Morphology of the distorted subducted Pacific slab beneath the Hokkaido corner, Japan

M.S. Miller a,∗, B.L.N. Kennett a,1, A. Gorbatov b,2

a Research School of Earth Sciences, The Australian National University, Mills Road, Building 61, Canberra, ACT 0200, Australia
b Geoscience Australia, GPO Box 378, Canberra, ACT 2601, Australia

Received 10 May 2005; received in revised form 1 January 2006; accepted 17 January 2006

Abstract

The intersection of the Japan and Kurile arcs is expressed as a cuspate feature at the trench, a bend in the Japanese islands, and a complex lithospheric structure and is known as the Hokkaido corner. The Pacific plate is subducting beneath the two arcs in the northwest Pacific at different velocities, which has resulted in an arc–arc collision and distortion of the subducting oceanic lithosphere. Using P and S wave tomographic images and seismicity the distorted shape of the subducted Pacific plate beneath the Hokkaido corner can be interpreted in three dimensions. The Pacific plate is imaged as continuous along the Japan–Kurile arc with dip angle increasing from south to north, but at the arc–arc junction the geometry is complex and appears crumpled. Beneath the Hokkaido corner there are two features in the tomography that are clearly imaged: a region of low velocity at approximately 50–150 km depth between 142.5–145◦E and 41–43◦N and a distorted, buckled lower slab boundary. These two unusual characteristics in the slab morphology are likely to be related to deformation of the subducted Pacific plate at the arc–arc junction.

Keywords: Subducted slab; Japan and Kurile arcs; Upper mantle; Tomography; 3D imaging; Arc–arc junction

1. Introduction

Along the northwest Pacific margin the Pacific plate is converging at a rate of approximately 8.2–9.2 cm/year to the northwest beneath the Kurile and Japan arcs (Seno et al., 1993; DeMets et al., 1994). At the Japan arc the Pacific plate is subducting approximately perpendicular to the arc, but is subducting obliquely at the Kurile arc, which results in an arc–arc collision. The junction of the two island arcs is expressed as a sharp cuspat feature and bend in the northern Japanese islands known as the Hokkaido corner (Fig. 1). The slab geometry beneath the Hokkaido corner is very complex and distorted as a result of the collision of the two arcs. The deformation of subducting plate at the arc–arc junction may be associated with interplate and lithospheric earthquakes that occur in the region (Suzuki and Kasahara, 1996; Katsumata et al., 2003) and expressed in the uplift of the Hidaka Mountains (Okada, 1983; Miyamachi and Motyia, 1984, 1987; Miyamachi et al., 1994; Kimura, 1996; Moriya et al., 1998). The unique setting and geological characteristics of the region results in a complicated model, but we present a new interpretation of the subducting slab morphology beneath the Hokkaido...
Corner using 3D ray tracing tomographic inversions and seismicity.

2. Previous studies

Initial studies of subduction zone structures along areas of sharp bends, such as the junction of the Japan and Kurile arcs, suggested the slab would be contorted or discontinuous (Isacks and Molnar, 1971). Later investigation of the subducting slab morphology beneath the northwestern Pacific integrated seismicity and seismic tomography data to define the geometry (Burbach and Frohlich, 1986; Zhou et al., 1990; Chiu et al., 1991; van der Hilst et al., 1991, 1993; Fukao et al., 1992; Zhao et al., 1992; Zhao and Hasegawa, 1993; Miyamachi et al., 1994; Gudmundsson and Sambridge, 1998; Motiya et al., 1998). Many of these studies suggested the Pacific plate changes dip near the Hokkaido corner from 40° to 50° at the Kurile arc to approximately 30° beneath the Japan arc and that the slab varies in thickness along the arc. Previous research has investigated the geometry of the slab beneath the northwest Pacific margin, but few studies have discussed the slab morphology at the Hokkaido corner in detail.

