Crustal structure and evolution of the Mariana intra-oceanic island arc

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ABSTRACT

A new high-resolution velocity model of the Mariana arc-backarc system obtained from active-source seismic profiling demonstrates velocity variations within the arc middle and lower crusts of intermediate to felsic and mafic compositions. The characteristics of the oceanic-island-arc crust are a middle crust with velocity of ~6 km/s, laterally heterogeneous lower crust with velocities of ~7 km/s, and unusually low mantle velocities. Petrologic modeling suggests that the volume of the lower crust, composed of restites and olivine cumulates after the extraction of the middle crust, should be significantly larger than is observed, suggesting that a part of the lower crust, especially the cumulates, is seismically a part of the mantle.

Keywords: seismic structure, intra-oceanic island arc, crustal growth, Izu-Bonin-Mariana arc.

INTRODUCTION

Oceanic island arcs are regarded as the prime location for the growth of the andesitic continental crust. However, this conjecture has largely been based on petrologic and geologic studies (e.g., Rudnick, 1995), and direct seismological detection of the andesitic continental crust beneath the arcs has remained elusive. Although a thick middle crust with a tonalitic (intermediate to felsic) velocity of 6 km/s (Christensen and Mooney, 1995; Kitamura et al., 2003) has been detected in the northern Izu arc (Suyehiro et al., 1996), the Aleutian arc has little or no middle crust with a P-wave velocity of 6 km/s (Holbrook et al., 1999; Shillington et al., 2004). Understanding crustal growth requires not only knowledge of the distribution of the tonalitic middle crust but also imaging of the velocity variations and heterogeneity within each crustal layer. In particular, the velocities of the middle and lower crusts and the upper mantle should vary progressively during crustal growth. During growth, the initial basaltic crust differentiates to produce a crust with intermediate to felsic components having higher SiO_2 content, and the residual dense mafic component of the arc crust should be removed either during arc growth, or during subsequent arc-accretion events (e.g., Kay and Kay, 1993; Jull and Kelemen, 2001). The nature of the crustal differentiation and the return of mafic components into the mantle are keys to understanding crustal growth.

The Izu-Bonin (Ogasawara)-Mariana oceanic island arc developed as an oceanic arc within a purely oceanic crust, without continental collision (e.g., Karig and Moore, 1975; Hall et al., 1995). Subduction initiated at 50–40 Ma, and an early initial arc with no backarc rifting formed the nucleus of what has since become the Kyushu-Palau Ridge, the present Mariana arc-backarc system, and northern Izu arc (Stern et al., 2003) (Fig. 1, inset). The backarc spreading rifted off a part of this early arc to form the Kyushu-Palau Ridge, to the west of the now-inactive Shikoku and Parece Vela Basins at 30 or 29 Ma, and rifting ceased at 15 or 16 Ma (Okino et al., 1994, 1998). The Miocene Mariana arc split into the currently active Mariana arc as a nonvolcanic margin and the inactive West Mariana Ridge by the Mariana Trough and backarc spreading center since 7 Ma (e.g., Stern et al., 2003), while the northern Izu arc continues to grow as an unrifted arc. For our seismic study of crustal growth, we conducted a deep seismic profile, with 106 ocean-bottom seismographs (OBSs) and an air gun array with a total capacity of 196.6 L (Takahashi et al., 2003) (Fig. 1).

P-WAVE VELOCITY MODELING TECHNIQUE AND RESULTS

The construction of a velocity model with high reliability and high resolution depends on the signal-to-noise ratio of OBS records. Because almost all our OBS records show clear first phases through not only the crust but also the mantle to maximum offsets in some cases of over 150 km (Takahashi et al., 2003), our data have sufficient quality and depth penetration to image the full crustal thickness of the Mariana arc-backarc system. Using these OBS records and our collinear reflection section, we constructed a P-wave velocity model from the Parece Vela Basin across the West Mariana Ridge and Mariana Trough to the Mariana arc by standard tomographic inversion and two-dimensional ray tracing techniques (Zelt and Barton, 1998; Zelt and Ellis, 1988; Zelt and Smith, 1992) (Fig. 2A). The interface locations and velocity contrasts were confirmed by minimizing traveltime residuals and by comparing waveforms between observed and synthetic data.

