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The stress state of the Sakhalin Island and adjacent territories

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Abstract. The present study presents the results of the stress tensor inversion in the Sakhalin-Island and adjacent territories. The method of cataclastic analysis of discontinuous displacements has been used to perform the stress reconstruction. The stress inversion has been performed on the basis of local focal mechanism solution catalog of earthquakes, NEID and Global CMT Project data. The calculations are carried out at three depths levels (0–6 km, 6–12 km and 12–18 km) for magnitude range (Mw) 3.0–7.0. The results of the stress reconstruction allowed us to obtain the new specific features of the tectonic stress field: orientation of the principal stress axes, stress ratio or Lode-Nadai coefficient and the types of stress (the geodynamic regimes). The tectonic stress field is less stable at depth between 6 and 12 km.

1. Introduction

The Sakhalin Island is the northern continuation of the Japan-Sakhalin Island arc. It traces the boundary of the North American (the Okhotsk micro-Plate) and Eurasian (Amur Plate) tectonic plates [1]. The modern geodynamics of the Sakhalin Island is determined by the interaction of these plates, and it is manifested in its high seismic activity. The thickness of the Earth's crust here is 30-35 km. Earthquakes are mainly confined to the crust and they are associated with deep faults. Almost all modifications of dislocations (faults) are encountered: normal faults, revers (thrust) faults, strike slip faults, and their complex combinations. The faults have meridional, latitudinal, northwestern and northeastern strikes. However, in general, most faults are grouped into two main systems: major sub-meridional and subordinate northwestern-latitudinal fault systems [2]. The main sub-meridional faults of the Sakhalin Island are: the Western-Sakhalin fault, the Central-Sakhalin fault and the Hokkaido-Sakhalin fault.

The most important characteristic which define the seismicity is the stress state of the geological environment [3-6]. Tectonic stress is one of the fundamental data sets in Earth sciences comparable with topography, gravity, heat flow and others [7]. The state of stress in the Earth’s crust is a reflection of the modern tectonic processes. Therefore, one of the urgent problems of tectonophysics, geotectonics and seismology is the reconstruction of tectonic stress fields in different in scale and structure geological environments.

It should be noted that numerous scientific studies have been conducted to investigate regional geodynamics and the state of stress in the Earth's crust [8-14; etc.]. The studies [13, 14] used the same approach that we applied for tectonic stress inversion but they analysed the entire Earth's crust without division into small depth ranges. The tectonic stress field is non-uniform even within simple geological structures and can be explained by the complexity of both lateral and deep structures.

The goal of the present study is to investigate the changes in the state of stress in the Earth’s crust of the Sakhalin Island and adjacent territories at different depth.

2. Regional seismicity

The first known mention of the earthquake on Sakhalin Island was in 1868 [15]. The first known systematic collection of data on earthquakes began in 1906 in the northern Sakhalin and in 1909 in the southern Sakhalin (since the first seismic stations had been set up by Japanese). Here is a summary of the most significant earthquakes greater then magnitude 5.5 that occurred from 1906 to 1994: the September 5, 1971 Moneron earthquake (MLH = 7.2, h = 17 ± 5 km); the March 15, 1924 Lesogorsk-Uglegorsk earthquake (MLH = 6.8, h = 18 ± 12–25 km); the January 22, 1909 Onor earthquake (M = 6.1, h = 22 km); October 2, 1964 Nogliki earthquake (MLH = 5.8, h = 10 km – till 1995 it was the strongest seismic event on the north of Sakhalin Island).

Thus, the Sakhalin Island belonged to a region with moderate seismic activity for a long time (until 1995). Past seismic catastrophes were unknown in Sakhalin Island before 1995 except those suggested from findings of paleoseismodislocations [12]. The first time that dwellers have experienced such a catastrophe in the Sakhalin Island history was on 27 May 1995. The devastating Neftegorsk earthquake occurred in Northern Sakhalin (Mw= 7.1, h = 18 km), killed almost 2000 people in the small town of Neftegorsk, caused damage and destruction of buildings and facilities. It was felt all over the Sakhalin Island, as well as over the closest part of the Eurasian continent. Surface fracturing was the most impressive effect of the Neftegorsk earthquake. The 37-km long right-lateral strike-slip fault with a horizontal displacement up to a maximum of 8 m [16].

