The SO294 CASCADIA CO2 project

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Introduction

The CASCADIA CO2 project was carried out as a secondary user of the SO294 cruise. The aim was to utilize four component ocean-bottom seismometers (OBS) investigating basalt complexes for their capabilities to serve as a storage site for CO_2 injection. Current geological CO_2 storage projects typically use porous reservoirs in sedimentary basins, such as depleted oil fields or saline aquifers. However, permanent trapping takes hundreds to thousands of years (Ajayi et al., 2019). CarbFix in Iceland has shown that sequestration in porous basalts has advantages over more traditional approaches, including high hydraulic permeability and rapid mineralization of CO_2, resulting in permanent storage (IEA GHG, 2017). The permanent sequestration of CO_2 in porous basalt rock means that, once mineralized, the CO_2 cannot escape or cause groundwater contamination or blowouts, making it a publicly acceptable model for carbon storage.

The CarbonSAFE Cascadia project investigated the potential of a site for CO_2 storage in the Cascadia Basin on the eastern flank of the Juan de Fuca Ridge (Figure 1, 2). The Canadian initiative Solid Carbon intends to continue this research and develop a test injection with supercritical CO_2. The legacy IODP boreholes are aligned in a NNE direction along the strike of the ridge segments but would not allow monitoring of the lateral extent of the injected gas plume. In order to avoid costly observation wells for a fundamental investigation of the physical parameters before and during the injection phase, geophysical remote sensing of subsurface parameters should provide an adequate database for modeling and monitoring. The CASCADIA CO2 project aims to investigate these possibilities, with OBS being used to develop depth models of the subsurface structure and distribution of compressional and converted shear wave velocities.

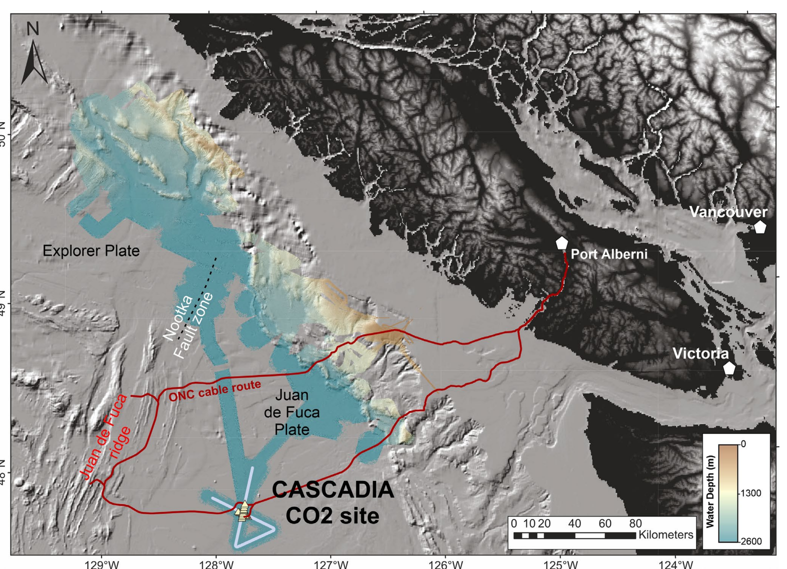

Figure 1. Map of study region of the Cascadia CO2 project on the Juan de Fuca plate, off Vancouver Island. Colored multibeam bathymetry is from SO294.

