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Spatial distribution of the contemporary stress field in the Kurile Wadati-Benioff zone by inversion of earthquake focal mechanisms

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ABSTRACT

The study addresses the spatial distribution of the contemporary stress field and stress regime in the Kurile Wadati-Benioff zone (WBZ) based on homogeneous data of earthquake focal mechanism solutions (FMS) and the inverse technique by Gephart and Forsyth (1984). The data set used consists of 829 Centroid Moment Tensor solutions (time period 1977–2010) and 38 FMS listed in previous studies for intermediate-depth and deep events that occurred prior to 1977.

The detailed analysis of the spatial distribution of orientation of *P* (compression) and *T* (tension) axes of the individual FMS relative to the local geometry of the subducting slab allowed the outlining of 19 WBZ subvolumes along and across the arc for which the stress field parameters and stress regime (based on the orientations of the principal stresses in a slab's reference frame and the value of *R*) were evaluated. The stress inversion results show that the shallow portion of the slab (5 WBZ subvolumes), is characterized by sub-horizontal and close to strike-normal maximum compression $\sigma 1$ and down-dipping minimum compression $\sigma 3$, the stress regime is of general tension. A two-planar stress pattern with slab-parallel or in-slab $\sigma 1$ and $\sigma 3$ in the upper and lower planes, respectively, is observed at intermediate depth all along the arc. An exception of this pattern is found for the slab segment beneath Iturup island where the upper plane is 'missing' and the orientations of principal stresses in the depth range 61–140 km are similar to these for the lower plane in the slab segment located to the south. Five sub-volumes have been outlined within the Kurile slab at depth greater than 220 km, each with their own characteristic focal mechanisms and stress distribution. The subvolume V1 (depth range 225–380 km), stretching along the entire arc, is characterized by $\sigma 1$ and $\sigma 3$ of SW and ENE orientation, respectively, the stress regime being compressional.

The results obtained for the deep portion of the slab indicate along-arc variations in the stress field. The southernmost deep segment of the slab (subvolume V2) is dominated by a tensional stress regime with strike-normal $\sigma 1$ and close to strike-aligned trending NE $\sigma 3$. The rest of the deep-seated WBZ subvolumes V3, V4 and V5, situated to the north of V2, are characterized by a compressional stress regime with slab-parallel or in-slab $\sigma 1$ and slab-normal or strike-normal $\sigma 3$. However, $\sigma 1$ is close to slab-parallel only within V4 in the central part of the arc. In the subvolumes V3 and V5, located to the south and north of V4, $\sigma 1$ rotates counterclockwise relatively to the slab-dip direction at about 50° and 60°, respectively.

The results obtained indicate that the main geodynamic forces that drive the presently active processes at different depths along the Kurile Wadati-Benioff zone are the slab pull and ridge push at shallow depths, unbending of the slab at intermediate depths causing the observed two-planar stress pattern, and the mantle resistance in the central and northern deep-seated slab segments. The stress inversion results indicate also additional forces that participate in the contemporary dynamics within several WBZ sub-volumes: lateral tension that modifies the $\sigma 3$ orientation from slab-parallel into strike-aligned, trending NNE and NE in the lower plane of segment K1-2, in the intermediate-depth subvolume beneath Iturup

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island, and in the deep subvolume V2; forces modifying the orientation of $\sigma 1$ within the subvolumes V1, V3 and V5 from slab-parallel into strike-aligned, trending SW, W and SW, respectively. The origin of these forces remains unsolved thus posing open questions for further investigations into the dynamics of the Kurile Wadati-Benioff zone.

1. Introduction

The Kurile subduction zone is located on the NW Pacific margin and extends for about 1300 km between Hokkaido and Shumshu islands (see Fig. 1). At a larger scale, it forms a part of the Northwest Pacific subduction system that includes the Kamchatka-Kuril-Japan-Izu-Bonin-Mariana subduction zone of about ~6550 km length (e.g. Schellart et al., 2007). The bathymetric map and the main structural and geographical units of the study area are presented in Fig. 1. The subduction of the relatively old and cold Pacific Plate (PA) below the Okhotsk microplate (OK), bounded by the Amur (AM), Eurasian (EU), North American (NA), and Pacific (PA) plates (Bird, 2003), is responsible for the generation of the Kuril Islands chain, the active volcanoes located along the entire arc and the deep offshore Kuril-Kamchatka trench.

According to the NNR-MORVEL56 model (Argus et al., 2011), the rate of convergence between PA and OK is estimated at 86 mm/a in the north (where the plate motion is normal to the Kurile trench) and 91 mm/a in the south (where the arc makes a 22–23° turn to the west and the plate subduction becomes oblique). The island arc being slightly convex to the east is subdivided transversely by the Ekaterina (ES) or Kunashiri (KS); Friza (FS) or Etorofu (ES); Bussol (BS), and Kruzenshtern (KS) straits. The deep and wide KS and BS straits divide the island arc into three main groups of islands: Northern, Central and Southern Kuriles. The trench-normal fracture zones Nosappu and Iturup, depicted in Fig. 1, represent paleo-transform faults in the subducting Pacific Plate (Hilde et al., 1976; Nakanishi, 1993) and play a special role in the contemporary seismotectonics of the southern part of the arc (e.g. Harada and Ishibasi, 2007; Kasahara et al., 1997).

The subducting slab seismicity is detected down to 650 km, showing a diffusive pattern in the depth range ~200–400 km (e.g., Fedotov, 1965; Hanuš and Vaněk, 1984; Gorbatov and Kostoglodov, 1997; Syracuse and Abers, 2006; Tarakanov, 1972).