Figure 2B illustrates the good resolution of the final velocity model. The interface and velocity nodes are spaced at 5 km intervals, equivalent to the closest OBS spacing. The resolution values are a measure of model reliability and vary from 0 to 1, where values exceeding 0.5 are conventionally regarded as reliable (Zelt and Smith, 1992). Based on this standard, almost all velocity nodes within the crust (except for the deepest parts of the middle and lower crusts, and the extreme ends of the profile) are reliable. Similarly, the interface nodes for the crucial boundaries between the middle and lower crusts and the Moho exceed 0.5, and thus they meet our reliability criterion and justify our interpretation of the thickness of the middle and lower crusts and the shape of the Moho.

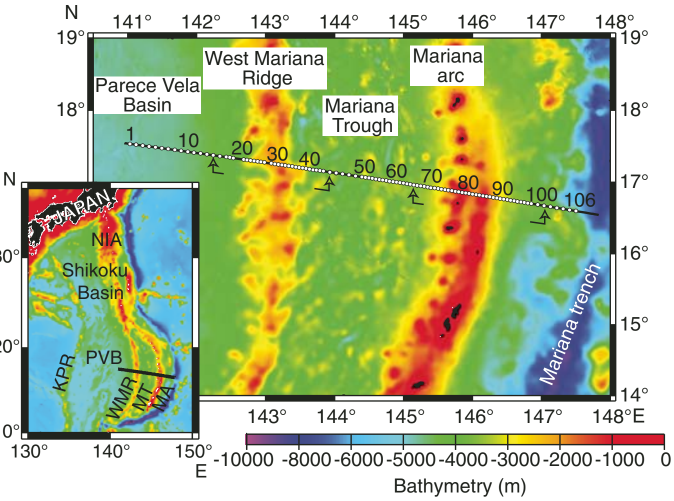

Figure 1. Bathymetry of Mariana arc-backarc system around our wide-angle seismic profile. Thick black line and open circles indicate locations of air gun shooting line and ocean-bottom seismographs (OBSs), respectively. Numerals denote site numbers of OBSs. Inset shows our profile superimposed on bathymetry of entire Izu-Bonin-Mariana arc, and locates Parece Vela Basin (PVB), West Mariana Ridge (WMR), Mariana Trough (MT), Northern Izu arc (NIA), Kyushu Palau ridge (KPR), Mariana arc (MA), and Mariana Trench. Open arrows indicate boundaries between the arc and backarc areas used to calculate crustal volumes.