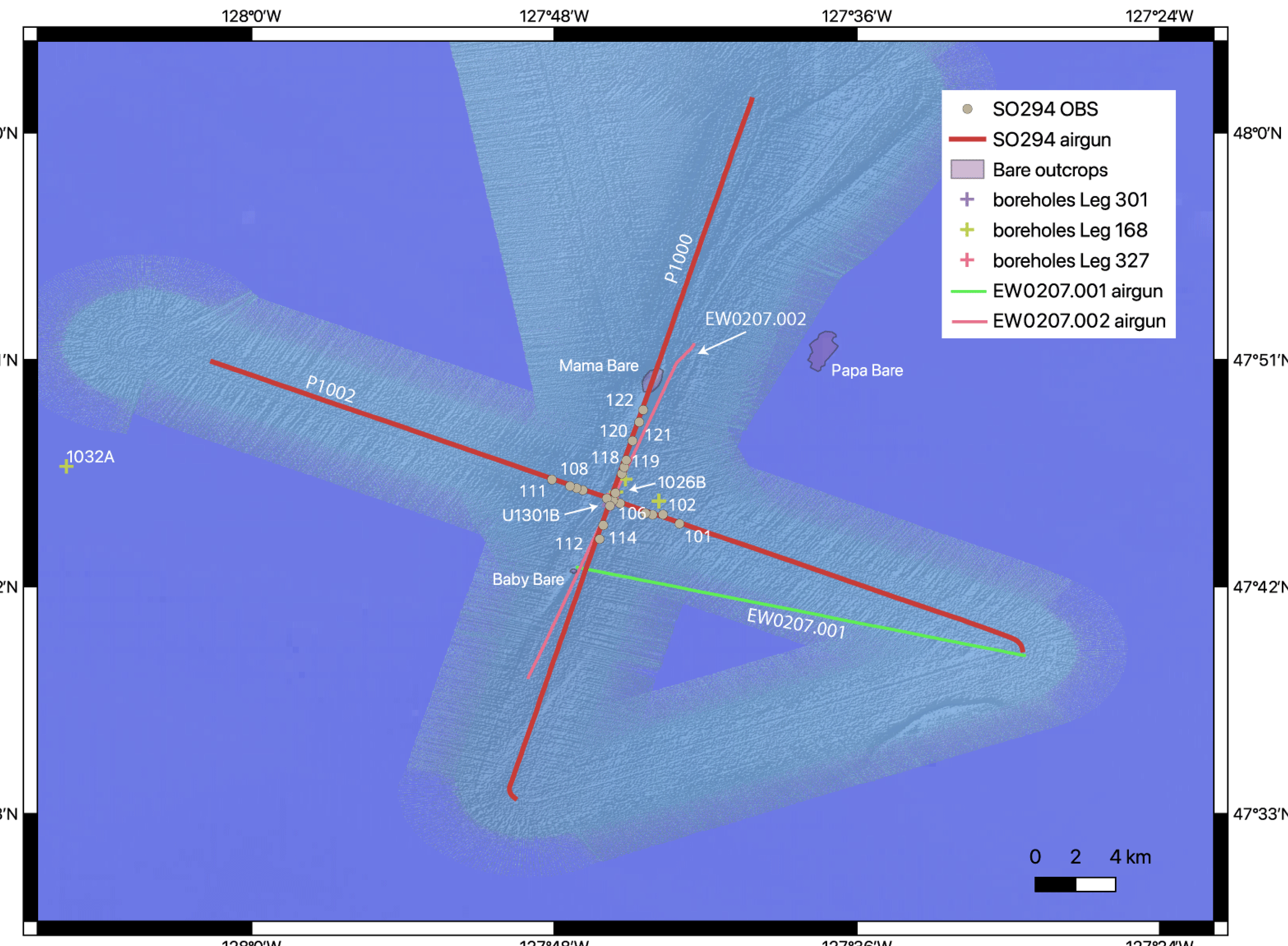

Figure 2. Detailed map of study region of the Cascadia CO2 project. Shown are two crossing seismic lines from SO294 (red lines), legacy seismic data from expedition EW0207, as well as SO294 OBS locations and legacy drill sites.

