# Crustal thickness beneath the Ryukyu arc from travel-time inversion

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First $P$-wave arrival times recorded by the seismic network in the Ryukyu arc were analyzed in order to image the lateral variation in crustal thickness beneath the Ryukyu arc. The results indicate a low $P_n$ velocity (7.5 km/s) in the Ryukyu arc and a relatively high $P_n$ velocity (7.9 km/s) in the Okinawa Trough. The crustal thickness changes between the northern-and-central Ryukyu arc (range 23–27 km) and the southern Ryukyu arc (range 29–44 km). The crustal thickness of the former is consistent with that in the northern-and-central Okinawa Trough, suggesting a flat Moho stretching from the Okinawa Trough to the Ryukyu arc. This flat Moho extends uniformly over a wide area. In contrast, the crustal thickness in the southern Ryukyu arc is consistent with the characteristics of the crustal structure whereby the Moho becomes shallower in the vicinity of the axis of the Okinawa Trough and deepens remarkably with increasing distance from the axis in the southern Ryukyu arc. These differences would be caused by the difference in rifting style between the northern-and-central Okinawa Trough and the southern Okinawa Trough.

**Key words:** Crustal thickness, Ryukyu arc, Okinawa Trough, rifting style, $P_n$ velocity.

## 1. Introduction

The Ryukyu arc is an approximately 1200-km-long island arc that runs along the Ryukyu Trench between Kyushu Island and Taiwan. The Philippine Sea plate subducts beneath the Eurasian plate northwestward. The Okinawa Trough, which is at the beginning of the rifting stage and extends toward the NW-SE (Sibuet *et al*., 1995), is located northwest of the Ryukyu arc.

The northern-and-central and southern parts of both the Ryukyu arc and Okinawa Trough have different characteristics. The Ryukyu arc and the Okinawa Trough are divided geologically into three blocks (northern part, central part, and southern part) that are bounded by the Tokara Strait and the Kerama Gap (Konishi, 1965) (Fig. 1). The southern Okinawa Trough (SOT) and the northern-and-central Okinawa Trough (NCOT) have different features. The NCOT is a gentle depression with a maximum bathymetric depth of 1000 m. In contrast, the SOT consists of a broad and flat basin with a bathymetric depth of 2000 m. In the northern-and-central Ryukyu arc, the volcanic front is located to the east of the axis position of the Okinawa Trough (Fig. 1); in the southern Ryukyu arc, the volcanic front is located at the axis of the Okinawa Trough.

Surveys conducted using an ocean bottom seismometer (OBS) have revealed a distinct difference in crustal structure between the northern-and-central Okinawa Trough and the SOT. The Moho in the NCOT is flat, with a crustal thickness of 26 km; in contrast, the crustal thickness is 18 km in the SOT. Several OBS surveys have been carried out in the Ryukyu subduction zones in order to image the crustal structures and OBS velocity models have been constructed to model crustal thickness and $P_n$ velocity for the various parts of the Ryukyu arc and Okinawa Trough. According to the respective models, the crustal thickness and $P_n$ velocity for the northern Ryukyu are 26 km and 7.6 km/s, respectively (Iwasaki *et al*., 1990); for the central Ryukyu arc, 26 km and 7.7–7.8 km/s, respectively (Nakahigashi *et al*., 2001); for the SOT, 15 km and 8.2 km/s, respectively (Lee *et al*., 1980); for the SOT, 18 km and 7.8 km/s, respectively (Hirata *et al*., 1990).

The results of a gravity anomaly analysis aimed at determining the crustal structure provides support for the results of the seismic survey. The crust model estimated from the gravity anomaly also reveals differences in crustal thickness between the central Okinawa Trough and the SOT (Sibuet *et al*., 1995). Although crustal thickness is generally regular in the NCOT, that in the SOT is thinner beneath the axis and thickens in increasing distance from the axis.

Therefore, according to the model predictions, crustal thickness is different between the NCOT and the SOT, and this difference may affect the crustal structure in the Ryukyu arc. The change in crustal thickness along the Ryukyu arc may yield clues to the tectonic process of the extension of the Okinawa Trough. With the aim of investigating the crustal structure along the Ryukyu arc, we imaged variations in crustal thickness and averaged $P_n$ velocity.

