

The deep structure of active continental margins of the Far East (Russia)

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[1] In the frame of the international project “InterMARGINS”, the research in the deep structure of active continental margins of the transition zone from the Eurasian continent to the Pacific was conducted along the deep cross-section of the tectonosphere including the lithosphere and the asthenosphere. The deep section profile runs across the Mesozoic structures of Sikhote Alin, rift structure of Tatar Strait, Cenozoic formations of Sakhalin, Kuril Basin of the Sea of Okhotsk, volcanic structures of Kuril Island Arc, Kuril deep trench and the Mesozoic plate of Northwest Pacific Basin. The length of the profile is 2000 km. The depth of penetration into the earth’s interior is 100 km. A distinctive feature of the transition zone structure is the asthenospheric layer occurrence in the upper mantle; diapirs of hot anomalous mantle branch off from this layer and processes going on in them cause the formation of the region geological structures. A correlation is noted between geological structures, tectonic and magmatic activity and the upper mantle structure. Tectonically active regions like island arcs and rift structures of marginal seas correspond to thick and most distinct asthenosphere generating magma. *INDEX TERMS:* 0905 Exploration Geophysics: Continental structures; 0930 Exploration Geophysics: Oceanic structures; 1645 Global Change: Solid Earth; 3001 Marine Geology and Geophysics: Back-arc basin processes; 3002 Marine Geology and Geophysics: Continental shelf and slope processes; *KEYWORDS:* deep structure, active continental margins, transition zone, upper mantle, marginal seas.

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Introduction

[2] The present stage of earth science progress is characterized by particular attention drawn to research in the deep structure of the planet owing to challenges of theoretical geodynamics, reliable prognosis of useful minerals hidden in the depth, seismic hazard, natural disaster prediction and mitigation of damage specifically the damage caused by earthquakes and volcanic eruptions, and environmental problems. Therefore one of the most important lines in the earth science is studying deep causes of geological phenomena in order to assess, predict and mitigate the danger of

natural disasters especially of those caused by earthquakes and volcanic eruptions.

[3] Many national and international programs were devoted to the studies of the deep structure of the earth’s interior; among them are the Upper Mantle Project, Geodynamic Project, the program “Lithosphere”, Geotraverse Project and others that were successfully implemented [Belousov, 1986; Kozlovskiy et al., 1987; Rodnikov, 1986]. Now more than 20 countries are participating in the international project “InterMARGINS”. Being interdisciplinary, this program is aimed at solving problems that cannot be solved but with international cooperation. They involve the studies of the deep structure of continental margins, rift genesis, sedimentation processes going on in continental slopes, research in seismogenic and subduction phenomena resulting in earthquakes and volcanic eruptions, geochemistry of rocks composing the crust, the studies of the role of fluids in useful mineral formation and many other problems.

[4] The Geophysical Center RAS conducts research on the project “Geodynamic models of the deep structure of active continental margins” in the frame of the international program “InterMARGINS”. The task of the project is con-

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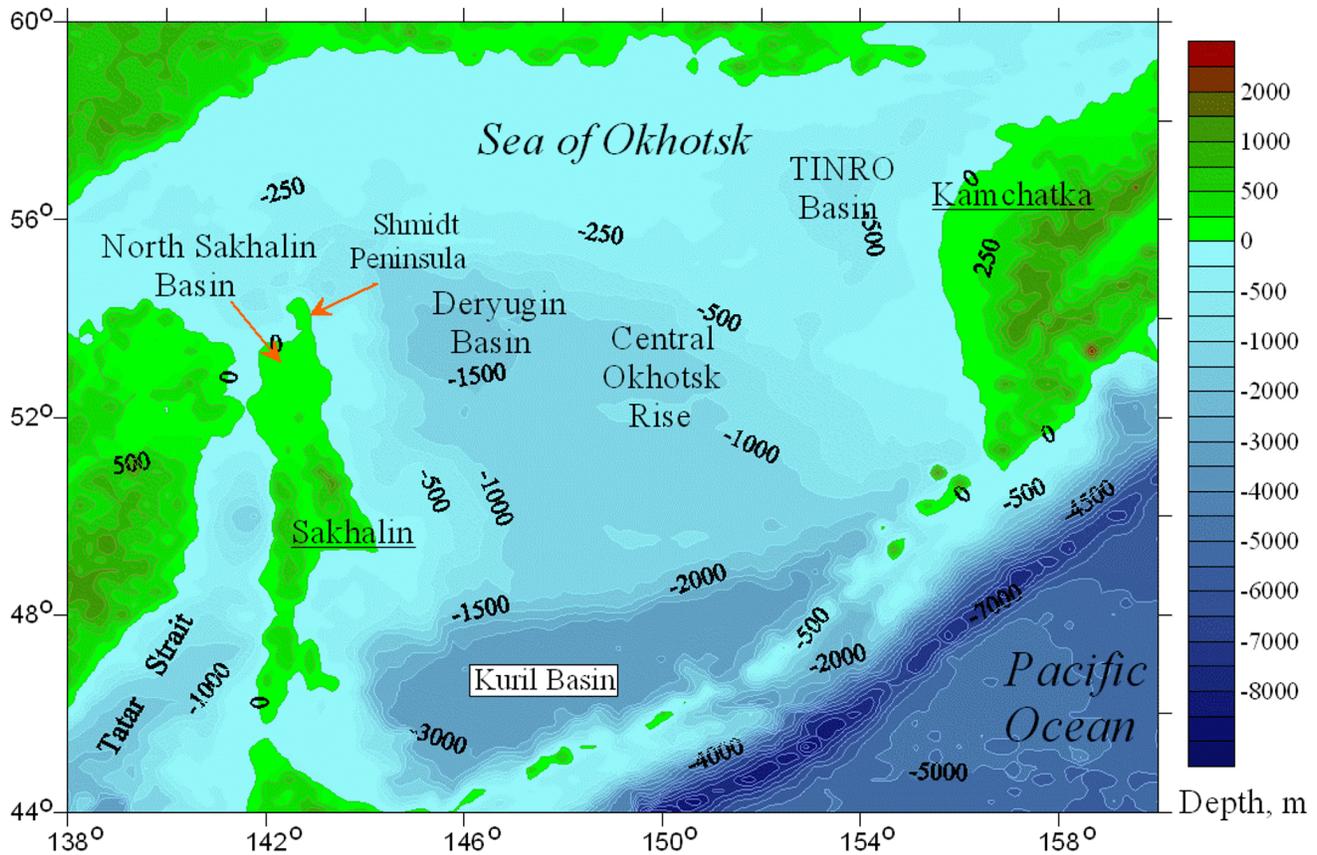


Figure 1. Map of the Sea of Okhotsk and adjacent areas showing the main geographical features.

structuring geodynamic models of active continental margins to study the deep structure of the earth's interior beneath seismically dangerous zones, volcanic structures, inorganic areas and sedimentary basins; revealing the role of deep processes going on in the mantle and specifically in the asthenosphere in the formation of major tectonic elements of continental margins and useful mineral formation.

[5] Geodynamic models of the deep structure of active continental margins are constructed as a result of combined interpretation of the total available geological and geophysical information on the basis of GIS technology. Geodynamic model construction was based on work carried out by the Geophysical Center RAS on the Geotraverse Project jointly with Japanese and Chinese scientists, on the data of the World Data Center for Solid Earth Physics and the results of new researches.