Several significant earthquakes have occurred in the Sakhalin Island since the catastrophic Neftegorsk earthquake in 1995: the August 4, 2000, Mw 6.8, Uglegorsk earthquake; the July – September Takoy swarm (the strongest earthquake in the sequence was magnitude 5.2); the August 17 (18), 2006, Mw 5.6 Gornozavodsk earthquake; the August 2, 2007, Mw 6.2 Nevelsk earthquake, the March 16, 2010, Mw 5.8 Uanga earthquake; the August 14, 2016, Mw 5.8 Onor earthquake.

Nowadays the Sakhalin Island and nearby territories are characterized by relatively high seismic activity. High-seismic zones coincide with a young newly-formed anticlinoria: the West Sakhalin anticlinorium in the south and the Northeast Sakhalin anticlinorium in the north of the Island. Zones of low seismic activity coincide with an ancient anticlinoria: the East Sakhalin anticlinorium (which is the part of the Hokkaido-Sakhalin folded system) in the central part of the island and the Susunai-Anivsky anticlinorium in the south of the island [17].

Thus there are three major earthquake zones in the southern, in the central and in the northern parts of Sakhalin Island separated by areas with rare epicenters of relatively weak earthquakes. In the northern Sakhalin, the zone of high seismic activity occupies almost the entire territory of the the Northern-Sakhalin Lowland. The highest concentration of earthquake epicenters is along the northeast coast (Okhinsky and Nogliksky regions). In the central part of the Sakhalin Island, zone of increased seismic activity is confined to the middle part of the West Sakhalin Mountains with the highest concentration of earthquake epicenters in the Uglegorsk region. In the southern Sakhalin, seismicity is concentrated in the southern part of the West Sakhalin Mountains and in the area of the Sea of Japan which is adjacent to the Moneron Island. High swarm activity was noted in Dolinsky region. One of the powerful swarms was the Takoy swarm in 2001. Areas with weak seismicity occupy almost the entire territory of the East Sakhalin Mountains in the central part of the Sakhalin Island, the Susunai and Tonino-Aniva Ridges and the Isthmus of Poyasok in the south of the island [18].

It should be mentioned that within the study area there are also deep focus earthquakes but they are not analyzed in the present paper. The deep-focus earthquakes with depths of 300–400 km are grouped between the Sakhalin and Hokkaido Islands along the Kuril-Kamchatka Depression of the Sea of Okhotsk.

3. A stress inversion method

Stress inversion is performed using the method of cataclastic analysis (MCA) of discontinuous displacements [19]. This method integrates some of the main principles of the theory of plastic deformation and a generalization of the results of rock failure experiments. The MCA algorithm realizes the principle of maximum energy dissipation of elastic deformation. This algorithm is similar to algorithms of well-known methods [20–23]. The earthquake focal mechanisms are the source of information on the state of stress of the Earth's crust. The method is based on the selection of the homogeneous sample set of earthquake focal mechanisms in the vicinity of each grid node for stress calculations.

4. Initial seismological data

Stress inversion was performed on the basis of seismic data on earthquake focal mechanisms obtained from the local network of seismic stations [10], the NIED F-net Catalogue (http://www.fnet.bosai.go.jp) and the Global CMT Project data (http://www.globalcmt.org).The regional catalog of focal mechanisms includes 536 events (425 – depth from 0 to 50 km and 111 depth from 230 to 620 km) and covers the region between 44° and 55°N latitude and 140° and 145°E longitude. The events occurred in the period from 1933 to 2018 with moment magnitudes between 2.0 and 7.7. The most representative range of magnitudes is from 4.0 to 5.0 (54%).

Reconstruction of the tectonic stress was performed using the STRESSseism software package and earthquake focal mechanism data for magnitude range, Mw 3.0–7.0, on a 0.1° × 0.1° grid at four depths: 1) 0–6 km, 2) 6–12 km, and 3) 12–18 km. Only earthquakes within each layer are used during the stress calculations. The earthquakes with magnitude less than 3.0 (17 events) and greater than 7.0 (7 events – the depth of all events is greater than 220 km except of 1971 Moneron earthquake) were not regarded.