## 2. Data and Method

We selected 96 events with depths $<20$ km and magnitudes $>3.5$ from the Japan Meteorological Agency (JMA) catalog. The $P_n$ travel time data from the 19 stations of the JMA network and one station from the National Research Institute for Earth Science and Disaster Prevention (NIED)

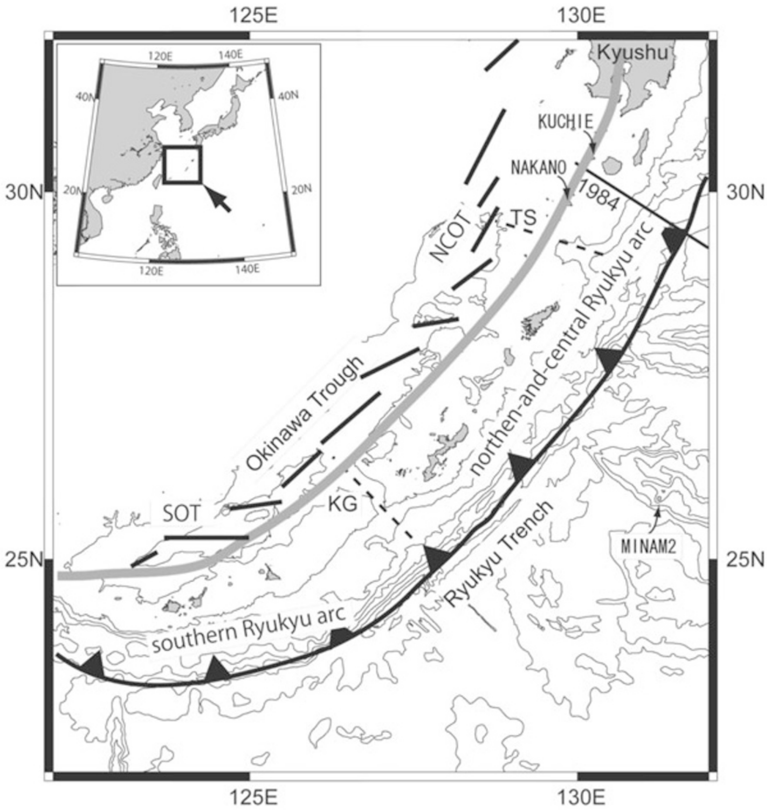


Fig. 1. Map of the Ryukyu arc showing major geologic structures. The solid lines show the axis position of the Okinawa Trough (Kimura *et al*., 1999). The dark line denotes the volcanic front (Sibuet *et al*., 1998). MIMAM2: Minami-Daito island; KG: Kerama Gap; TS: Tokara Strait; NCOT: northern-and-central Okinawa Trough; SOT: southern Okinawa Trough; 1984: seismic refraction profiles studied by Iwasaki *et al*. (1990).

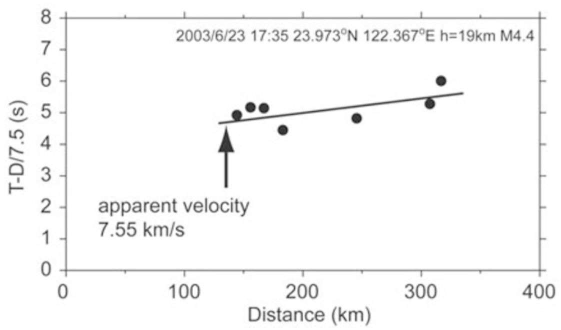


Fig. 2. Example of travel-time diagrams for an earthquake. Reduction velocity is 7.5 km/s. Solid circles show travel time data.

network were used to investigate the variations in crustal thickness. Almost all of these stations are distributed along the Ryukyu arc. Data from a station located in the Philippine Sea plate (MINAM2) were also included in the study.