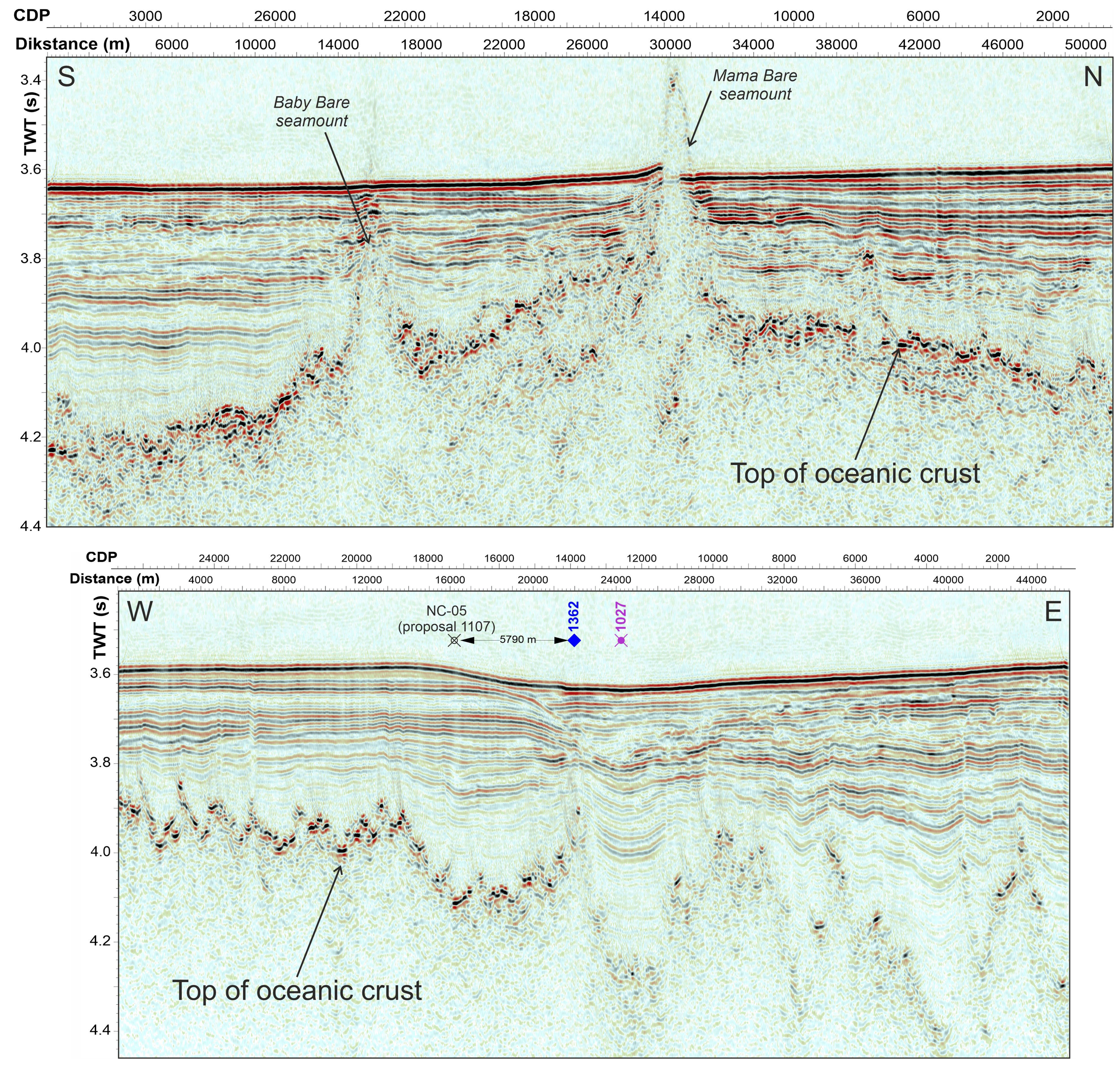

Figure 3. top: Seismic profile P1000; bottom: Seismic profile P1002.

Methods

Based on reflection seismic lines (Figure 3), an initial structural model was created, and steep-angle reflections in the OBS data were assigned to the horizons of the reflection lines. Using the PASTEUP code (Fujie et al., 2008), the travel times of the reflections and refracted waves from the sediment, basement, and Moho were identified and picked. Using forward modeling of all 21 OBS data sets, a Vp velocity model was first created (code MODELING by Fujie et al., 2008). The Vp model was used as the initial model for tomographic inversion according to Korenaga et al. (2000). Variants of the initial models and grid resolutions were investigated in the tomography model, and a grid with a horizontal grid width of 125 m and a vertical grid width of 75 m was selected as a reference for further processing. For both models of profiles P1000 and P1002, the structures of the sediment cover depicted in the multichannel seismic data could be modeled in the velocity profile. In addition to the multichannel seismic data, variations in the velocity-depth distribution indicate slight structuring within the basement. Increased velocities below the Mama Bare structures and the Baby Bare structure suggest that the roots of the structures extend to a depth of 3.5 km. Model P1002 shows a decrease in velocities towards the east below the basement. Reflections from the Moho are modeled with a depth of 10 km, and show a horizontal layering on both profiles.

