# Crustal structure of the Mariana volcanic arc : Possible continental growth in an intra-oceanic Island arc


Eiji Kurashimo Stanford University and University of Tokyo (ekura@eri.u-tokyo.ac.jp)
Simon Klemperer Stanford University, California, USA
Andrew Calvert Simon Fraser University, British Columbia, Canada
Narumi Takahashi Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan


## 1. Introduction

○Motivation

Growth of continental crust in oceanic island arcs is an open question. Published velocity models for the central Aleutian arc [e.g. Holbrook et al., 1999] have no tonalitic mid-crustal layer and it is unlike continental crust (Figure 1). But published velocity models for the northern Izu-Bonin arc [e.g. Suyehiro et al., 1996] show a tonalitic mid-crustal layer of 6.0-6.3 km/s (Figure 2). These results suggest that the central Aleutian arc crust has a mafic bulk compostion, in contrast to the tonalitic composition of the northern Izu-Bonin arc. The northern Izu-Bonin arc and the central Aleutian arc are considered as two end members. What controls the composition of crustal growth at an intra-oceanic island arc?

○ Tectonic setting

The Izu-Bonin-Mariana (IBM) region is the classic example of an intra-oceanic arc — back-arc system. The IBM island-arc is built on old oceanic crust without continental collision. The modern volcanic arc of the Mariana arc system has been active only since c. 7 Ma, and presumably formed on back-arc oceanic crust (the Mariana Trough) created during rifting of the now inactive West Mariana Ridge from the now inactive frontal arc. A frontal arc (uplifted remnant Eocene arc) was intermittently active from c. 43-7 Ma. Investigating structural variation along the arc provides fundamental knowledge about crustal growth.

○ Our study

In 2002, a seismic refraction/wide-angle reflection survey studied the forearc and active arc of the Mariana island-arc system at 14.5° to 18.5° N in the MARGINS 'Subduction Factory' focus area. North-south seismic profiles along the strike of the active and frontal arcs were intended to contrast the structure of a juvenile and active arc with that of a mature but inactive arc. A third north-south profile, 50 km trenchward of the frontal arc in c. 3.5 km water depth, may provide details of an early phase of forearc spreading and volcanism at the time of initiation of the Mariana subduction zone, c. 50-40 Ma. Comparing velocity models within the Mariana arc, we discuss the crustal evolution process of the Mariana arc.

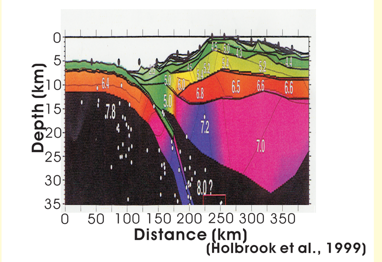


Figure 1 P-wave velocity structure across the central Aleutian island-arc. Velocities (white numbers) are contoured every 0.2 km/s from 5.0 to 7.2 km/s. The central Aleutian arc has no felsic Mid-crustal layer.

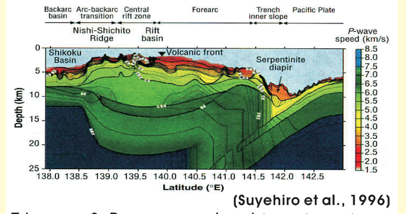


Figure 2 P-wave velocity structure across the Izu-Bonin arc along 32° 15′ N. The contour interval is 0.1 km/s. The northern Izu-Bonin arc has a felsic mid-crustal layer of 6.0-6.3 km/s

## 2. Experiment

As part of the NSF-MARGINS Izu-Bonin-Mariana Subduction Factory project, a seismic refraction/wide-angle reflection survey was conducted over the Mariana arc in 2002 using R/V Ewing airguns and 52 ocean bottom seismographs (OBS) deployed in 3 arc-parallel lines along the active volcanic arc, the frontal arc and forearc (Figures 3 and 4).

**Data acquisition**

Survey Area: Mariana volcanic Arc between 14.5° and 18.5° N

Survey length : about 2600 km of the arc-parallel and perpendicular lines

Source information
Source : R/V Maurice Ewing airgun source (10,810 c.i.)
Shot interval : 200m except along the deep-water forearc line, which had a 250m shot interval

Receiver information
Receiver : 52 Ocean Bottom Seismographs (OBS)
Sensor: 2Hz vertical sensor and hydrophone
Sampling frequency: 125Hz
Receiver interval:
active arc 10km, frontal arc 15km, forearc 20km

