Journal of Asian Earth Sciences 146 (2017) 76–89

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Full length article

P-wave tomography of subduction zones around the central Philippines and its geodynamic implications

Jianke Fan[a,b,*], Dapeng Zhao[c], Dongdong Dong[a,b], Guangxu Zhang[a,b]

[a] Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China
[b] Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266071, China
[c] Department of Geophysics, Tohoku University, Sendai 980-8578, Japan

ARTICLE INFO

Keywords:
Seismic tomography
Manila Trench
Philippine Trench
Proto South China Sea slab
Subduction dynamics
Earthquakes

ABSTRACT

High-resolution tomographic images are obtained by inverting a large number of arrival-time data of local earthquakes and teleseismic events to depict the 3-D crustal and upper mantle structure beneath the central Philippines. Our tomographic results show that the subducted South China Sea slab beneath the southern segment of the Manila Trench steepens and tears, resulting in migration of the locus of active volcanism in the Macolod Corridor, due to the collision between the Palawan microcontinental block and the Philippine Mobile Belt. The subduction of the Philippine Sea Plate along the Philippine Trench started at 10–12°N or south of 12°N, the central part of the trench, from at least ~10 Ma estimated from our tomographic images. Our results reveal clearly a high-velocity anomaly in and around the mantle transition zone, which is interpreted as the subducted Proto South China Sea slab that sinks deeper southeastward, being well consistent with geological results that the age of collision between the Palawan microcontinental block and the Philippine Mobile Belt becomes younger from the south to the north. This collision zone can be divided into northern and southern segments, demarcated by the salient point of the collision zone, which is probably the boundary between the South China Sea slab and the Proto South China Sea slab, and may be ascribed to the complete consumption of the two slabs.

1. Introduction

The Philippines is made up of the aseismic Palawan microcontinental block and the seismically active Philippine Mobile Belt, being surrounded by subduction zones, including the discontinuous Manila-Negros-Sulu-Cotabato Trench system in the west and the East Luzon Trough-Philippine Trench system in the east (Fig. 1). Most of the convergence between the Eurasian Plate and the Philippine Sea Plate is accommodated by the subduction zones around the Philippines, which is responsible for the tectonic evolution of this region (e.g., Bautista et al., 2001; Yumul et al., 2003). The convergence between the Eurasian Plate and the Philippine Sea Plate that cannot be accommodated by the subduction zones is absorbed by the Philippine Fault, a major left-lateral strike-slip fault zone, which transects the whole Philippines longitudinally (e.g., Yumul et al., 2008 and references therein). The subduction and consequent events, such as collision and emplacement of ophiolite, render the Philippines a unique region to study how the island arc system evolves.

So far, many studies of this island arc system have been made for understanding the dynamic processes of the subduction system (e.g., Besana et al., 1997; Bautista et al., 2001; Yumul et al., 2003, 2008; Queaño et al., 2007; Doo et al., 2015). However, the tectonic evolution of the Philippines has not been well understood. For example, the subduction polarity reversal from the Manila Trench to the Philippine Trench, the initiation time of the Philippine Trench, the transition from subduction to collision, and the proto subduction zone before the collision, are still debatable. In particular, the existence of the subducted Proto South China Sea (PSCS) slab is still controversial due to the absence of direct evidence (e.g., Hutchison, 2010). Although it is widely considered that the PSCS slab has subducted beneath Borneo, a high-velocity (high-V) anomaly corresponding to the PSCS slab has not been imaged clearly beneath Borneo by previous tomographic studies (Curtis et al., 1998; Rangin et al., 1999a). Rangin et al. (1999a) claimed to have imaged the subducted PSCS slab beneath the present South China Sea (SCS), north of its expected position, but their results were denied by Hall (2002). The absence of a corresponding high-V anomaly beneath Borneo may indicate that there is no relict of the subducted PSCS slab there, or the slab could not be imaged clearly due to the lower resolution of the previous tomographic images. A surface-wave tomography (Curtis et al., 1998) shows that the subducted PSCS slab

---

[*] Corresponding author at: Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China.
E-mail address: fanjianke@qdio.ac.cn (J. Fan).

http://dx.doi.org/10.1016/j.jseaes.2017.05.015
Received 20 February 2017; Received in revised form 4 May 2017; Accepted 9 May 2017