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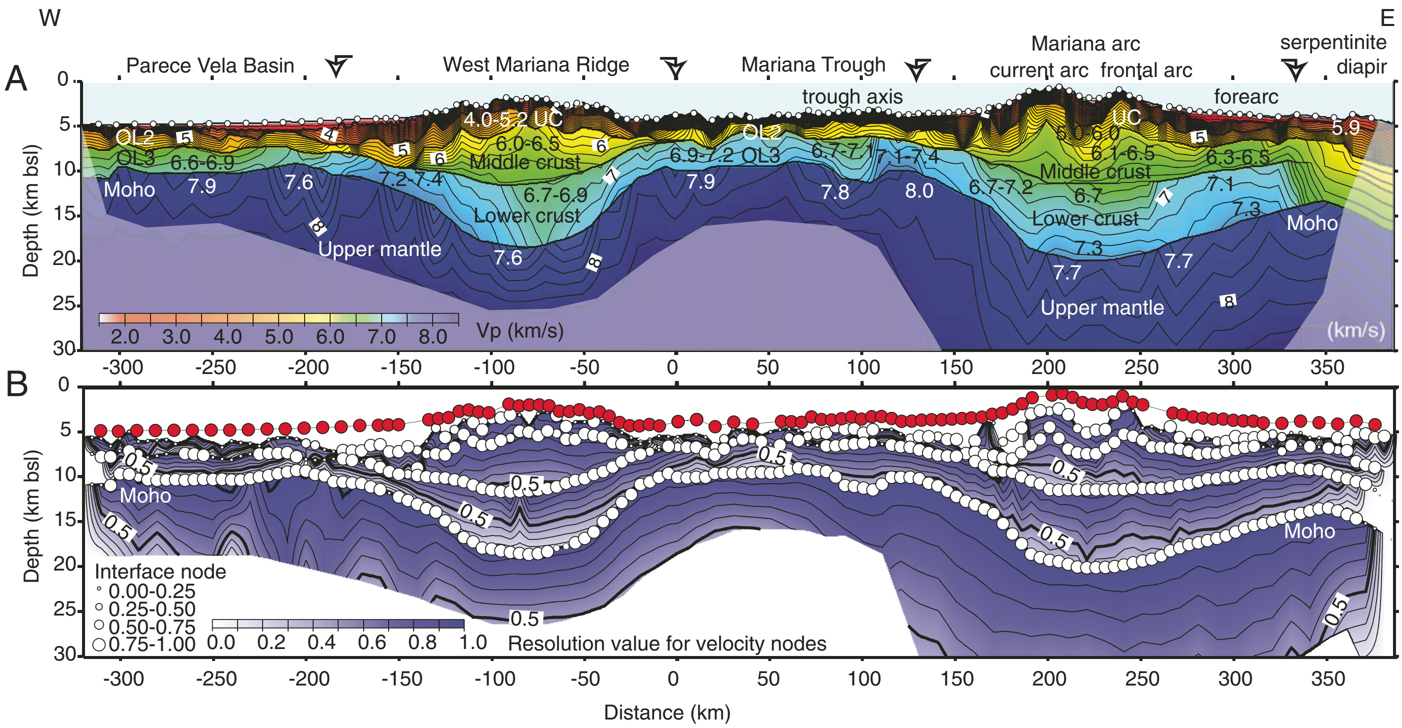

Figure 2. Final velocity model of Mariana arc-backarc system and its resolution. A: Final model. Solid circles indicate ocean-bottom seismograph (OBS) locations. Numerals denote P-wave velocity (Vp) (km/s). Open arrows indicate boundaries between arc and backarc areas used to calculate crustal volumes. UC, OL2, and OL3 are upper crust and oceanic layers 2 and 3, respectively. Dark shading shows region of seismic-ray penetration; bsl—below sea level. B: Resolution of final model. Resolutions of velocity nodes are indicated by color scale with contour spacing of 0.1, and those of interface nodes are shown by size of open circles. Red circles indicate OBS locations.

Another measure of the quality of the fit is that almost all residuals are below 150 ms, which is less than one period of the dominant frequencies of 5 Hz in the OBS data.

The Mariana arc consists of the active arc initiated in the Pliocene ~ 30 km west of the Eocene-to-Miocene frontal arc and its forearc basin (Stern et al., 2003; Crawford et al., 1981). The Moho depth is ~20 km beneath the volcanic front. The crust has four distinct layers separated by rapid increases and/or contrasts in seismic velocity. We identify these as a sedimentary layer (2.0–4.5 km/s), upper crust (4.5–6.0 km/s), middle crust (6.1–6.5 km/s), and lower crust (6.7–7.3 km/s). Specifying the boundary between the arc and the backarc based on the shape of the Moho (Fig. 2A), their volumes are 311 km^3/km of arc length, 588 km^3/km, 591 km^3/km, and 1349 km^3/km, respectively, which represent proportions of 11%, 21%, 21%, and 48%, respectively (Table 1). These layers exhibit significant lateral heterogeneity: the average velocity of the middle crust is somewhat faster in the forearc than elsewhere, and it is slowest adjacent to the backarc Mariana Trough; the velocity of the lower crust (7.1–7.3 km/s) beneath the forearc is significantly higher than that beneath the active arc (6.7–7.3 km/s). The sub-Moho velocities, at ~7.7 km/s, are significantly less than the global average of 8.1 km/s.