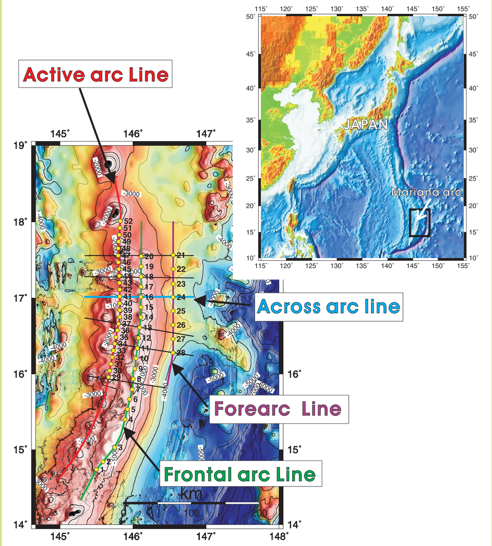


Figure 3 Maps showing the location of our seismic refraction/wide-angle reflection survey over the Mariana arc. Circles mark OBS locations.

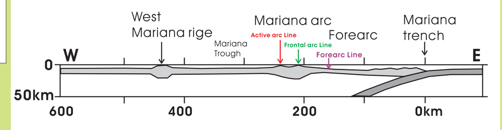


Figure 4 Cartoon of the cross section of the Mariana convergent margin.

## 3.Data

We classified the observed refraction phases on the basis of the general trends of travel-time slope. Since apparent velocities of the refraction phases are affected by sea-floor topography, we applied the static correction of a water delay to the seismic sections (Figure 5). The seismic section with the water-bottom correction was useful to make the phase identifications. As shown in the example (Figure 5), later reflection arrivals (Moho reflection and sub-Moho reflection) are observed. Figure 6 shows the generalized phase pattern observed along the survey lines, and color codes used for ray diagrams in Figures 7-10.

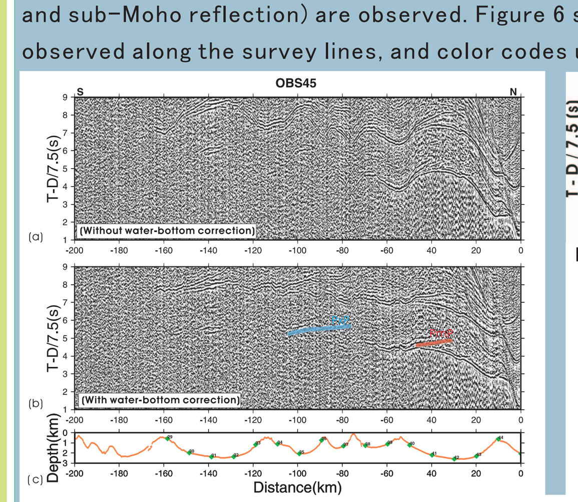


Figure 5 Example of observed data for OBS45 along the active arc survey line. The horizontal axis represents the source receiver offset. The reduction velocity is 7.5 km/sec. 1-12Hz bandpass filter, predictive deconvolution filter and 1 s automatic gain control are applied. (a) Observed seismograms without water-bottom correction. (b) Observed seismograms with water-bottom correction. (c) Bathymetry

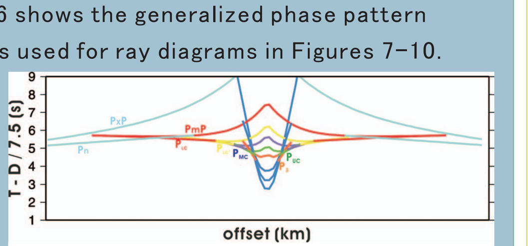


Figure 6 Generalized phase pattern. These phases are observed along the survey lines. $P_3$, $P_{UC}$, $P_{MC}$, $P_{LC'}$, $P_{LC}$, Pn denote the refraction arrivals from the basement layer, upper crust, middle crust, the upper part of the lower crust, the lower part of the lower crust and the uppermost part of the mantle. $P_{LC'}$ phase was only observed along the northern part of the forearc line. PmP and PxP denote the reflection arrivals from the Moho interface and the sub-Moho interface.

## 4. Analysis

We applied direct tau-p mapping and tau-sum inversion (Diebold and Stoffa, 1981; Shinohara et al., 1994) to airgun data to obtain 1-D models of the shallow structure beneath each OBS. Next, the 2-D velocity structure along the survey line was derived by 2-D ray tracing using first arrivals and later phases to derive the shapes of velocity interfaces and velocities. Trial-and-error forward modeling was used to determine the velocity structure. Theoretical travel times and seismograms are calculated by ray theory (Cerveny and Psencik, 1983; Hirata and Shinjo, 1986). The initial 2-D velocity model was constructed from 1-D models under individual OBSs. The sedimentary layer and the basement were derived from the MCS reflection record. We obtained models which can explain observed travel times within 0.1 s error and gross features of amplitudes reasonably well (Figures 7, 8, 9 and 10). Independent of these 2D velocity models, we carried out true 3D first arrival tomography of the entire data set [Calvert et al., 2005] (Figure 13).

