P-wave Tomographic Imaging of the Northern Pacific

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Abstract. A three-dimensional (3D) ray tracing technique was applied in global tomographic inversion to obtain tomographic images of the North Pacific. The data reported by the Geophysical Survey of Russia (1955 - 1997) combined with the catalogs of the International Seismological Center (1964-1991) and the U.S. Geological Survey National Earthquake Information Center (1991-1998) and then the full catalog was reprocessed. The large and sparse system of observation equations was solved by using the iterative LSQR algorithm. A subhorizontal high velocity anomaly was revealed just above the 660 km discontinuity beneath the Aleutian subduction zone. This high-velocity feature was observed up to latitudes $\sim 70^o$N and was interpreted as a remnant of the subducted Kula plate that disappeared by ridge subduction at about 48 Ma. Another positive velocity perturbation feature was revealed beneath the Chukotka peninsula and Okhotsk Sea, extending from $\sim$ 300 to $\sim$ 660 km of depth and then either further extending down to $\sim$ 800 km (Chukotka) or deflecting along the 660-km discontinuity (Okhotsk Sea). This high-velocity anomaly was interpreted as a remnant slab of the Okhotsk plate accreted to Siberia at $\sim$ 55 Ma. A prominent negative seismic velocity anomaly was found oceanward of the Kamchatka-Aleutian trench junction, with a 300 to 500 km-wide cylindrical column of low velocity anomaly ($\sim$ -2%) that extends from a depth of greater than 900 km to shallower than 200 km. The column is almost vertical at depths up to $\sim$ 400 km and rises obliquely to the north up to $\sim$ 200 km, above which it deflects subhorizontally under the ocean floor at the northern end of the Emperor seamounts. The subhorizontal deflection occurs in a NW direction in fair agreement with the moving direction of the Pacific plate. The overlying seafloor is unusual in terms of topography and gravity and is characterized by anomalously high heat flow, which may be attributed to the thermal effect of the mantle plume.

1 Introduction

The Northwest Pacific is one of the most active seismic regions of the world (Figure 1). The old Pacific plate subducts below the North America plate causing abundant seismic and volcanic activity in the region. Many tomographic studies have focused their interests on the Northwest Pacific region (e.g., Zhou and Clayton, 1990; van der Hilst et al., 1991, 1993; Fukao et al., 1992; van der Hilst et al., 1997). These studies revealed the configurations of subducted slabs and their possible relations to tectonic histories. Nevertheless, these studies have focused mainly on the subduction zones to the south of the Kurile arc ($<\sim 50^o$N). The subduction zones further to the north, Kurile- Kamchatka and Aleutian, have generally been excluded from detailed analyses of tomographic images. To date only few tomographic studies have been performed for the Aleutian arc (e.g., Engdahl and Gubbins, 1987; Widiyantoro, 1997) and for the Kamchatka arc (e.g., Gorbatov et al., 1999). All these studies placed their main emphasis on the velocity anomalies associated with the Wadati-Benioff zones, because of the limited spatial coverage of travel time data and the resultant lack of resolution. In an attempt to overcome this difficulty, we intensively collected arrival time data from the observatories of the Geophysical Survey of Russia, and incorporated these data into global tomography with the aim of refining understanding of tectonic processes in the North Pacific.

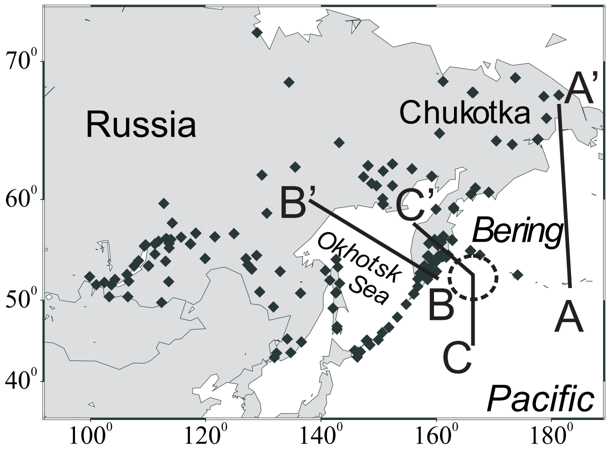

Fig. 1. Cross-section locations. Solid lines with letters at their ends mark the positions of the profiles that appear in Figs 2 and 3. Solid diamonds are seismic stations of Geophysical Survey of Russia. Dashed circle denotes the approximate location of the Meiji Guyot.