Chiu et al. (1991) were pioneers in three-dimensional imaging of subducting slabs in the Western Pacific. They defined the top of the subducting Pacific plate as an envelope of selected hypocenters and used this data to illustrate the slab surface in three dimensions. Their models for the Japan and Kurile arcs did not illustrate any distortion in the slab, but detailed the contrast in subduction angle of the gently dipping central Japan zone and the steeply dipping Kurile zone in the north. The transition was featured as a smooth surface with
curved, fan shaped contours in their models. They found that shallow to intermediate depth seismicity was not disrupted at the Hokkaido corner and noted that seismic waves propagated efficiently from events in the Kurile and Hokkaido areas to the stations on the eastern coast of Hokkaido, therefore suggested a continuous slab.

An inverse method was applied to P and S wave data from local events by Miyamachi et al. (1994) to model the three-dimensional velocity structure beneath northern Japan. This inversion proposed the top of the Pacific plate ranged in depth from 50 to 170 km and the subduction angle was greater beneath Hokkaido than along northeastern Japan. The upper slab boundary in their model exhibited a gentle curved shape that approximately mirrored the trench shape, but without a sharp bend often seen at the Hokkaido corner. The estimated thickness of the subducting slab ranged from 90 km along the Kurile arc and 110 km along the northern Japan arc from the local earthquake data.

An alternative approach was used to create a three-dimensional model of subducting slabs along the Western Pacific by contouring slab-related seismicity to approximate the top of the slab and the bottom defined as a constant 200 km thick oceanic lithosphere (Gudmundsson and Sambridge, 1998). The morphology was simplified since the slab extent was based on earthquakes and a projection of constant thickness, yet slab complexity and general characteristics of the geometry along the arc were well defined. The model depicted the bend at the Japan–Kurile arc junction and the associated change in dip along the plate boundary as a smooth curved shape in their regionalized upper mantle model and provided another method to model the slab morphology.

Early investigations were limited by lower resolution images making smaller scale structures more difficult to resolve and made assumptions to simplify the modeling process. As technology and data quality has improved more recent studies have been able to define the geometry of the Japan–Kurile arc–arc junction in more detail using enhanced methodology. Katsumata et al. (2003) recently investigated the geometry of the deep seismic zone associated with the subducting Pacific plate beneath the Hokkaido corner using hypocenters from events between July 1999 and July 2001. Their work confirmed the change in dip of the subducting plate on each side of the arc–arc junction, but the lateral transition of the subduction angle was more significant than in previous models by Miyamachi et al. (1994) and Hasegawa et al. (1994).

3. Tomographic controls
   The models presented in this study are based on regional body wave joint tomographic inversion of Gorbatov and Kennett (2003) together with a new P-wave tomographic inversion were produced from the same arrival-time data. The detailed joint inversion datasets used an inversion algorithm introduced by Gorbatov and Kennett (2003) to include 3D ray tracing. In this method the trajectory of seismic-ray propagation between source and receiver through the three-dimensional structure of the earth is included, which improves the resolution of gradients and strong variations in wave speeds. The joint inversion used P and S arrival-time data with the same source and receiver from the global catalog of Engdahl et al. (1998), which are plotted in Fig. 2. In order to optimize data coverage and ensure the final images can be directly compared, single rays with both P and S readings were picked for events and stations within the study area.

The surrounding Western Pacific mantle structure was parameterized into a non-overlapping grid of 5° × 5° with 16 layers ranging from 35 to 200 km down to a total depth of 1600 km. The study area consisted of a grid of 19 layers with cells 0.5° × 0.5° in the uppermost mantle, 1° × 1° in the transition zone and lower mantle, and 2° × 2° beneath continents to a depth of 1500 km. The final dataset contained 900,000 pairs of P and S ray paths and used the ak135 model as reference (Kennet et al., 1995). This nested iterative approach resulted in P and S models that were then used in a non-linear joint tomographic inversion for bulk-sound and shear wave speed inversions (Gorbatov and Kennett, 2003). Then a separate P-wave tomographic inversion was obtained with a similar non-linear scheme using the same dataset as in the joint tomography and with the same inversion parameters, but using a standard tomographic formulation. Although the inversion schemes used for joint tomography and the P-wave tomography are different, the three inversions can be compared with careful consideration of the smoothing (damping) parameters. We present a subset of the previously published shear wave-speed model and the new P-wave model to illustrate the structure of the subducting Pacific plate beneath the junction of the Japan and Kurile arcs.