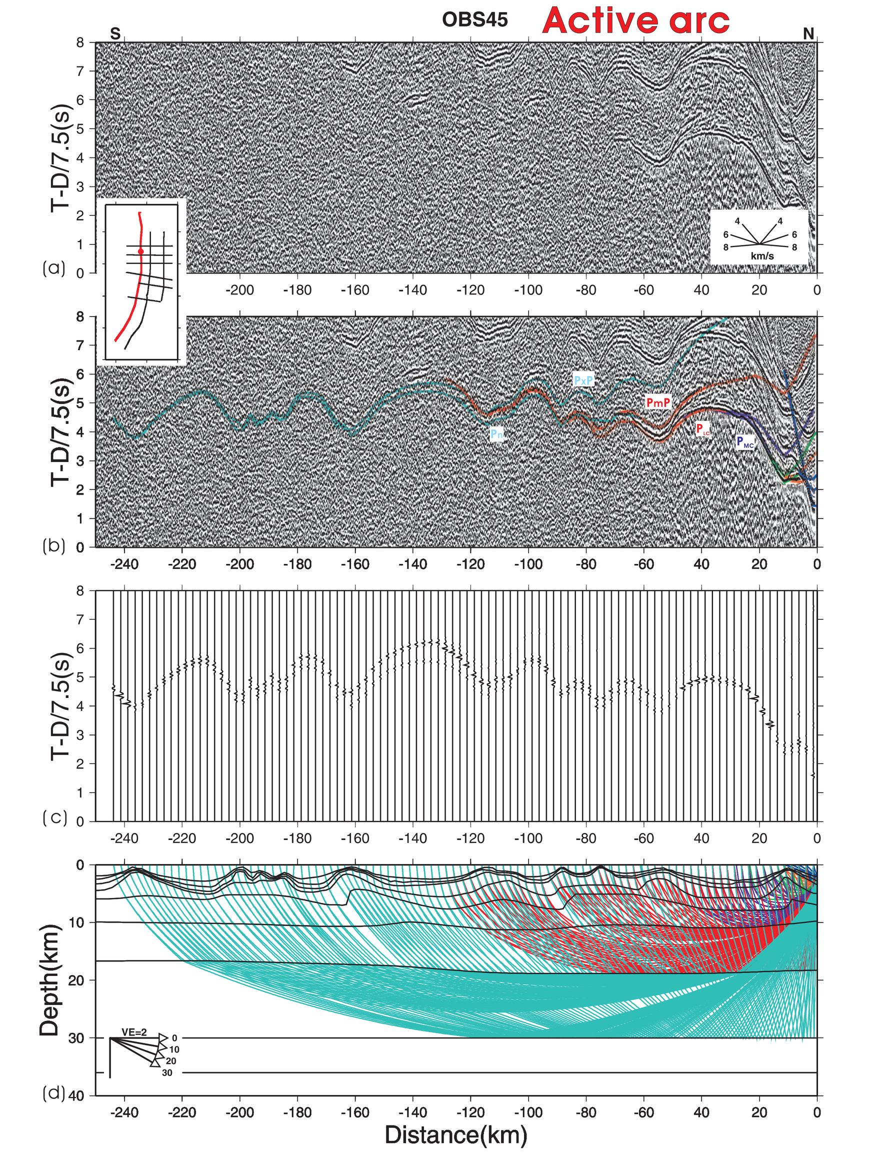


Figure 7 Seismograms and ray diagrams for OBS45 (active arc line). The horizontal axis represents the source receiver offset. (a) Observed seismograms. The reduction velocity is 7.5 km/sec. 1-12Hz bandpass filter, predictive deconvolution filter and 1 s automatic gain control are applied. (b) Calculated travel times from the final crustal model (Figure 11) superimposed on the observed seismograms. (c) Ray theoretical synthetic seismograms. (d) Ray diagram. Ray paths and calculated travel times correspond by color (See Figure 6 for description of phases).

