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Structure of oceanic crust in back-arc basins modulated by mantle source heterogeneity

Ingo Grevemeyer[1], Shuichi Kodaira[2], Gou Fujie[2] and Narumi Takahashi[2]
[1]GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel 24148, Germany
[2]Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama 236-0001, Japan

ABSTRACT

Subduction zones may develop submarine spreading centers that occur on the overriding plate behind the volcanic arc. In these back-arc settings, the subducting slab controls the pattern of mantle advection and may entrain hydrous melts from the volcanic arc or slab into the melting region of the spreading ridge. We recorded seismic data across the Western Mariana Ridge (WMR, northwestern Pacific Ocean), a remnant island arc with back-arc basins on either side. Its margins and both basins show distinctly different crustal structure. Crust to the west of the WMR, in the Parece Vela Basin, is 4–5 km thick, and the lower crust indicates seismic P-wave velocities of 6.5–6.8 km/s. To the east of the WMR, in the Mariana Trough Basin, the crust is ~7 km thick, and the lower crust supports seismic velocities of 7.2–7.4 km/s. This structural diversity is corroborated by seismic data from other back-arc basins, arguing that a chemically diverse and heterogeneous mantle, which may differ from a normal mid-ocean-ridge–type mantle source, controls the amount of melting in back-arc basins. Mantle heterogeneity might not be solely controlled by entrainment of hydrous melt, but also by cold or depleted mantle invading the back-arc while a subduction zone reconfigures. Crust formed in back-arc basins may therefore differ in thickness and velocity structure from normal oceanic crust.

INTRODUCTION

When continents break apart, continental crust and lithosphere are stretched until breakup occurs and seafloor spreading forms a new ocean basin. Breakup is commonly assumed to be controlled by magma that ascended from the deep mantle up to higher levels, weakening the continental lithosphere and eventually causing the breakup of the continental plate (e.g., White and McKenzie, 1989). Consequently, magmatism during the rifting process and seafloor spreading are controlled by pressure-release partial melting of a fertile mantle (e.g., Korenaga et al., 2002). Yet, plate convergence and retreating subducting slabs may also cause rifting of continents or islands arcs, as well as opening of back-arc basins (e.g., Platt, 2007). In such cases, the subducting slab is an important control on the pattern of mantle flow, melt extraction, and composition of melts (e.g., Davies and Stevenson, 1992). It is generally envisioned that melts delivered under the volcanic arc are overturned and reintroduced beneath the back-arc spreading ridge by subduction-induced corner flow (Martinez and Taylor, 2002), in turn affecting back-arc crustal accretion (Dunn and Martinez, 2011). However, water is also released from the downgoing slab and entrained into the mantle (e.g., Hasenclever et al., 2011), causing enhanced melting.

Volcanic passive continental margins and rifted margins of island arcs share some similarities in structure, like high-velocity lower-crustal rocks in the vicinity of the continent-ocean transition zone (COT) or the island-arc–back-arc basin transition zone. Volcanic margins are characterized by P-wave velocities of Vp = 7.1–7.4 km/s (Hopper et al., 2003; White et al., 2008), while margins of island arcs and crust in back-arc basins may show even faster velocities of 7.2–7.6 km/s (Takahashi et al., 2008, 2009; Arai and Dunn, 2014). At volcanic margins, fast lower-crustal velocities are related to hotter mantle, producing MgO-rich melts (White and McKenzie, 1989; Korenaga et al., 2002). At rifted margins of islands arcs, fast lower-crustal velocities are probably related to hydrous differentiation, producing cumulates with mafic-to-ultramafic composition and higher-than-usual seismic velocity at the bottom of the crust (Eason and Dunn, 2014).

When rifting persists, breakup occurs, and seafloor spreading takes over, creating new oceanic crust. In back-arc basins, crust emplaced in the vicinity of the arc is generally affected by the hydrous melts entrained from the arc or slab into the melt rising below the spreading axis. For the Lau Basin (southwestern Pacific Ocean), Martinez and Taylor (2002) observed that crustal formation, and hence seismic structure, is a function of the distance to the arc. In the early stage after breakup, crust emplaced at close distance to the arc is suggested to form high-velocity lower crust (Arai and Dunn, 2014). With greater time since rifting, and hence distance to the arc, decreasing entrainment of hydrous melts is going to favor normal oceanic crust.