[6] The research in the deep structure of active continental margins of the Far East was conducted along a geotraverse compiled on the basis of combined interpretation of geological and geophysical data. The cross-section runs across the Mesozoic structures of Sikhote Alin, rift structure of Tatar Strait, Cenozoic formations of Sakhalin, Kuril Basin of the Sea of Okhotsk, volcanic structures of Kuril Island Arc, Kuril deep trench and the Mesozoic plate of Northwestern Basin of the Pacific (Figure 1). The length of the profile is 2000 km. The depth of penetration into the earth's interior is 100 km.

Data Used

[7] The research of the deep structure of active continental margins of the Far East is carried out on the basis of combined interpretation of geological and geophysical data. To construct geodynamic models of sedimentary basins we use the results of geological, seismic, petrological, geothermal, magnetic, electromagnetic and gravimetric research. Geophysical fields, the geological structure of sedimentary cover, the structure of the crust and the upper mantle, location of deep faults, volcanoes and their magmatic centers, distribution of earthquake foci, depths of occurrence of the asthenosphere and diapirs, paleo and modern subduction zones, distribution of deep temperatures are shown in geodynamic models. To construct geological sections a great body of geological data were used including drilling and r/v voyages data summarized in papers [Biebow *et al.*, 2000; Bogdanov and Khain, 2000b; Filatova and Rodnikov, 2006; Obzhirov *et al.*, 1999; Rodnikov *et al.*, 1996, 2005; Sergeev, 2006]. Consolidated crust was constructed on the basis of seismic profiles made in different years. They were interpreted with the use of new methods, which gave additional information on the structure of the crust [Piip and Rodnikov, 2004]. Seismic waves velocities abruptly change in the Okhotsk Sea region from 7.8 km s^{-1} beneath island arcs and sedimen-

tary basins to 8.2 km s^{-1} beneath stable areas of the crust. The asthenosphere in the upper mantle is separated mostly from geothermal data [Rodnikov *et al.*, 1996]. The asthenosphere is a layer in the mantle where the matter is under temperature close to melting temperature and in this case the viscosity in it decreases, and under certain conditions, magmatic centers appear. The upper surface of the asthenosphere is assumed to be $1000\text{--}1200^\circ\text{C}$ that is the temperature of upper mantle rocks partial melting with consideration for deep fluids influence [Rodnikov *et al.*, 1996; Smirnov and Sugrobov, 1980]. The separation of the asthenosphere is corroborated by tomography research data [Bijwaard *et al.*, 1998] and seismic observations [Kosminskaya *et al.*, 1987; Rodnikov *et al.*, 1996]; electromagnetic research in the upper mantle separated high-conductivity layers, which suggests the existence of partially melting zone beneath sedimentary basins [Kaplun, 2002; Lyapishev *et al.*, 1987; Nikiforova *et al.*, 1980].

[8] **Tectonic position.** The Okhotsk Sea region forms a lithosphere plate located between North American, Eurasian and Pacific plates (Figure 2).

[9] The Okhotsk Sea plate is bounded by deep faults, for the major part strike-slip faults, and in the southeast it is bounded by a recent subduction zone that is Benioff zone. Its basement is heterogeneous from crystalline the Paleozoic-Mesozoic revealed in the continent, in Sakhalin and Kamchatka to the Mesozoic-Cenozoic in water area of the Sea of Okhotsk [Rodnikov *et al.*, 1996]. The plate was finally formed in the Late Cretaceous and it was overlapped with a cover of sedimentary and volcanogenic sedimentary rocks in the Cenozoic. The thickness of the crust is approximately 28–32 km decreasing to 24 km in the Deryugin Basin and to 15 km beneath the Kuril Basin.

[10] The Okhotsk Sea plate belongs to intensely deformed structures from geological and geophysical data and the results of analysis of the recent crustal movements. The origin of the plate structure is determined by general geodynamic settings which were formed by the end of the Paleocene [Filatova and Rodnikov, 2006], and in this case according to [Gatinskiy and Rundkvist, 2004; Gatinskiy *et al.*, 2005], the directions of horizontal displacement vectors in general agrees with the assumption that the range of velocities measured experimentally is related to the Pacific plate effects. But it is likely that to some extent, the deformation of the Okhotsk Sea plate structures was also caused by Eurasian continent moving eastwards with Baikal rift development [Tamaki and Honza, 1985]. Structural dislocations inside the plate may be related to extensions in the Kuril Basin, Tatar Strait and Deryugin Basin caused by upwelling of asthenosphere diapirs, which reached their peaks in the Miocene.

[11] Sedimentary basins were formed in the conditions of the Okhotsk Sea crust destruction caused by rifting in the Cenozoic. It is assumed that extensional conditions started in the Paleocene but they were manifested most intensely in the Late Oligocene – Middle Miocene, which resulted in the formation of grabens, semi-grabens and pull-apart deep basins with oceanic and thin sub-continental crust [Rodnikov *et al.*, 1996]. In the Late Miocene and Pliocene, compression

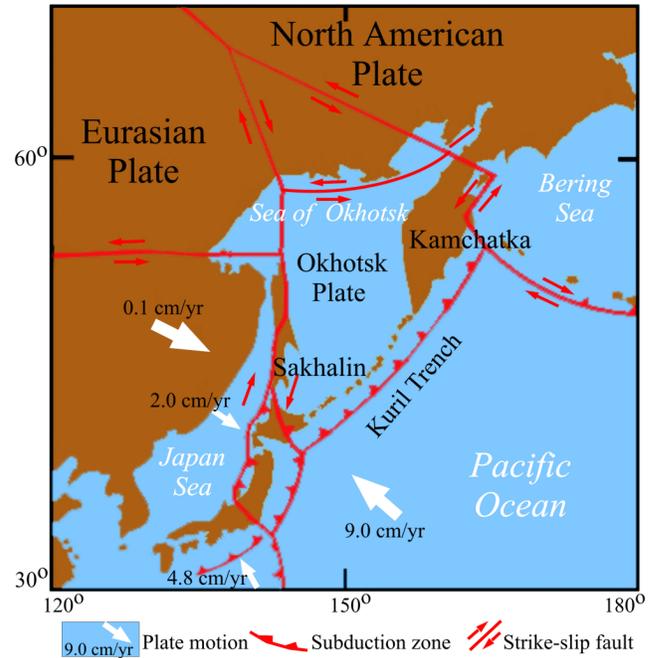


Figure 2. Tectonic sketch map of the Okhotsk Sea region. 1 – velocity of plate movement from GPS data; 2 – subduction zones; 3 – faults [Biebow *et al.*, 2000; Kiratzi and Papazachos, 1996; Maruyama *et al.*, 1997; Rodnikov *et al.*, 2001].

conditions were activated, which resulted in the formation of reversed faults, strike-slip faults and thrusts [Biebow *et al.*, 2000].

[12] **Heat flow.** The distribution of heat flow values along the geotraverse is taken from the global heat flow catalog [Pollack *et al.*, 1991] and heat flow maps [Smirnov, 1986; Smirnov and Sugrobov, 1980; Tuezov, 1988]. It is high in the deep basins and troughs of marginal seas and relatively low in the continental structures of the Far East and Kuril area of the Pacific (Figure 3).