Based on these Vp models, the converted shear waves were modeled next. The reflection point of the seismic ray path was used as the reference point for the conversion (Zhu et al., 2020). The grid sizes of the velocity models were retained. Both Vs models show no distinct structures below the basement. In the Vs model of profile P1000, no significant velocity variations within the sediments can be observed along the profile. At the top of the basement, the Mama Bare and Baby Bare structures stand out due to slightly increased Vs velocities. South of the Mama Bare structure, there is a noticeable local reduction in velocity, which decreases to a depth of about 8 km, coincident with an event in the reflection seismic data. In the Vs model of the intersecting profile P1002, limited areas with reduced velocities can be observed. These velocity anomalies coincide with small depressions in the topography of the basement top.

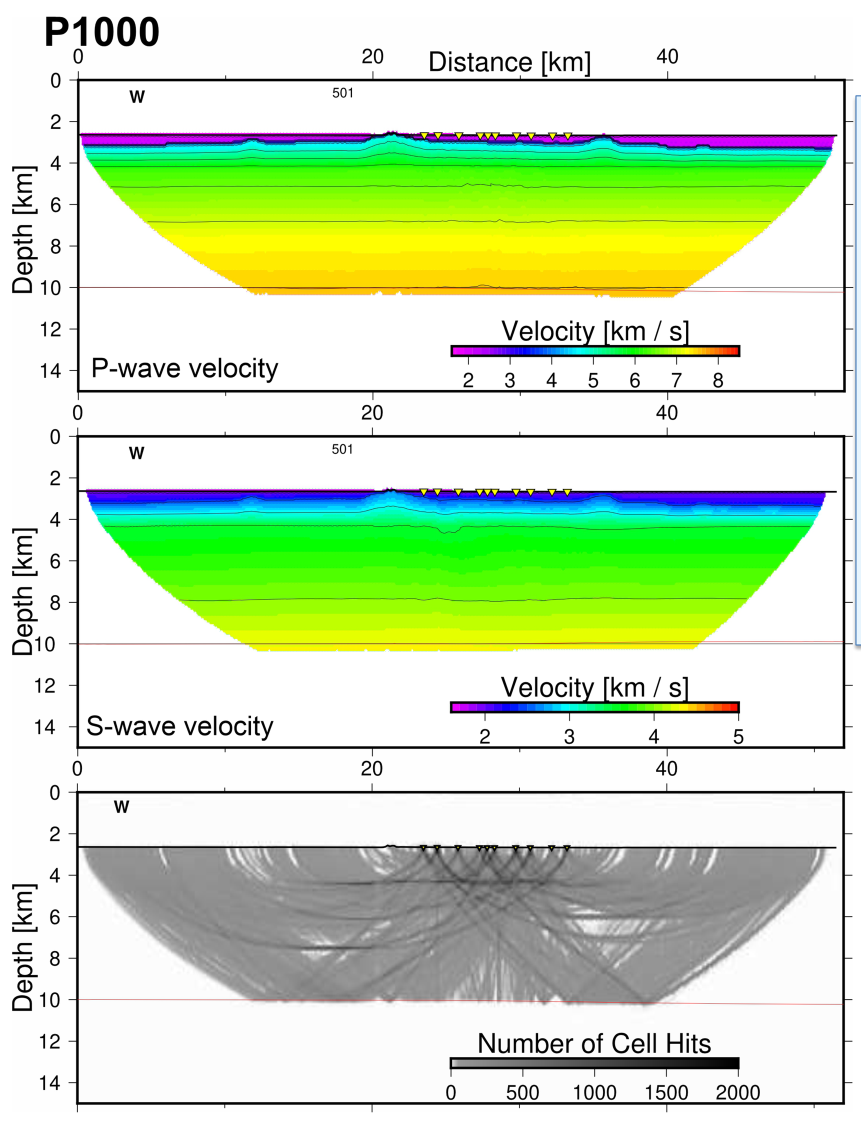

Figure 4.
Final results for P1000 of ray-tracing and tomographic inversion.

