Earth and Planetary Science Letters 427 (2015) 262–271

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

A new regime of slab-mantle coupling at the plate interface and its possible implications for the distribution of volcanoes

Manabu Morishige

Institute for Geothermal Sciences, Graduate School of Science, Kyoto University, Noguchibaru, Beppu, Oita, 874-0903, Japan

ARTICLE INFO

Article history:
Received 2 April 2015
Received in revised form 22 June 2015
Accepted 6 July 2015
Available online 25 July 2015
Editor: B. Buffett

Keywords:
slab-mantle coupling
3D flow
subduction zone
distribution of volcanoes
plate interface

ABSTRACT

We investigate the effects of a thin, low viscosity layer just above the subducting slab on 3D thermal and flow structure in the mantle wedge by taking Northeast Japan as an example. The low viscosity layer assumed here is needed to explain the observed low surface heat flow and low seismic attenuation in the forearc by decoupling the mantle from the subducting slab. We find that when the viscosity in the low viscosity layer is sufficiently low, along-arc component of the flow arises inside the layer and produces along-arc temperature variation. It can also be considered as the along-arc changes in the degree of slab-mantle coupling at the plate interface. The onset time and the characteristic wavelength of the 3D flow depend on the viscosity and the extent of the low viscosity layer. In order to explain the observed spatial and temporal changes in the distribution of Quaternary volcanoes in Northeast Japan, the viscosity and the thickness of the low viscosity layer need to be $<5 \times 10^{18}$ Pa s and $\sim$6 km, respectively. The model proposed here is based on an assumption which is simpler and better constrained by observations compared to previous models. Therefore, it could be an alternative explanation of the distribution of volcanoes in Northeast Japan.

1. Introduction

It has been proposed that the distribution of volcanoes has a regular spacing along the volcanic front. For example, the spacing in Aleutians, Alaska, Cascades, and Indonesia is ∼70 km, and that in Japan is ∼95 km (e.g., Marsh, 1979). In contrast, de Bremond d'Ars et al. (1995) reexamined the volcano spacing for 16 subduction zones and showed a different view that most volcanic arcs have ribbonlike shapes, not linear ones, and no characteristic spacing between volcanoes is observed. While it is still unclear whether the volcanoes distribution has a characteristic spacing or not, Tamura et al. (2002) demonstrated that the "clusters" of volcanoes have a characteristic spacing by taking northeast Japan as an example. It appears that some other regions show similar features. We can see a good correlation between the clusters of volcanoes and low seismic wave velocity anomalies in the mantle wedge beneath the back arc in Cascades (Gao and Shen, 2014) and Izu–Bonin–Mariana (Isse et al., 2009), whose characteristic wavelengths are ∼300 and ∼500 km, respectively. It suggests that increasing the number of geophysical studies including the detailed image of seismic wave velocity will allow us to find the along-arc variation in the mantle wedge structure which is correlated with the volcanoes distribution in other subduction zones as well.

In this paper, we consider northeast Japan as the study area for the following two reasons. First, to our knowledge, northeast Japan is the only clear example at present where several lines of evidence suggest the along-arc variation of volcanoes distribution as we will show later. Second, northeast Japan has a relatively simple tectonic settings (Fig. 1). In this region the subduction of Pacific plate occurs nearly normal to the trench and the age of the incoming plate is relatively uniform (130–140 Myr; Müller et al., 2008). There is also little variation in subduction angle (e.g., Zhao et al., 1997) and the down-dip limit of the occurrence of interplate earthquakes (Kita et al., 2010). It makes northeast Japan the ideal place to study the volcanoes distribution, which can be considered as the basis when other subduction zones are studied.

Tamura et al. (2002) find that the distribution of Quaternary volcanoes in this region forms clusters whose characteristic wavelength is 79 ± 16 km (Fig. 1). The clusters may have formed gradually since 14 Ma when the opening of Japan Sea mostly ceased (Kondo et al., 1998). Also, we can observe a good correlation between the locations of the clustering of the volcanoes, high topography, negative Bouguer gravity anomaly along the coast of Japan Sea, an inclined low seismic wave velocity in the mantle wedge, and the distribution of deep, low-frequency earth-

---

E-mail address: mmorishige@bep.vgs.kyoto-u.ac.jp.

