

Impact of seamounts on the hydration of subducting plates

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ABSTRACT

The subduction of seamounts greatly affects arc volcanism, earthquakes, and tectonic deformation of the overriding plate, but their role during bending and hydration of the incoming plate at subduction zones is poorly understood. Here, we present seismic tomographic results along three profiles from the Middle America Trench offshore northern Costa Rica. The crustal

and upper mantle P-wave velocities decrease towards the trench, with the onset of velocity reduction at ~70 km from the trench axis indicating bend-faulting, alteration, and hydration of the incoming plate. The most prominent low velocity anomaly of 7.6-7.8 km/s in the upper mantle occurs beneath a seamount at the outer rise, indicating enhanced hydration with ~2.4 wt% water content, compared to ~1.1-1.3 wt% in the subducting plate away from the seamount. Near the seamount, extremely low heat flow ($<10 \text{ mW/m}^2$) supports vigorous hydrothermal recharge of seawater. Our results reveal that subducting seamounts efficiently increase the permeability of the oceanic crust prior to subduction, facilitate the migration of seawater into the mantle, exert control on widespread serpentinization and potentially promote water recycling back into the Earth's interior.

INTRODUCTION

Bending of the incoming oceanic plate at deep-sea trenches leads to pervasive fracturing of the lithosphere at the outer rise and outer slope, facilitating hydration of the lithosphere, and eventually governing the transport of water into the Earth's interior (e.g., [Peacock, 1990, 2001](#); [Ranero et al., 2003](#)). This process has an important control on the circulation of volatiles (e.g., water, CO_2) between the hydrosphere and lithosphere. In subduction zones, dehydration of the subducting slab occurs and governs intra-slab intermediate-depth earthquakes ([Peacock, 2001](#)) and arc magmatism ([Cooper et al., 2020](#)), with the associated hazards; it also fuels deep-sea biological environments ([Peacock, 1990](#)). Finally, the amount of the subducted seawater is critical to understanding the Earth's water cycle. The P-wave velocity (V_p) reduction and increase in V_p/V_s from previous wide-angle seismic

(WAS) studies suggest 10-20% of serpentinization occurs in the upper mantle prior to subduction (e.g., [Grevemeyer et al., 2007, 2018](#); [Fujie et al., 2016](#)). In contrast, observations from seismic anisotropy indicate a limited average serpentinization of ~6-9% confined to the fault zones (e.g., [Miller et al., 2021](#)). It is often assumed that the flux of crustal water is fairly uniform in all subducting oceanic plates, as the quantity of water below topmost crustal layer (layer 2A) is relatively constant. In contrast, the water content in layer 2A is heterogeneous and increases with age up to ~58-70 Ma due to progressive hydrothermal activity ([Kardell et al., 2021](#); [Li et al., 2024](#)).

However, the global oceanic lithosphere is not uniform in structure, but is instead modulated by potentially 100,000 seamounts ([Yu et al., 2024](#)), which can greatly enhance hydrothermal circulation and geochemical exchange on the ridge flanks ([Harris et al., 2004](#)). Seamounts can promote hydrothermal circulation across distances >50 km within the oceanic crust ([Fisher et al., 2003](#)), leading to mass flux estimates of $\sim 10^{14}$ kg/yr globally, which ultimately affects subseafloor microbial ecosystems ([Harris et al., 2004](#); [Hutnak et al., 2008](#); [Fisher & Wheat, 2010](#)). In addition, the loading of volcanic edifices and magmatic intrusions during the building of seamounts deforms the pre-existing oceanic structure (e.g., [Watts et al., 1985](#)), creating a structurally heterogeneous lithosphere with varying porosities and volatile contents. Seamount subduction may impact tectonic erosion, interseismic coupling, seismogenesis, and fluid transportation (e.g., [Kodaira et al., 2000](#); [Marcaillou et al., 2016](#)). However, the impact of hydrothermal circulation through seamounts on subduction processes ([Fisher & Wheat, 2010](#)) and their role in slab hydration remain poorly understood.

