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Ancient subduction zone in Sakhalin Island

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ABSTRACT

The northern part of Sakhalin Island is an area of recent intensive tectonic movements and hydrothermal processes, as well as a place of accumulation of useful minerals. The deep structure of the lithosphere beneath the region of the Neftegorsk earthquake of May 27, 1995 in North Sakhalin, which killed residents and caused significant destruction, is examined in this paper. Our geodynamic model shows that North Sakhalin consists of the North Sakhalin Basin, Deryugin Basin and an ophiolite complex located between them. The Deryugin Basin was formed in place of an ancient deep trench after subducting the Okhotsk Sea Plate under Sakhalin in the Late Cretaceous–Paleogene. The North Sakhalin Basin was formed on the side of the back-arc basin at that time. The ophiolite complex is fixed in the position of ancient subduction zone that was active in the Late Cretaceous–Paleogene. Approximately in the Miocene, the subduction of the Okhotsk lithosphere apparently ceased. The remains of the subduction zone in the form of an ophiolite complex have been identified from geological and geophysical data. On the surface, the subduction zone is manifested as deep faults stretched along Sakhalin. It is probable that the Neftegorsk earthquake was a result of activation of this ancient subduction zone.

1. Introduction

Current developments in geosciences are characterized by special attention to research into the deep structure of the Earth used to resolve theoretical problems of geodynamics, to explore effectively for mineral deposits at depth, to research the problem of seismic hazards, to forecast and reduce damage from natural disasters (in particular those caused by earthquakes and volcanic eruptions), and also to solve environmental problems. Furthermore, continental margins are characterized by high seismicity, volcanic eruptions and other natural cataclysms. In fact, approximately one-third of the human population lives within the continental margins, meaning they live in a risk zone. In light of this, the continental margins of the Sea of Okhotsk are the object of detailed studies under international and national geophysical projects (Biebow et al., 2000; Rodnikov et al., 2002, 2008).

The obtained results of the projects are the basis for creation of an interdisciplinary informational database that can be used to construct geodynamic models of the deep structure of active continental margins of the earth. This database has been applied to construct a deep structure model of the lithosphere in the region of the devastating Neftegorsk earthquake that occurred in the northern part of Sakhalin (magnitude 7.1 Mw) on May 27, 1995. The International Seismological Centre provides this information (International Seismological Centre, 1997).

2. Information about data

Combined geophysical and geological data were collected for North Sakhalin in order to create a deep structure model of the lithosphere in the region of the Neftegorsk earthquake. The geophysical and geological datasets were derived from drilling results of research vessels summarized from various papers (Biebow et al., 2000; Bogdanov and Khain, 2000; Filatova and Rodnikov, 2006; Grannik, 2003; Khanchuk, 2000; Obzhirov et al., 1999; Rodnikov et al., 1996, 2008, 2011; Sergeyev, 2006). The seismicity data is available in Kondorskaya (1997) and Starovoit (2009). A consolidated crust was constructed on the basis of seismic profiles collected during the last several decades (Piip and Rodnikov, 2004). In the Okhotsk Sea region, seismic velocities change abruptly at the Moho boundary from 7.8 km/s beneath island arcs and sedimentary basins to 8.2 km/s beneath stable areas of the crust. The existence of the asthenosphere in the upper mantle is determined from geothermal research (Rodnikov et al., 1996), tomography and seismic observations (Bijwaard et al., 1998; Kosminskaya et al., 1987; Zhao et al., 2010). The temperature of the upper surface of the asthenosphere is assumed to be 1000–1200 °C at which the upper mantle rock is partially molten (Rodnikov et al., 1996; Smirnov and Sugrobov, 1980). A high-conductivity layer in the upper mantle, which appears to be associated with the existence of a partial melt zone beneath the sedimentary basins (Kaplun, 2002; Liapishev et al., 1987; Nikiforova et al., 1980), was identified via electromagnetic research.

The components of this article also include information about the earthquakes (Ivashchenko et al., 1997; Katsumata et al., 2004; Oscorbin et al., 2001; Rogozhin, 1996; Rogozhin et al., 2011; Tobita et

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al., 1998) and the geology of North Sakhalin and nearby areas (Alekseychik et al., 1963; Bogdanov and Khain, 2000; Rodnikov et al., 1996; Rozhdestvensky, 1986, 1988; Streltsov, 2005).

3. Okhotsk Sea region

Recent Pacific margins encompass island arcs and deep trenches, seismically active subduction zones and back-arc basins that accompany island arcs. The major unit of active margins is the subduction zone, which determines the relief forms, deep structure, tectonics, seismicity, magmatism and the formation of useful minerals. The island arc magmatism is one of the most significant manifestations of deep processes going on in subduction zones, which allows us to study the structure of ancient subduction zones in the greatest detail. The interrelationships between the recent volcanic belts of island arcs and the subduction zones are well-known. The chain of active andesite volcanoes on the island arcs is commonly located above seismic focal zones, containing magmatic chambers at a depth of 70–100 km. By analogy with recent seismic focal zones, ancient subduction zones are seen as structural elements of ancient active ocean margins and are represented by ophiolite sutures. Such ancient ophiolite complexes were discovered in the Schmidt Peninsula along the eastern shore of Sakhalin (Alekseychik et al., 1963; Raznitsin, 1982; Rozhdestvensky, 1988). The ophiolites of Sakhalin separate the North Sakhalin Basin from the Deryugin Basin in the Sea of Okhotsk (Fig. 1). North Sakhalin, where the Neftegorsk earthquake occurred, covers the Schmidt Peninsula and the North Sakhalin plain, which is formed of loose sandy–argillaceous deposits of the Neogene age. This area and the adjacent shelf of the Sea of Okhotsk contain the basic oil and gas deposits of Sakhalin.