http://dx.doi.org/10.1016/j.epsl.2015.07.011

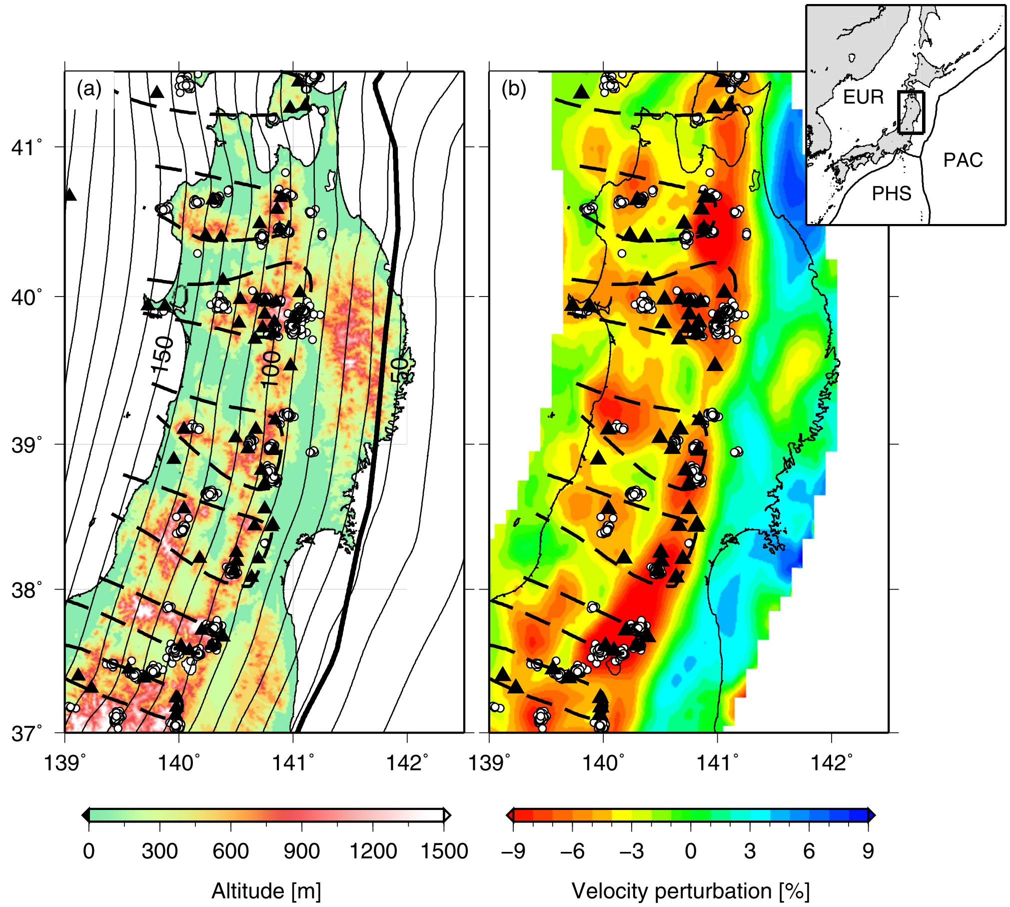

Fig. 1. Observations in northeast Japan. (a) Color shows altitude (Hasegawa and Nakajima, 2004). Thin black lines show slab surface every 10 km depth (Zhao et al., 1997; Kita et al., 2010). Thick black line shows the down-dip limit of interplate earthquakes (Kita et al., 2010). (b) Color shows S-wave velocity perturbations along the inclined low velocity regions in the mantle wedge (Hasegawa and Nakajima, 2004). In (a) and (b), dashed lines show the clusters of volcanoes distribution (Tamura et al., 2002). Black triangles show the locations of Quaternary volcanoes (Honda et al., 2007). White circles show the locations of deep, low-frequency earthquakes in the lower crust which are located by Japan Metrological Agency. The upper right figure is a map around the study area. Thick black line shows the study area. Thin black lines show the plate boundaries. PAC, PHS, and EUR stand for Pacific, Philippine Sea, and Eurasian plates, respectively.

quakes in the lower crust (e.g., Hasegawa and Yamamoto, 1994; Tamura et al., 2002; Hasegawa and Nakajima, 2004, Fig. 1). These observations suggest that the clustering of the volcanoes is related to the presence of partial melting in the mantle wedge, the degree of which changes in the along-arc direction (Tamura et al., 2002). The direct cause of the along-arc variation in the degree of partial melting is still debatable. It could be due to lateral variations in water content or variations in temperature. Here we focus on mechanisms that may cause lateral variations in temperature due to modifications of the 2D corner flow in the mantle wedge.

There are two types of previous numerical studies which produce the spatial and temporal variations in the thermal structure in the mantle wedge by subduction of an oceanic plate which is uniform in the along-arc direction. The first approach assumes small-scale convection of a thermal origin (e.g., Honda and Yoshida, 2005; Wirth and Korenaga, 2012) and the second approach assumes small-scale convection of a chemical origin (e.g., Zhu et al., 2009).

For the small-scale convection of a thermal origin, it is demonstrated that when the viscosity of the mantle wedge is uniformly low enough ($\sim 10^{18}$ Pa s), the bottom part of the overriding plate delaminates and small-scale convection arises (e.g., Honda and Yoshida, 2005; Wirth and Korenaga, 2012). One possible mechanism to produce such a weak region is hydration of the mantle wedge (e.g., Hirth and Kohlstedt, 2003; Karato and Jung, 2003). However, the distribution of water in this region is likely to be complex (e.g., Iwamori and Zhao, 2000). Also, a recent experimental study shows that the effects of water on viscosity might be small (Fei et al., 2013). Incorporation of dislocation creep may also help decrease the viscosity in some part of the mantle wedge where strain rate is high (e.g., Jadamec and Billen, 2010, 2012). Behn et al. (2007) also proposed a small-scale convection which is similar to those in Honda and Yoshida (2005) and Wirth and Korenaga (2012), although they consider foundering of arc lower crust which is chemically denser than the surrounding mantle.

In the second approach assuming small-scale convection of a chemical origin (e.g., Zhu et al., 2009), the viscosity and density of the material around slab surface decrease due to the effects of water and partial melting, and it rises as cold plumes. The detailed shape and wavelength of the plumes strongly depend on the assumed viscosity and density of the partially molten rocks. These parameters are controlled by several factors including the efficiency and rate of melt extraction, grain size, and the geometry of partial melt (e.g., Karato, 2008), although these are not fully understood. Also, this model mainly focuses on the general behavior of the mantle wedge and does not focus on a specific subduction zone. Therefore, the plate age, subduction angle, and plate speed used in their model may be different from those observed in northeast Japan subduction zone, making a direct application of their model to this region more difficult.

In this paper, we propose a new type of 3D flow in the mantle wedge as a possible explanation of the spatial and temporal variations in the distribution of volcanoes in northeast Japan. The