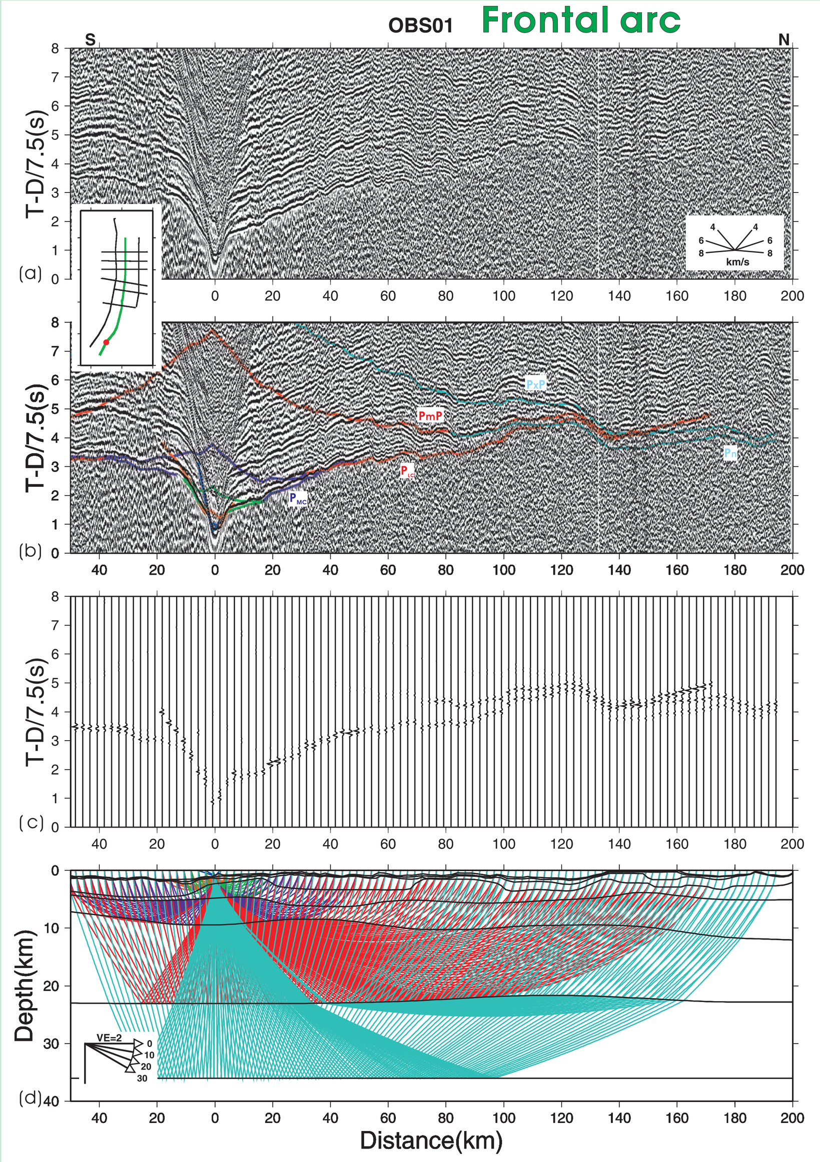


Figure 8 Seismograms and ray diagrams for OBS01 (frontal arc line). See Figure 7 for detailed explanations.