In this study, we present Vp models along three trench perpendicular WAS lines spanning an ~80-km-long section of the Middle America Trench (MAT), where the ~23 Myr Cocos Plate formed at the East Pacific Rise (EPR) subducts beneath northern Costa Rica (Fig.1A&1B). Our results reveal extremely low upper mantle velocities beneath a seamount at the outer rise, which exceeds the Vp reduction to either side, indicating enhanced hydration and serpentinization at the seamount.

DATA AND METHODS

We use three ridge-perpendicular WAS refraction lines to study the impact of bending-related faulting at the MAT from north to south: profiles ANE, p200e, and p50 (Fig.1A). Line p200e was collected during RRS James Cook cruise JC228 (2022/23). Thirty-seven ocean-bottom-seismometers (OBSs) were deployed along this 250-km-long profile, with collocated multibeam bathymetry, heat flow, and multi-channel seismic data (Fig.1). This line crosses a ~1.1 km high seamount at the outer rise.

To reveal the lateral structural variation of the subducting plate, we also re-examine two legacy seismic lines, ANE and p50, using the same approach and parameterization as for p200e (Fig.1A). In the north, 10 OBSs were deployed along 220-km-long line ANE in 2008, which have been used to determine mantle anisotropy (Miller et al., 2021). To the south, a 140-km-long line p50 consists of 19 stations acquired in 2003 and was analyzed by Ivandic et al. (2008).

All OBS stations recorded clear crustal refraction (Pg), Moho reflection (PmP), and upper mantle refraction (Pn) arrivals (Supplemental Material Figs.S2A-S5A, Tab.S1¹). Picked travel-times were inverted using a joint seismic refraction and reflection tomographic approach

(Korenaga et al., 2000) to generate velocity models. A Monte-Carlo method was used to test the deviation of Vp and Moho depth. For detailed information about the data collection, processing, and modeling procedures, refer to [Supplemental Material](#).

COMPARISON OF VELOCITY STRUCTURES

Overall, our results display a ~5-6 km thick incoming crust with a typical two-layer (layers 2 and 3) oceanic crustal structure at the MAT, overlain by ~500 m of sediments. Crustal thickening of 3-4 km is observed beneath the seamount crossed by line p200e ([Fig.2](#)). All three profiles display a systematic trench-ward crustal Vp reduction across the outer rise, with comparable extent and degree ([Figs.2D-F, 3A](#)). The layer 3 velocities are generally reduced by ~0.1-0.2 km/s, showing the onset of bending at ~70-80 km from the trench. However, along p200e, Vp reduction in the upper mantle is detectable ~110 km from the trench, yielding a strong anomaly with a wider extent ([Figs.2D-F, 3B](#)). The maximum upper mantle Vp reduction along p200e is ~0.6 km/s, compared to only ~0.2-0.3 km/s along lines ANE and p50.

Owing to different modeling approaches and the selection of the starting model, there are small discrepancies between the Vp results in this study and previous models ([Miller et al., 2021; Ivandic et al., 2008](#)), but the main features of the models are consistent. A detailed comparison is provided in [Supplemental Material](#).

DISCUSSION

The velocity reduction in the crust and upper mantle at the outer rise is observed in subduction zones globally and is interpreted as a result of fracturing, alteration, and hydration of the subducting plate under the bending-related tensional stress (e.g., [Grevenmeyer et al.,](#)