Previous studies on stresses in the Kurile Wadati-Benioff zone (WBZ) were based on an analysis of the spatial distribution of the *P* (pressure) and *T* (tension) axes of earthquake FMS (e.g., Averyanova, 1975; Balakina et al., 1993; Chen et al., 2004; Fujita and Kanamori, 1981; Glennon and Chen, 1993; Kao and Chen, 1994, 1995; Lundgren and Giardini, 1990; Myhill, 2012; Simbireva et al., 1976; Stauder and Mualchin, 1976; Sykes, 1966; Veith, 1977; Zlobin et al., 2011) and composite mechanism solutions (Horiuchi et al., 1975). The results of previous studies show that the *P* and *T* orientation of earthquake FMS in the shallow portion of the Kurile WBZ (0–60 km) indicate a stress field with prevailing down-dipping tension and a sub-horizontal compression normal to the trench with resulting thrust and reverse faulting (e.g., Averyanova, 1975; Balakina et al., 1993; Simbireva et al., 1976; Stauder and Mualchin, 1976; Zlobin et al., 2011).

The stress pattern within the intermediate-depth and deep portions of the Kurile WBZ found in previous studies are not in full agreement. According to different authors, the dominant stresses in the intermediate depth range are as follows: down-dip tension and down-dip compression in the northern and southern ends of the Kuriles-Kamchatka region, respectively, and a complex stress pattern for the rest of the arc (Horiuchi et al., 1975); horizontal compression and tension to the north and south of Bussol strait, respectively (Simbireva et al., 1976); a heterogeneous stress field along the entire arc (Balakina et al., 1993); down-dip tension in the southern Kurile and down-dip compression in the northernmost part of the slab (Kao and Chen, 1994; Myhill, 2012); down-dip compression and horizontal tension (Zlobin et al., 2011); a two-planar stress distribution (Fujita and Kanamori, 1981; Kao and Chen, 1994; Stauder and Mualchin, 1976; Sykes, 1966; Veith, 1977). It should be noted that the two-planar stress distribution was identified in different segments of the Kurile WBZ: in the southern Kurile arc (Sykes, 1966), in the central and northern Kurile arc (Kao and Chen, 1994; Stauder and Mualchin, 1976; Veith, 1977), and in all Kurile segments (Fujita and Kanamori, 1981).

The results of the early studies, based on few FMS, show that north-dipping tensional stresses dominate in the deep portion of the southern Kurile WBZ (Stauder and Mualchin, 1976), while the central and northern parts of the subducting slab are characterized by down-dip compression (Isacks and Molnar, 1971; Stauder and Mualchin, 1976). The composite mechanism solutions evaluated by Horiuchi et al. (1975) indicate predominant down-dip compressional stresses all along the arc. Glennon and Chen (1993), based on an analysis of 27 FMS large earthquakes that occurred below 200 km depth, concluded that the strain field within the deep portion of the WBZ is segmented both along its strike and dip: while

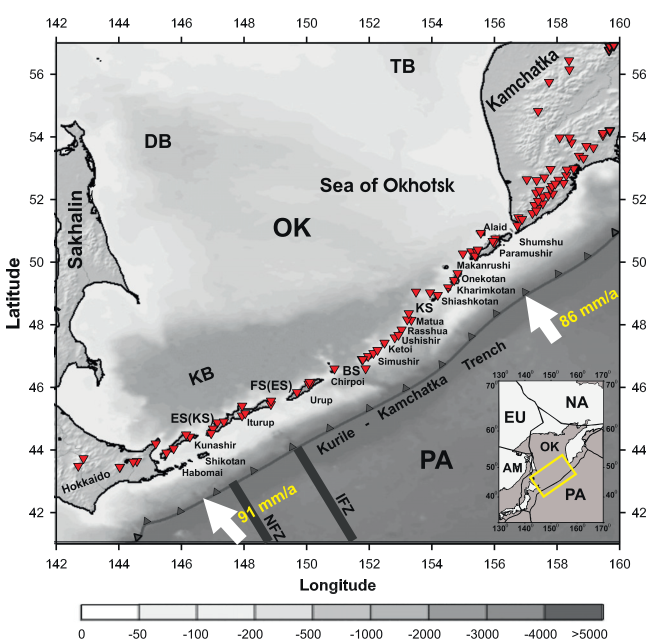

Fig. 1. Location, bathymetry and main geographic and structural features of the Kurile-Kamchatka region. The bathymetry is from ETOPO1 (Amante and Eakins, 2009). Arrows show the orientation and rate of the relative convergence between the Pacific plate (PA) and Okhotsk microplate (OK) according to NNR-MORVEL56 model (Argus et al., 2011). The active volcanoes (Simkin and Siebert, 1994) are marked by full reverse triangles, the trench axis is denoted by serrated line. The abbreviations used are as follows: DB, KB, TB – Deryugin, Kurile and Tinro basins, respectively; ES (KS), FS (ES), BS, KS – Ekaterina (Kunashiri); Friza (Etorofu); Bussol and Kruzenshtern straits, respectively; NFZ and IFZ – the Nosappu and Iturup fracture zones (Hilde et al., 1976; Nakanishi, 1993). The inset map shows the location of the Kurile-Kamchatka region and the OK plate bounded by the Amur (AM), Eurasian (EU), North American (NA), and Pacific (PA) plates, the plates and the plate boundaries, marked by a heavy line, are after Bird (2003), the box outlines the study area.