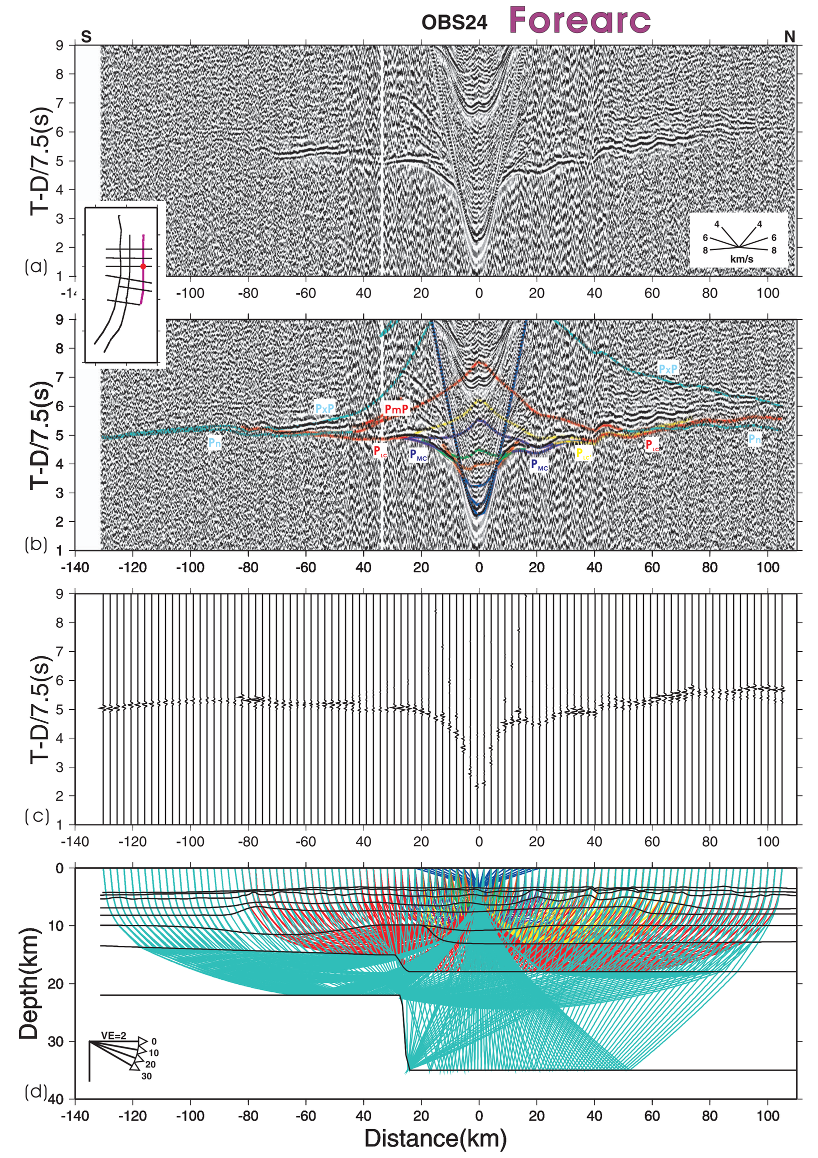


Figure 9 Seismograms and ray diagrams for OBS24 (forearc line). See Figure 7 for detailed explanations.

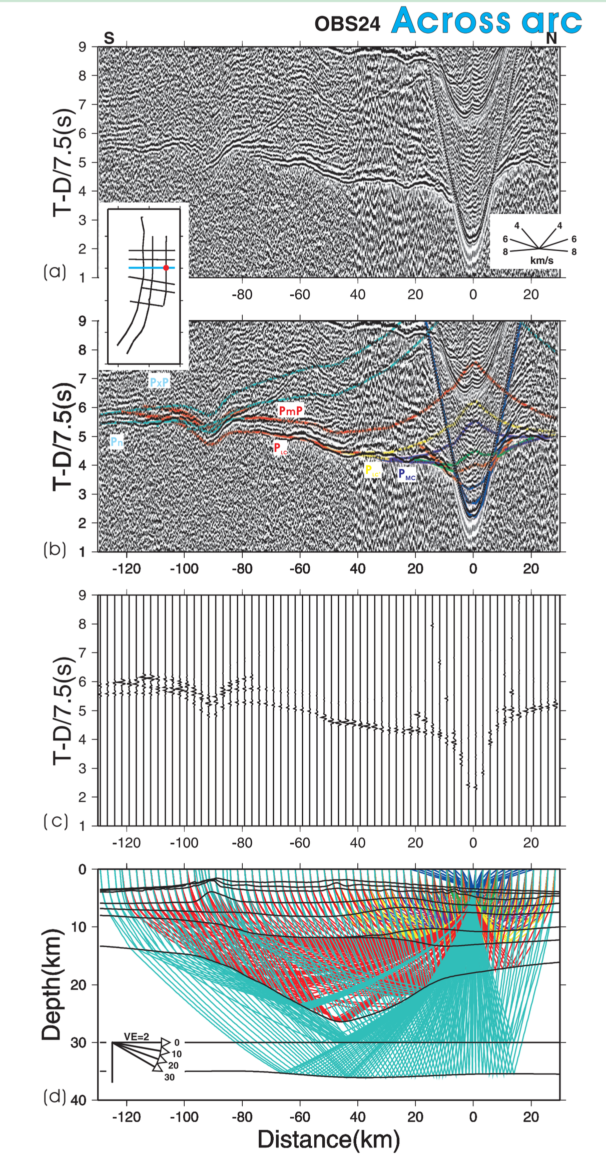


Figure 10 Seismograms and ray diagrams for OBS24 (across arc line). See Figure 7 for detailed explanations.

## 5. Results and Discussion

### ○Active arc (Figure 11a)

- A 2 - 5 km thick tonalitic mid-crustal layer with P-wave velocity 6.1 - 6.5 km/s
- A 6 10 km thick lower crust with P-wave velocity 6.7 - 7.0 km/s
- The crustal thickness is 16-18km.
- The uppermost mantle velocity (Pn) is 7.5 km/s.
- The depth of the Sub Moho reflector is about 30 to 36km.

### ○Frontal arc (Figure 11b)

- A 3 - 7 km thick tonalitic mid-crustal layer with P-wave velocity 6.1 - 6.5 km/s
- A 11 15 km thick lower crust with P-wave velocity 6.7 - 7.0 km/s
- The crustal thickness is 20-26 km.
- The uppermost mantle velocity (Pn) is 7.7 km/s.
- The depth of the Sub Moho reflector is about 36km.