All the procedures for the formation of homogeneous samples of earthquake focal mechanisms were accomplished for 195, 532, and 109 quasi-homogeneous domains; each homogeneous sample set of earthquakes contained at minimum six and at maximum 10 earthquakes.

5. Results and discussion

The stress inversion shows that in the Southern Sakhalin, at depth of 0–6 km, the axes of the algebraically minimum principal stress (maximum compression stress), σ_3, have a stable subhorizintal orientation (dominant azimuth (Az) is 263–295°) and plunge at an angle (Pl) of 0–12°. At depth 6–12 km, these axes start to change their orientation: in the east part of the Southern Sakhalin the axes are oriented to the south, south-west (Az 203°, 198°; Pl 17–24°); in the central (the Tym-Poronaysk depression – (Az 77°, 83°; Pl 11°)) and northern Sakhalin (the North Sakhalin Plain – (Az 40–70°; Pl 16–69°)) – to the east; between the 51st and 52nd parallels these axes are oriented subverticaly to the south-east (Az 50–90°; Pl 68–85°). At depth 12–18 km, in the southern Sakhalin (between Moneron and Sakhalin Islands), the principal stress axis of maximum compression, σ_3, is still oriented subhorizontal (Az 96–109°, 282–296°; Pl 5-6°); in the central part (the Tym-Poronaysk depression), the axes of the maximum deviatoric compression, σ_3, in comparison with the axes at depth 6–12 km, change direction to the opposite one (Az 251°; Pl 17°; in the north part of Sakhalin Island, these axes have north-east and south-west direction with low plunge angle (Az 63–78°, 251–264°; Pl 5–18°).

The orientation of the principal stress axis, σ_1, is less stable (figure 1 d–f).This axis dips at a steep angle (61–90°), and its direction varies from south to north: the orientation of this axis changes from east, north-east to south-west.

The intermediate principal stress axis, σ_2, has submeridional orientation and dips almost everywhere at an angle of 0–220°.

The described tendency in the orientation of the principal stress axes is reflected in the type of stress state (geodynamic regime): most of the studied region for all depth is characterized by horizontal compression, with the exception of areas in the north (between the 51st and 52nd parallels) and in the east part of Southern Sakhalin, where the geodynamic regime is horizontal extension. Local areas of horizontal and vertical shear (shear in the horizontal plane) are also observed for the crust of Northern and Southern Sakhalin.

After the first stage, the Lode – Nadai coefficient (varies from –1 to +1) is calculated (figure 2 d– f), which characterizes the shape of the stress ellipsoid. The Lode–Nadai coefficient corresponds to the stress tensor for pure shear, $0.2 \leq \mu_\sigma \leq 0.2$ (i.e., the deviatoric stresses of the maximum compression and tension have almost equal absolute values), almost everywhere, but some places are excluded (see figure 2 e, f). There are large spatial domains in the crust of the east part of the Southern Sakhalin, in central and Northern Sakhalin where the Lode–Nadai coefficient is close to the uniaxial compression range ($\mu_\sigma \geq 0.6$). Domains in which the Lode–Nadai coefficient represents nearly uniaxial tension are located in the crust of the Southern (6–12 km) and Northern Sakhalin (6–18 km).

