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Insights into initial continental rifting of marginal seas from seismic evidence for slab relics in the mid-mantle of the Woodlark rift, southwestern Pacific

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ABSTRACT

The initiation and evolution of marginal seas, especially those developing under a convergent setting, is one of the more enigmatic aspects of plate tectonics. Here, we report the presence of slab relics in the mid-mantle of the Woodlark rift in the southwestern Pacific based on a new map of the topography of the mantle discontinuities from a receiver function analysis and evidence from body-wave tomography. The widespread mantle transition-zone thickening rules out active mantle upwelling, and the revealed slab relics in both the upper and middle mantle may hydrate the upper mantle, which can be expected to further weaken the overlying lithosphere. Such a process can then promote initial continental rifting when this lithosphere is exposed to tensional stress like slab-pull stretching originating from the nearby active subduction.

INTRODUCTION

The theories of seafloor spreading and plate tectonics have been applied to explain the origin and development of major oceans and continents such as the opening of the Atlantic and the breakup of Gondwanaland. However, these theories fail to explain the extension found in the active continental margins of the western Pacific (Fig. 1A), where 75% of marginal seas in the world are concentrated, formed dominantly in the Cenozoic (Karig, 1971; Wang et al., 2019). Uncertainty about causative mechanisms arises because most of the available observations were collected from inactive or very mature marginal seas (Fig. 1A), which are mostly no longer embedded in the geodynamic setting responsible for their early rifting. As a result, much of the relevant active structures may have disappeared or been significantly altered by later tectonic events. The incipient Woodlark rift in the southwestern Pacific provides a rare opportunity to characterize the early-stage evolution of continental rifing at a still-forming marginal sea.

Situated within the oblique and rapidly convergent (~110 mm/yr) zone between the Australian and Pacific plates, the Woodlark rift in southeastern Papua New Guinea is developing at the western tip of the Woodlark Basin (Fig. 1B) and is the only place in the western Pacific spanning the transition from initial continental rifting (10–15 mm/yr) to active seafloor spreading (20–40 mm/yr) of marginal seas (Taylor et al., 1999; Wallace et al., 2014). This makes the Woodlark rift a perfect locale for deciphering the mechanism for the initial continental rifting of marginal seas. The time of rifting initiation is still under debate, within the range of 3.6–8.4 Ma, before which multiple phases of Cenozoic subduction, obduction, and orogenesis (Fig. 1) occurred (Baldwin et al., 2012; Holm et al., 2016). In this study, we conducted the first receiver function (RF) study of the mantle transition zone (MTZ) structure beneath the Woodlark rift (Fig. 1) based on all available broadband seismic data. Our observations firstly rule out the involvement of active mantle upwelling and further highlight the role of slab relics in promoting rifting, which has rarely been discussed before.

EXISTENCE OF SLAB RELICS IN THE MID-MANTLE

We mapped the topography of the 410 km and 660 km mantle discontinuities by conducting moveout correction and stacking of receiver functions under a non-plane-wave assumption. The whole study area is revealed to have widespread MTZ thickening (261 ± 16 km) especially at the center of the Woodlark rift (289 ± 13 km) (Fig. 2C; Figs. S7C and S8C in the Supplemental Material[1]); for details on previous seismic studies, data processing, and result descriptions, see the Supplemental Material. The presence of water or thermal anomalies in the MTZ would theoretically contribute to a negative correlation between the depths of the 410 km and 660 km mantle discontinuities, and a normal MTZ would bring a largely positive correlation. The resulting low cross-correlation coefficient of 0.14 in general is consistent with the revealed MTZ thickening (Fig. 2D). We interpret the MTZ thickening as indicating the presence of cold thermal anomalies possibly associated with slab relics or foundered lithospheric fragments. This interpretation is supported by the presence of high-velocity anomalies in the MTZ under the rift zone in several global velocity models, although their resolution is generally too low to discern details of the distribution and geometry of the hypothesized relics (Fig. 3; Figs. S2–S5 and S9). Delaminated cratonic lithosphere has been recently modeled to be able to sink into the MTZ (Peng et al., 2022), but plate reconstructions of the

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[1]Supplemental Material. Figures S1–S9 and Table S1. Please visit https://doi.org/10.1130/GEOL.S.24143001 to access the supplemental material; contact editing@geosociety.org with any questions.