Here, we report constraints from crustal and upper-mantle tomography along seismic profile MR101c shot by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) aboard the R/V *Kaiyo* during cruise KY03–06 (Fig. 1). The profile surveyed the Western Mariana Ridge (WMR), an island arc in the northwestern Pacific Ocean with rifted margins on either side. Seafloor spreading occurring after breakup opened two back-arc basins: the Parece Vela Basin (PVB) in the west, and the Mariana Trough Basin (MTB) in the east. Our results challenge the view of a simple relationship between enhanced melt delivery near the volcanic front and diminished melting farther away from the arc because the structures of the PVB and MTB differ profoundly from each other and from normal oceanic crust.

GEOLOGICAL SETTING

The Izu-Ogasawara (Bonin)-Mariana island arc was created when subduction of the Pacific plate began during the Eocene, and has since undergone dramatic changes in its orientation, shape, and location (Sdrolias, and Müller, 2006). At 29–30 Ma, back-arc spreading initiated in the

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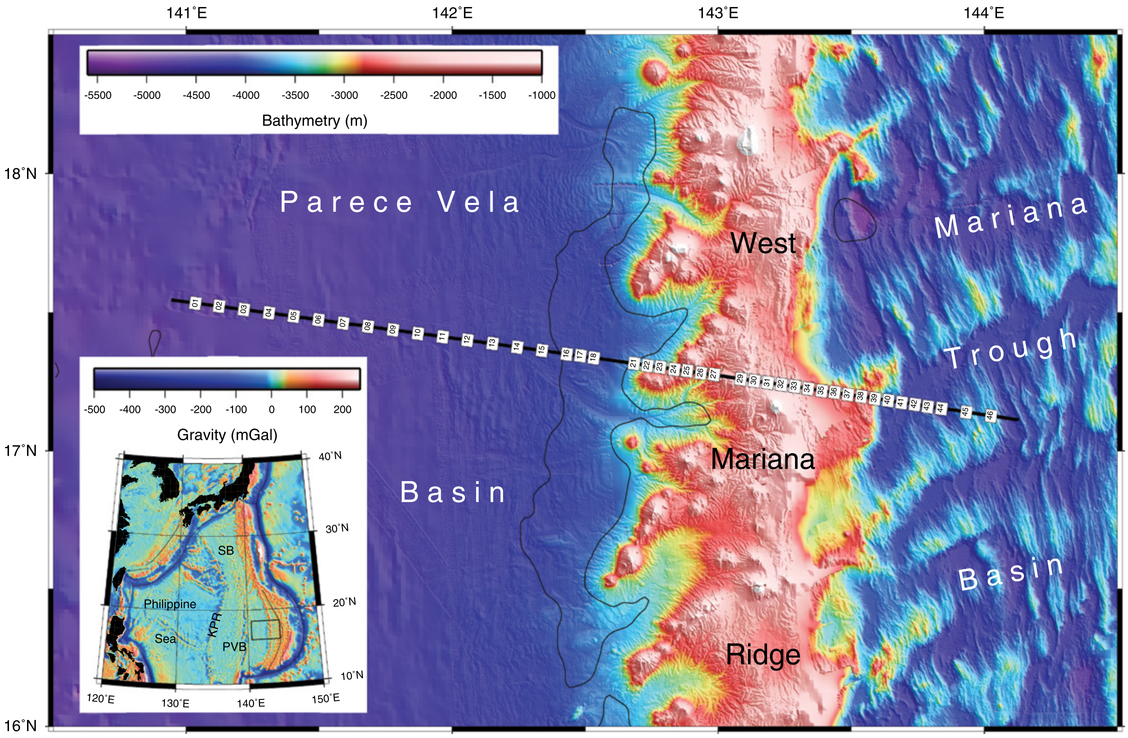

Figure 1. Bathymetric map of the West Mariana Ridge and adjacent back-arc basins in the Philippine Sea, and layout of the study's seismic profile. Inset shows the gravity field in the study area (Sandwell et al., 2014), and black isoline indicates gravity low. SB—Shikoku Basin; PVB—Parece Vela Basin; KPR—Kyushu-Palau Ridge.