2 Data and Method

The P-wave arrival time data reported by Geophysical Survey of Russia (1955 - 1997) was added to the catalogs of the International Seismological Center (ISC) (1964-1994) and the U.S. Geological Survey's National Earthquake Information Center (NEIC) (1995- 1998). We then reprocessed the combined dataset that includes events and arrival times not reported in the ISC and NEIC catalogs. The ak135 reference model (Kennett et al., 1995) was perturbed by 2% in the mantle and 10% in the crust during hypocentral redetermination. Events with epicentral shifts greater than 25 km were removed from the dataset. Finally, the hypocenters were redetermined using the ak135 velocity model for the earthquakes not relocated by Engdahl et al. (1998). For the earthquakes relocated by Engdahl et al. (1998), we adopted their hypocentral parameters which are considered to be reliable enough because of their extensive reprocessing procedure using P, S, PKiKP, PKPdf, and the use of teleseismic depth phases pP,pwP, and sP in the relocation. All data were corrected for the Earth ellipcity and station elevations. A three-dimensional ray tracing technique based on the "pseudo-bending" method (Koketsu and Sekine, 1998) was used to generate data kernels. This inversion technique was presented in detail by Gorbatov et al., (2000) and Widiyantoro et al., (2000). The LSQR algorithm (Page and Sanders, 1983) was used to solve a large and sparse system of equations. One iteration consists of data kernel generation procedure and consequent solution using the LSQR algorithm. The ak135 Earth's model (Kennett et al., 1995) was adopted as the initial Earth model for the first iteration. The 3D velocity structure and hypocentral parameters were extracted simultaneously in each iteration. Three iterations were performed with 3D raytracing using the velocity model from the previous iteration.