3.1. Tectonic structure

The Okhotsk Sea region is a lithospheric plate of the transition zone from the Asian continent to the Pacific. The region is located in the contact zone of three lithospheric plates: Eurasian, North American and Pacific (Fig. 2). The Okhotsk Sea Plate was formed in the Late Cretaceous (Rodnikov et al., 1996). In the Cenozoic, it was covered by a layer of sedimentary and volcanogenic rocks. The thickness of the crust varies from 35–40 km under Sakhalin and the Kuril Islands to 8–10 km under the Kuril Basin. The majority of the sedimentary basins were formed in the Cenozoic. According to the geothermal data, the upper surface of the asthenosphere is on the 1000–1200 °C isotherms that indicate partial melting conditions. The asthenosphere is located in the upper mantle of the Sea of Okhotsk at a depth of 50–70 km and beneath the northwestern basin of the Pacific at a depth of approximately 100 km. From the asthenosphere, the diapirs go up to a depth of 20–30 km under the sedimentary trough of the Tatar Strait and Kuril Basin (Rodnikov et al., 1996). Beneath the Deryugin Basin, where a high heat flow is observed (Smirnov and Sugrobov, 1980), the asthenosphere reaches the base of the crust, causing an active tectonic regime that manifests in volcanic, seismic and hydrothermal activity (Rodnikov et al., 2002). Beneath the North Sakhalin Basin, which contains almost all Sakhalin oil and gas fields, the asthenosphere is located at a depth of approximately 70 km (Kharakhinov, 1996).

3.2. Seismicity

The location of the Okhotsk Sea Plate in the contact zone of the three lithospheric plates (Fig. 2) caused a high seismicity on its boundaries (Fig. 3). The vast majority of earthquakes are confined to the Kuril Island Arc. The Pacific plate is subducted under the Kuril Island Arc, forming a seismic focal zone traced to a depth of 700 km. In the west, the Okhotsk Sea Plate is bounded by deep faults extending along Sakhalin where earthquakes are localized in the crust. On the active continental margins of the Russian Far East, a considerable number of earthquakes occur continuously. About 80% of the energy from all the earthquakes in Northern Eurasia is present on the continental margins. The 1994 earthquake near the Southern Kuriles (magnitude 8.4), the 1995 Neftegorsk earthquake (North Sakhalin, magnitude 7.1), the 1997 Kronotsk earthquake (East Kamchatka, magnitude 7.9), and the 2007 Nevelsk earthquake (Tatar Strait, magnitude 6.2) are among the largest earthquakes over the last 10 years (Levin and Tikhonov, 2009; Vasilenko et al., 2001; Yunga and Rogozhin, 2000).

4. Deep structure geodynamic model of the Neftegorsk earthquake region

The Neftegorsk earthquake was a 7.1 Mw (7.6 Ms) (International Seismological Centre, 1997) earthquake that occurred in North Sakhalin, which consists of sandy–argillaceous sediments of Neogene

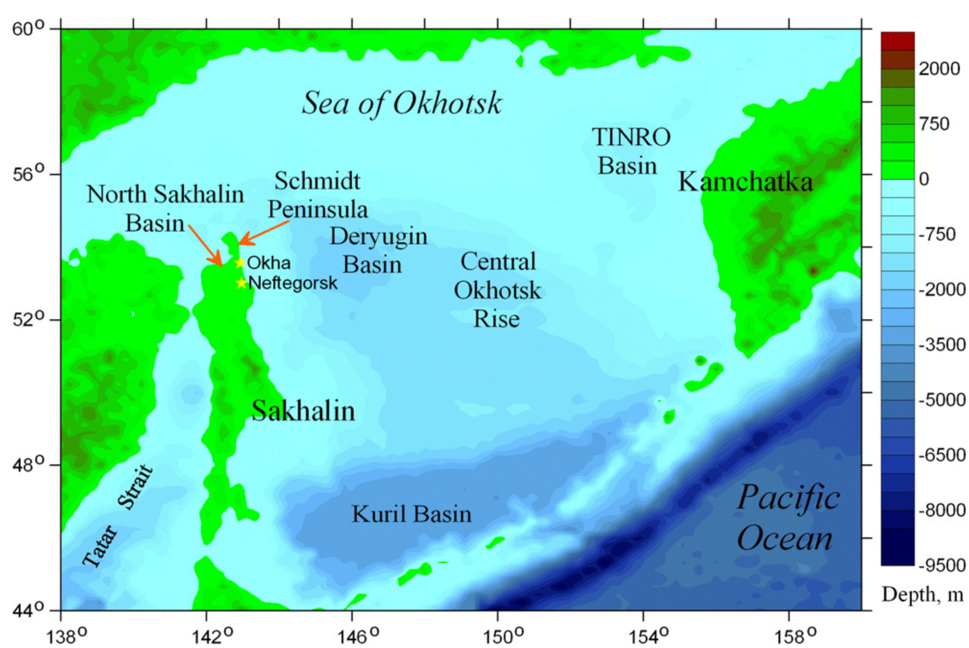

Fig. 1. Bathymetry chart of the Sea of Okhotsk (Rodnikov et al., 2002).