### ○Forearc (Figure 11c)

- A robust change (~7 km to ~11 km) in basement thickness over a very narrow zone
- The thickness of the mid-crustal layer is 2-6 km (in the south, 6.1-6.7 km/s; in the northern, 6.1-6.5km/s).
- A 3-5km thick lower crust with P-wave velocity 7.2-7.4 km/s
- The uppermost mantle velocity (Pn) is 7.9 km/s
- The depth of the Sub Moho reflector is about 20 to 35 km.

### ○Across arc (Figure 12a)

- The middle crust thins westward toward the Mariana trough and eastward toward the Mariana trench.
- The crust is thickest beneath the frontal arc. This result coincides with the 3-D first arrival tomography results [Calvert et al., 2005] (Figure 13)

### ○Active arc vs. Frontal arc

- P-wave velocities within the upper part (0 to 6km below sea floor) of the active arc crust are lower than in frontal arc (Figure 14).
- Both arcs have a middle crust layer which is also represented in the Izu-Bonin arc (Figures 1 and 12b).

- The middle crust is thickened in the more mature frontal arc.
- The thickness of the middle crustal layer beneath the active arc line varies laterally and greater thickness appear to correspond to active volcanoes (Figure 15).

→ These results suggest that a large volume of the continental-type crust is predominantly generated below the volcanoes.

- The lower crust of the frontal arc is also thicker than that of the active volcanic arc crust.

→ The crustal thickness difference may be attributable to the different periods of time for which the frontal arc and the active arc have been active. However, the thickness of the crust is clearly not simply proportional to the duration of arc's existence.

- The upper-mantle velocity beneath the active volcanic arc is rather slower than that beneath the frontal arc.

→ We speculate this low-velocity region indicates partial melts or crust-mantle mixing.

### ○Comparison with other arc and continental crust

- The averaged velocity-depth functions of the Mariana arc (both active arc and frontal arc) are higher than that of average continental crust (Figure 14).
- Similar to the Izu-Bonin arc, both the active and frontal arcs have a "tonalitic" mid-crustal layer.
- Our model shows no crustal layer comparable to the high-velocity layer with 7.3 < Vp < 7.7 km/s that occupies the deepest 15 km of Aleutian arc crust (Shillington et al., 2004). Our Sub-Moho region (7.5 < Vp < 7.9 km/s) may correspond to the deepest Aleutian crust.
- The crustal structure of the frontal arc is more similar to that of the Izu-Bonin arc than to the Aleutian arc based on the crustal thickness and existence of the tonalitic mid-crustal layer.