[13] Heat flow variations in Sikhote Alin only make 39–56 mW m^{-2} . In Kuril area of the Pacific, the heat flow mean values are 52 mW m^{-2} . The lowest values, which make 22 mW m^{-2} , are noted in deep Kuril-Kamchatka trench. The heat flow mean values for the Kuril Island Arc are 118 mW m^{-2} and the highest values reaching 790 mW m^{-2} are noted in the western part of the island arc. Heat flow mean values in Sakhalin amount to 76 mW m^{-2} . High heat flow is noted in Tatar Strait (123–132 mW m^{-2}) and in the Deryugin Basin where it reaches 200 mW m^{-2} . Besides, high heat flow values are established in the Kuril Basin of the Sea of Okhotsk, where it reaches 346–354 mW m^{-2} [Rodnikov *et al.*, 1996].

[14] **Magnetic field** (Figure 4). Anomalous magnetic field of the Okhotsk Sea region is characterized by various orientation of anomalies extension and different configurations and values of the anomalies [Rodnikov *et al.*, 1996].

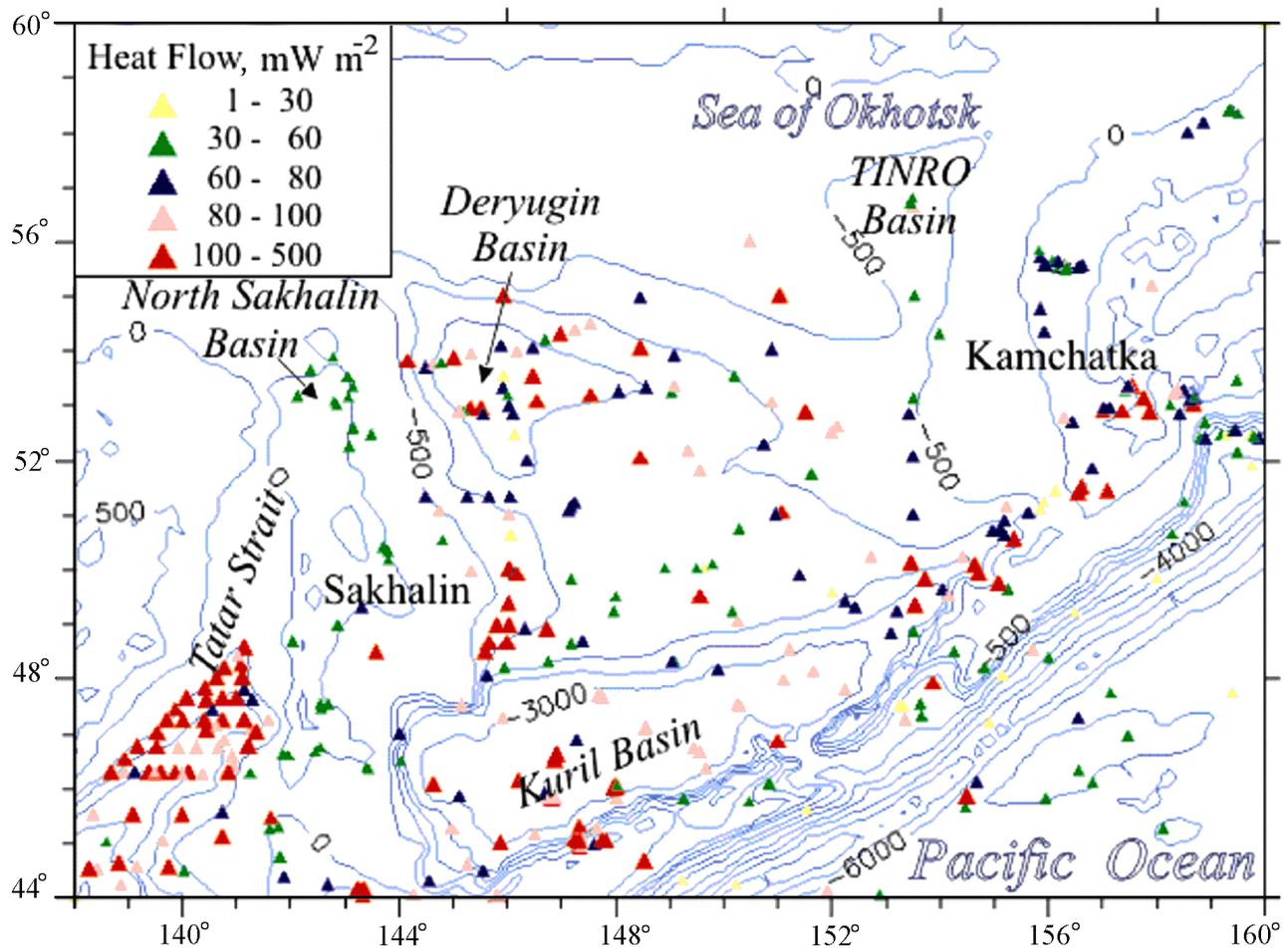


Figure 3. Spatial distribution of heat flow measuring points (mW m^{-2}) in the Okhotsk Sea region [Pollak *et al.*, 1991; Smirnov, 1986].

[15] Magnetic field anomalies for the major part show linear northwestward and northeastward extension. Magnetic field of Sikhote Alin is characterized by positive anomalies extended along deep faults and reaching values from 300 to 600 nT, which are related to magmatic body masses. In Tatar Strait, a chain of individual maximums is distinguished, which approximately coincide with the axis of greatest depths of the strait. Generally, in Sakhalin, negative magnetic field is noted. Individual positive linear anomalies are related to intrusive and effusive basic and ultra-basic bodies. Along eastern Sakhalin in the Sea of Okhotsk, the East Sakhalin positive magnetic anomaly extends, which reaches values of 1200–1400 nT. This anomaly locates in the East Sakhalin ophiolite belt where ultrabasic and basic rocks are exposed in Schmidt Peninsular and in East Sakhalin mountains. This belt separates North Sakhalin from the Deryugin Basin. The Deryugin Basin and Kuril Basin are characterized by weak negative anomalies with the amplitude of -200 nT, which are related to nonmagnetic sedimentary rocks composing the basins. The anomalies are

isometric. Nearer to the islands, they assume linear character.

[16] Going toward Kuril Islands the magnetic field becomes differentiated and varies from -300 nT to $+400$ nT. Volcanic arc corresponds to a narrow zone of disturbed magnetic field with local positive and negative anomalies of individual volcanic constructions superimposing the general negative horizontal background [Gainanov *et al.*, 1968]. Local positive anomalies and negative anomalies commonly associated with them are confined to submarine volcanoes. The span of the anomalies is often more than 1000 nT [Pushcharovskii, 1992]. Northwest extension of the magnetic field anomalies is associated with deep faults breaking the Kuril Island Arc into separate blocks [Rodnikov *et al.*, 1996].