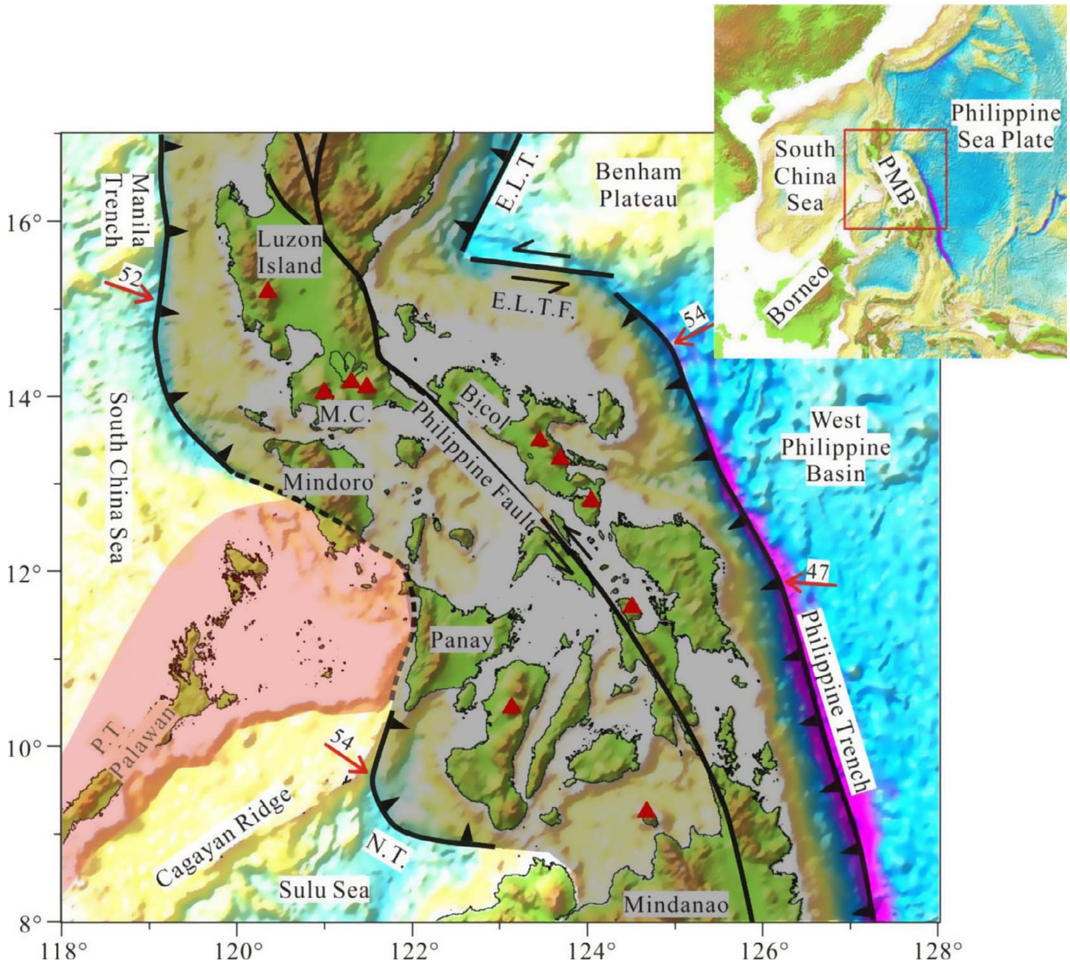

Fig. 1. Tectonic background in and around the central Philippines. The bathymetric data are from Smith and Sandwell (1997). The saw-toothed lines denote trench axes, the dashed line denotes a collision zone, and the solid lines are active faults. The red arrows and the adjacent numbers indicate the convergence rates (mm/year) between the South China Sea plate, the Philippine Sea plate, and the Sulu Sea plate (Rangin et al., 1999b). The red triangles denote active volcanoes. The pink shaded area shows the extent of the Palawan microcontinental block, whereas the gray shaded area shows the extent of the Philippine Mobile Belt in the study region. E.L.T., the East Luzon Trough; E.L.T.F., the East Luzon Transform Fault; M.C., the Macolod Corridor; N.T., the Negros Trench; P.T., the Palawan Trough; PMB, the Philippine Mobile Belt. The red box in the inset map shows the location of the present study region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

exists south of Palawan, but it disappears to the west beneath Borneo. However, the surface-wave tomography is not very robust because of its lower resolution (Curtis et al., 1998). Hitherto, a high-resolution tomography of the crust and upper mantle beneath the Philippines is scarce, which is essential for clarifying structural heterogeneities and geodynamics of the region.

In this work, we use a large number of P-wave travel-time data of local earthquakes and teleseismic events to determine a high-resolution tomographic model of the crust and upper mantle beneath the central Philippines, which sheds new light on the deep structure and tectonic evolution of this complex island arc system.

2. Data and method

We conducted tomographic inversions using two sets of P-wave arrival-time data, which are selected from the updated International Seismological Centre (ISC) Bulletins from 1964 to 2011 (see Engdahl, 2006 for details). One data set consists of local earthquakes; the other set is composed of teleseismic events. The data selection is based on the following criteria: (1) each earthquake was recorded at more than 4 seismic stations in the study region (Fig. 2a); (2) the absolute values of travel-time residuals of the local earthquakes are smaller than 5.0 s; and (3) the teleseismic events are located at an epicentral distance of 30–100° from the center of the study region to avoid the effects of complex structures at the core-mantle boundary and in the upper mantle outside the study volume (Zhao et al., 1994, 2013). As a result, our data sets contain 32,135 arrival times of 3126 local earthquakes and 19,316 arrival times of 2463 teleseismic events. Fig. 2 shows the distribution of the seismic stations and selected earthquakes used in this study.

The tomographic method of Zhao et al. (1994, 2012) is used to invert the travel-time data of the local and teleseismic events simultaneously. For the local events, raw travel-time residuals smaller than 2.0 s are used in the tomographic inversion. In contrast, relative travel-time residuals of the teleseismic events are used in the tomographic inversion for determining the deep structure of the study region. For each teleseismic event, theoretical travel times from the hypocenter to the recording stations are calculated for the iasp91 Earth model (Kennett and Engdahl, 1991), which are then subtracted from the observed travel times to obtain raw travel-time residuals. After that, relative travel-time residuals are obtained by removing the mean residual over all recording stations from the raw residuals. The use of relative residuals can reduce greatly the effects of hypocentral mislocation and origin times of the teleseismic events, as well as structural heterogeneities outside the study volume (Zhao et al., 1994, 2013).

The distributions of the mean relative travel-time residuals of the teleseismic events at every stations are displayed in Fig. 3, which show early arrivals associated with the subducting slab mainly near the coast of the South China Sea and the Philippine Sea, coinciding with the distribution of the trenches around the Philippines (Fig. 3a–d), whereas