2018; Fujie et al., 2016). Prior to subduction, the onset of Vp reduction suggests that pervasive normal faulting occurs at c.a. 70 km from the MAT offshore of northern Costa Rica (Figs. 2D-F, 3A), consistent with increasing porosity caused by crustal faulting interpreted from a decreasing electrical resistivity along line ANE at 60-80 km from the MAT (Naif et al., 2015). In this region, the structural fabric of the incoming plate created at the EPR is parallel to the trench axis (Fig. 1A). The reactivation of these faults may control plate deformation and bending (e.g., Ivandic et al., 2008). Both multi-channel seismic data (Ranero et al., 2003) and seismicity (Lefeldt et al., 2009) indicate that bending-related normal faulting at the MAT could extend into the upper mantle. The acceleration of hydrothermal circulation and deep percolation of seawater along the bending-related cracks and fractures significantly change the geochemical composition and water content of the subducting plate, promoting alteration to form hydrous minerals such as chlorite, amphibole, and serpentine (Christensen & Salisbury, 1975; Carlson & Miller, 2003). The upper mantle of the subducting slab is a major carrier of water into the subduction zone, affecting arc volcanism and seismogenesis (Cooper et al., 2020; van Keken et al., 2011) and, therefore, the degree of mantle serpentinization is critical to discuss the subducting water flux.

Assuming that serpentinization occurs uniformly in the upper mantle and accounts for all the Vp reduction, we estimate that the maximum serpentinization along lines ANE and p50 is ~10.1% and ~8.9%, corresponding to water contents of ~1.2 wt% and ~1.1 wt%, respectively, following the equations of Carlson & Miller (2003). These values are consistent with the previous Vp results at the MAT (Grevemeyer et al., 2007, 2018), but they likely represent an

upper bound as the decrease in V_p , produced by serpentine/water filled cracks and/or wide damaged zones, is not considered (e.g., [Miller & Lizarralde, 2016](#)). Seismic anisotropy results along line ANE suggested that hydration is limited to fault zones, reducing water storage to ~ 0.9 wt% ([Miller et al., 2021](#)), which is lower than our estimation. Our results at the MAT reflect a moderately hydrated lithosphere of a young, hot subducting plate that has a shallow neutral plane at ~ 6 km below the Moho ([Lefeldt et al., 2009](#)) limiting the depth and extent of serpentinization. The southward decreasing velocity anomaly matches the decreasing dip of the subducting slab ([Syracuse & Abers, 2006](#)) and a narrowing of the area affected by bending observed in the bathymetric data ([Fig.1A; Ranero et al., 2008](#)), suggesting a systematic southward decrease of fracturing and hydration ([Van Avendonk et al., 2011](#)).

In contrast to this general trend, along profile p200e, we observe the pronounced V_p reduction of 0.2-0.6 km/s in the upper mantle underlying the seamount, which may be caused by the presence of highly serpentinization with degree of $\sim 19.2\%$ (i.e., ~ 2.4 wt% H_2O) ([Figs.2B,2E,&3B](#)). We suggest that the seamount is characterized by an increased permeability and hence facilitates the water percolation and migration during the bending process, increasing the hydration of the upper mantle ([Fig.3C](#)). Seamounts on spreading ridge flanks contribute to the crustal heat loss and fluid exchange between the oceanic lithosphere and hydrosphere due to the high porosity of extrusive volcanic edifice and volcanoclastic materials, and thin sedimentary covers (e.g., [Fisher & Wheat, 2010](#)). In our study area, extremely low heat flow (< 10 mW/m²) occurs close to the seamount (HF2304 & HF2302), whereas heat flow increases to ~ 10 -30 mW/m² at ~ 10 km away from the seamount (HF2303 & HF2301) and to > 150

mW/m² to the south of 9°55'N (HF2309 & HF2305) (Fig.1C). Therefore, we infer that this seamount provides a recharge site for hydrothermal circulation, comparable to a similar-scale seamount, *Tengosed*, on the Cocos Plate away from the trench (Hutnak et al., 2008) and consequently the hydrothermal recharge in the shallow crust probably exists before bending. The seamount at p200e protrudes ~1.1 km above the surrounding seafloor, generating enough pressure difference to drive hydrothermal flow. In contrast, small seamounts or knolls may serve as discharge sites (Fisher et al., 2003), or both recharge and discharge sites (Hutnak et al., 2008), making them less supportive at supplying a continuous downward flux of seawater.