Top: P-wave velocity

Middle: S-wave velocity

Bottom: Ray coverage achieved

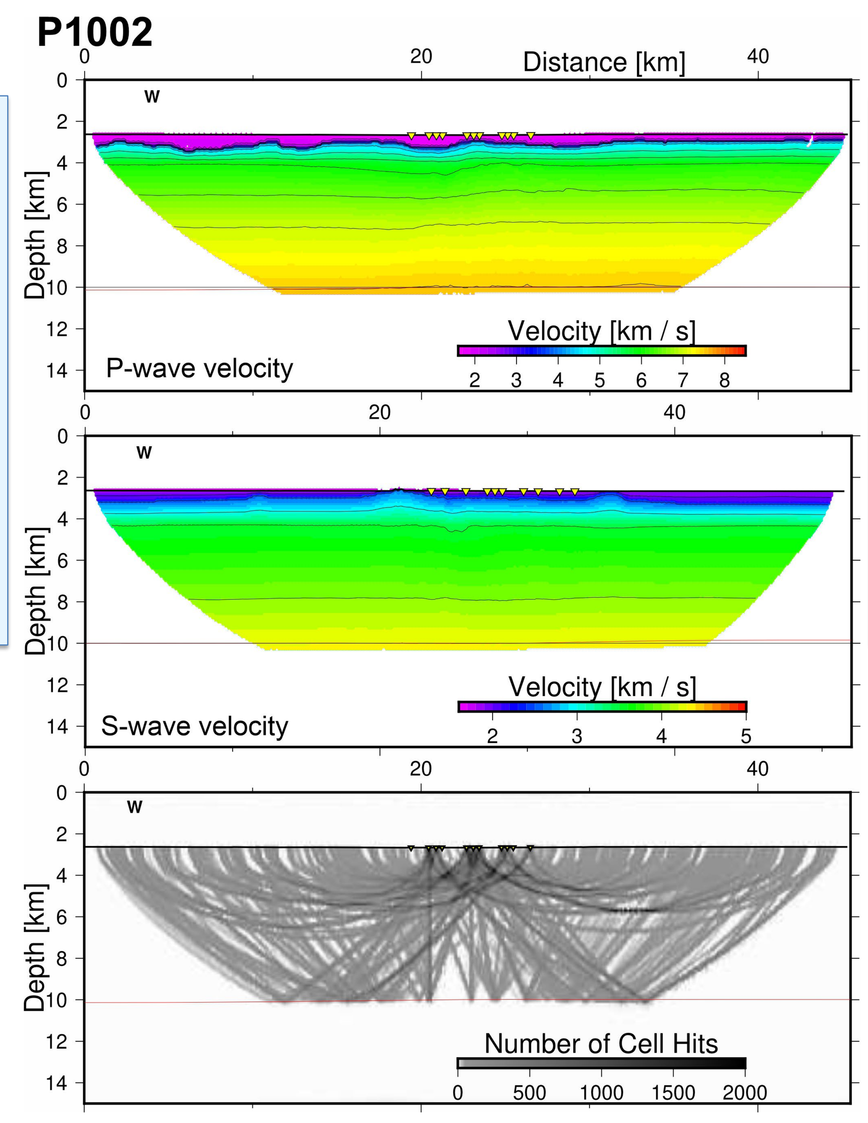

Figure 5.
Final results for P1002 of ray-tracing and tomographic inversion.

