Velocity model in deep seismic zone under Izu-Bonin, Japan

Guoming Jiang, Guibin Zhang
China University of Geosciences, Beijing

Abstract

Deep earthquakes can provide the deep information of the Earth directly, but their focal mechanism is not clear yet. We have collected the arrival time data generated by the deep earthquakes with depth greater than 400 km under Izu-Bonin and used them to study the velocity anomaly in deep seismic zone. To increase the reliability of results, we have used the double-difference relocation method to relocate the deep earthquakes with high precisions. And then the differential residuals created by event-pairs are inversed to obtain the optimal velocity anomaly. As a result, the velocity anomaly in deep seismic zone is averagely 11.29% lower than the iasp91 model. The relocated earthquakes are separated into two layers when considering the lower velocity zone. This lower velocity anomaly might be cause by the metastable olivine. Therefore, the focal mechanism of deep earthquakes greater than 400 km might be related to the metastable olivine phase transformation.

Introduction

Deep earthquakes with depths greater than 70 km generally exist in the subducted slab, which can provide deep information of the Earth directly, such as the velocity in the slab. However, their focal mechanisms are little known. Recent studies suggest that the focal mechanism of deep earthquake greater than 400 km seems to be related to the velocity structure of deep seismic zone (Iidaka and Suetsugu, 1992; Koper et al., 1998; Kaneshima et al., 2007; Jiang et al., 2008, 2015; Jiang and Zhao, 2011), in which the velocity is lower than the 1-D velocity model, such as the iasp91 Earth model (Kennett and Engdahl, 1991). In general, the velocity in the slab is higher than the 1-D velocity model because the slab is cold (e.g., Zhao, 2004). The reason why the lower velocity zone exists in the deep slab might be associated with the faster speed of the subduction for the older slab, for example the subducted Pacific slab beneath Japan. The lower temperature inside the subducting slab might destroy the equilibrium transformation of olivine phases and the metastable olivine may be produced when the slab plunged into the mantle transition zone (Bina et al., 2001). Iidaka and Suetsugu (1992) have ever studied the velocity model in the slab under the Izu-Bonin, Japan, by the forwarding modeling of travel times of deep earthquakes and found that the velocity in the deep seismic zone was 3% lower than the J-B velocity model. This result is doubtable because the data used were few and the event relocation precision was poor. In the present study, we have used more data to study the velocity model of deep seismic zone under Izu-Bonin and proposed a new method to increase the reliability and the precision of result.

Method

During this study, we have firstly downloaded the arrival time data of deep earthquakes from the Japan Meteorological Agency recorded from June 2002 to January 2015 and selected 28 deep earthquakes occurred under Izu-Bonin (Fig. 1). To remove the effect of velocity heterogeneity in the slab, we have used the differential residuals of travel time data to constraint

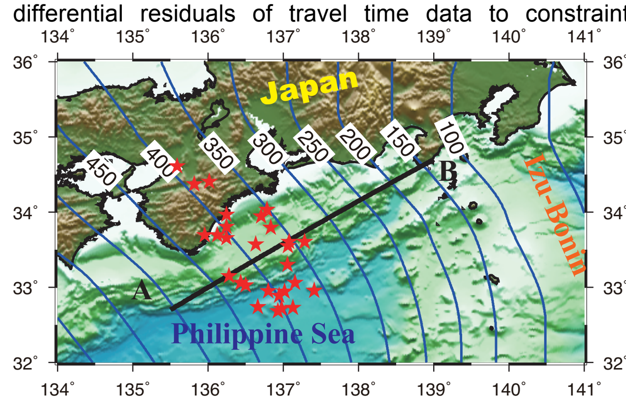

Fig. 1 Distributions of deep earthquakes (red stars). The curved blue lines represent the contour depth distribution of the upper boundary of the Pacific plate (UBPP).

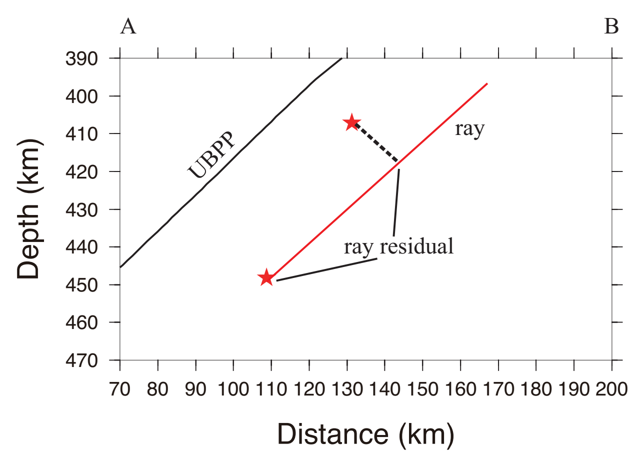

Fig. 2 Illustration of how to form an event-pair. The red stars represent the deep earthquakes and the red line denotes the ray from the deeper event.

the velocity perturbation of deep seismic zone, which was adopted in the previous study (Jiang et al., 2015). But, the criteria to generate the differential residuals are changed. If the distance from one deep event to a ray of the other deep event is less than 10 km (Fig. 2), then these two deep events can form an event-pair and the difference of travel time residuals between these two events at a common station is called the differential residual, which mainly reflects the velocity anomaly between these two deep events.