The West Mariana Ridge is a part of the Miocene arc that developed before the Mariana Trough opened in late Miocene time (e.g., Crawford et al., 1981). The Moho depth is ~17 km. The crust apparently consists of the same four layers as in the Mariana arc, a 2.2–4.0 km/s sedimentary layer, a 4.0–5.2 km/s upper-crustal layer, a 5.6–6.5 km/s mid-crustal layer, and a 6.7–7.4 km/s lower-crustal layer. Their volumes are 271 km^3/km, 358 km^3/km, 535 km^3/km, and 883 km^3/km, and their relative proportions are 13%, 17%, 26%, and 43%, respectively (Table 1). As in the Mariana arc, the lower crust of the West Mariana Ridge exhibits its lowest seismic velocity adjacent to the Mariana Trough (6.7–7.2 km/s), in contrast to the western part, which has higher velocities of 7.2–7.4 km/s. The sub-Moho velocity is again slow at 7.6 km/s.

DISCUSSION

Common Structural Characteristics of the Northern Izu Arc and the Mariana Arc

The crusts of the Mariana arc, West Mariana Ridge, and northern Izu arc share important commonalities (Fig. 3), including the relatively laterally uniform upper crust with a velocity of 4.5–6.0 km/s, middle crust with a velocity of 6.0–6.5 km/s, and lower crust with a velocity of 6.8–7.3 km/s (Suyehiro et al., 1996). Based on petrologic studies (e.g., Kitamura et al., 2003; Christensen and Mooney, 1995), the compositions of the upper, middle, and lower crusts are interpreted to be basaltic, tonalitic, and gabbroic, respectively. The volumes of the sedimentary, upper-crustal, middle-

TABLE 1. COMPARISON OF SEISMOLOGICALLY MEASURED CRUSTAL VOLUMES

Layer (km^3/km)		Mariana arc (km^3/km)	West Mariana Ridge (km^3/km)	Northern Izu arc (km^3/km)	Continental crust (km)
Seismological Estimate	Sediments	311	271	496	
	Upper crust	588	358	732	7
	Middle crust	591	535	963	19
	Lower crust	1349	883	2455	18
Petrologic Estimate	Estimated restites	1773–1098	1605–994	2889–1788	
	Estimated cumulates	833–642	705–532	1293–983	
	Estimated lower crust (restites + cumulates)	2606–1740	2310–1526	4182–2771	

Note: Seismological calculations for Mariana arc, West Mariana Ridge, and northern Izu arc were made over arc width of 205 km, 180 km, and 275 km, respectively. Values in continental crust column indicate layer thicknesses (Rudnick and Fountain, 1995; Zelt and Forsyth, 1994). Petrologic estimates of the volumes of differentiated restites and cumulates, and their sum (estimated lower crust) assume 25%–35% partial melting in order to produce an andesitic layer equivalent to the observed middle crust.