4. Tomographic images
   The tomographic images presented have a maximum depth of 900 km and over the region between 136°–149° E and 37°–48° N. The large number of seiss-
mic stations and earthquake events in the area, recorded
teleseismic events, and small cell size allow for the
structure of the subducting slab to be well resolved.
A convenient way to measure the data coverage is the
sum of the lengths of the ray segments traversing each
cell. This is illustrated in Fig. 3 with ray density plots,
which show very consistent high ray density across the
regions where subduction zone features are expected
beneath the Japan and Kurile arcs. Detailed resolu-
tion tests using a synthetic model, in Gorbatov and
Kennett (2003), concluded the image of the subducted
slab could be recovered along its complete extension
using the same inversion parameters as in the observed
data.

Fast wavespeed anomalies used to define the subduct-
ing slab in the P-wave inversion and shear wave-speed
images are clearly imaged down to at depth of least
700 km (Figs. 4–6). The dip of the Pacific plate decreases
from north to south along the Japan–Kurile arc, consis-
tent with previous studies (Chiu et al., 1991; van der
Hilst et al., 1993; Miyamachi et al., 1994; Katsumata et
al., 2003), and is illustrated in the cross sections through
the P-wave and shear wave-speed tomographic models
(Figs. 4 and 5). Beneath the Kurile arc the subducting
slab is dipping at approximately 50° and the seismicity
falls within the high velocity zone (Figs. 4 (K–K′) and 5
(B–B′ and C–C′)). Beneath the Japan arc the Pacific slab
is well defined as dipping at approximately 30° and then
gradually transitions into a horizontal structure above the
660 km discontinuity (Fig. 4 (J–J′)).

An interesting low velocity feature is present in the
tomographic images, which suggests a complex shape
5. Three-dimensional morphology

The complex morphology of the subducting Pacific plate beneath northern Japan and the Kurile islands has been interpreted from a combination of seismicity and seismic tomography. A three-dimensional visualization of the slab geometry beneath the Hokkaido corner was created by systematically picking the top and bottom of the slab from the P-wave inversion in Figs. 4–6. The top and bottom of the slab was defined by picking the maximum gradient of velocity in the P-wave model, which compensates for the lower resolution in the northern portion of the model where there are fewer seismic stations. The high velocity anomalies that were used to define the slab geometry are subjective, but with care in picking the maximum gradient rather than a constant value contour the slab structure can be extracted irrespective of amplitude of the velocity perturbations.

The interpreted points were then used to create a schematic model of the subducting Pacific plate in the neighborhood of 41–43°N, 145–147°E, and 50–150 km depth. This feature lies approximately below the Hokkaido corner, where the Japan and Kurile arcs meet at a point (Fig. 1). A series of slices through the P-wave and shear wave-speed models at the Hokkaido corner show the anomalous feature in the upper mantle (Figs. 5 and 6). The P-wave images have lower amplitudes in comparison to the shear wave-speed images, but both illustrate the prominent low velocity feature in the upper 150 km to the west of the slab. The shear wave speed images have stronger fast velocity perturbations that illustrate an approximately linear top of the subducting plate, but a discontinuous lower boundary. The bottom of the subducting slab appears crumpled in the upper mantle in both P and S inversions, unlike the top slab surface, which is a more smooth and coherent feature (Fig. 6). It appears that the subducting Pacific plate at the Hokkaido corner becomes very distorted and does not bend smoothly at the arc–arc junction.
Fig. 4. Cross-sections of the P-wave velocity perturbation from locations shown in Fig. 1 with hypocenters of events during 1967–2002 with magnitude greater than 4.5 from the NEIC/USGS catalog as yellow dots. Cyan colors represent fast velocity perturbations and Brown colors represent slow velocity perturbations relative to ak135 (Kennett et al., 1995). Cross-section K–K′ illustrates the relatively steep dipping Pacific plate beneath the Kurile arc and J–J′ shows the more shallow dipping slab beneath the Japan arc. The Z units are in km depth. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of the article.)