The load of the volcanic edifice may lead to the flexure of the underlying oceanic plate and, therefore, may have formed fractures and faults during volcano emplacement (Fig.3C). In addition, the contact between the volcanic edifice and the neighboring oceanic crust exhibits two narrow low velocity regions of <6.5 km/s (Fig.2B), suggesting that highly fractured or altered crust surrounds the seamount which may represent important pathways for water migration (Fig.3C), although these features are not evident in bathymetry. If the water content in the upper mantle decreases linearly from ~1.2 wt% beneath line ANE to ~1.1 wt% beneath line p50, the background water content without the impact of seamount would be ~1.15 wt% along p200e; thus, the contribution of water due to the seamount is ~1.3 wt%. Our results indicate that seamounts form sites of highly increased permeability in the oceanic crust and thereby facilitate migration of large amounts of water into the upper mantle. The sporadic seamounts in the Guatemala Basin (e.g., Hutnak et al., 2008), for example, have developed a fluid-rich subducting plate, which is supported by the geochemistry of arc volcanoes (Morris

et al., 1990) and velocity anomalies in the mantle wedge and subducting slab (Syracuse et al., 2008).

Assuming other volcanic edifices of similar size can trap similar volumes of water, we estimate that subducting seamounts contribute $\sim 2.2 \times 10^3$ Tg/Myr of water flux in the upper mantle to the deep Earth globally. This value is significantly lower than the estimation of water captured in porous volcanoclastics of the seamounts based on an electromagnetic study (5.5×10^6 – 9.4×10^6 Tg/Myr; Chesley et al., 2021). This amount of water, however, cannot be neglected given its role in mantle serpentinization and its capacity to significantly modify volatile content and chemical composition in the deep mantle. Moreover, hydrated mantle, rather than crust or sediments, is a dominant supplier of subducted water to the volcanic arc as indicated by geochemical observations (Cooper et al., 2020). Additional water flux into the upper mantle caused by seamounts at trenches would greatly affect magma productivity at arcs and the genesis of intermediate-depth earthquakes by dehydration embrittlement (e.g., Cooper et al., 2020; Marcaillou et al., 2016). Note that we may have underestimated the water flux as even buried seamounts may be hydrogeologically active (Norvell et al., 2023), which can potentially be an additional source for water flux, but further geophysical evidence is needed to estimate water flux at deep beneath subducting buried seamounts.

In summary, our results reveal that seamounts efficiently increase the permeability of the oceanic crust prior to subduction, facilitate the migration of seawater into the mantle, exert control on widespread serpentinization, and notably promote water recycling back into the Earth's interior (Fig.3C). Based on the Vp reduction, we estimate that global subducting

seamounts contribute $\sim 2.2 \times 10^3$ Tg/Myr of water flux in the upper mantle to the deep Earth.