[17] In the Northwest Pacific Basin abutting the Kuril Island Arc, the systems of linear magnetic anomalies were revealed of the age ranging from 108 million years to 160 million years [Hilde *et al.*, 1977]. The anomalies of the continental slope of the deep-sea trench have the general northeastern extension, which is disturbed by transverse anomalous

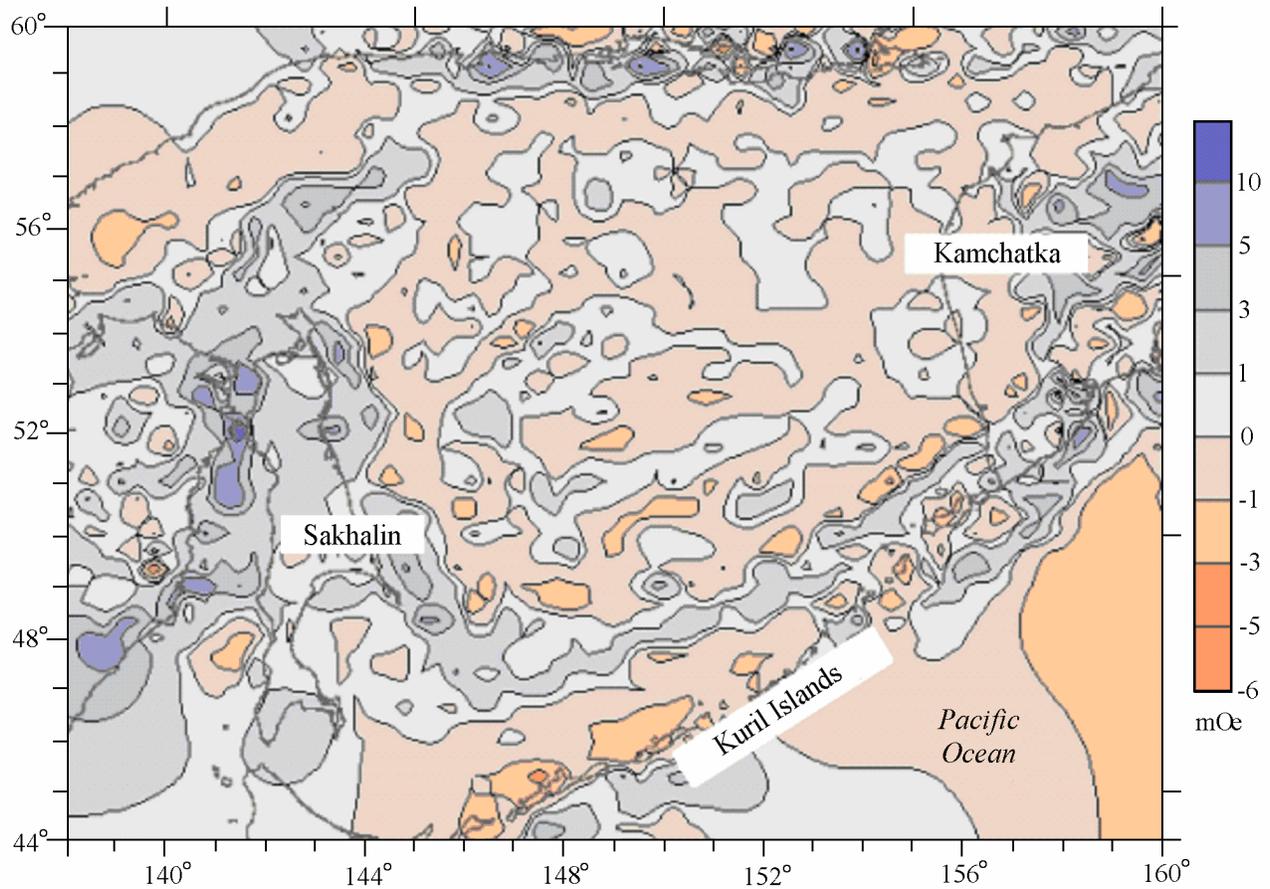


Figure 4. Map of anomalous magnetic field of the Okhotsk Sea region [Makarova, 1977; Racey et al., 1996].

zones. In the southern area of the trench slope, the linear northeastern anomalies parallel to the trench axis look as if they continue band anomalies of the Pacific plate but are less distinct [Sergeyev and Krasnyi, 1987].

[18] **Electromagnetic research.** The results of magnetic telluric sounding in Sikhote Alin [Kaplun, 2002; Nikiforova et al., 1980] showed that the lithosphere thickness beneath Sikhote Alin structures makes 100–120 km. In the west, it increases up to 220 km. Beneath Sakhalin, electric conduction layer in the upper mantle is located at depths of 80–90 km subsiding down to 120 km toward the west shore of the island [Vanyan and Shilovskiy, 1983]. Under the western area of Tatar Strait immediately beneath the volcanogenic belt, Sikhote Alin continental structures are likely to be in contact with transition zone structures from magnetotelluric observation data. In the crust of Sakhalin, a conduction layer is established as well, which is at a depth of 15 km and has total longitudinal conductivity of approximately 40 S [Vanyan and Shilovskiy, 1983].

[19] In the Kuril Basin of the Sea of Okhotsk along the geotransverse, electromagnetic research was conducted with the use of gradient magnetic variation sounding [Lyapishev et al., 1987]. According to the geoelectrical model selected, a layer of specific conductivity of $0.3\text{--}0.5\text{ S m}^{-1}$ and inte-

gral conductivity of approximately 15,000 S was separated in the depth range from 30 to 65 km in the upper mantle. The nature of the layer is associated with partial melting and its occurrence is confined to the basin. At a depth of more than 100 km, one more conduction layer may be distinguished [Lyapishev et al., 1987]. The obtained results are in agreement with deep temperatures in the upper mantle, seismic and other geophysical data.

[20] Beneath Iturup Island of the Greater Kuril Ridge the depth up to electric conduction layer amounts to 100–130 km and beneath Shikotan Island of the Lesser Kuril Ridge it is 75–80 km [Rodnikov et al., 1996]. From data of [Alperovich et al., 1978] the depth down to electric conduction layer beneath Iturup Island is 60–80 km.

[21] **Gravitational field** (Figure 5). Gravitational field of the Sea of Okhotsk shows medium values of free-air anomalies. Gravitational field is characterized by dramatically contrasting structure in the area of modern subduction zone and relatively even changes in other areas. In the northern Okhotsk Sea positive gravitational anomalies prevail. The largest values of anomalies (up to +50 mGal) are associated with basic rocks exposed on the Akademii Nauk uprise. A narrow minimum of anomalies is located to the north of the elevation, separating it from the Insti-