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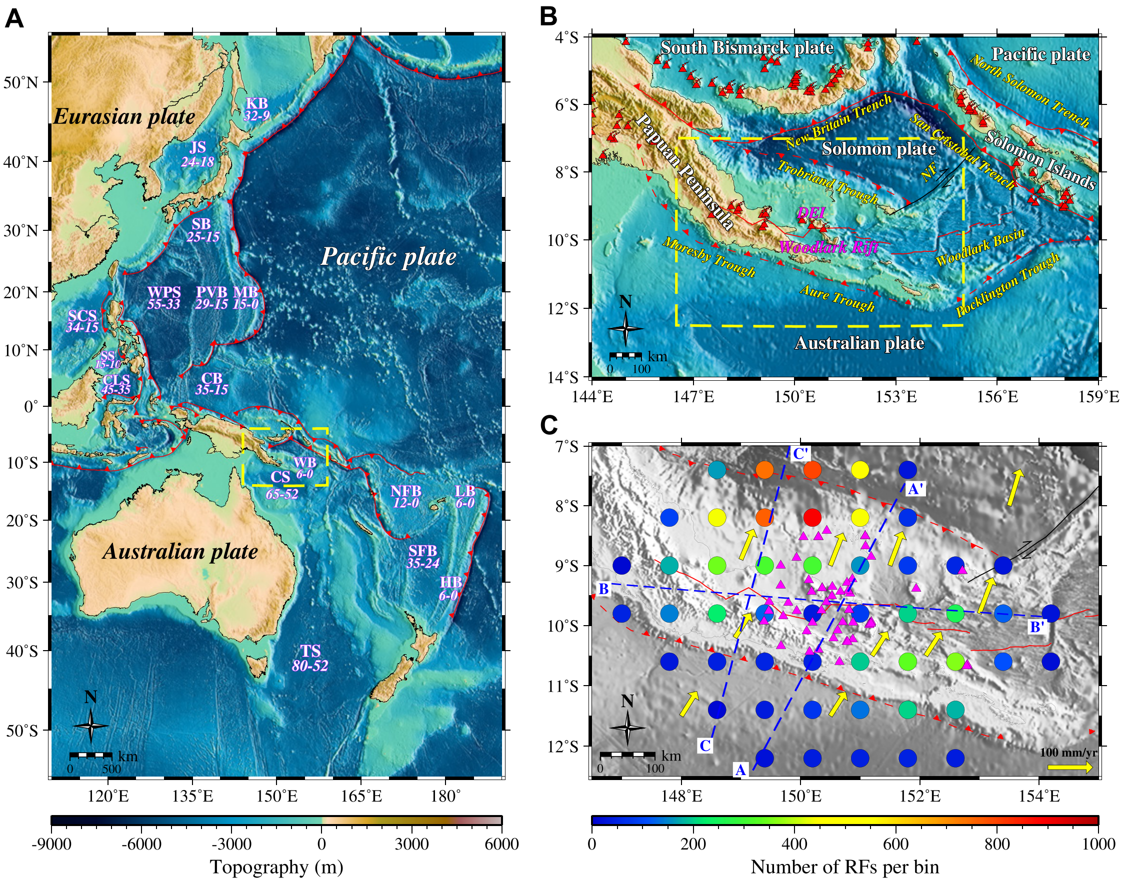