However, there exists strong coupling between the locations of deep events and the velocity anomaly. To solve this problem, Pavlis and Booker (1980) proposed a method to separate the parameters between the deep hypocenter and the velocity model. We have tried to use this method to estimate the velocity model but failed because the condition number of coefficient matrix of hypocenters is too large to calculate the singular values of this matrix correctly. To remove the effect of hypocenter location errors, we have used a modified double-difference relocation method to relocate the deep events with high precisions (Jiang and Zhao, 2011; Jiang et al., 2015).

In the previous study, a forward modeling of differential residuals was used to obtain the velocity anomaly of deep seismic zone (Jiang et al., 2015). In the forward modeling method, the velocity anomaly was given manually and the optimal one was determined according the minimum of absolute differential residuals. The obtained result might drop in a local minimum. In this present study, we have adopted an inverse idea to estimate the velocity anomaly automatically. Firstly, a partial derivative of travel time to the velocity along a residual ray (Fig. 2) is calculated by using the 3-D ray tracing method (Zhao et al., 1992). Secondly, these derivatives form a coefficient matrix. The velocity anomaly in the slab but deeper than 400 km is considered as the unknown parameter. Here, the number of parameter is only one. Therefore, an over-determined function is constructed. Finally, a singular value decomposition (SVD) method is used to calculate the general inverse of coefficient matrix and the velocity anomaly is then obtained. In addition, this calculation process generally runs for a few iterations until the velocity anomaly keeps stable. For example, once the velocity anomaly is obtained, the hypocenters are relocated again after the velocity updates and then the partial derivatives are calculated newly to form the coefficient matrix and a new velocity anomaly will be then inversed.

Results

Fig. 3 shows the velocity anomaly of each iteration. The initial value is assigned as 0%. After 6 iterations, the velocity anomaly keeps stable. When the iteration is up to 12, the velocity anomaly keeps constant as -11.29%, which indicates that the velocity anomaly in the deep seismic zone is very low. This feature of lower velocity is also found in the Pacific slab under Japan Sea and northeastern China, but the amplitude of velocity anomaly obtained here is much larger than that in other places (e.g., Jiang et al, 2008, 2015; Jiang and Zhao, 2011). This low velocity zone might be caused by the metastable olivine.

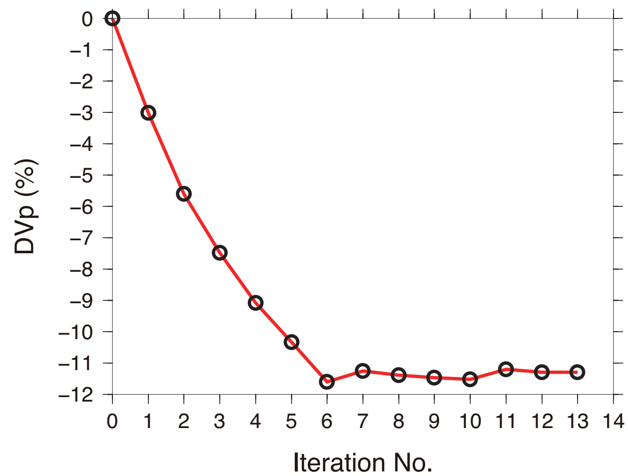

Fig. 3 Velocity anomaly of the deep seismic zone (DVp, %) varies with the iterations.

Considering the velocity anomaly with -11.29%, the deep earthquakes are relocated (Fig. 4). The result shows that the relocated events could be separated into two layers: one of which is about 10 km far away from the upper boundary of Pacific slab and the other about 30 km (Fig. 4b). Most relocation errors are less than 1.0 km and the errors in horizontal are larger than that in deep. This feature of two-layer was also detected by Iidaka and Furukawa (1994), but their earthquake depths were from 350 km to 400 km, which is shallower than that we used.