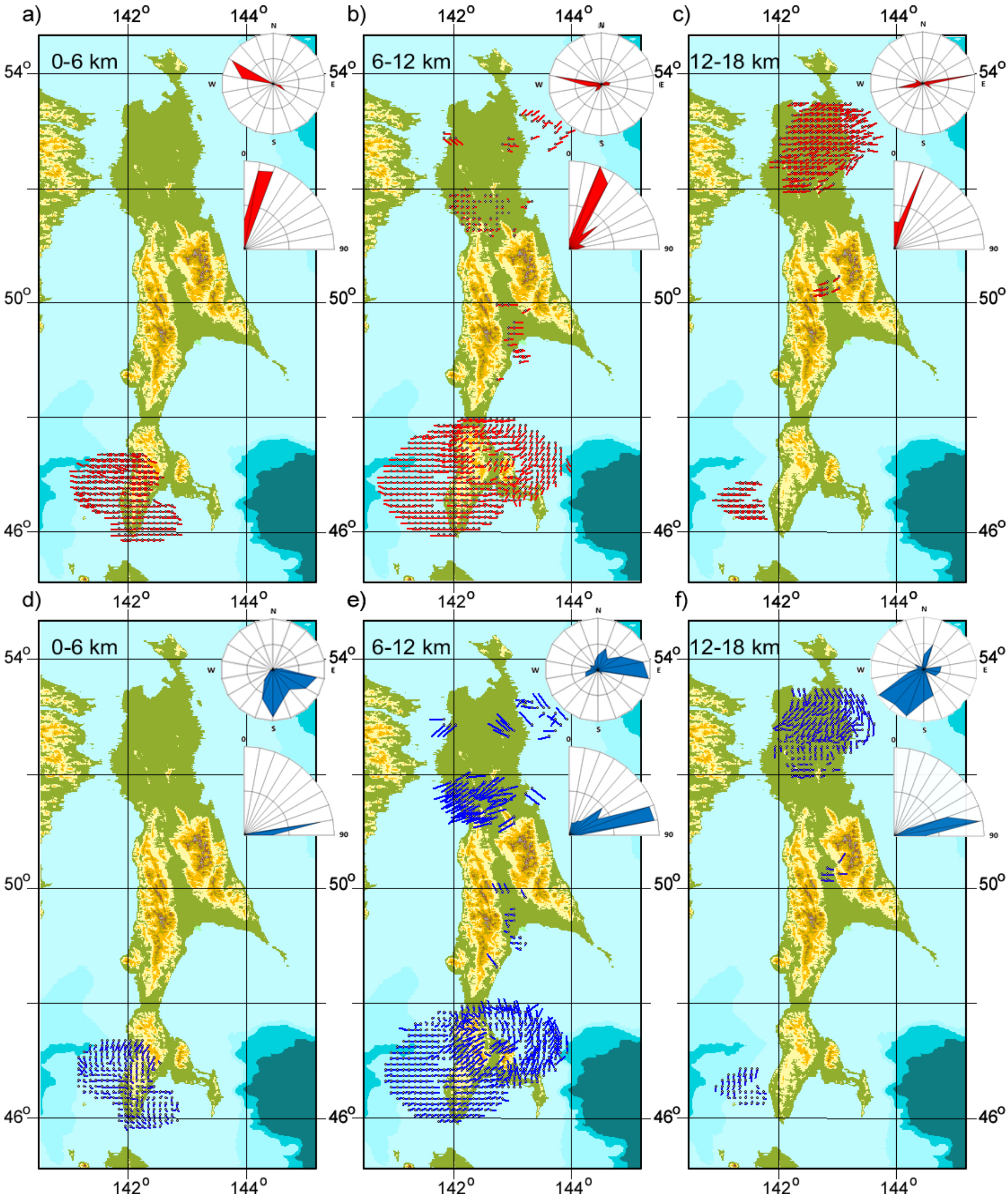

Figure 1. A projection of the principal stress axes σ_3 (a–c) and σ_1 (d–f) onto a horizontal plane. In the upper right corner, circle diagrams show various azimuths and dip angles of the principal stress axes σ_3 and σ_1.