Figure 1. Marginal seas and study region. (A) Topographic map showing distribution of major marginal seas along the western Pacific. Red toothed lines represent currently active subductions. Yellow dashed rectangle highlights the study area. Ages of marginal seas (in Ma) just below each corresponding shortened site name are summarized by Wang et al. (2019). CB—Caroline Sea Basin; CLS—Celebes Sea; CS—Coral Sea; HB—Havre Basin; JS—Japan Sea; KB—Kurile Basin; LB—Lau Basin; MB—Mariana Basin; NFB—North Fiji Basin; PVB—Parece Vela Basin; SB—Shikoku Basin; SCS—South China Sea; SFB—South Fiji Basin; SS—Sulu Sea; TS—Tasmania Sea; WB—Woodlark Basin; WPS—West Philippine Sea. (B) Tectonic setting of southeastern Papua New Guinea. Red lines indicate rifting axis. Solid and dashed red toothed lines correspond to currently active and fossil trenches, respectively. Red triangles represent Cenozoic volcanic centers. DEI—D'Entrecasteaux Islands; NF—Nubara fault. (C) Distributions of broadband seismic stations (purple triangles) and receiver function (RF) coverage. Colored circles indicate number of RFs for each bin with radius of 0.8°, according to ray piercing points at 535 km depth. Blue dashed lines delineate cross sections in Figure 3. Yellow arrows show absolute plate motions determined from the NNR-MORVEL56 model (Argus et al., 2011).

period since 52 Ma display an absence of cratonic lithosphere in our study area (Wu et al., 2016). Fossil subduction systems bounding the rift zone have been proposed to have occurred at different periods (Webb et al., 2014; Holm et al., 2016; Benyshek and Taylor, 2021). A northward-directed subduction of a Jurassic–Cretaceous oceanic basin (Pocklington Sea) in the Late Cretaceous existed along the Aure-Moresby-Pocklington Troughs, and its cessation was followed by continental collision and underthrusting of the northern Australian continental margin beneath an outboard proto–New Guinea terrane at ca. 12 Ma (Baldwin et al., 2012; Webb et al., 2014; Holm et al., 2015). Subsequent slab breakoff and associated lithospheric delamination have been suggested to explain the heavy rare earth element (REE)–depleted geochemistry of the contemporaneous magmatic rocks (Holm et al., 2015). Fragments of a fossil slab are characterized as high-velocity anomalies detected at ~130–220 km depth in a recent tomographic study (Yu et al., 2022). A short-lived southward subduction zone along the Trobriand Trough was suggested to have initiated in the early to middle Miocene and was possibly triggered by the arrival of the Ontong Java Plateau (Taylor and Huchon, 2002; Holm et al., 2015; Benyshek and Taylor, 2021). The onset of northward subduction at the New Britain and San Cristobal Trenches has generated a slab-pull force (Webb et al., 2014) and may have terminated the southward subduction of the Solomon plate at the Trobriand Trough, which would have left a dangling slab at shallow depth. This fossil slab has been systematically observed as high-velocity anomalies either from Rayleigh- (Jin et al., 2015) or body-wave tomography (Eilon et al., 2015, 2016; Yu et al., 2022) with observable intermediate-depth seismicity (Abers et al., 2016). Prominent negative radial anisotropy (Yu et al., 2022) indicates the presence of currently sinking detached slab segments (Fig. 3). Our new MTZ measurements offer independent geophysical evidence of past slab subductions beneath the Woodlark rift and importantly provide clear evidence that the detached slab relics have dropped into the MTZ (Fig. 3D). The downwelling of these slab relics can further induce mantle upwellings and thermal anomalies at their surrounding areas, which may explain the observed MTZ thinning at the western Woodlark Basin (Fig. 2C) in the eastern part of our study region.

Additional peaks with stacking amplitudes comparable to those of the 410 km and 660 km discontinuities are also revealed around the 300 km and 730 km depths (Fig. 3; Figs. S2–S5), although they are not present consistently in the study area. Comparable additional discontinuities in other areas have been interpreted as compositional heterogeneities segregated from the residue of subducted slabs (Williams and Revenaugh, 2005) such as the fossil slab of the Proto–South China Sea (Yu et al., 2021). The presence of these additional discontinuities thus offers corroborating evidence for the existence of slab relics in the MTZ.