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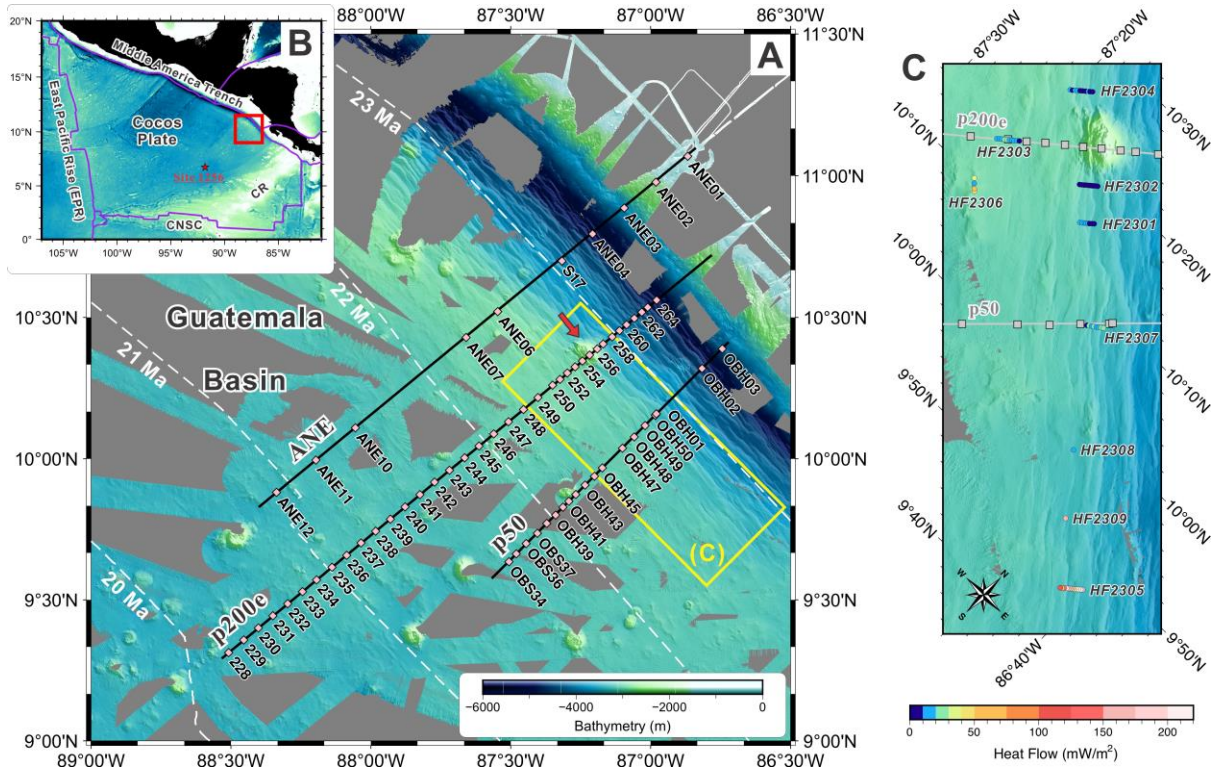
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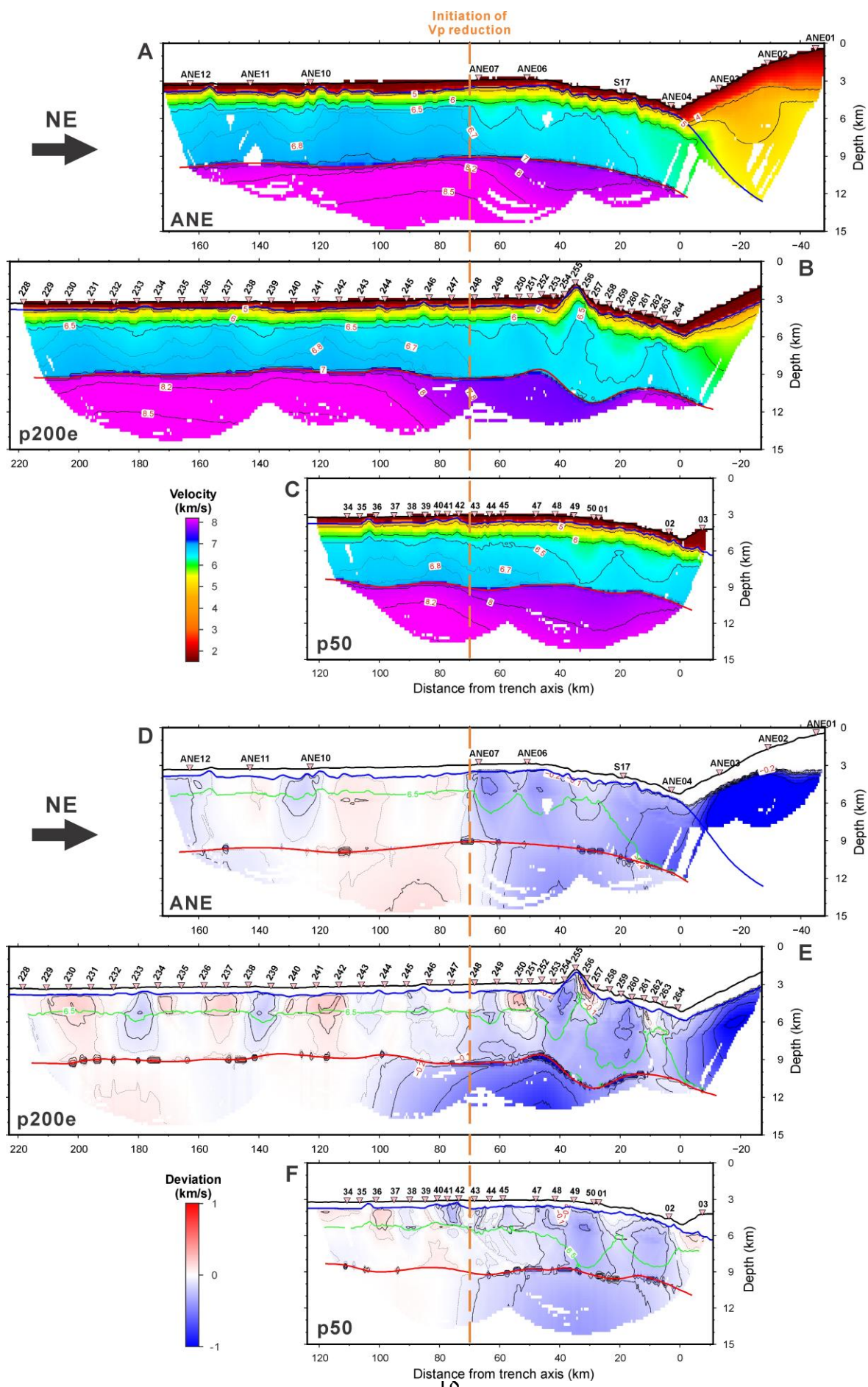
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322 Figure 1. (A) Map of the subducting Cocos Plate and the layout of wide-angle seismic (WAS)
 323 lines. Black lines and pink rectangles show the WAS lines and the locations of ocean-bottom-
 324 seismometers, respectively. Dashed white lines are seafloor isochrons from [Seton et al.](#)
 325 [\(2020\)](#). The red arrow marks the seamount located at the outer rise. (B) Inset shows the
 326 Cocos Plate, with the red rectangle marking the study area in (A) and the red star indicating
 327 the position of ODP Site 1256. Purple lines are the plate boundaries. (C) Heat flow
 328 measurement area during JC228, which is marked as yellow rectangle in (A). Circles denote
 329 heat flow stations, colored by heat flow value.