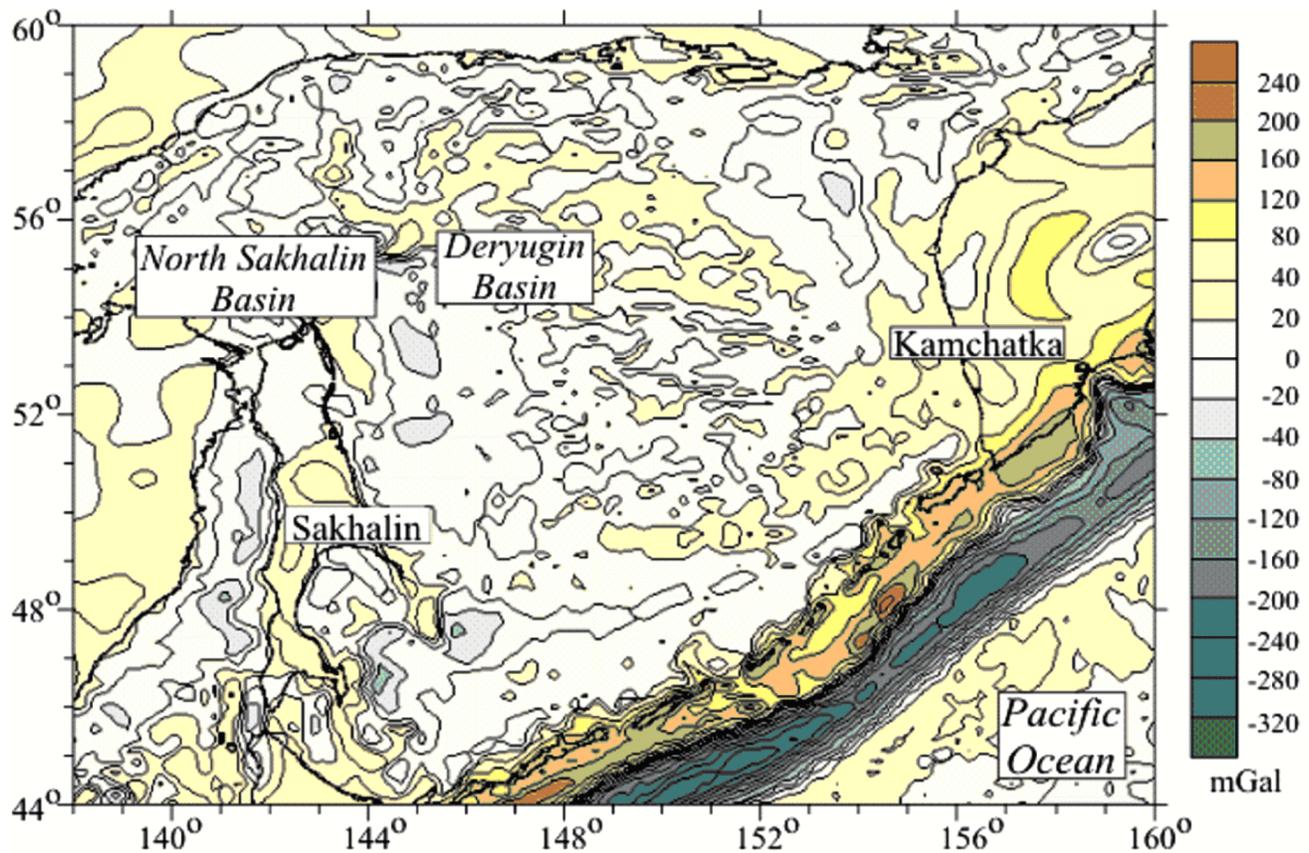


Figure 5. Map of gravitation field (free-air anomalies) of the Okhotsk Sea region [Sandwell and Smith, 1997].

tuta Okeanologii uprise. Weakly anomalous gravitational field characterizes the Kuril Basin, for the major part, but in the northeast a positive anomaly up to 25 mGal was discovered [Baldyrev *et al.*, 1993; Rodnikov *et al.*, 1996]. Positive values of anomalies (up to 20–30 mGal) characterize a narrow zone extending along East Sakhalin and showing ophiolite belt (Mesozoic subduction zone); in the Deryugin deep basin, negative values of anomalies are noted, which is typical of deep trenches. Seismic focal zone identified as subsiding oceanic plate has increased density. Decreased density is noted beneath the Kuril Island Arc. In geoid heights map, the transition zone region under investigation is located in the area of positive values of geoid heights reaching 20 m in the Sea of Okhotsk and bounded by negative values from continental and oceanic sides [Sandwell and Smith, 1997].

[22] **Seismicity.** The location of the Okhotsk Sea plate in the contact zone of three lithospheric plates (Eurasian, North American and Pacific) caused high seismicity in its margins (Figure 6).

[23] In the active continental margin of the Far East a large number of earthquakes commonly occur. It accounts for eighty percent of the total energy of earthquakes in North Eurasia [Yunga and Rogozhin, 2000]. The largest earthquakes that occurred in the last 10 years are Shikotan earthquake in southern Kurils of 1994 (magnitude $M=8.4$ and

the source depth is approximately 65 km), Neftegorsk earthquake in Sakhalin of 1995 ($M=7$) and Kronotskoe in eastern Kamchatka of 1997 ($M=7.9$).

[24] The highest seismic activity is noted along the Kuril Island Arc. There the Pacific plate subducts under the continent, forming a seismofocal zone, which is traced to the depth of 700 km. In the west, the Okhotsk Sea plate is bounded by deep faults extending along Sakhalin. There the earthquakes for the major part are localized in the crust. In the Kuril Island Arc the majority of earthquakes are confined to depth up to 100–150 km and seismic activity maximum is at depths of approximately 30–40 km [Tarakanov, 1978]. At depths greater than 100–150 km seismic activity abruptly decreases, and a sharp fracture of focal surface is noted at depths of 200–300 km. Sakhalin seismicity is associated with sub-meridian deep faults [Rodnikov *et al.*, 1996] bounding the Okhotsk Sea lithospheric plate and separating it from the Eurasian plate. Plate movements relative to each other as well as spreading processes going on in the rift structure of Tatar Strait cause active seismicity. Earthquakes distribution along the geotraverse is shown in Figure 7.

[25] **Volcanism.** The Kuril Island Arc is an area of intense recent volcanism manifestations. Different authors distinguish from 68 to 160 surface volcanoes [Aprodov, 1982; Fedorchenko *et al.*, 1989; Gorshkov, 1967; Pushcharovskiy,