Shikoku Basin and PVB (Okino et al., 1998), sundering the Kyushu-Palau Ridge (KPR) and forming a pair of conjugate rifted margins (Fig. 1). Volcanic activity along the arcs diminished at 27 Ma, and there is little evidence of volcanic activity between 23 and 17 Ma (Taylor, 1992). Arc volcanism was reactivated along the WMR at ca. 15 Ma (Scott et al., 1981), when the opening and seafloor spreading in the Shikoku Basin and PVB ceased, leaving behind an abandoned back-arc basin. The reactivated arc affected the rifted eastern margin of the KPR, and most of it is today buried beneath the remnant WMR.

At ca. 5 Ma, the Mariana Trough opened, rifting the WMR from the modern Mariana volcanic arc and establishing seafloor spreading in the MTB, which is still forming new oceanic crust at the center of the MTB.

STRUCTURE OF BACK-ARC BASINS

Along profile MR101c, 46 ocean bottom seismometers recorded excellent active-source seismic reflection and refraction P-wave data, which were inverted (see the Supplemental Material[1]) using TOMO2D software (Korenaga et al., 2000; https://people.earth.yale.edu/software/jun-korenaga) to yield a high-resolution image of the crustal structure of the WMR and adjacent back-arc basins (Figs. S1–S4 in the Supplemental Material). Results revealed marked structural differences between the western and eastern rifted margins of the WMR and between the structure of the PVB and MTB (Figs. 2 and 3). The WMR is ~120–150 km wide and towers ~2 km over the 4–4.5-km-deep adjacent back-arc basins. Its crust has a thickness of up to 14 km, and the ridge is covered by a thin sedimentary blanket <500 m in thickness. The WMR did not develop any distinct middle crust, but rather it can be divided into an upper crust and a lower crust. The 4–5-km-thick upper crust has a strong velocity gradient, increasing from ~3 km/s to 6 km/s at ~4 km below the seafloor. The lower crust is characterized by a much lower gradient; velocity increases from ~6 km/s to 6.8–6.9 km/s at the base of the crust. Below that, the upper mantle has rather low velocities of <7.5 km/s.

The structure of both passive margins of the WMR is highly asymmetric, indicating a rather abrupt transition into the MTB and a more gradual transition into the PVB. Thus, toward the east, approaching the MTB, crustal thickness changes abruptly, and the crust-mantle boundary or Moho rises from ~15 km to 11 km at km 185 of the seismic profile. At that location, seafloor morphology indicates abyssal hill fabric, supporting the interpretation that the crust has been emplaced by seafloor spreading (Fig. 2A). This interpretation is supported by its seismic structure, indicating a 2–3-km-thick, high-gradient, layer 2–type upper crust, and a low-gradient, layer 3–type lower crust (e.g., Grevemeyer et al., 2018). The crust, however, is up to 7 km thick, and a distinct feature is a high-velocity lower crust.

The western constructional margin of the WMR reveals a 60-km-wide transition zone, where high velocities of 7.2–7.5 km/s occur in the lower crust. Unfortunately, sedimentation has masked the basement topography, and thus we could not use basement relief to define underlying tectonic domains. However, the velocity anomaly tapers off at the western edge of a prominent gravity low (Fig. S4) stretching along the margin. Similar gravity anomalies have been observed along a number of continental margins (Watts, 1988) and are attributed to flexural loading and juxtaposition of thick crust against thin crust, and thus gravity can be used to approximate the westward extension of the remnant arc. Based on the gravity anomaly, the transition from the WMR to back-arc spreading crust may occur to the west of the gravity low at km 150 of the seismic line. Approaching the margin (km 160–200), crust above the high-velocity lower crust mimics the structure of a flexural sedimentary basin. However, fast velocities of >5 km/s may suggest a volcaniclastic origin for the sedimentary deposits.

The PVB is ~500 m deeper than the seafloor of the MTB to the east. Further, it is covered by ~500–800 m of sediments, supporting a basement depth of >5–5.5 km and reflecting the greater age of the PVB when compared to the MTB. The seismic velocity structure of the crust in the PVB indicates the typically layered structure of crust formed by mid-ocean-ridge processes. A key feature is the strong structural variability on either side of the WMR, revealing lower-crustal velocities of 7.2–7.4 km/s in the MTB and 6.7–6.9 km/s in the PVB. Further, the

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[1] Supplemental Material. Description of methods and supplemental Figures S1–S5. Please visit https://doi.org/10.1130/GEOL.S.13262834 to access the supplemental material, and contact editing@geosociety.org with any questions.