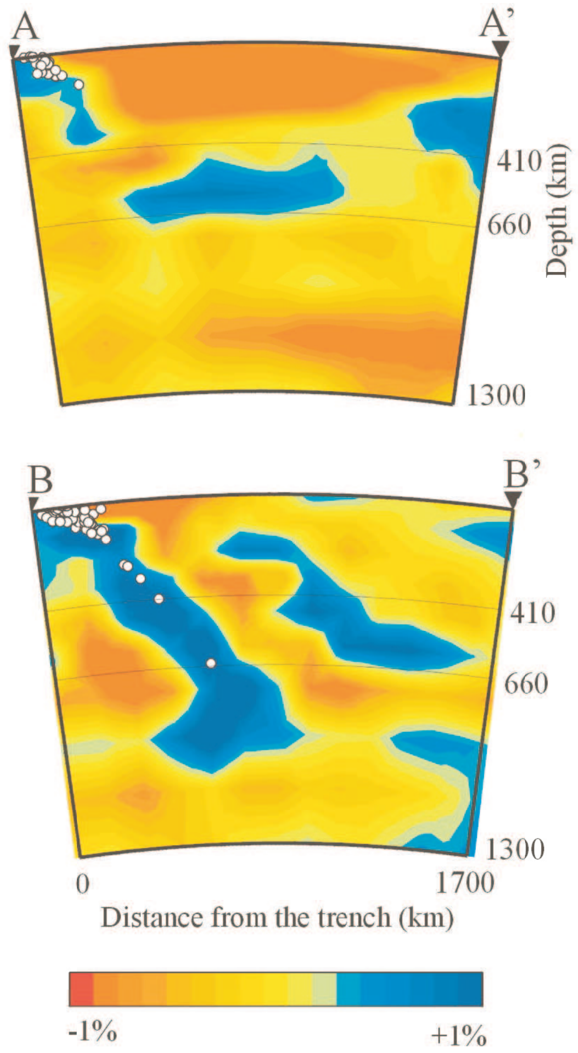

Fig. 2. Cross-sections of the P-wave velocity model a) through Aleutian subduction zone, AA' b) across the Kamchatka peninsula, BB'. Velocity perturbations are shown in percent relative to the reference model ak135 (Kennett et al. 1995).

3 Velocity anomaly mapping

Figure 2a shows the presence of a prominent high-velocity zone spreading far behind the Aleutian arc at depths of ~ 600 km beneath the Bering Sea in the area defined by $\sim 60^oN, \sim 70^oN, \sim 165^oE, and \sim 190^oE$. The slab-related anomaly extends below the maximum depth of the Wadati-Benioff zone across both the eastern and central Aleutian arc. There is, however, a large gap between this slab-related anomaly and a high velocity anomaly with a broad spread above the 600-km discontinuity beneath the Bering Sea. Checkerboard resolution tests indicate that this gap is a resolvable feature. The cross-section BB' (Figure 2b) through Kamchatka peninsula gives us a typical image of the northern Kurile to souhern Kamchatca arc. The Wadati-Benioff zone extends down to the bottom of the upper mantle at 660-km depth. The high velocity zone associated with this Wadati-Benioff zone extends below the maximum depth of seismicity, kinks backward against the subduction direction below the 660-km discontinuity and reaches a depth of about 900 km, in qualitative agreement with the seismic image obtained by Van der Hilst et al. (1991) for the northern Kurile arc. This high velocity zone probably represents the subducted slab of the Pacific plate. The cross- section on Figure 2b indicates the presence of another remarkable high velocity zone behind the Kurile-Kamchatka arc, running subparallel to the presently subducting slab. This high velocity zone dips to the northwest, extends from ~ 200 km to ~ 660 km depths, and spreads subhorizontally above the 660-km discontinuity. As it goes further northeastward, the high velocity zone begins to be deeper, below the ~ 400 km depth and reaches the 660-km discontinuity without a significant horizontal spread. Figure 3 shows a prominent low-velocity column underneath the Pacific Plate, with a perturbation of the order of -2% on its axis relative to the ak135 Earth model. This cylindrical column has its bottom slightly below ~ 900 km depth, and has maximum diameters (in plan view) of ~ 500 and ~ 300 km in the NS and EW directions, respectively with its center roughly at $(\sim 167^oE, \sim 46^oN)$. Certainly, the diameter estimation is affected by complex shape of the detected mantle plume and spatial parameterisation of the model. The conduits of plumes are usually estimated to have a diameter of ~ 100-200 km (e.g. Nataf, 2000), which could be difficult to image precisely. The column is almost vertical up to depths of ~ 400 km, above which it rises obliquely to the north so that its horizontal cross-section is centered roughly at $(\sim 167^oE, \sim 52^oN)$ at a depth of ~ 200 km. The northern half of this cross-section corresponds geographically to the southern half of the Meiji Guyot. The shallower extension of the low velocity column can be traced subhorizontally as a teardrop-shaped structure (in plan view) in the NW direction along the trend of the Meiji Guyot at the northern end of the Empereor seamounts. This feature could be seen in the depth range 160-340 km. Thus, the low velocity column consists of three parts, a deep part extending vertically through depths ~ 900 to ~ 400 km, the middle part rising obliquely to the north up to ~ 300 km depth, and the upper part extending subhorizontally to the NW direction in a depth range from ~ 300 to ~ 100 km.