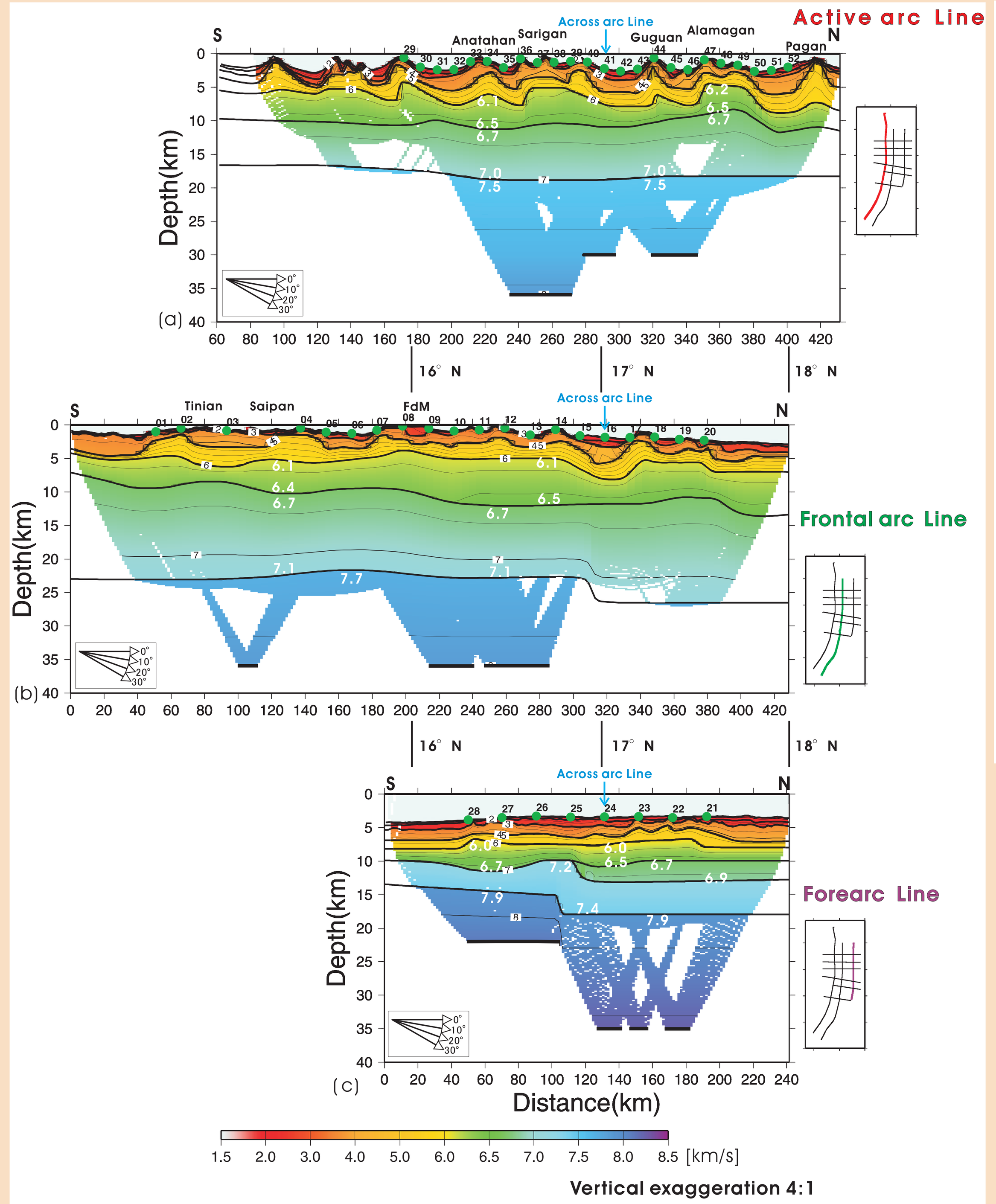


Figure 11 P-wave velocity structures (along arc) derived by a 2-D ray-tracing method. The horizontal axis represents the distance from southern end of the survey line. OBS positions are denoted by circles. P-wave velocities are shown using a color scale. Only regions constrained by rays corresponding to picked arrivals have been colored. The contour interval is 0.2 km/s. Thick lines mark boundaries constrained by observed deep reflections.

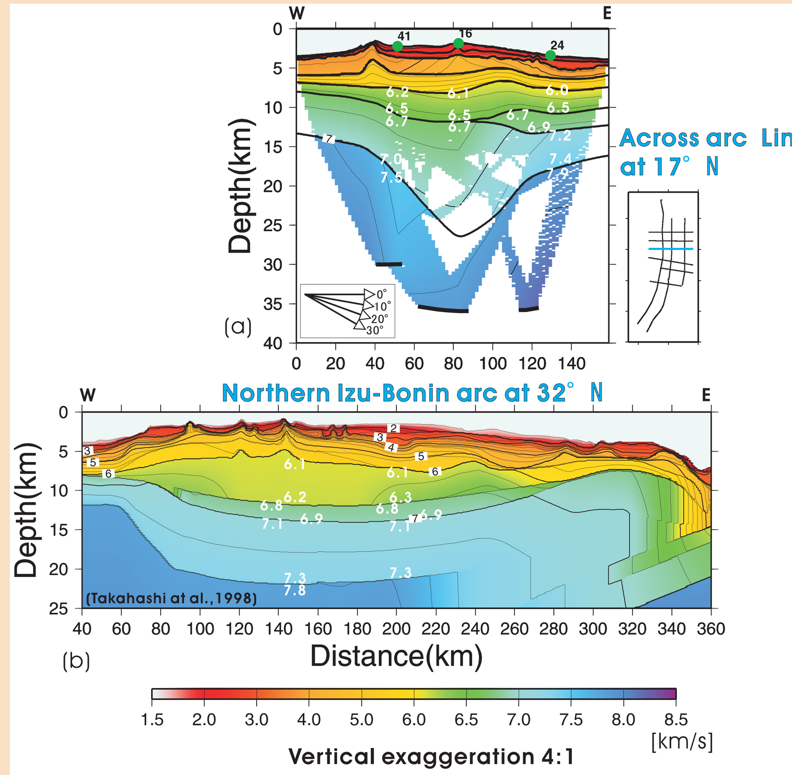


Figure 12 Comparison of (a) across arc section at 17° N with (b) northern Izu-Bonin arc at 32° N. The horizontal axis represents the distance from western end of the survey line.