The revealed slab relics in the upper mantle and MTZ of the Woodlark rift have probably originated from a combination of recent and ancient subductions. Both global (Argus et al., 2011) and regional (Wallace et al., 2014) geodetic studies indicate that the whole study area is moving northward at a speed of ~60 mm/yr (Fig. 1C). Once isolated slab relics detach from the subducted plate and begin to freely drop into the deep mantle, they should be situated south of the prior plate boundary. The slab sinking rate has been determined to change from 4 to 8 cm/yr as estimated from a tomography-

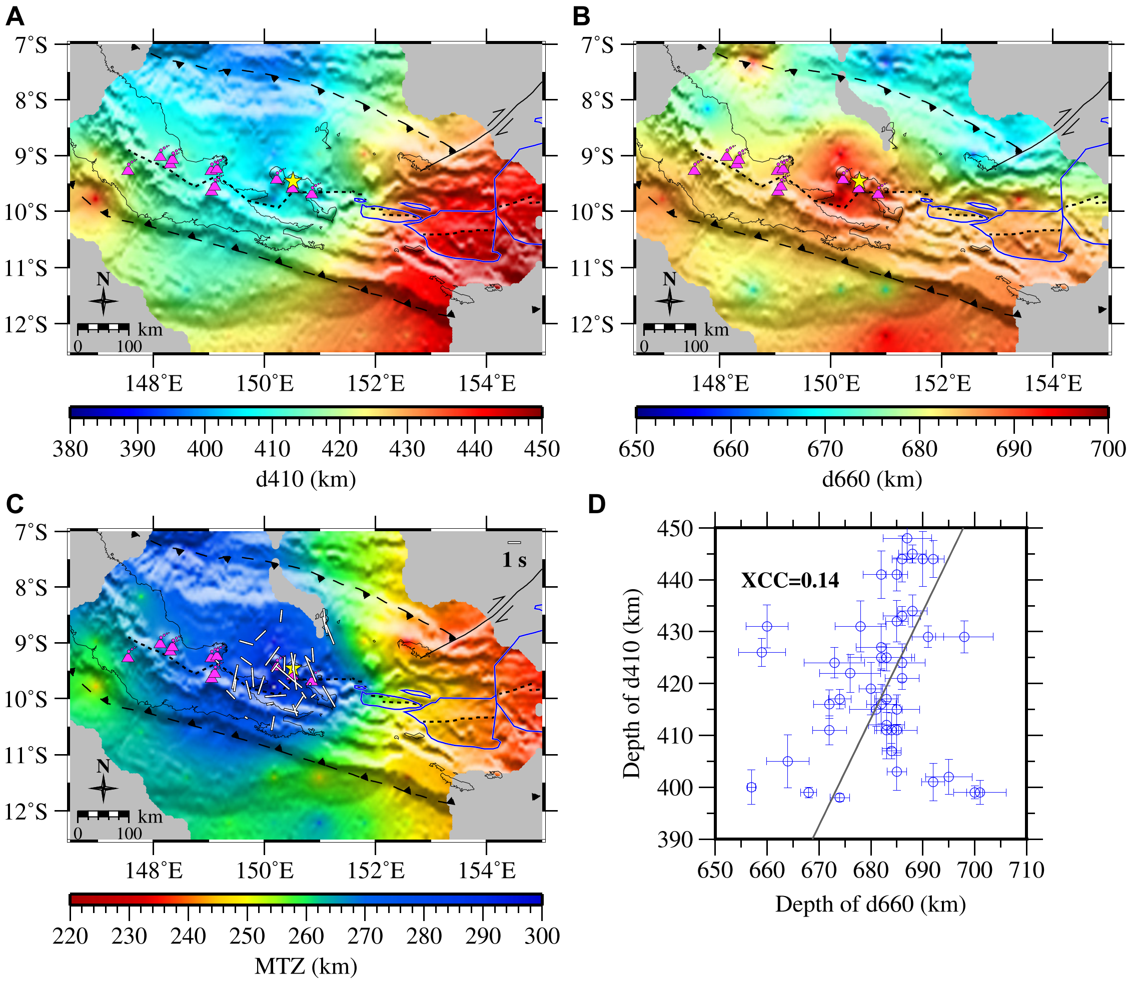

Figure 2. Resulting mantle transition zone (MTZ) measurements from receiver function analysis. (A–C) Contour maps of the observed MTZ thickness and apparent depths of the 410 km (d410) and 660 km (d660) discontinuities. Yellow star indicates position of exhumed youngest ultra-high-pressure rocks, and blue lines depict the oceanic part of the Woodlark Basin (Baldwin et al., 2004). White bars in C are station-averaged shear-wave splitting measurements (Eilon et al., 2014). (D) Correlation between apparent depths of d410 and d660. Error bars: stand deviations of MTZ measurements. Thick gray line represents best-fit but with a low cross-correlation coefficient (XCC) of 0.14.

based plate reconstructions for the Philippine Sea and East Asian plate (Wu et al., 2016); a recent study estimates sinking rates to generally fall in the range of 1–5 cm/yr based on analysis of the Pacific subductions (Peng and Liu, 2022). The slab detachment presumably occurred at a depth of ~200 km based on tomographic images of the still-attached part of the slab (Fig. 3). Assuming the occurrence of slab detachment at ca. 5 Ma (Holm et al., 2015) and a sinking rate of 4 cm/yr, the slab segments from the Trobriand subduction would have dropped to ~400 km depth and be situated 300 km south of the current surface expression, which is generally consistent with the distributions of the high-velocity anomalies. The short duration of the fossil subductions bounding the Woodlark rift may thus be insufficient to explain the presence of slab relics in the lower MTZ. Thus, contributions from ancient subductions are needed, like the long-lasting southwest-dipping subduction of the Pacific plate, which initiated in the early Cenozoic (Baldwin et al., 2012; Benyshek and Taylor, 2021). A slab remnant is also inferred to be currently in the lower MTZ under the Woodlark rift from plate reconstructions for the past 52 m.y. and interpreted as a newly discovered East Asian Sea slab (Wu et al., 2016).