Fig. 5. Three-dimensional (A) P-wave tomographic model and (B) shear wave-speed model sliced along the cross-sections shown in Fig. 1 (A–A′ to F–F′) to illustrate the Pacific plate subducting beneath the Japan and Kurile arcs. Fast perturbations are in cyan and slow perturbations are in brown relative to ak135 (Kennett et al., 1995). The Asian coastline is in purple, plate boundary is a broken black line, and Quaternary volcanoes from the Smithsonian volcano index are plotted as yellow triangles. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of the article.)

The detailed morphology of the slab at the Hokkaido corner is illustrated in Fig. 8(A and B) using contour maps of the top and bottom of the interpreted slab surfaces. The depth of the top and bottom of the slab is contoured in 10km increments down to a maximum depth of 260km. The slab appears to have a generally smooth surface except along the bottom of the slab near the Hokkaido corner. The steepening of the subduction angle from south to north along the arc and the complex shape is apparent in
the rapid change in dip in the slab surface (Fig. 6B). The bottom of the slab has a more contorted morphology, which illustrates the complex nature of the junction of the Japan and Kurile arcs. The contour maps present a more complex and detailed image of the slab morphology than those contour maps produced by Miyamachi et al. (1994) and Katsumata et al. (2003). The most distorted region is at the Hokkaido corner, which is located at approximately 42.5°N and 145-146°E (Figs. 5-8B).
6. Discussion

Hokkaido is a unique region because it lies at the junction of two subduction zones that are both seismically and volcanically active. The Hidaka Mountains, which strike approximately NE–SW on the island of Hokkaido, are an expression of the collision of the northern Japan and southern Kurile arcs. Many of the studies done in this region have focused on the crustal structure and its relationship to the arc–arc junction, but few have investigated the slab morphology beneath this region.

Moriya (1986), Moriya et al. (1998) and Miyamachi and Moriya (1984, 1987) investigated the structure beneath the Hidaka Mountains using seismic observations and their models suggest the complex velocity structure of the area is due to the oblique collision of the northern Japan (Honshu) and southern Kurile arcs. It was proposed that the variation of rate and angle of convergence along the arc (Fig. 1) resulted in a complex overlap structure in the crust and in the transition zone. Miyamachi and Moriya (1994) imaged an inclined low velocity zone at a depth to 70 km beneath the Hidaka Mountains. Miyamachi et al. (1994) suggested that this depth coincided with the location of the top of the slab and could be interacting; they speculated on the thickness of the Pacific plate based on seismic velocity distribution (range of 90–110 km), but the lower plate boundary was an unknown parameter in their models.

Katsumata et al. (2003) also studied the seismicity in the region to image the shape of deep seismic zone at the Japan–Kurile arc junction. In the process of modeling the seismic zone they found an unusual cluster of...
intra-plate earthquakes where the dip of the Pacific plate changes at the Hokkaido corner. Focal mechanisms for this near vertical linear cluster were interpreted to have predominately extensional characteristics. From these results they suggest this cluster is a slab-cracking zone that could develop into a slab tear due to the rapid lateral change in subduction angle at the arc–arc junction (Katsumata et al., 2003). This near vertical cluster is located at a depth range of 50–110 km near 42.5° N and 143.5° E. Although the new model presented here does not image a tear, a low velocity anomaly in the slab as seen in the tomographic images in Figs. 5 and 6 is located in the same region.