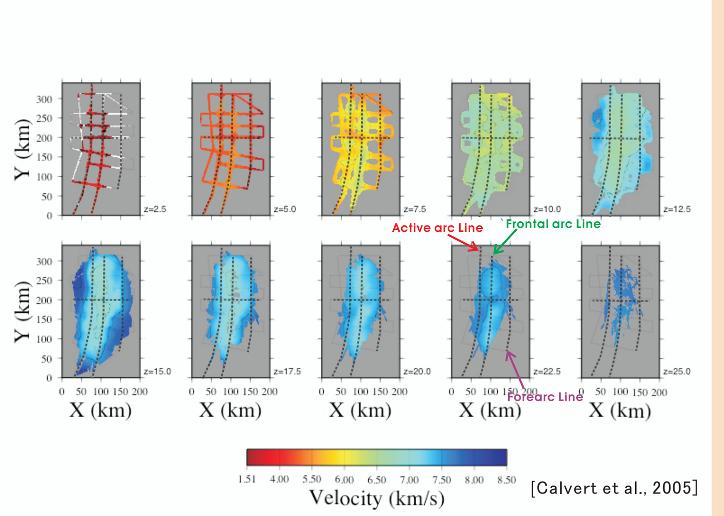


Figure 13 Horizontal slices through the 3D velocity model beneath the Mariana island-arc at 14.5° to 18.5° N. Broken lines indicate our survey lines. The contour interval is 0.5 km/s.

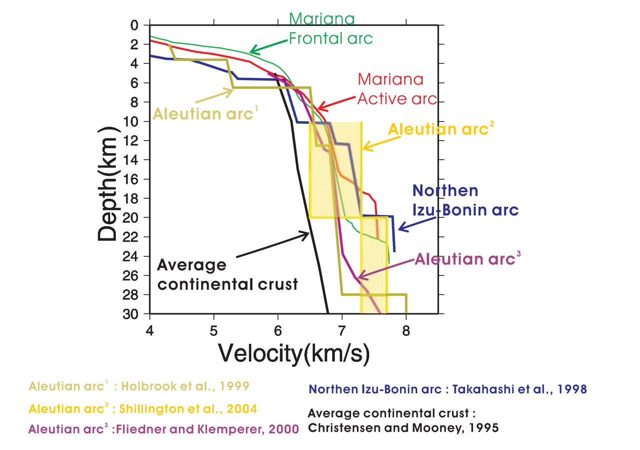


Figure 14 Comparison of Mariana arc velocity-depth functions with the velocity function of northern Izu-Bonin, Aleutian arc and average continental crust. The vertical axis is the depth from the sea floor. The averaged velocity-depth functions of Mariana arc were calculated from only regions constrained by rays corresponding to picked arrivals.

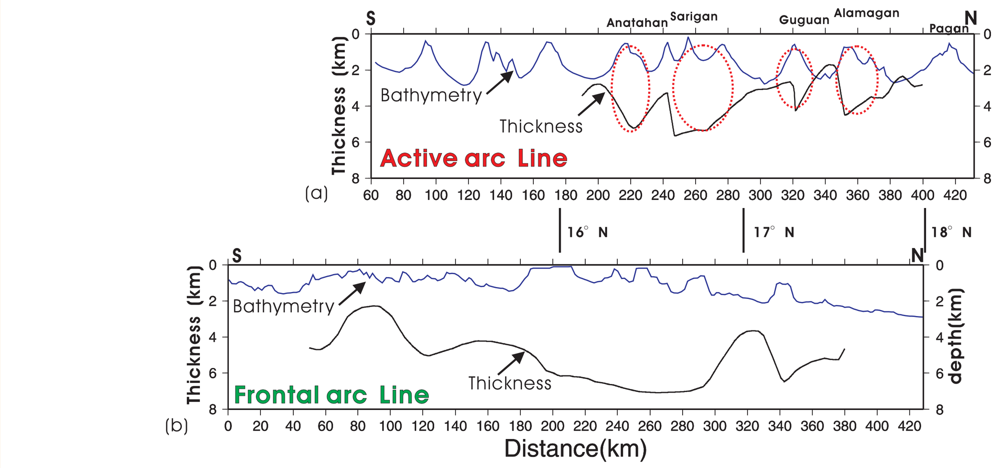


Figure 15 Variation of middle crustal thickness along the survey lines. Blue line indicates the sea floor. Black line indicates the thickness of the middle crust (Vp=6.1-6.5km/s). The horizontal axis represents the distance from southern end of the survey line. (a) active arc line (b) frontal arc line. The thickness of the middle crustal layer beneath the active arc line varies laterally and is thicker beneath active volcanoes.


## Acknowledgements

This study was made possible by the dedication of the Captain and Crew of the R/V Maurice Ewing and shipboard science parties EW-0202 and EW-0203, including OBSIP staff. Funding was provided by the NSF MARGINS program.