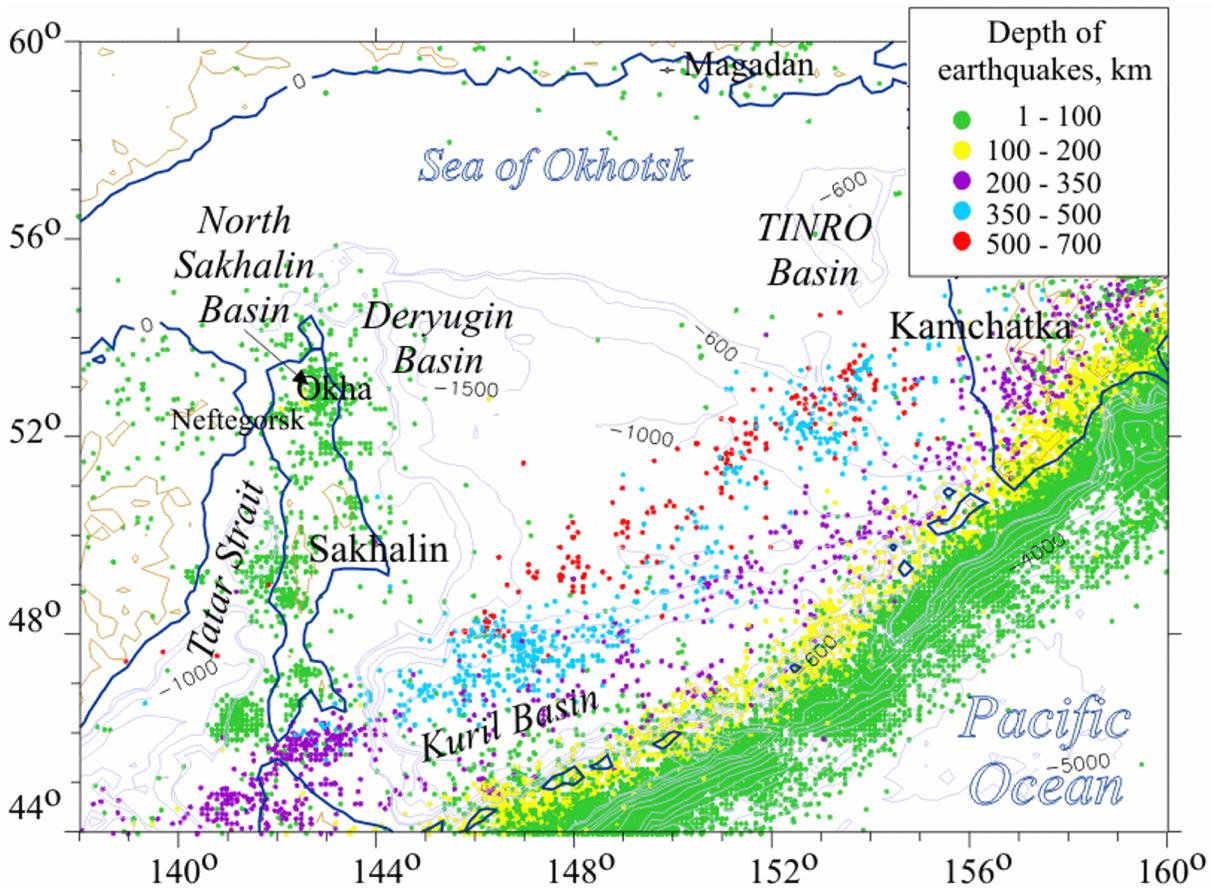


Figure 6. Spatial distribution of earthquakes in the Okhotsk Sea region from data of NEIC US GS (<http://neic.usgs.gov/neis/epic/>).

1992]. Twenty-nine of them erupted in historic time and six are in solfataric stage [Fedorchenko *et al.*, 1989; Simkin and Siebert, 1994]. From different assessments, the number of submarine volcanoes varies from 96 to 104 [Bondarenko and Rashidov, 2004; Gorshkov, 1967; Pushcharovskiy, 1992; Rashidov and Bondarenko, 2003; Zatonskii *et al.*, 1961].

[26] In the opinion of V. A. Rashidov [Rashidov and Bondarenko, 2004], reliable data on submarine volcanic activity manifestations in this region are lacking although data of various catalogs are available [Gushchenko, 1979; Simkin and Siebert, 1994; and others].

[27] Both surface and submarine volcanoes form volcanic chains oriented at different angles to the general strike of the Kuril Island Arc. Surface and submarine volcanoes of the Kuril Island Arc are composed of rocks from basalt to rhyolite composition. Normal and sub-alkali rocks are separated ranging from low-potassium to high-potassium series. Low titanium and magnesia contents and high aluminum hydrate content are characteristic of the Kuril Island Arc lavas [Fedorchenko *et al.*, 1989; Pushcharovskiy, 1992].

[28] Forty submarine volcanoes and mountains of different age are located immediately in the geotraverse area [Bondarenko and Rashidov, 2004; Pushcharovskiy, 1992]; about 40 large surface volcanic constructions and more than 160

minor volcanic cones are situated in Iturup Island [Luchitskii, 1974], across which the deep section runs. Nineteen surface volcanoes are the Quaternary [Fedorchenko *et al.*, 1989] and in nine of them historic eruptions were noted beginning since 1778 [Gushchenko, 1979; Simkin and Siebert, 1994]. Among submarine volcanoes, we find both table mounts and point mounts. The former seem to be encompassing Iturup Island and the latter are at a distance from the island. Depths above table mounts increase with distance from the island, which may testify to subsidence of the island arc slope on the Okhotsk Sea side towards Kuril deep basin and may be related to its formation [Pushcharovskiy, 1992]. The structure of three volcanoes is discussed in the paper (Figure 8).

[29] Krylatka submarine volcano is located at 17 km to north-northwest of Przhivalskiy Cape of Iturup Island. It is noted that at the end of the last century this volcano was at the stage of gashydrothermal activity [Rashidov and Bondarenko, 2004]. It is a cone-shaped construction of sub-meridian extension with a flat top at a depth of 300 m. The dimensions of the top are 4.3×6.5 km and it is somewhat extended in sub-meridian direction (Figure 9). The volcanic structure is separated from Iturup Island with a neck of a depth of approximately 900 m. The steepness

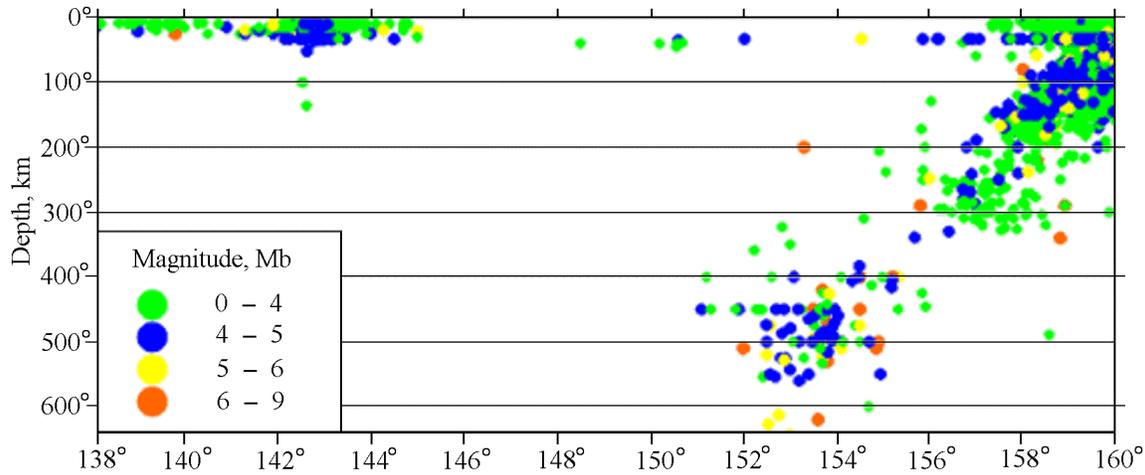


Figure 7. Section showing distribution of earthquake hypocenters in two-degree zone (profile coordinates: 53.0°N, 138.0°E; 53.0°N, 160.0°E).

of slopes increases from 15° in the lower part to 20–25° in the upper part [Pushcharovskiy, 1992; Rashidov and Bondarenko, 2004]. The basement of the structure in the north and west is covered with 700-meter thick sedimentary deposits of sub-horizontal bedding. In records of echo-sounder measurements in the center of Krylatka submarine volcano flat top, acoustic anomalies are noted in the water mass in the depth range of 210–250 m, which may be caused by gas-hydro-thermal activity. From dredging the volcano structure, basalts, andesite-basalt, andesite, dacite-andesite and rhyolite were revealed [Erokhov et al., 1975; Ostapenko et al., 1986; Pushcharovskiy, 1992]. Krylatka submarine volcano is located in the area of negative anomaly magnetic field (ΔT)_a.