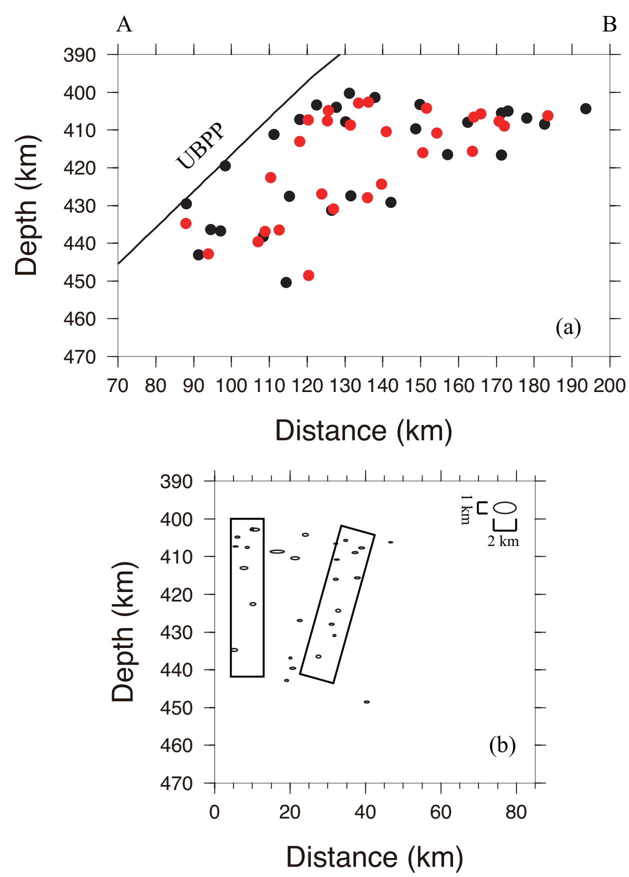

Fig. 4 (a) Vertical view of relocation result along a profile line AB shown in Fig. 1. The black and the red dots represent the original and the relocated events, respectively. (b) Relocation errors. The scale is shown in the upper-right corner. The horizontal axe denotes the distance from the UBPP.

Conclusions

In this study, we have used the travel time data from deep earthquakes in the Pacific slab under Izu-Bonin to study the velocity anomaly of deep seismic zone. To increase the reliability of our results, we used the modified double-difference relocation method to relocate the deep earthquakes with errors less than 1 km and inversed the differential residuals to obtain the optimal velocity anomaly directly. The result shows that the velocity anomaly of deep seismic zone is averagely 11.29% lower than the 1-D Earth model, such as the iasp91 model. This lower-velocity zone might be related to the metastable olivine. We have relocated the deep earthquakes in the case with the lower-velocity zone and found that the deep earthquakes can be separated into two layers. The focal mechanism of deep earthquakes might be related to the metastable olivine.

Acknowledgments

We thank the Japan Meteorological Agency for providing the arrival time data. We also thank Prof. Zhao (Tohoku University, Japan) for providing the program of 3-D ray tracing. This research was partially supported by grants from the Beijing Higher Education Young Elite Teacher Project, and the Ministry of Education and the Fundamental Research Funds for the Central Universities in China.

References

Bina, C.R., Stein, S., Marton, F.C., Van Ark, E.M., 2001. Implications of slab mineralogy for subduction dynamics. Phys. Earth Planet. Inter. 127, 51-66.

Iidaka, T., Suetsugu, D., 1992. Seismological evidence for metastable olivine inside a subducting slab. Nature 356, 593-595.

Iidaka, T., Furukawa, Y., 1994. Double seismic zone for deep earthquakes in the Izu-Bonin subduction zone. Science, 263, 1116-1118.

Jiang, G., Zhao, D., Zhang, G., 2008. Seismic evidence for a metastable olivine wedge in the subducting Pacific slab under Japan Sea. Earth Planet. Sci. Lett. 270, 300-307.

Jiang, G., Zhao, D., 2011. Metastable olivine wedge in the subducting Pacific slab and its relation to deep earthquakes. J. Asian Earth Sci. 42, 1411-1423.

Jiang, G., Zhao, D., Zhang, G., 2015. Detection of metastable olivine wedge in the western Pacific slab and its geodynamic implications. Phys. Earth Planet. Int., 238: 1-7.

Kaneshima, S., Okamoto, T., Takenaka, H., 2007. Evidence for a metastable olivine wedge inside the subducted Mariana slab. Earth Planet. Sci. Lett. 258, 219-227.

Kennett, B., Engdahl, E., 1991. Traveltimes for global earthquake location and phase identification. Geophys. J. Int. 105, 429–465.

Koper, K.D., Wiens, D.A., Dorman, L.M., Hildebrand, J.A., Webb, S.C., 1998. Modeling the Tonga slab: Can travel time data resolve a metastable olivine wedge? J. Geophys. Res. 103 (B12), 30079-30100.

Pavlis, G.L., Booker, J.R., 1980. The mixed discrete-continuous inverse problem: Application to the simultaneous determination of earthquake hypocenters and velocity structure. J. Geophys. Res., 85, 4801-4810.

Zhao, D., 2004. Global tomographic images of mantle plumes and subducting slabs: insight into deep Earth dynamics. Phys. Earth Planet. Inter. 146, 3-34.

Zhao, D., Hasegawa, A., Horiuchi, S., 1992. Tomographyic imaging of P and S wave velocity structure beneath northeastern Japan. J. Geophys. Res. 97, 19909-19928.