IMPLICATIONS FOR INITIAL CONTINENTAL RIFTING OF MARGINAL SEAS

Our observations may help clarify the driving mechanisms for the initial continental rifting of marginal seas. A mantle plume or asthenosphere upwelling, as previously hypothesized for explaining the evolution of marginal seas along the western Pacific by Miyashiro (1986), would be expected to induce widespread MTZ thinning and develop an anisotropy with dominant vertical fast direction. However, the existence of such a model beneath the Woodlark rift is ruled out based on the resulting opposite measurements of MTZ thickening (Fig. 2C; Figs. S7C–S8C; Table S1), the dominance of high-velocity anomalies in the MTZ (Fig. S9), significant azimuthal anisotropy (Eilon et al., 2014) (Fig. 2C), and systematic positive radial anisotropy of the observed low-velocity anomalies in the upper mantle under the rift zone (Fig. 3; Yu et al., 2022). The absence of a well-defined Wadati-Benioff zone (Eilon et al., 2015; Abers et al., 2016) and the revealed discontinuous slab segments (Yu et al., 2022), which appear as isolated high-velocity anomalies in tomographic images (Fig. 3), suggest that the southward subduction at the Trobriand Trough may be quite slow or inactive (Taylor and Huchon, 2002; Wallace et al., 2014). The conventional back-arc spreading model associated with active roll-back subduction (Karig, 1971) therefore cannot be applied to the Woodlark rift. However, the negative radial anisotropy of the subducted slab segments (Fig. 3) implies that they are still sinking (Yu et al., 2022). Fast orientations of azimuthal anisotropy from shear-wave splitting analysis display a dominantly extension-parallel pattern (Eilon et al., 2014), which is generally consistent with the directions of the absolute plate motions (Fig. 2C) based on the NNR-MORVEL56 model (Argus et al., 2011). Joint analysis of geologic, geodetic, and reflection data (Ott and Mann, 2015) indicates that continental rifting at the Woodlark rift is facilitated by plate rotations (Wallace et al., 2014), which are primarily driven by the slab-pull forces from the northward subduction of the Solomon plate (Fig. 1B).