A total of 744 first $P$-wave arrival time data were selected from all of the events that occurred from January 1997 to August 2003. The epicentral distances are in the range of 150–550 km from the stations (Fig. 2). Ray paths for the data set are shown in Fig. 3. Most of these $P_n$ arrivals passed along the Ryukyu arc. The travel time residuals were inverted for station delays and event delays using the modified time-term equation (Hearn *et al*., 1994):

$$t_{ij} = a_i + b_j + \sum d_{ijk} S_k$$

where $a_i$ is the static delay for station $i$, $b_j$ is the static delay for event $j$, $d_{ijk}$ is the distance traveled by ray $ij$ in mantle cell $k$, and $S_k$ is the slowness (inverse of $P_n$ velocity) of cell $k$. The $P_n$ velocity in the cell has been changed in three areas: the Okinawa Trough (OT) area, Ryukyu arc (RA) area, and the Philippine Sea plate (PHS) area (Fig. 3). The boundary between the Philippine Sea plate and the Ryukyu arc is set to the position of the Ryukyu Trench, while that between the Ryukyu arc and the Okinawa Trough is set to the position of the western margin of the Ryukyu arc, where the Ryukyu arc is separated from the Okinawa Trough by faults. The delay between the stations at NAKANO and KUCHIE, which are located north of the Ryukyu arc, has been fixed to 2.6 s using the velocity structure (Iwasaki *et al*., 1990). Figure 4 shows the variation in root mean square (RMS) travel time residuals as a function of $P_n$ velocity in each area. It can be seen from this figure that the minimum RMS travel time residuals of $P_n$ velocity in the Philippine Sea plate cannot be constrained well. We then imaged the RMS, fixing the $P_n$ velocity of the Philippine Sea plate at 8.0 km based on the refraction survey in the Philippine Sea plate (Murauchi *et al*., 1968; Nishizawa *et al*., 1983; Iwasaki *et al*., 1990; Kodaira *et al*., 1996). The minimum RMS is 0.57 s when the $P_n$ velocity beneath the Okinawa Trough and the Ryukyu arc are 7.9 and 7.5 km/s, respectively.

Errors in the inversion were examined using the bootstrap method (Hearn and Ni, 1994). The averaged error in the station delays is 0.2 s. The maximum error in the station

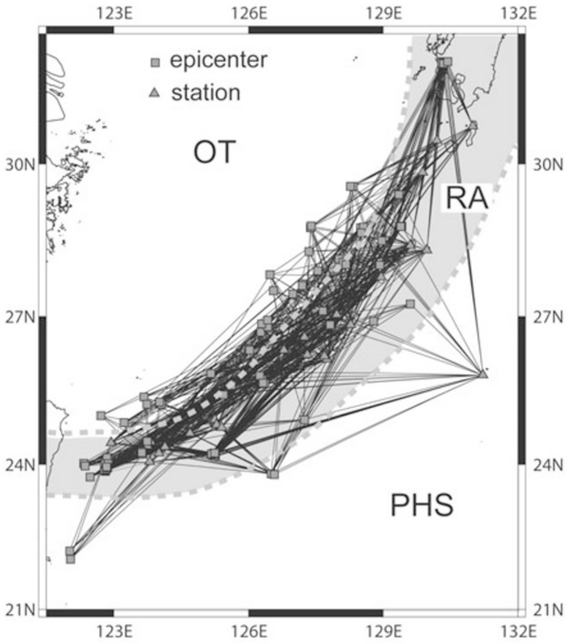


Fig. 3. $P_n$ ray paths used for the inversion. Solid triangles and squares denote the epicenters and locations of seismic stations, respectively. OT: Okinawa Trough area; RA: Ryukyu arc area; PHS: Philippine Sea plate area.

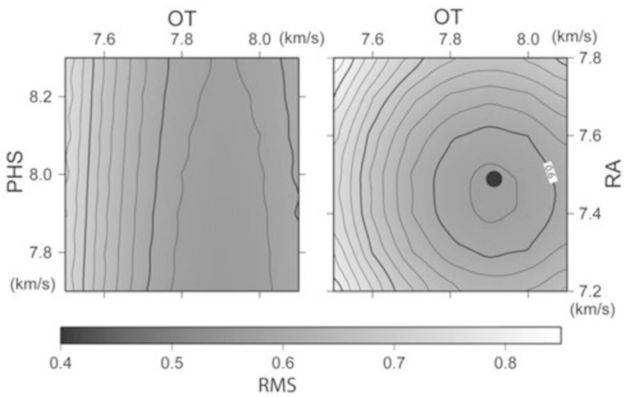


Fig. 4. Distribution of RMS travel time residual for various combinations of the average $P_n$ velocity.

delays is 0.5 s and the maximum error in the $P_n$ velocity estimation is <0.1 km/s. The largest errors in station delays occur at the Minami-Daito Island (MINAM2), which is located in the Philippine Sea plate.

