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High strain rate zone in central Honshu resulting from the viscosity heterogeneities in the crust and mantle

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Abstract

A linear zone with high strain rates along the backarc side of central Honshu (the so-called Niigata–Kobe Tectonic Zone) has been revealed by the dense GPS array (GEONET) operated by the Geographical Survey Institute of Japan. In order to explore the origin of this zone, we examine rheological heterogeneities in the crust or mantle above a subducting slab, which possibly contribute to the high strain rates. We calculate velocity profiles at the surface of the upper plate due to loading and unloading of the subducting Philippine Sea plate using a 2-dimensional finite element method. From the numerical experiments, we find that the high strain rates can be reproduced by viscosity heterogeneities either in the crust or the mantle. If viscosity heterogeneity in the crust is an origin, the conditions to be satisfied are (i) an effective elastic thickness of 5 km for short-term loading (10^2–10^3 yr), (ii) a low viscosity ($<10^{19}$ Pa s) in the lower crust beneath the zone, with a normal viscosity ($>10^{21}$ Pa s) in the ambient lower crust, and (iii) a uniform viscosity of 10^{19} Pa s in the upper mantle. On the other hand, if viscosity heterogeneity in the mantle is an origin, the conditions to be satisfied are (i) an effective elastic thickness of ~30 km for short-term loading, (ii) a low viscosity ($\sim10^{18}$ Pa s) at least down to a depth of 60 km in the zone and to a depth of 10 km further seaward below the Moho depth, and (iii) a viscosity of 10^{20} Pa s in the ambient mantle. The crust heterogeneity model contradicts the 15-km cut-off depth of intraplate seismicity and the ~20-km effective elastic thickness previously inferred from gravity and topography in central Honshu. The fact that Quaternary active faults and intraplate earthquakes are not particularly concentrated in the zone also favours the mantle viscosity heterogeneity model. Thus, we prefer the mantle heterogeneity model. We suggest that upward movement of water dehydrated from the subducting Philippine Sea and Pacific plates, partial melting of the mantle above the Pacific plate, and serpentinization in the wedge mantle above the Philippine Sea plate are possible origins of the low viscous

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upper mantle. Possible low viscosities in the upper mantle wedge presented in this study seem to provide important constraints for subduction processes of oceanic plates and strain accumulation processes in the upper plate.

Keywords: high strain rate zone; viscosity heterogeneity; back-slip; Philippine Sea plate; wedge mantle; dehydration; serpentinization; partial melt; Niigata–Kobe tectonic zone

1. Introduction

The dense Global Positioning System (GPS) array developed by the Geographical Survey Institute of Japan (GEONET) has revealed the presence of a high strain rate zone northwest of central Honshu [1]. This high strain rate zone, ~500 km long in the NE–SW direction and ~100 km wide (Fig. 1), suffers contraction in the WNW–ESE direction (~10^{-7}/yr), which is a few times larger than in the surrounding regions [1]. Because this zone has been called the Niigata–Kobe Tectonic Zone, we use NKTZ to denote it, even if it might not be a Quaternary tectonic feature as shown below. Fig. 1 also shows the tectonic elements where NKTZ is present. Beneath central Honshu, the Philippine Sea plate is subducting in the northwest direction along the Nankai and Sagami Troughs. Further to the east, the Pacific plate is subducting beneath the northern Honshu (the Okhotsk plate) and the Philippine Sea plate along the Japan and Bonin Trenches, respectively.

Several previous studies have attempted to explore the origin of NKTZ. Hashimoto and Jackson [2] detected the high strain rate zone from analyses of traditional geodetic data, such as triangulation, prior to the deployment of GPS. On the basis of the block-fault model proposed by Matsu'ura et al. [3], they interpreted the high strain rate zone by means of slip deficit on the faults at block boundaries. Since continuous GPS data became available, a sharp transition in velocity vectors (e.g., with respect to Eurasia) was noticed along NKTZ after removing the interplate locking effects at subduction zones, and some studies [4,5] proposed NKTZ to be a plate boundary, such as a boundary between the Eurasian and Okhotsk (North American) plates.

However, Quaternary crustal deformation in the Japanese islands does not evidently indicate a feature like a plate boundary [6–11]. For example, active faults are not particularly concentrated in this zone (see Fig. 1 of [6] and Fig. 3 of [8]). Historical intraplate earthquakes also do not show concentration in this zone (see Fig. 1 of [6] and Fig. 4 of [8]). Iio et al. [12] regarded NKTZ as an intraplate deformation zone, and proposed a qualitative model for the origin of NKTZ. In their model, the lower crust beneath NKTZ has a much lower viscosity than that in the ambient lower crust; they believe that this is caused by dehydration from the subducting Pacific plate. They also noted that the observed GPS velocity vectors are fairly uniform seaward of NKTZ, and explained this by a decoupling zone in the wedge mantle above the Philippine Sea plate, in addition to the weakened lower crust below NKTZ.

Hyodo and Hirahara [13] quantitatively investigated the model proposed by Iio et al. [12] using a 3-dimensional viscoelastic finite element model, in which the elastic crust having a thickness of 30 km is floating over the viscoelastic asthenospheric mantle, and the upper plate is loaded by interseismic locking and unlocking of the Pacific plate at the southernmost Japan Trench. They showed that the high strain rates in the zone can be realized by either of the two models with locally weakened crust: (1) the crust beneath NKTZ has an elastic thickness of 15 km and 50% reduction in rigidity and (2) the crust beneath NKTZ has an elastic thickness of 5 km. They preferred the former model, because the 5-km elastic thickness of the crust is too small compared with the 15-km cut-off depth of intraplate seismicity in this region [14,15]. The fairly uniform GPS velocities seaward of NKTZ are obtained in their model by introducing a viscoelastic mantle with a viscosity of ~10^{19} Pa s and a long loading interval between interplate earthquakes (~1000 yr). Note also that Wang et al. [16] showed that the viscoelastic mantle can produce more uniform deformation of the forearc in the Cascadia subduction zone than the elastic mantle.

Although the models of Hyodo and Hirahara [13] explain the high strain rates nicely, we note that there