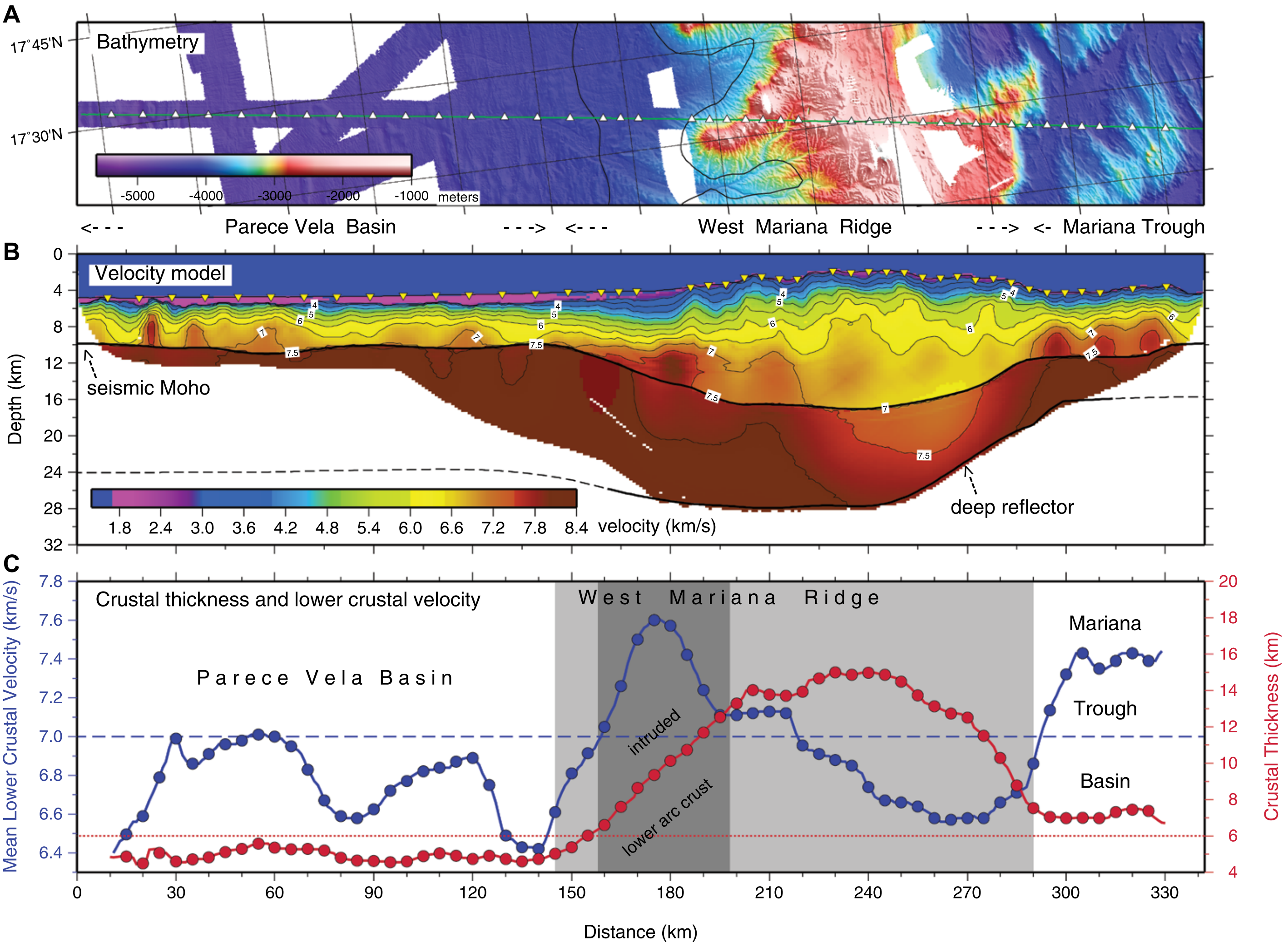

Figure 2. Seismic results from the West Mariana Ridge (northwestern Pacific Ocean). (A) Bathymetry along seismic profile MR101c across the West Mariana Ridge. (B) P-wave velocity model. (C) Mean lower-crustal velocity (blue) and crustal thickness (red). Reference velocity of 7 km/s for normal lower crust formed at mid-ocean ridges is shown by the blue dashed line; reference crustal thickness of 6 km is given by the dotted red line.

crust has a thickness of 4–5 km; i.e., much thinner in the PVB than in the westernmost part of the MTB, where crust is ~7 km thick.