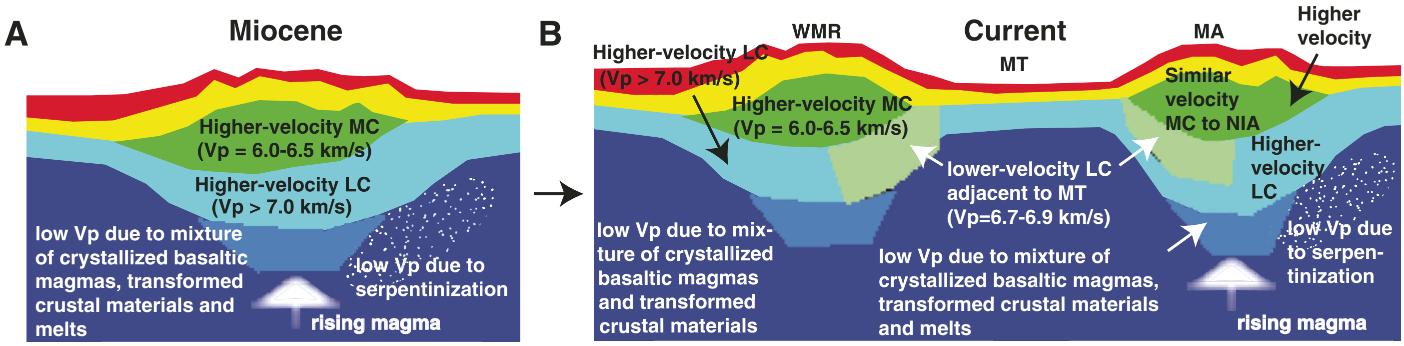

Figure 3. Schematic interpretation of crustal growth of Mariana arc-backarc system: Northern Izu arc (NIA), Kyushu Palau ridge (KPR), Parece Vela Basin (PVB), West Mariana Ridge (WMR), Mariana Trough (MT), Mariana arc (MA), and Mariana Trench. MC—middle crust; LC—lower crust. A: Miocene. B: Current.

crustal, and lower-crustal layers in the northern Izu arc are 496 km^3/km, 732 km^3/km, 963 km^3/km, and 2455 km^3/km, and their proportions are 11%, 16%, 21%, and 53%, respectively (Table 1). It might be expected that the proportions of the three arcs would be roughly similar; however, the proportion of the lower crust in the West Mariana Ridge seems to be lower than that of the northern Izu arc. Hence, it is important to investigate how arc magmatic evolution might produce these structural characteristics.

The discovery of low velocities just beneath the Moho, now also recognized beneath the volcanic front of the northern Izu arc (Kodaira et al., 2006), may be a key to understanding the crustal growth history. Candidate causes for the low sub-Moho velocity in island arcs include melt, serpentinized mantle, crystallized basaltic magmas, and the transformation of crustal materials into upper mantle. All four scenarios probably occur beneath the currently active Mariana arc (Fig. 3). However, neither melts nor serpentinized mantle can cause the observed low mantle velocity on the backarc (eastern) side of the inactive West Mariana Ridge, away from the volcanic front. Presently, the West Mariana Ridge cannot preserve serpentinized mantle due to the lack of a water source from a subducting slab and a higher mantle temperature than that of the Mariana arc (Hyndman and Peacock, 2003).

Crustal Growth using the Seismic Structure and the Petrologic Model

In this section, we interpret the crustal growth represented by the aforementioned crustal structure and the slow mantle velocity. It is widely accepted that the underplating of mafic magmas produces high velocities in the lower crust (e.g., Fountain, 1989). We assume that the velocity variations within each layer represent petrologic and geological diversity and depend on the relative mafic component (Behn and Kelemen, 2003). One petrologic scenario for crustal growth (Tatsumi, 2000) is that tonalitic middle crust is produced by the anatexis of the basaltic lower crust that is produced by differentiation of a primary, mantle-derived basaltic magma. The existence of an obducted tonalitic pluton at the northern tip of the Izu arc where the arc collides with the Japan arc supports the aforementioned mechanism; the tonalite is thought to be produced by the partial melting of a differentiated basaltic component of the Izu arc (Kawate and Arima, 1998). Based on this petrologic constraint, together with the appropriate compositions of primary and differentiated arc basalt magmas, and experimentally inferred melting regimes of 25%–35% partial melting (Beard and Lofgren, 1991), the volume of both restite and cumulate can be calculated from the observed volume of the upper and middle crusts.