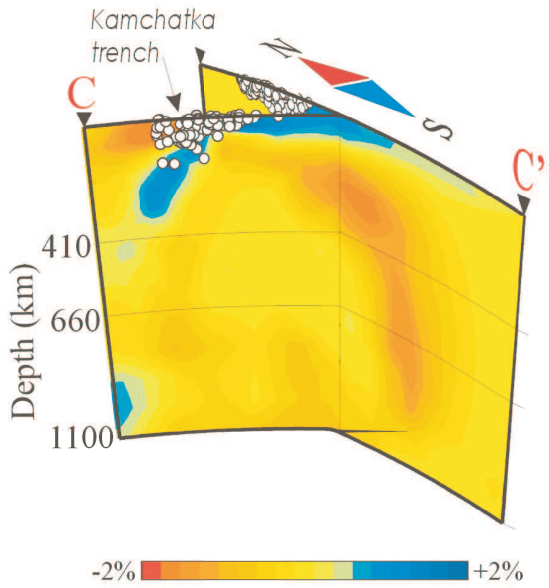

Fig. 3. Tomographic image of the mantle plume (cross-section CC'). See Fig. 1 for location.

4 Discussion and Conclusion

For the Aleutian arc, we have identified two high velocity anomalies, one associated with the Wadati-Benioff zone and the other flattening above the 660-km discontinuity. The high velocity anomaly associated with the Wadati-Benioff zone can be interpreted straightforwardly as representing the lithospheric slab subducted from the Aleutian trench. According to this interpretation, the subducted slab now reaches a depth somewhat greater than that of the leading edge of the Wadati-Benioff zone. The Aleutian arc has a long history of normal subduction of the Kula plate which was succeeded by ridge subduction at $\sim$ 48Ma (Lonsdale, 1988; Lithgow-Bertelloni and Richards, 1998). Based on this subduction history, we suggest that the high velocity anomaly horizontally spreading at the depths of $\sim$ 600 km beneath the Bering Sea represents the relic of the subducted slab of the Kula plate. We also postulate that the remarkable gap between this remnant slab anomaly and the one associated with the Wadati-Benioff zone is diagnostic of the ridge subduction at $\sim$ 48Ma. For the northern Kurile to Kamchatka arcs we also have distinguished two high velocity anomalies, one associated with the Wadati-Benioff zone and the other running subparallel in the backarc region. The high velocity zone associated with the Wadati- Benioff zone can be directly related to the subducted slab from the Kurile-Kamchatka trench. The high-velocity zone subparallel to the subducted Pacific plate can be seen clearly below the Chukotka peninsula and Okhotsk Sea. This anomaly zone may be interpreted as a relict of the subducted Okhotsk plate. The subducted slab penetrates into the lower mantle down to a depth of $\sim$ 800 km below Chukotka peninsula while it becomes sub-horizontal in the mantle transition zone below Okhotsk Sea. The Pacific plate has been imaged as a high velocity anomaly associated with the slab subducted beneath Kamchatka and Aleutian arcs. The low-velocity structure imaged oceanward of the Kurile -Aleutian trench junction deflects in the NW direction in fair agreement with the moving direction of the Pacific plate, suggesting that the plume conduit is deflected by the mantle shear flow due to the lithospheric plate motion. This shallow, subhorizontal portion of the mantle plume lies beneath Meiji Guyot. Meiji Guyot is an old seamount for which a "minimum" age of 62 Ma was estimated from the K-Ar dating of altered basalts at the DSDP site 192 (Creager et al., 1973). Smirnov and Sugrobov (1980) observed unusually high heat flow (higher than $80mW/m^2$) in the Meiji Guyot region and they suggested that the thermal thickness of the underlying plate is 2-3 times less than expected from the normal oceanic plate of the corresponding age. The seafloor of Meiji Guyot is characterized by anomalously high heat flow and by near absence of gravity low at the flank of this seamount. We interpret these features as the surface manifestation of the process of thermomechanical erosion of the lithosphere by the mantle plume.

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