DISCUSSION

When compared to the WMR, the KPR provides marked differences in structure. Most importantly, the KPR does not show any evidence for fast velocities of 7.2–7.5 km/s in the COT zone, such as those observed at the western margin of the WMR. Thus, the P-wave velocity of the lower crust of the western margin of the PVB is <7.0 km/s (Nishizawa et al., 2007), supporting a strong asymmetry of the conjugate margins. One explanation might be that the fast lower crust at the western margin of the WMR is related to island-arc magmatism, rather than being related to breakup. Thus, after breakup of the KPR and spreading in the PVB, there is little evidence for arc magmatism between ca. 29 and 20 Ma, but arc volcanism was reactivated at 20–17 Ma (Scott et al., 1981), when the opening of the Shikoku Basin and PVB ceased. Therefore, the fast lower crust of the western margin of the WMR might have been formed by melts accumulating at the base of crust while arc volcanism was reestablished along the WMR, overprinting the old passive margin. Further, the rejuvenated volcanic arc activity of the WMR can account for the large amount of volcaniclastic sediments on the western flank of the WMR and the asymmetric sedimentary cover of the adjacent PVB, with the eastern basin to the east of 140°E acting as depocenter for volcaniclastic products from the active WMR arc, and little sediment covering the basin to the west of the now-extinct PVB ridge axis.

In the MTB, both conjugate margins indicate clear similarities in structure, providing fast lower-crustal velocities in the COT and after onset of seafloor spreading (Takahashi et al., 2008), supporting a common origin. In general, the structure of the back-arc crust of the MTB shares similarities with the Lau Basin and the arc to back-arc transition zone of the Izu-Bonin arc, as both basins indicate fast lower-crustal velocities, often exceeding 7.2 km/s (Crawford et al., 2003; Takahashi et al., 2009; Arai and Dunn, 2014). In the eastern Lau Basin, fast lower crust correlates with thicker crust (Arai and Dunn, 2014), as observed along the eastern portion of our profile in the MTB (Fig. 3). Some other areas, however, lack any correlation between lower-crustal velocity and crustal thickness (Takahashi et al., 2009; Nishizawa et al., 2011).

Eason and Dunn (2014) proposed a petrological model to explain high lower-crustal velocities and crustal stratification. Their model was based on the observation that lava samples from the Lau Basin show arc-like compositional enrichments and tend to be more vesicular and differentiated than typical mid-ocean-ridge basalt (MORB). They therefore proposed that slab-derived water might have been entrained in the near-arc ridge system, where it is not only enhancing mantle melting, but is also governing