## 3. Results

The station delays between the northern-and-central Ryukyu arc (range 2.4–3.8 s) and the southern Ryukyu arc (range 2.9–4.6 s) are an indication of differences in features between these two areas. The station delay at TAMAG2 station reaches 3.8 s, that at MINAM2 (PHS) reaches 1.7 s, and those near the Okinawa Trough range from 2.6 to 2.9 s. The errors of the station delays are less than 0.5 s.

The station delays were converted to crustal thickness assuming a mean crustal velocity and mean mantle velocity of 5.9 and 7.5 km/s, respectively (Table 1). The station delay at MINAM2 is converted to crustal thickness assuming a mean crustal velocity and mean mantle velocity of 6.0 and 8.0 km/s, respectively (Murauchi *et al*., 1968).

The estimated crustal thickness is shown in Fig. 5. For the southern Ruykyu arc, it ranges from 29 to 44 km; for the northern-and-central Ryukyu arc, 23–37 km; for the Moho, 27–29 km near the Okinawa Trough. Crustal thickness at MINAM2 is estimated to be 16 km. The errors in the crustal thicknesses are <5 km.

The $P_n$ velocities in the Ryukyu arc and Okinawa Trough are 7.5 and 7.9 km/s, respectively. To check the results, we added the random noise of 20 km for the horizontal vector and 10 km for the vertical vector to the hypocenters and calculated the inversion. The maximum change in the station delays is 0.3 s, corresponding to a change in crustal thickness of 3 km. The changes in $P_n$ velocities are 0.1 km/s.

## 4. Discussion

Based on our study results, the $P_n$ velocity in the Okinawa Trough is 7.9 km/s; as such, it is similar to that obtained from refraction experiments in the Okinawa Trough (Lee *et al*., 1980; Hirata *et al*., 1990; Nakahigashi *et al*., 2001). The time-term inversion of $P_n$ in the Kyushu area indicated that the $P_n$ velocity beneath the Kyushu is 7.7 km/s. A refraction experiment in the south Kyushu area showed the $P_n$ velocity to be 7.8 km/s (Ono *et al*., 1978). It would therefore appear that the $P_n$ velocity beneath the Okinawa Trough is similar to that beneath Kyushu Island. In contrast, the $P_n$ velocity beneath the Ryukyu arc is 7.5 km/s. The results of an earlier study in the northern Ryukyu arc suggested that the $P_n$ velocity is ≤7.6 km (Iwasaki *et al*., 1990). Consequently, the $P_n$ velocity beneath the Ryukyu arc is close to that beneath the Kyushu Island.

The crustal thickness ranges from 23 to 37 km in the northern-and-central Ryukyu arc. The crustal thickness at the center of the NCOT, based on data from refraction seismic surveys and gravity anomaly, has been estimated to be 26 km (Sibuet *et al*., 1995). Thus, the crustal thickness in the NCOT and northern-and-central Ryukyu arc changes gradually from 23 km to 37 km, showing a flat Moho. This suggests that the extension area of crustal thinning is wide in the NCOT.

The crustal thickness ranges from 29 to 44 km in the southern Ryukyu arc. The crustal thickness at the center of the SOT, based on data from refraction seismic surveys and gravity anomaly, is estimated to be 18 km (Sibuet *et al*., 1995). Thus, the crustal thickness in the SOT and Ryukyu arc changes abruptly from 18 to 44 km, suggesting that the crustal thinning and extension concentrates in the axis of SOT.

The difference in crustal thickness between the northern-and-central Ryukyu arc and the southern Ryukyu arc reflects the rifting style. Seno and Yamanaka (1998) analyzed the stress distribution in the subducting slab and investigated the state of stress in the backarc, pointing out that the active rifting was caused by plume in the NCOT and passive rifting in the SOT. The plume beneath the northern Okinawa Trough has been imaged by seismic tomography as a low-velocity zone at a depth of 40 km (Sadeghi *et al*., 2000). The heating of the lithosphere by the plume decreases the crustal strength uniformly over a wide area.