A different explanation for the shallow low velocity zone and earthquake cluster found by Katsumata (2003) near the Hokkaido corner can be explained by its position beneath a cluster of Quaternary volcanoes in central Hokkaido (Figs. 1, 6, and 9). The low velocity zone in the upper mantle extends from approximately 125 km to near the surface beneath the Tokachi, Daisesia, Nipesotos-Upepesanke, and Shikaribetsu volcanic groups along B–B’. These volcanoes in central Hokkaido (Figs. 1, 5, 6, and 9) are composed of a series of overlapping andesitic to dacitic lava domes and strato-volcanoes trending perpendicular to the plate boundary. The correlation between this series of volcanoes that trend along a line running NW–SE, which is unlike the other volcano groups in Hokkaido, and the presence of a low velocity anomaly (LVZ) in the mantle wedge is evidence for magma generation and conduits to the volcanoes (Fig. 9).

Similar low velocity zones interpreted as the source and path of magma for volcanoes have been imaged in other regions in Japan and South America (Nakajima et al., 2001; Wyss et al., 2001; Tamura et al., 2002; Husen et al., 2003), but not in this specific region. The low velocity in both P-wave and shear wave speed images do not appear continuously along the Japan arc, as noted in
previous research (Tamura et al., 2002), but there appears to be a basic correlation between volcanic groups and low velocity zones in the mantle wedge. Cross-section B–B in Fig. 6 images the localized low velocity zone extending from about 125 km depth up to the near surface where the volcanic group is located, which contrasts the more typical mantle wedge geometry features such as those observed in E–E. This low-velocity feature is also present in the recent work of Wang and Zhao (2005) (in their Fig. 9 sections E–E and F–F) using a different data set, but is neither commented upon nor interpreted.

The position of the cluster of volcanoes in central Hokkaido lie above the most crumpled and distorted portion of the subducting Pacific plate. The contour maps in Fig. 6 illustrate the position of the volcanoes relative to the top of the slab, which are at approximately the same depth as the other active volcanoes in the area (~150 km depth). The position of these volcanoes relative to the main volcanic front and is similar to location of the Klyuchevskoy and Shiveluch volcanic groups north of ~55° N on the Kamchatka peninsula (Gorbatov et al., 1997). The Kamchatka volcanoes are shifted west of the main axis of the volcanic front and lie above a portion of the slab that has changed dip and become shallower (Figs. 8 and 9). West of this uplifted area beneath central Hokkaido, where the cluster of volcanoes are located, the depth of the top of the slab is deeper and thicker due to the change in dip and thickness of the slab. Above this thickened oceanic lithosphere there appears to be a gap in the volcanic front. Beyond the gap there is a cluster of stratovolcanoes in southwest corner of Hokkaido, including Usu, Shikotsu, Komagata-take, among others, which are at least 200 km away from the closest volcano in central Hokkaido. Tokachi (Figs. 1, 6, and 9). It is possible that the gap in the volcanic front may be due to the thickened slab beneath this region, which is due to the collision of the Japan and Kurile arcs. The subducting slab morphology beneath the Hokkaido corner is very complex, but through the combination of seismicity, tomography, and plate velocities the complexity can be understood in terms of the collision of the Japan and Kurile arcs. The subducted plate beneath the northwestern Pacific margin is continuous, but changes geometry as the slab subduction angle decreases from north to south as the slab thins. Directly beneath the Hokkaido corner a low velocity zone in the upper mantle (70–125 km depth) is imaged, which may be related to volcanism in the area or another result of the collision of the two arcs. The present complex state of the Kurile and northern Japan arcs with apparent crumpling may be a result of the evolution of the arc–arc junction, which appears to have retreated to its present position over the last 15 million years.

References


Motya, T., 1986. Collision of forearc and overlapped deep seismic zone in the transitional zone between the Northern...