The slab relics revealed in both the upper mantle and MTZ of the Woodlark rift (Fig. 3) can be expected to release hydrous materials. These hydrous materials are expected to trigger self-buoyant upwellings, which have been modeled to be conveyed by sublithospheric small-scale convection and further induce par-

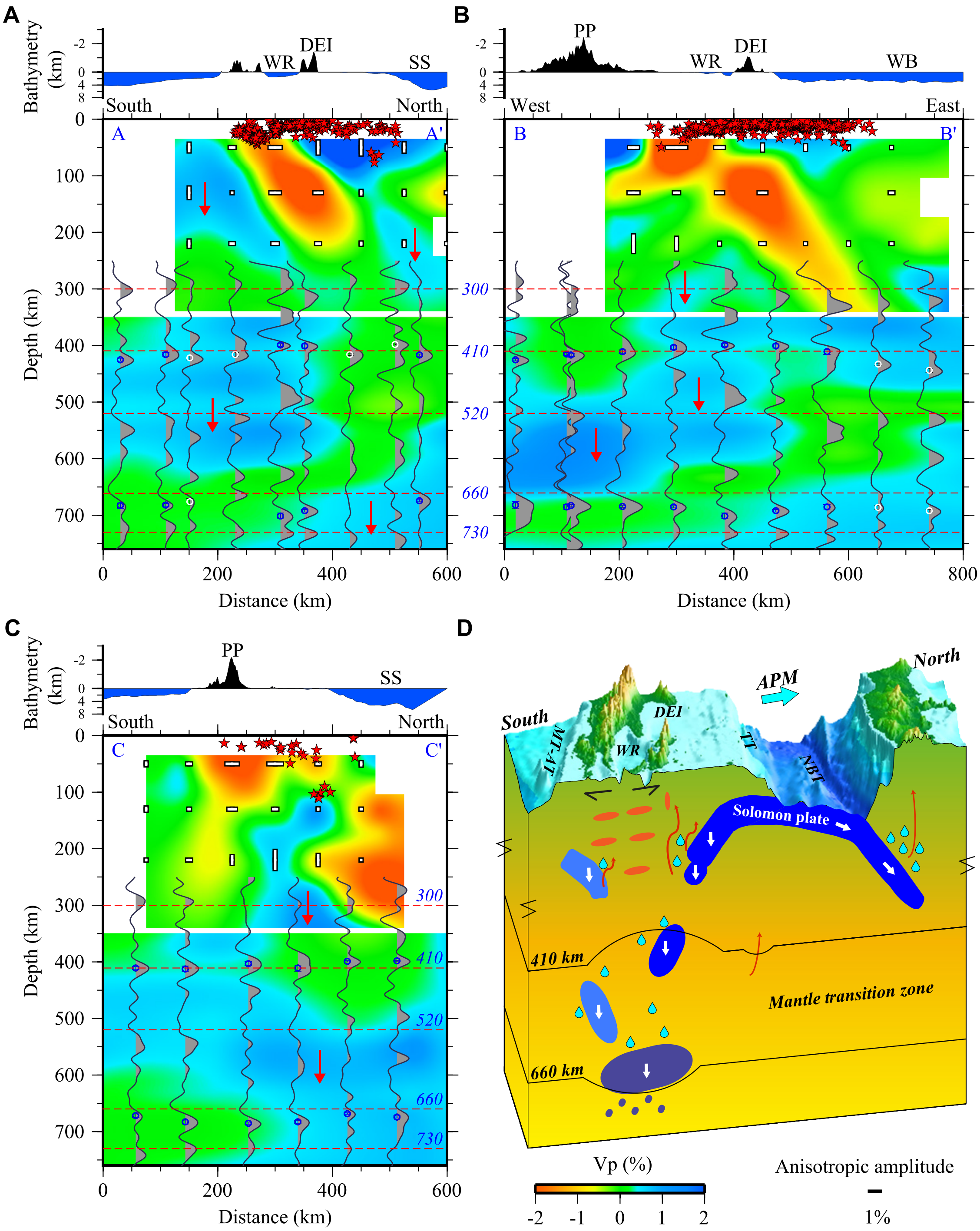

Figure 3. Vertical display of mantle transition zone (MTZ) results and fossil slab dynamics. (A–C) Cross sections of the bathymetry, receiver function traces, and velocity anomalies along the three profiles shown in Figure 1C. Black curves are receiver function traces with peaks filled with gray. Red dashed lines indicate mantle discontinuities at the depths of 300, 410, 520, 660, and 730 km, respectively. Velocity anomalies of the upper mantle and MTZ in the lower panels are from regional (Yu et al., 2022) and global (Simmons et al., 2015) tomography models for depths above and below 350 km, respectively. Vertical and horizontal white bars indicate radial anisotropy with faster velocity in the vertical and horizontal directions, respectively, which is obtained from radial anisotropy teleseismic travel-time tomography (Yu et al., 2022). Red stars are local earthquakes (Abers et al., 2016). Red arrows display inferred downwelling motions of slab relics. Circles show well-defined peaks of the 410 km and 660 km discontinuities, with blue ones having MTZ thickness at least 255 km; error bars are stand deviations. DEI—D'Entrecasteaux Islands; PP—Papuan Peninsula; SS—Solomon Sea; WB—Woodlark Basin; WR—Woodlark rift. (D) Conceptual diagram demonstrating the role of slab relics in promoting the Woodlark rift. Cyan drops represent water released from slab dehydration. Red arrows represent dehydration melting or small-scale mantle upwelling related to downwelling of slab relics. Note that geometry and exact positioning of fragments (dark blue) are symbolic because these details are not resolved well by the tomography. Orange ellipses denote decompression melting, with their long axis corresponding to primary strain orientations. APM—absolute plate motion; NBT—New Britain Trench; MT-AT—Moresby Trough–Aure Trough; TT—Trobriand Trough.