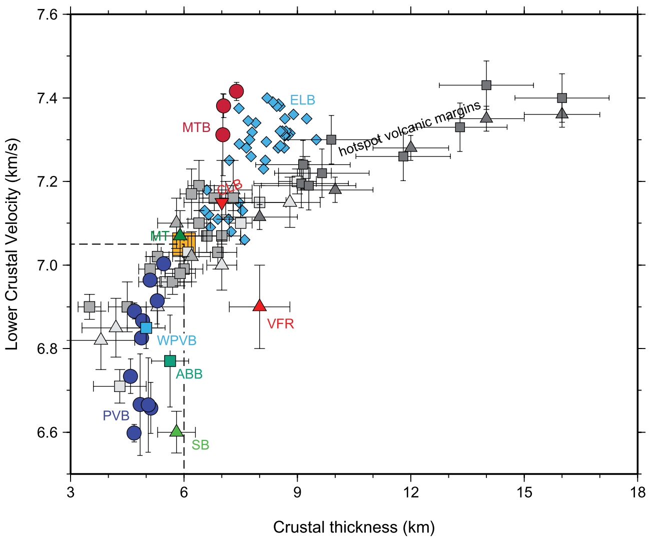

Figure 3. Classification of crust based on lower-crustal velocity and crustal thickness; melting of pyrolytic mantle at normal mantle temperature should form 6-km-thick oceanic crust (orange square; Sallares et al., 2005). Depending on the tectonic setting, oceanic crust may deviate from the reference as indicated by the gray symbols (light gray—slow and ultraslow spreading ridges; gray—fast spreading ridges [Grevemeyer et al., 2018); dark gray—hotspot provinces [Hopper et al., 2003; White et al., 2008]). Colored symbols are back-arc spreading centers: blue circles—Parece Vela Basin (PVB, northwestern Pacific Ocean; this study); red circles—Mariana Trough Basin (MTB; this study); light blue diamonds—Eastern Lau Basin (ELB, southwestern Pacific Ocean; Arai and Dunn, 2014); green triangle—Mariana Trough spreading center (MT; Takahashi et al., 2008); blue square—western Parece Vela Basin (WPVB; Nishizawa et al., 2007); light green triangle—Shikoku Basin (SB; Nishizawa et al., 2011); green square—Algerian-Balearic Basin (ABB, western Mediterranean Sea; Booth-Rea et al., 2018); red triangle—Valu Fa Ridge in the southern Lau Basin (VFR; Turner et al., 1999); red inverted triangle—Central Lau Basin (CLB; Crawford et al., 2003).

magmatic differentiation and crustal formation. In their model, ~0.5–1.0 wt% water in near-arc parental melts may lead to crystallization of a mafic cumulate layer, which is represented by the observed fast seismic velocities.

The most important observation from our seismic survey is that crust underlying two different back-arc basins immediately after breakup, and hence at close distance to the volcanic front, is remarkable different. The thick crust in the MTB is consistent with the observation that onset of seafloor spreading nucleated at sites where magmatism continues from arc volcanism, through rifting to back-arc spreading (Oakley et al., 2009), supporting entrainment of arc melts into the upwelling zone of the developing spreading center (Taylor and Martinez, 2003). Earliest seafloor spreading in the PVB dates back to 30 Ma (Sdrolias and Müller, 2006), and arc magmatism may have terminated at 29–27 Ma (Scott at al., 1981). We would therefore expect mixing of melts from the arc into the spreading center, though the waning arc magmatism may have reduced the generation of hydrous melts. Thus, the crust in the PVB should either show the impact of hydrous melting, or it should at least represent normal oceanic crust. However, crust in the entire PVB is unexpectedly thin (Fig. 2; Fig. S5), and its velocity structure reveals a lower-crustal velocity that is too slow when compared to normal oceanic crust (Grevemeyer et al., 2018; Christeson et al., 2019), which is several percent slower than that predicted by melting of a pyrolytic MORB mantle source (Fig. 3). Interestingly, the slow lower-crustal velocity found in the PVB is not unique to the basin; it has also been observed in other back-arc settings (Fig. 3), including the Valu Fa Ridge, close to the Tonga arc (Turner et al., 1999), and the Algerian-Balearic Basin (Booth-Rea et al., 2018), which opened behind a retreating slab in the Miocene in the western Mediterranean Sea.

The marked crustal heterogeneity of different back-arc basins may suggest that hydrous melts entrained from the arc cannot be the sole factor controlling crustal structure, as we would expect that entrained water would cause two end members of crust, grading from normal oceanic crust emplaced away from the arc to much thicker crust and faster lower crust in close proximity to the arc (Arai and Dunn, 2014). Instead, the fact that crust in the entire PVB is thinner and slower than normal oceanic crust may require a mantle source that differed from a mid-ocean-ridge–type mantle. Opening of the PVB coincided with a lack of arc volcanism and hence may support a major change in the geometry and/or dynamics of subduction at ca. 30 Ma, which should have affected the amount of hydrous melt entrained into the mantle, either by mantle wedge corner flow (e.g., Taylor and Martinez, 2003) or by slab melting (e.g., Hasenclever et al., 2011). Further, slab breakup (Scott and Kroenke, 1981) and reconfiguration of subduction may have allowed subslab mantle to mix with the back-arc mantle, probably trapping either cold mantle or mantle depleted by prior seafloor spreading, in turn explaining the thin crust in the PVB. In extreme cases, opening of back-arc basins elsewhere even nurtured unroofing of mantle (e.g., Prada et al., 2016). We therefore argue that in back-arc systems, an inherently heterogeneous mantle governs melting, causing the observed diversity of back-arc crust, which may deviate profoundly from normal oceanic crust.

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