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An integrated geodynamic model of the Nankai subduction zone and neighboring regions from geophysical inversion and modeling

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ABSTRACT

I investigate large-scale deep crustal structures of the Nankai subduction zone and neighboring region using regional magnetic and gravity anomalies, heat flow measurements, and earthquake hypocenters. It is found that ages, dip angles, and geothermal states of the subducting slab have direct influences on mantle wedge serpentinization. The weakest serpentinization observed in the Nankai forearc region is associated with the youngest downgoing plate of the Shikoku Basin. Conspicuous gravity anomalies identified in the forearc region are coincidental spatially with magnetic anomalies after the reduction to the pole, a mathematical procedure that helps relocate magnetic sources and boundaries, and allows us to more easily interpret magnetic data. It is argued that these patches of magnetic and gravity anomalies are caused by the same sources of anomalous density and magnetization, and are linked directly to preexisting structures such as magnetic anomalies and their boundaries in the subducting oceanic crust. Since the gravity and magnetic anomaly patches are found to be closely related to interplate seismogenic behaviors in the Nankai subduction zone, I suggest that major magnetic boundaries in the Shikoku Basin are likely weak places for slab tears that trigger seismic segmentations along the subduction zone.

Application of the Parker–Oldenburg algorithm to Bouguer gravity anomalies yields a 3D Moho topography. Curie-point depths are also estimated from the magnetic anomalies with reduction to the pole using a windowed wavenumber-domain algorithm. Window sizes are found to have little effects on the average Curie-point depths other than lowering lateral resolutions. A wide zone of deep Curie depths is identified in southwest Japan, relating to strong influence from the subduction of the relatively young and warm Shikoku Basin crust of the Philippine Sea plate. Curie depths so obtained can be correlated well with heat flow measurements, which cluster around a theoretical curve when the average thermal conductivity is about 3.0 W/(m °C). Using constraints from both Curie depths and heat flow, I also model the shallow geothermal field of the subduction zone. Earthquake hypocenters plotted against Moho and Curie depths and geothermal fields on three transects confirm early studies that downdip limits of seismogenic zones along the Nankai plate boundary do not extend down to the island arc Moho and their temperatures are more or less close to 350 °C. Geothermal field has direct influences on earthquake distributions in the overriding island arc and accretionary prism, within the subducting oceanic lithosphere, and along the interplate boundary.

1. Introduction

The Nankai subduction zone located offshore southwest Japan (Fig. 1) is a place where great thrusting earthquakes (M ∼ 8.0) occur repeatedly along the plate boundary (Ando, 1975). Although earthquakes are common on a subduction environment forming the well known Benioff zone, these interplate thrusting earthquakes occur in the very shallow portion of the subduction zone, where the plate boundary between the underthrusting oceanic crust of the Shikoku Basin and the overthrusting Japan arc and accretionary wedge is apparently locked and shows quiet seismicity before a sudden rupturing by a megathrusting earthquake (Ishida, 1995). This seismically coupled zone, also known as seismogenic zone or coseismic rupture zone, is currently being extensively studied (e.g., Kimura et al., 2008).

In revealing deep structures of subduction zones, seismology has been the most powerful tool due to its abilities in providing high-resolution reflection or velocity images. These types of data have been acquired in the Nankai Trough area, with exceptional coverage (e.g., Moore et al., 1990, 2007; Kodaira et al., 2000, 2006; Park et al., 2002; Nakanishi and Honda, 2000; Nakanishi et al., 2002, 2009; Bangs et al., 2009). Examples of cutting edge work from the

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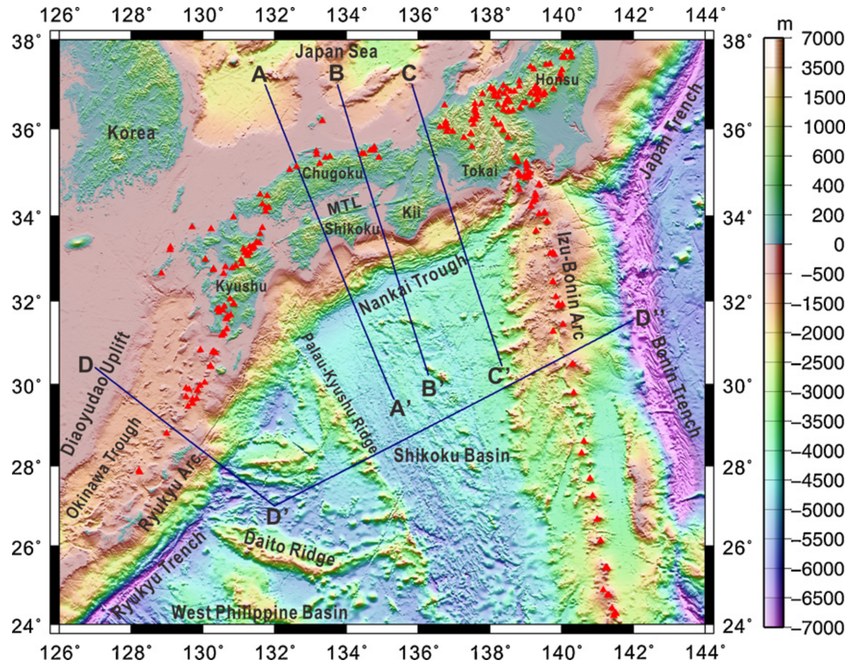

