stratigraphic detail below the 5×5 km patch of the seismic survey down to a depth of about 8 km. The final step will be to build a grid for reactive flow simulations in selected layers below the seismic survey, using petrophysical correlations between seismic velocity, electrical resistivity, bulk density (from gravity data, cores, and well logs), and flow properties such as porosity and permeability. Reactive flow simulations using the digital twin—and based on the reactive mineralogy of the CRBG (known from analysis of samples and lab experiments)—will help to refine coarse estimates of the region's permanent geologic sequestration potential and to site possible large-scale demonstration projects. The project will issue a final report in October to Washington Department of Commerce, which funded the research. All data will be public at the end of the project. An appendix will include recommendations on strategic policy and legislative initiatives designed to provide a framework for commercialization of permanent geologic carbon sequestration in Washington State.

Acknowledgements

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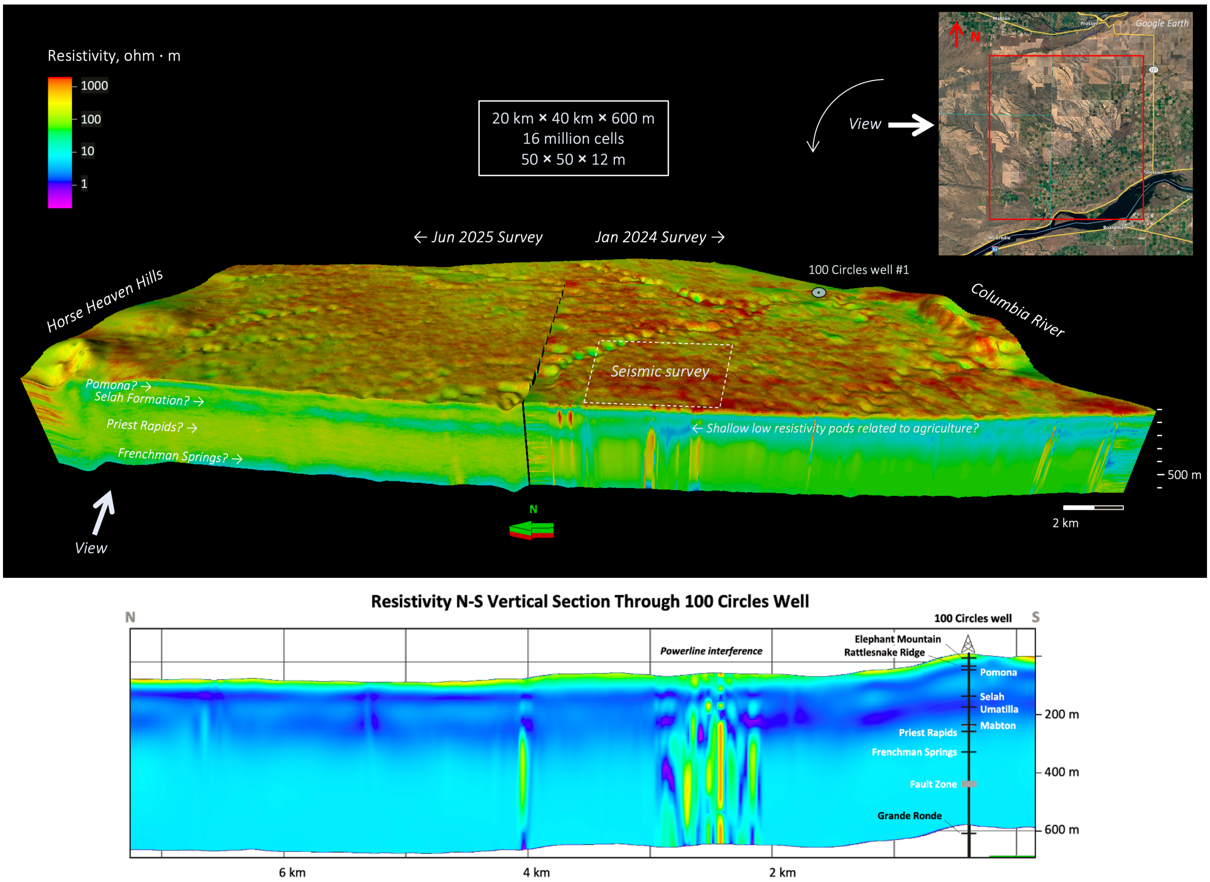

Figure 4 *(TOP) 3D rendering of an initial digital twin comprising the top 600 m of (part of) the CRBG. Pixel colors code electrical resistivity according to the scale at upper left. The 5×5 km patch of the seismic survey is outlined on the rendering. A 5-m thick permeable flow top with 20% effective porosity below that patch can hold at least 1 million tons of CO_2 mixed with water. (BOTTOM) Vertical N-S section through the model passing through the deep 100 Circles #1 well. Formation tops seen in well logs identify stratigraphic layers visible on the front face of the image.*

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