[30] The base of the volcano is outlined by negative isolines of the anomalous magnetic field of intensity 100–130 nT. To the west, southwest and south of the near-top part of the structure positive local anomaly is located, which amounts to 96 nT, and to the east of the near-top part of the structure, local positive anomalies of intensity of 230 nT and 150 nT are noted. Above the near-top part of the structure a change is observed from smooth to high-frequency alternating anomalous field. High-frequency anomalous magnetic field may be caused by young lava flows [Babayants et al., 2005; Rashidov and Bondarenko, 2004]. Rocks composing the submarine volcano structure are magnetized in the direction of modern magnetic field. Effective magnetization of rocks corresponds to rocks of andesite-basalt series.

[31] Atsonupuri volcano (Figure 10) is situated in the southern Iturup to which it is linked with an isthmus of height of 30 m [Gorshkov, 1967]. It is a stratovolcano with the central cone in caldera. The base diameter at sea-level is about 6 km. Absolute height is 1205 m. The crater dimensions are 400×600 m and the depth is approximately 150 m [Aprodov, 1982; Gorshkov, 1967; Gushchenko, 1979]. In the eastern part of the cone a small area of flat atrio and remnants of soma crest are saved. The size of soma is approximately 2 km. The height of soma crest is 900 m. The elevation of the central cone above the soma is approxi-

mately 300 m [Aprodov, 1982; Gorshkov, 1967; Gushchenko, 1979].

[32] Berutarube volcano is located at the southern end of Iturup Island. It is a shield strato-volcano of a diameter of approximately 10–11 km superimposed on Neogene rocks. The absolute height of the volcano is 1222 m [Gorshkov, 1967]. On the top, a destroyed crater of a diameter of 2.5–3 km is located with truncated Holocene cone of the base diameter of about 1 km in it. Two lava flows are noted that erupted from the cone, and in its base in craters, solfataras are found [Aprodov, 1982; Gushchenko, 1979]. The volcano is composed of andesite-basalt [Fedorchenko et al., 1989].

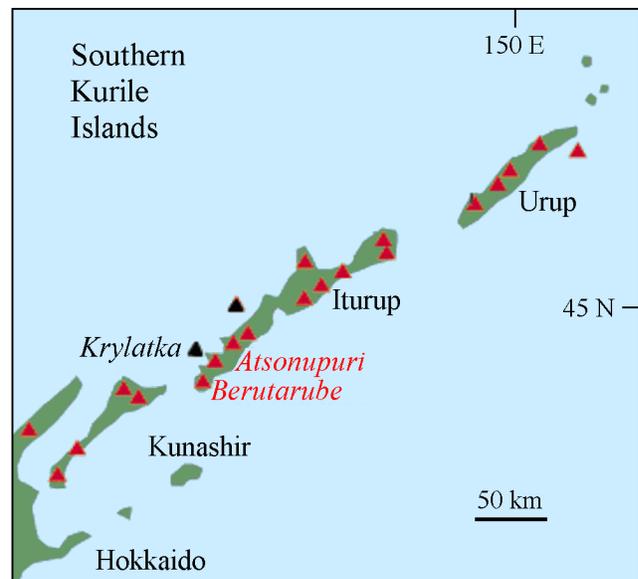


Figure 8. Volcanoes of the Kuril Islands. Red triangles indicate surface volcanoes and black triangles indicate submarine volcanoes.

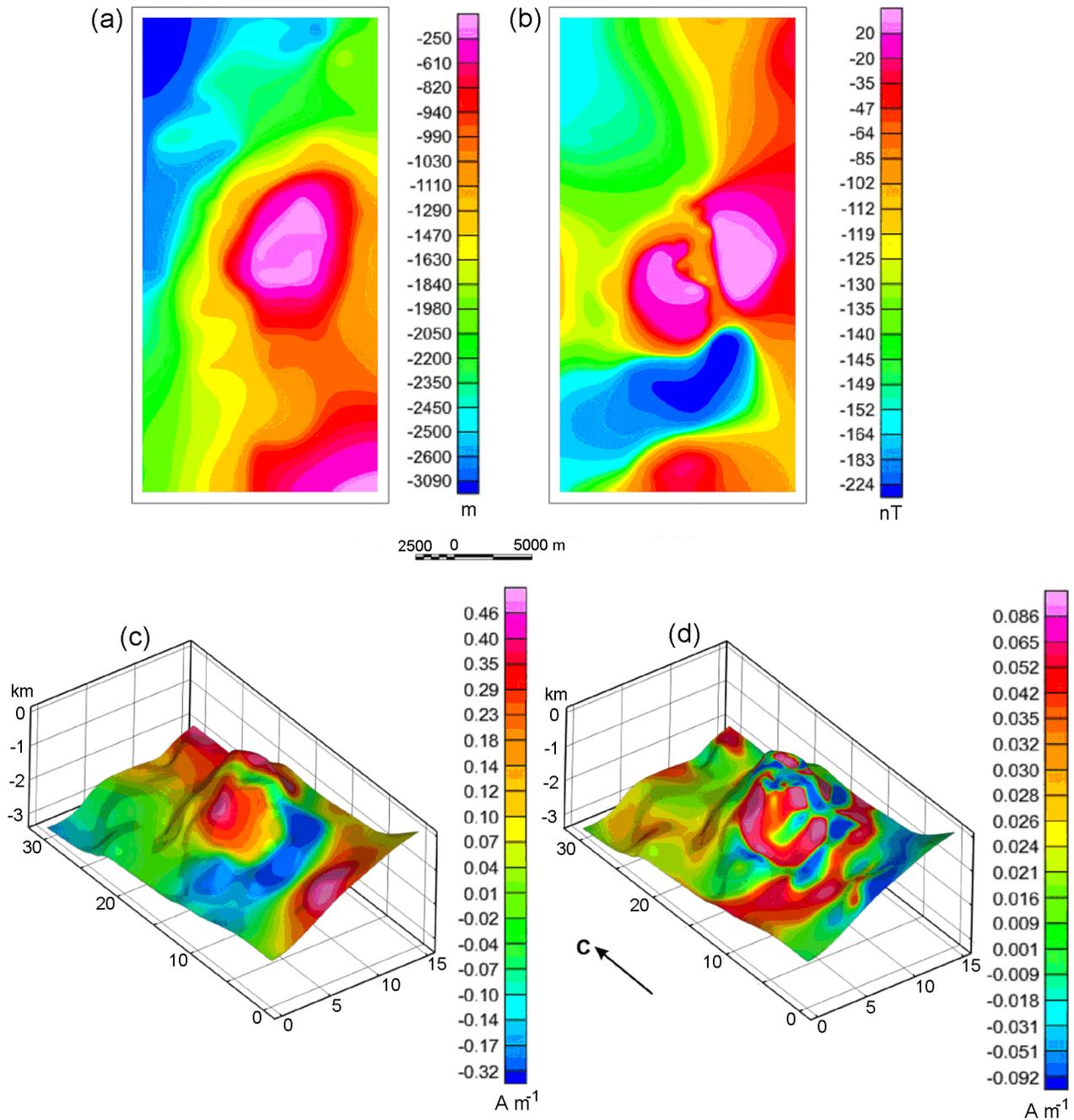


Figure 9. Krylatka submarine volcano: a – bathymetry; b – anomalous magnetic field (ΔT); c – distribution of effective magnetization of the volcano shown on the volcano surface; d – distribution of local effective magnetization of the volcano shown on the volcano surface [Babayants *et al.*, 2005].