tial melting at the base of the lithosphere (Long et al., 2019; Balázs et al., 2022). The 520 km discontinuity (Fig. 3) is visible, in some places with split peaks, which indicates an increased water content (van der Meijde et al., 2003) or a fertile mantle in the mid-MTZ possibly enriched by the segregated high-Ca materials from the subducted oceanic crust (Deuss and Woodhouse, 2001; Saikia et al., 2008). The Woodlark rift is revealed to possess a relative paucity of melt as suggested from body-wave tomography (Eilon et al., 2015) while exceptional low-velocity anomalies and high Vp/Vs ratios are observed in its upper mantle (Eilon et al., 2015; Jin et al., 2015), which may be attributed to compositional heterogeneities including water released from the slab relics (Fig. 3D). A small amount of ascending hydrated mantle can also explain the slight disturbance of dominantly extension-parallel fast orientations and isolated small azimuthal anisotropy (Eilon et al., 2014) locally observed within the rift zone (Fig. 2C), which is supported by the small negative radial anisotropy at the edge of the high-velocity anomalies (Fig. 3). In addition, certain portions of adakitic melts with light REE– and large-ion lithosphere element (LILE)–enriched signatures at this rifting area have been reported to be formed by the involvement of hydrous mantle peridotite (Haschke and Ben-Avraham, 2005). We conclude that, at least in this case at the Woodlark rift, the initial continental rifting of marginal seas is mainly driven by slab pull from nearby subductions and is promoted by slab relics via hydrating the upper mantle.

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