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Slab stagnation and detachment under northeast China

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ABSTRACT

Results of tomography models around the Japanese Islands show the existence of a gap between the horizontally lying (stagnant) slab extending under northeastern China and the fast seismic velocity anomaly in the lower mantle. A simple conversion from the fast velocity anomaly to the low-temperature anomaly shows a similar feature. This feature appears to be inconsistent with the results of numerical simulations on the interaction between the slab and phase transitions with temperature-dependent viscosity. Such numerical models predict a continuous slab throughout the mantle. I extend previous analyses of the tomography model and model calculations to infer the origins of the gap beneath northeastern China. Results of numerical simulations that take the geologic history of the subduction zone into account suggest two possible origins for the gap: (1) the opening of the Japan Sea led to a breaking off of the otherwise continuous subducting slab, or (2) the western edge of the stagnant slab is the previous subducted ridge, which was the plate boundary between the extinct Izanagi and the Pacific plates. Origin (2) suggesting the present horizontally lying slab has accumulated since the ridge subduction, is preferable for explaining the present length of the horizontally lying slab in the upper mantle. Numerical models of origin (1) predict a stagnant slab in the upper mantle that is too short, and a narrow or non-existent gap. Preferred models require rather stronger flow resistance of the 660-km phase change than expected from current estimates of the phase transition property. Future detailed estimates of the amount of the subducted Izanagi plate and the present stagnant slab would be useful to constrain models. A systematic along-arc variation of the slab morphology from the northeast Japan to Kurile arcs is also recognized, and its understanding may constrain the 3D mantle flow there.

1. Introduction

Subduction zones are the focus of many earth scientists, as they are the world's geologically active regions. In particular, the fate of subducting slabs is of interest, because of their important role in the thermal/chemical evolution of the earth. Studies of the interaction between a subducting slab and the phase changes in the mantle transition zone have a long history (e.g., see the comprehensive review by Fukao et al., 2009; also see Wolstencroft and Davies, 2011, and Christensen, 2001, for numerical studies). Combining global tomography models with the results of numerical simulations, early scenarios of convection with phase changes described how, once the cold slab stagnated at the 660 km endothermic phase transition, it would sink rather abruptly because of the accumulation of cold material supplied by the subduction zone (Honda et al., 1993; Tackley et al., 1993). This simple view was consistent with global tomography models at the time, which showed a gap (absence or weak evidence of the existence of a high-speed anomaly) between the horizontally lying (stagnant) slab in the transition zone and the high-speed anomaly in the lower mantle (Fukao et al., 1992). However, subsequent studies have shown this scenario was overly simplistic. Christensen's (1996) results on a general behavior of the slab demonstrated that the slab could subduct almost continuously through the endothermic phase transition because of temperature-dependent viscosity.

The important question then arises, what was the origin of the gap? Christensen (1996) also showed that trench migration is important in controlling the degree of stagnation of the slab. This implies that the local tectonic situation should be considered in order to understand the present slab morphology.

Although there are many numerical studies related to the interaction between the phase transitions and the mantle convection, they are usually treated as a general problem to constrain how the slab stagnates in the transition zone. Considering the complexity of the problem, especially the geological factors, it is probably better to set up the problem in a specific region so that we can compare the numerical results to direct to observations, rather than seek a general principle.

Recognizing this point, Honda (2014) tried to adopt this approach by combining the seismic tomography model, the geologic history and numerical simulations of the region around the Japanese Islands. He concluded that the gap observed under northeastern China was produced by the opening of the Japan Sea, and he estimated the strength of slab to be $O(100\ \mathrm{MPa})$. However, his model was too simple; the bottom of the mantle is 2000 km, the age of the subducting slab and

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the thermal expansivity are constant, and the viscosity structure used has a rather peculiar feature. This viscosity model, mimicking that of Mitrovica and Forte (2004), has a thin, low-viscosity channel around 660 km. However, a more recent model presented by Forte et al. (2010) shows a quite vague low-viscosity channel.

Thus, in this paper, I revise the analysis of the tomography model and modeling study presented by Honda (2014). The area of the tomographic analysis is expanded both horizontally and vertically, using an upgraded tomography model. This model suggests a systematic change from the Kurile arc to the northeast Japan arc. These results are used as constraints on a series of 2D numerical models. The models have a depth range of 2900 km. Depth-dependent thermal expansivity is used and the viscosity structure is similar to the model described by Forte et al. (2010), without the weak low-viscosity channel around 660 km. This viscosity model is also similar to the one used by Steinberger et al. (2012). Furthermore, the models presented here take into account a more detailed subduction history of the area around the Japanese Islands (see Section 3), including the ridge subduction around 60 Ma (Seton et al., 2012, 2015) and the opening of the Japan Sea around 20 Ma (Yoshida et al., 2013). As a result, I found that the following factors were important in controlling the slab stagnation and the formation of the gap: (a) the spreading in the back-arc, i.e., the opening of the Japan Sea; (b) the age of the subducting plate, representative of the subduction of a ridge; and (c) the effects of the phase changes in the transition zone. Thus, the conclusions obtained in this paper are somewhat different from those of Honda (2014) who attributed the origin of the gap to the opening of the Japan Sea alone.