333 Figure 2. Results of seismic tomographic inversion. (A-C) shows the velocity structure of
334 profiles ANE, p200e, and p50, respectively. (D-F) presents the corresponding velocity
335 deviations that were calculated based on the reference velocity from the unaltered oceanic
336 domain (cyan bars in A-C) along each line. The thick black, blue, red lines show the
337 boundaries of seafloor, basement, and Moho, respectively. The dashed orange line marks the
338 initiation of Vp reduction.
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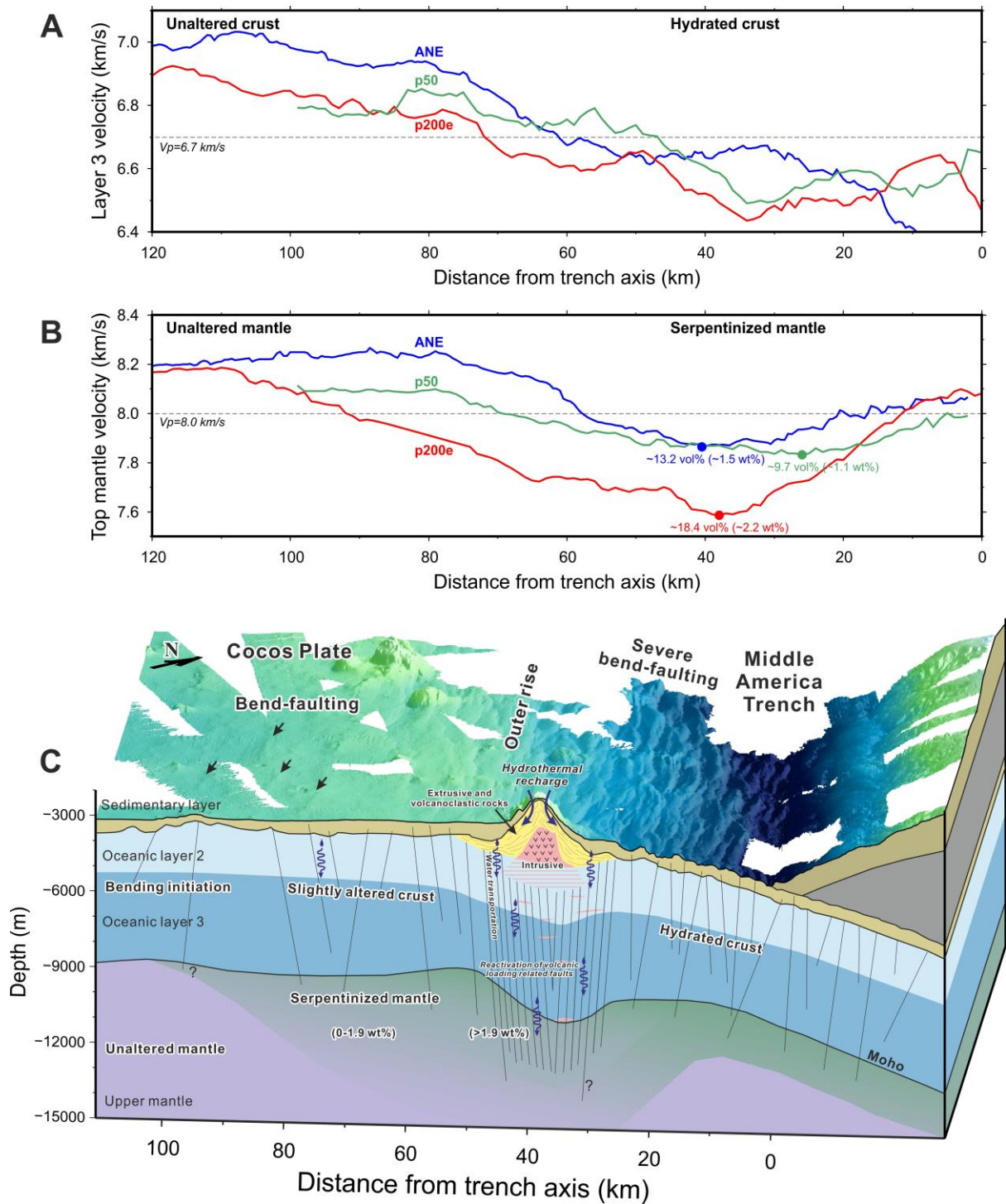


Figure 3. (A) The variation of layer 3 velocity and (B) upper mantle velocity with distance from trench axis, which are extracted from 0.5 km above and below the Moho boundary, respectively. Colored dots mark the maximum serpentinized degree (vol%) and water content (wt%) along each line estimated from V_p based on Carlson & Miller (2003). (C) 3D conceptual

345 model illustrating the role of the seamount at outer rise in entrainment of seawater into the crust
346 and upper mantle. Black arrows mark the onset of bend-faulting observed from bathymetry.

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348 ¹Supplemental Material. Detailed information about heat flow data collected in cruise JC228,
349 and data acquisition, processing, and model assessment of WAS lines p200e, ANE, and p50.

350 Please visit <https://doi.org/10.1130/XXXX> to access the supplemental material, and contact
351 editing@geosociety.org with any questions.