The anatexis model used in our calculations is given in the Appendix.[1] In most modern subduction zones, arc magmas and their solidified products (the arc crust) are derived from primary basaltic magmas generated in the mantle wedge. At the juvenile stage of arc evolution, the mantle-derived basalt magma forms the initial arc crust, which is most simply composed of differentiated basalt and cumulate layers. This model regards the basaltic materials underplated at the bottom of the crust as a part of the "crust." The differentiated basalt layer is then remelted by basaltic underplating to produce tonalitic magmas (Tatsumi, 2000) that form the middle crust with a characteristic velocity of 6 km/s, and restites. Since the major product of surface volcanism at least in oceanic island arcs such as the Izu-Bonin-Mariana is basaltic (Tamura and Tatsumi, 2002), it may be reasonable to assume differentiated basalt, which is produced from a mantle-derived primary basalt magma by crustal anatexis and the subsequent fractionation of cumulates, erupts to form the upper crust.

Our anatexis model allows us to calculate the expected volumes of restites and cumulates (together forming the petrologic lower crust) from the seismologically measured volume of the upper and middle crusts (Appendix; Table 1). A crucial observation made in all the three arcs is that the seismologically measured volume of the lower crust is much smaller than the petrologically inferred combined volume of the restites and cumulates (Table 1). Our seismologically observed lower-crustal volumes fall within the range of our estimated restite volumes (Mariana arc and northern Izu arc), or are somewhat smaller (West Mariana Ridge). In the Mariana arc and northern Izu arc, this implies that dense cumulates are now seismologically part of the mantle and that the restites correspond to the lower crust, as suggested by previous petrologic studies (e.g., Kay and Kay, 1993; Jull and Kelemen, 2001). In the West Mariana Ridge, dense mixtures of restites and cumulates might also have become a part of the upper mantle due to gravitational instability (e.g., Jull and Kelemen, 2001), possibly causing slow mantle velocity.

Table 1 also indicates a major difference between the oceanic island arcs and the average continental crust (e.g., Zelt and Forsyth, 1994). Our observations of the volume ratios of the lower crust to the middle crust in the oceanic island arcs range from 1.65 (West Mariana Ridge) and to 2.54 (northern Izu arc), but that of the continental crust is less than 1.0. Thus, continuing transfer of the lower-crustal material into the mantle may be an important part of the crustal evolution process.

Our crustal growth model begins with the underplating of primitive basalts. Because the Eocene portion of the Izu-Bonin-Mariana arc includes high-Mg andesites or boninites (e.g., Stern and Bloomer, 1992; Straub, 2003), it is possible that a boninitic crust existed there before the underplating of primitive basaltic magmas. Further, the same transformation of the crust during the crustal growth process should occur, and restites should still be present in the seismologically determined mantle, because the boninitic material should continue to be differentiated by heat supplied from the underplating of primitive basalts.

[1]GSA Data Repository item 2007046, Appendix (petrologic crustal growth model) and Table DR1 (composition of each magma, restites, and cumulates), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

In the previous petrologic discussion, we used the shape of the Moho to specify the boundary between the backarc and arc regions. A likely source of error in the estimation of the volumes of each crustal layer, required to apply this petrologic model, is the difficulty involved in specifying the arc-backarc boundary to within ~10 km. This leads to uncertainties in the lower-crustal volume of up to 50–100 km^3/km. Our robust conclusion that the transformation of the cumulate crust into the seismic upper mantle is required in order to explain the observed middle-crustal volume is not affected by this relatively small uncertainty.

Our observations and calculations indicate the presence of cumulates and restites, produced during crustal growth, below the Moho. However, the lateral lower-crustal heterogeneity remains an issue to be understood. This velocity variation could be strongly related to crustal growth, and relevant to the formation of the continental crust, because the velocities are close to that of typical lower continental crust. In particular, it seems important that the lower-velocity lower crust, <7 km/s, is located beneath the current volcanic fronts of both the Mariana arc and northern Izu arc, beneath the frontal arc within the Mariana arc, and beneath the regions within the Mariana arc and West Mariana Ridge adjacent to the Mariana Trough. This lateral velocity variation within the lower crust is relatively reliable, as shown by the high resolutions achieved in our model (Fig. 2B). Our current geochemical model is too simple to simulate this lateral variation, which therefore remains a target for future geochemical modeling.

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