Top: P-wave velocity

Middle: S-wave velocity

Bottom: Ray coverage achieved

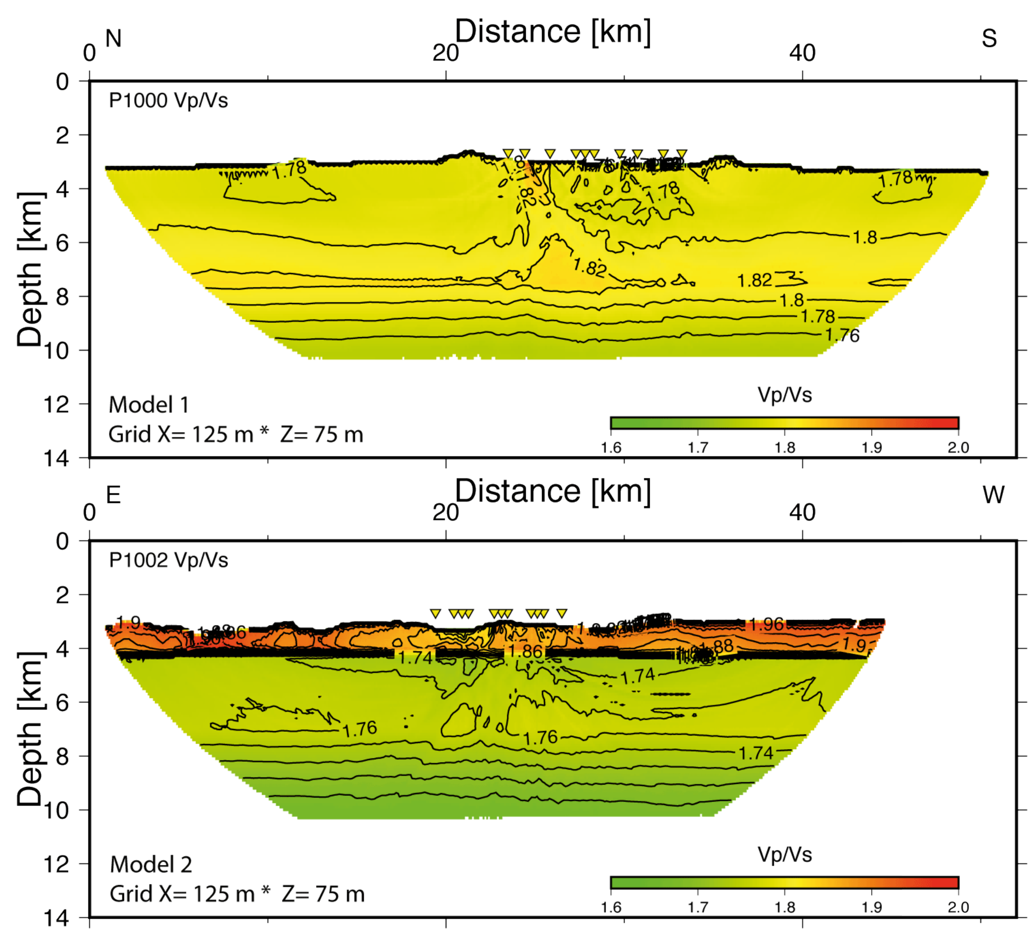

Figure 6.Calculated Vp/Vs ratio for:
Top: Profile P1000; Bottom: Profile P1002

Results

In profile P1000, the basement is characterized by a balanced Vp/Vs ratio down to a depth of approximately 6 km, from which the 'Mama Bare' and 'Baby Bare' structures do not stand out. South of 'Mama Bare', the observed reduced Vs values are reflected by a locally elevated Vp/Vs ratio (1.82). This anomaly, approximately 2 km wide, dips to a depth of 8 km. The intersecting profile P1002 is characterized by a relatively high Vp/Vs ratio down to a depth of 4 km. This is caused by the comparatively low Vs velocities. Other areas of locally increased Vp/Vs ratio increase up to a ratio of 1.9. From a depth of 4 km, the Vp/Vs ratio is relatively balanced up to a depth of 7 km, with average values of around 1.75 (P1002), which is slightly lower than the average of 1.8 in profile P1000. For further investigation of potential signatures of deeper structures in the OBS data, mirror imaging was applied to the wavefield of the first water multiples (Grion et al., 2007). The hydrophone data from 19 OBS stations along lines P1000 and P1002 were migrated individually and then stacked to map lines P1000 and P1002 accordingly. The OBS data could not reveal any additional coherent phases within the basalt layer. In order to better image the complex and rugged geometry of the basalt layers without aliasing, a denser shot spacing and a denser receiver spacing would be necessary.

Profile P1002 runs perpendicular to the spreading axis of the Juan de Fuca Ridge (JDF) and depicts the upper edge of the basement with a correspondingly rough topography, which is also reported in other studies (Kim et al., 2019; Nedimović et al., 2009). Profile P1000 with the 'Baby Bare' and 'Mama Bare' seamount structures runs parallel to the JDF. Heat flow studies in the vicinity of profiles P1000 and P1002 (Hutnak et al. ,2006) describe the region of the study area as dominated by conductive heat transport. Wheat et al. (2004) surveyed the region around the Bare Outcrop Group with the submersible Alvin and describe, in addition to largely conductive heat transport, the flow of ground water through the basement from 'Grizzly Bare' to 'Baby Bare' and 'Mama Bare'. The anomalies in the Vp/Vs ratio presented here suggest that at least 'Mama Bare' may contribute to further heat flow via deeper roots.

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