Fig. 1. Regional topography and bathymetry map. AA′, BB′, CC′ and DD′D″ are four geophysical transects shown in Figs. 11–13, and 5, respectively. Red triangles indicate Quaternary volcanoes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

past few years include a sea-land wide angle seismic experiment, with 100 ocean bottom seismometers and land stations along a single profile (instrument spacing of about 3 km) (Nakanishi et al., 2009). Numerous high quality 2D multichannel reflection seismic lines exist (e.g., Moore et al., 1990; Park et al., 2002), and finally there is even an unprecedented 3D multichannel seismic block at the frontal portion of the Nankai Trough accretionary wedge (Moore et al., 2007; Bangs et al., 2009). But still seismological studies are often limited either by the distribution of seismometers or by the cost. 3D earthquake tomography so far can only be carried out onshore, and 3D seismic reflection or refraction studies offshore are too expensive while 2D studies fall short of 3D coverage and lateral resolution.

Analyses of potential field data such as gravimetric and magnetic anomalies are well complementary to seismic studies in providing large regional coverage and extra constraints on physical properties such as magnetization, density, temperature, and elasticity. For example, free-air gravity lows have been recently found to be correlative to earthquake's seismic moments and asperity areas (Wells et al., 2003; Song and Simons, 2003), and local increases in trench-parallel gravity anomalies appear to be related to the physical conditions along the plate interface that favor rupture termination (Llenos and McGuire, 2007). A conspicuous high Bouguer gravity anomaly patch located off the southern end of the Kii Peninsula (Figs. 1 and 2) is found to be coincidental with a high velocity zone in the crust, which may control the segmentation and synchronization of the rupture zones (Honda and Kono, 2005; Kodaira et al., 2006) or could be a asperity prone to great subduction earthquakes. The well known 1944 Tonankai and 1946 Nankai events all occurred around this high Bouguer gravity anomaly patch (site C in Fig. 2).

Kido and Fujiwara (2004) noticed that landward weakening in observed magnetic anomalies in the Shikoku Basin cannot be explained solely by the depth and/or temperature increases in the downgoing slab but more likely by low-temperature chemical oxidation effects. They also interpreted the sources of several dipole magnetic anomalies found onshore to be a series of fossil serpentine diapirs involved during the accretionary process (Kido et al., 2004). Similarly, modeling on a significant spatial offset between high Bouguer gravity and magnetic anomalies in the Cascadian margin also reveals mantle wedge hydration and serpentinization there (Blakely et al., 2005).

Several attempts have been made to study the Curie-point depths from magnetic anomalies and their possible links to geothermal field and seismicity on the Japan Island (Okubo et al., 1985, 1989, 1991; Okubo and Matsunaga, 1994; Tanaka et al., 1999; Tanaka and Ishikawa, 2005), and possible correlations between Curie-point depths and seismogenic layer thickness in the overriding plate are implied (Okubo and Matsunaga, 1994; Tanaka and Ishikawa, 2005). However, these studies are confined either to the land areas or to small regions and can therefore offer only limited views on regional tectonic problems such as the subducting process of the Philippine Sea Plate along the Nankai Trough. The Curie point is considered as a point within the Earth where the temperature is high enough (~550 °C) to annul rock's ferromagnetism. Thus estimating Curie depths from the inversion of magnetic anomalies offers a direct insight into the lithosphere's geothermal field, the direct detection of which has remained as one of the greatest challenges in Earth sciences.

Despite extensive studies already made in the region, there is still a large uncertainty on what have caused the forearc gravity and magnetic anomalies and how and why they are connected with seismogenic segmentation. Subsurface temperatures are thought as a primary controlling factor on the crustal seismicity distributions in the overriding crust (e.g., Sibson, 1982; Okubo and Matsunaga, 1994; Tanaka and Ishikawa, 2005) and on the seismogenic zone extensions along the plate interface (e.g., Tichelaar and Ruff, 1993; Hyndman et al., 1995), since temperature controls the rheological state of rock masses and phase transition of subducted sediments along the interplate boundary (Moore and Saffer, 2001). Yet in the past, deep geothermal fields of the Nankai subduction zone were estimated primarily from thermodynamic numerical modeling incorporating very simplified geometries and many assumed parameters. It is well known that there are large uncertainties in the assumed parameters, and just for an example the conductivity can vary considerably from the surface to just a few