Table 1. Station delay and crustal thickness.

| Station | Latitude | Longitude | Station delay (s) | Error (s) | Crustal thickness (km) | Error (km) |
|---|---|---|---|---|---|---|
| YONAJ2 | 24.450 | 122.944 | 2.9 | 0.2 | 29 | 2 |
| IRIOM2 | 24.383 | 123.751 | 3.6 | 0.3 | 34 | 2 |
| HATOMA | 24.464 | 123.824 | 4.0 | 0.2 | 38 | 2 |
| KUROSH | 24.237 | 124.009 | 3.8 | 0.2 | 37 | 2 |
| ISHIG2 | 24.364 | 124.143 | 3.0 | 0.3 | 29 | 3 |
| TARAMA | 24.641 | 124.702 | 3.8 | 0.3 | 36 | 3 |
| IKEMA | 24.920 | 125.249 | 4.4 | 0.3 | 42 | 3 |
| MIYKJ2 | 24.815 | 125.294 | 4.2 | 0.3 | 40 | 3 |
| OKIGUS | 24.760 | 125.406 | 4.6 | 0.3 | 44 | 3 |
| KUMEJ2 | 26.326 | 126.786 | 2.8 | 0.3 | 27 | 3 |
| AGUNI | 26.589 | 127.242 | 3.0 | 0.2 | 29 | 2 |
| IHEYA | 27.035 | 127.967 | 2.9 | 0.2 | 29 | 2 |
| TAMAG2 | 26.138 | 127.749 | 3.8 | 0.2 | 37 | 2 |
| KUNIGA | 26.832 | 128.275 | 2.7 | 0.2 | 27 | 2 |
| TOKUNO | 27.785 | 128.952 | 3.2 | 0.2 | 31 | 2 |
| MINAM2 | 25.819 | 131.221 | 1.7 | 0.5 | 17 | 4 |
| NAKANO | 29.842 | 129.875 | 2.6 | 0.0 | 26 | 0 |
| AMAMI | 28.412 | 129.605 | 3.1 | 0.2 | 30 | 2 |
| KUCHIE | 30.462 | 130.195 | 2.6 | 0.0 | 26 | 0 |
| ZMM | 26.229 | 127.306 | 2.4 | 0.3 | 23 | 3 |

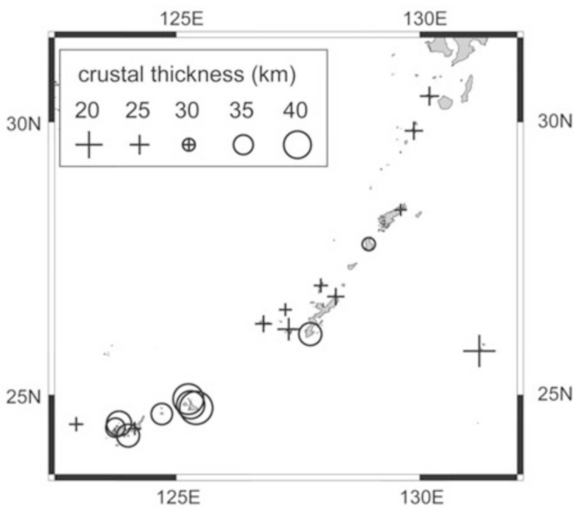


Fig. 5. Distribution of crustal thickness.

Rifting is generated in weak regions. Consequently, rifting and uniform extension would occur over a wide area in the NCOT, resulting in the flat Moho.

In contrast, since passive rifting occurs in the SOT, the heating of lithosphere by the plume is not significant and can thus be ignored. Since the major magmatism is limited to the volcanic front, heating by the magmatism would concentrate beneath the volcanic front in the SOT. This weakens the crustal strength locally beneath the volcanic front, resulting in the concentration of extensional strain beneath the volcanic front and, consequently, generating the difference in crustal thickness beneath the axis of the SOT and the southern Ryukyu arc.

## 5. Conclusions

The $P_n$ inversion shows the crustal structure beneath the Ryukyu arc. The result shows that the crustal thickness perpendicular to the trench is flat along the northern-and-central Ryukyu arc and the Okinawa Trough and changes abruptly along the southern Ryukyu arc and Okinawa Trough. These results suggest that the extension of the Okinawa Trough occurs over a wide area between the Okinawa Trough and the Ryukyu arc in the northern-and-central area, as compared to being concentrated in the axis of the trough in the south area. The $P_n$ velocity in the Ryukyu arc is 7.5 km/s.

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