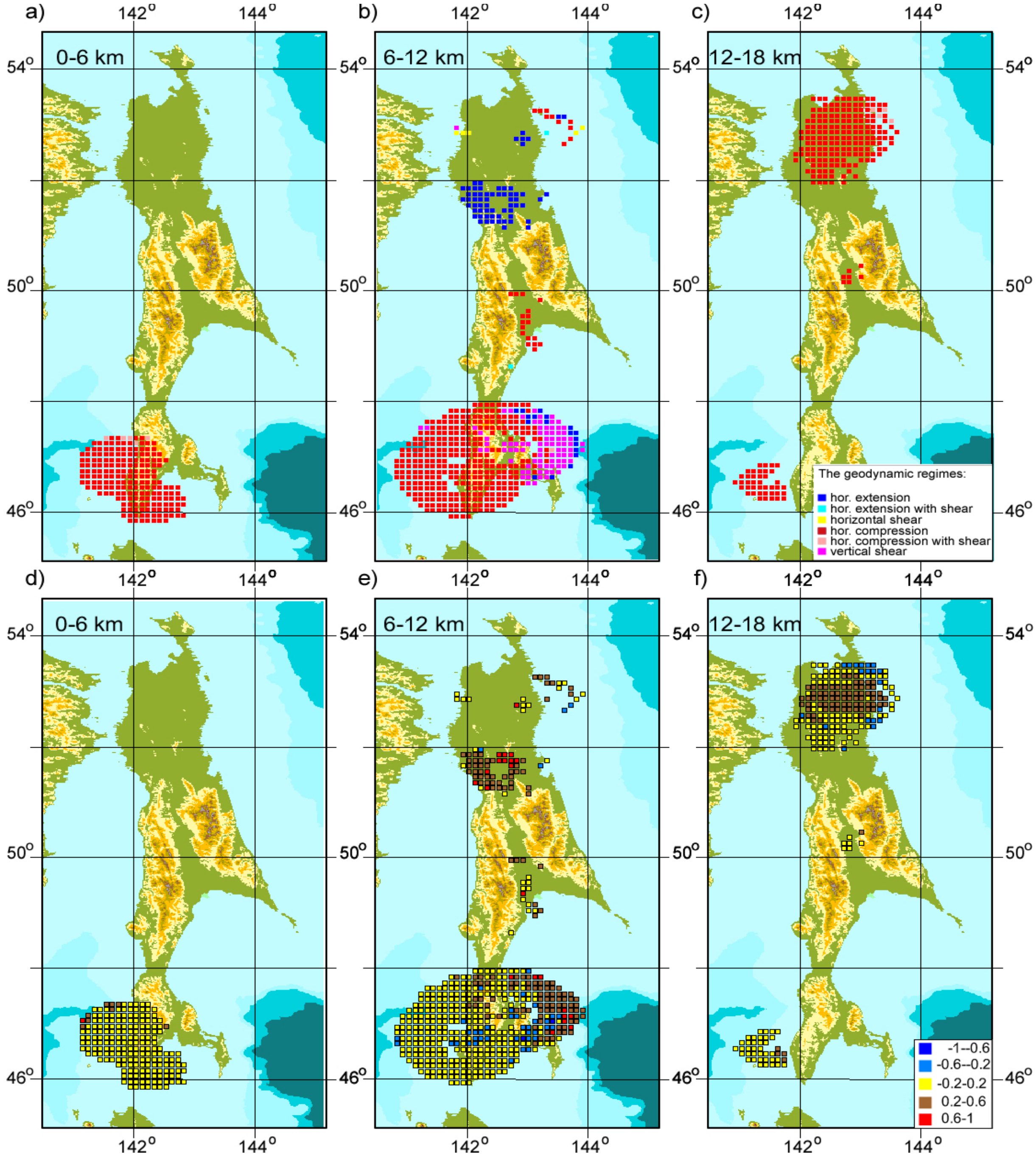

Figure 2. The types of stress, i.e., the geodynamic regimes (a–c) and the Lode–Nadai coefficient, μ_σ (d–f). 1 horizontal extension, 2 – horizontal extension with shear, 3 – horizontal shear, 4 – horizontal compression with shear, 5 – horizontal compression, and 6 – vertical shear.

Such changes in the principal stress orientation from sub-horizontal to sub-vertical can be explained by the evolution of the surface topography of the crust rather than differences in the rock properties.

6. Conclusion

New data on the modern tectonic stress field have been obtained in the Sakhalin Island and adjacent territories for the depth 0–18 km, on the basis of method of cataclastic analysis of discontinuous displacements. Based on the calculations, a sharp variability of the tectonic stress field with depth (0– 18 km) was revealed. Spatial inhomogeneities of the stress field are noted in the Northern Sakhalin and in the east part of Southern Sakhalin. At all analyzed depth, tectonic stress field is the most stable in the west part of Southern Sakhalin.

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