Recently, in the same vein, Seton et al. (2015) constructed 3D models that integrated paleo plate reconstructions and compared them to current tomography models. They found a general agreement between numerical results and observations, and concluded that the slab gap produced by the subduction of the ridge, which is the plate boundary between the Izanagi and Pacific plates, was the origin of the gap under northeastern China. Ongoing work with phase transitions and simulated back-arc spreading provides more detailed analysis of the slab morphology. Thus, the present study may become a supplement to their works.

2. Conversion from the tomography result to the temperature

Following the procedure described in Honda (2014), the conversion from the fast velocity anomaly to the low-temperature anomaly was conducted for the new tomography model NECCES_P1NT. Since NECCES_P1NT includes data from the NECESSArray project (Obayashi et al., 2012), which deployed the dense network in northeast China, the resolution under this region is better than in previous tomography model used by Honda (2014).

For the sake of completeness, I briefly describe the method below. The potential temperature T (Celsius degree) is estimated by.

$$T = T_0 erf\left(\frac{z}{2\sqrt{\kappa t_{plate}}}\right) + \alpha\delta T_{seismic} \qquad (1)$$

where T_0 is the deep mantle potential temperature (= 1330 °C), z is the depth, κ is the thermal diffusivity ($=10^{-6}$ m ^{2}/s), t_{plate} is the age of plate (= 48 Myr) equivalent to the surface heat flux of ~70 mW/m ^{2} and $\delta T_{seismic}$ is obtained by converting the fast velocity anomaly to the low-temperature anomaly using the smoothed version of Karato's (2008) $\partial \ln(\text{P-wave speed})/\partial T$ (Fig. 1a).

Since the magnitude of the seismic velocity anomaly is more susceptible to the method of inversion, I introduce the multiplicity factor α. α was chosen so that the temperature at the boundary between the upper and lower mantle became the estimate of the critical potential temperature (570~600 °C), above which the earthquakes do not occur (Emmerson and McKenzie, 2007). This choice was based on the assumption that potential temperature also controls earthquakes in the lower mantle.

Fig. 1b shows the calculated lowest temperature with different αs (1.5, 2.5 and 3.5). Of these, I selected $\alpha = 2.5$, which makes the estimated lowest temperature around 600~700 km nearly equal to the critical potential temperature (note that the estimated lowest temperature increases below 600~700 km).

Fig. 2 shows only the cold-temperature anomaly, which is supposed to represent the slab, obtained by the procedure described above.

The high-temperature anomalies are omitted in this figure to simplify the argument, as are vulnerabilities of low-velocity anomalies by factors other than temperature such as water and melt (see the review by Shito et al., 2006).

As shown before for the shallower tomography model (Honda, 2014), the new results display the gap (indicated in Fig. 2 by the red circles) under northeastern China (Fig. 2b) and the Philippine Sea (Fig. 2c). Note that the cold-temperature anomaly under the Okhotsk Sea appears to be continuous throughout the whole mantle (Fig. 2a), although the resolution there may be inferior to that under the Japan Sea (see Fukao et al., 2001).

In the following discussions, I attempt to construct a geodynamic model that can explain the temperature model shown in Fig. 2b. As

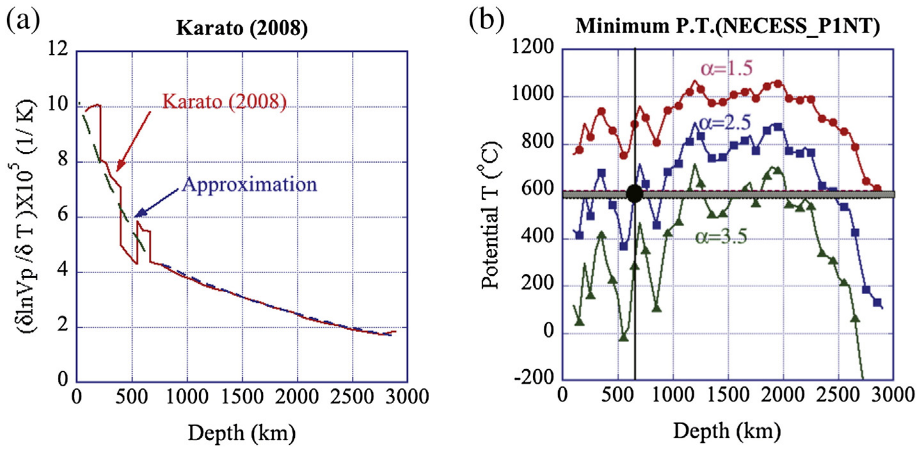

Fig. 1. (a) Conversion coefficient from the temperature anomaly to the P-wave velocity anomaly. The solid line shows the estimate by Karato (2008) and the dashed line shows the smoothed version used in this study; (b) the lowest temperature at depth estimated from the seismic tomography model with three different αs, that is, 1.5 (line with filled circles), 2.5 (line with filled rectangles) and 3.5 (line with filled triangles). The gray zone shows the range of critical potential temperatures above which earthquakes do not occur (Emmerson and McKenzie, 2007). The large filled circle shows the point that is suitable for explaining the absence of the earthquakes in the lower mantle.