Deep Structure

[33] The research in the deep structure was conducted along geotraverse constructed on the basis of combined interpretation of geological and geophysical data (Figure 11). The thickness of the crust in the Sea of Okhotsk varies from 35–40 km beneath Sakhalin and the Kuril Islands to 10 km

beneath the Kuril Basin. The crust is divided into the basement and sedimentary cover. The basement rocks are exposed in the framing of the Sea of Okhotsk in Sakhalin, Kamchatka, Shantarskie Islands and the Kuril Island Arc and were brought up from underwater elevations with dredge. The basement age ranges from the Paleozoic to the Mesozoic. The sedimentary basin comprises individual abysses where its thickness reaches 12 km. For the major part it is



Figure 10. Atsonupuri volcano. Photo by A. Rodnikov, 1963.

composed of sedimentary rocks and partially of volcanogenic sedimentary rocks of the Late Cretaceous–Cenozoic. In the Late Cretaceous, sedimentation went on in rifting-causing

conditions and was accompanied by considerable volcanic activity. Deep-sea basins were formed that were composed of volcanogenic-siliceous sediments gradually replaced with more shallow-water rocks up the section. In the Cenozoic, most of the sedimentary basins were formed. The deposits of those times as an unbroken cover overlapping the underlying formations contain almost all oil and gas complexes of the Sea of Okhotsk.

[34] **Sikhote Alin Region** being western continental framing of the Okhotsk Sea plate encompasses Middle Cretaceous orogenic belt of Sikhote Alin [Bogdanov and Khain, 2000a], which in the west abuts the ancient continental margin of Asia represented there by Bureinskiy and Khankaiskiy massifs (Figure 12).

[35] The orogenic belt of Sikhote Alin comprises rocks of different age (from the Paleozoic-Mesozoic to Neocomian) and of different origin (with predominant oceanic, marginal seas and island-arc complexes). All the formations were accreted to the eastern margin of Asian continent as a result of their dislocations on the shifts that accompanied transform boundary, which formed in the Middle Cretaceous between the Asian continent and Kula plate [Khanchuk, 2000; Natal'in et al., 1994; and others]. Middle Cretaceous orogeny,

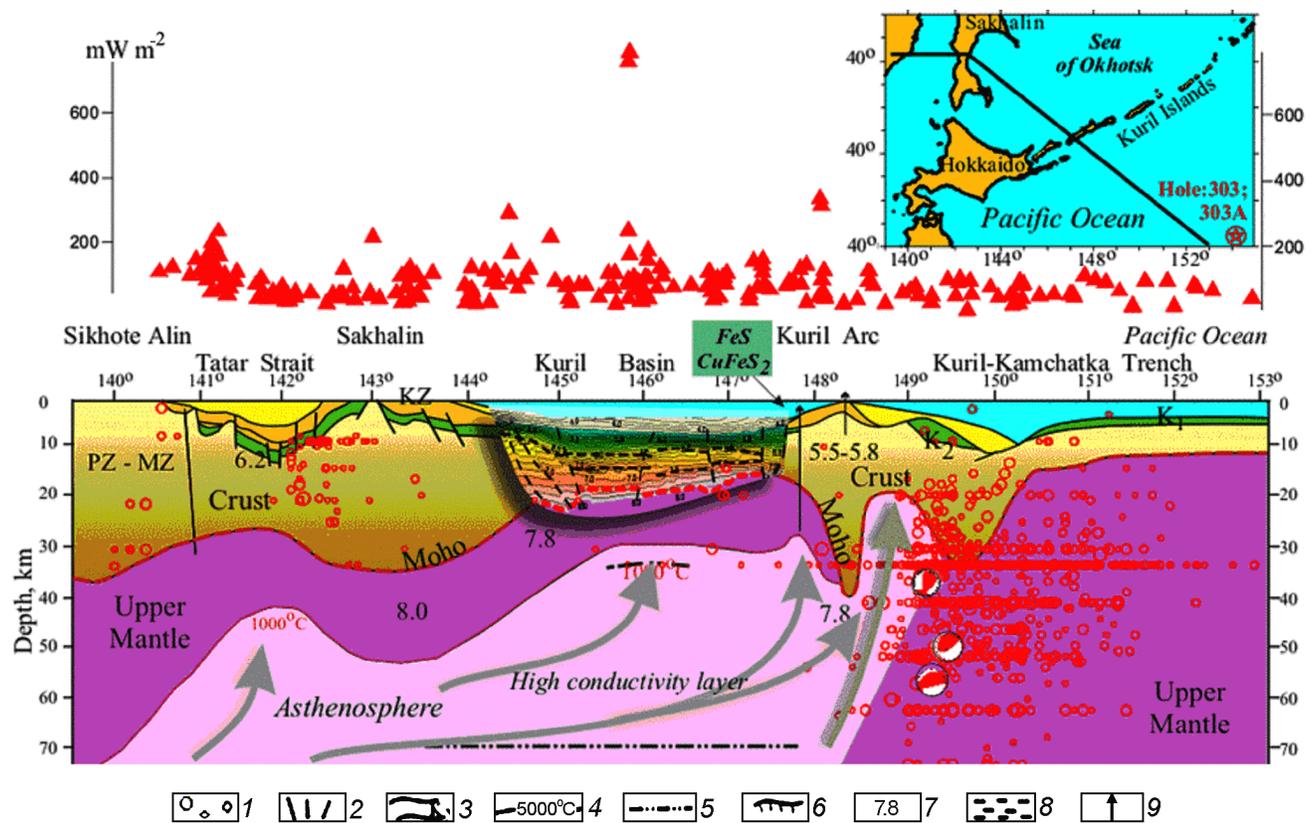


Figure 11. Geotraverse of the Okhotsk Sea region [Belousov and Udintsev, 1981; Bikenina et al., 1987; Bogdanov and Khain, 2000; Piip and Rodnikov, 2004; Rodnikov et al., 1996, 2001; Smirnov and Sugrobov, 1980; Zlobin, 1987]. At the right top the geotraverse position is shown. Below the distribution of measured values of the heat flow ($mW m^{-2}$) is shown along the profile. PZ – Paleozoic, MZ – Mesozoic, KZ – Cenozoic, K₂ – Upper Cretaceous. 1 – location of earthquake hypocenters; 2 – faults; 3 – geological layers; 4 – isotherm, °C; 5 – boundaries of high conductivity layer; 6 – Moho discontinuity; 7 – seismic velocities, $km s^{-1}$; 8 – water mass; 9 – volcanoes.

which was widely manifested in the periphery of the Pacific [Filatova, 1998], in Sikhote Alin manifested itself in the formation of complex scaly-thrust structures, shows of metamorphism and granite formation and in the appearance of strike-slip basins and magmatism. Middle Cretaceous accretion processes considerably enlarged the continent margin and increased its thickness almost up to 40 km.

[36] All those structures are overlapped by volcanic-plutonic associations of East Sikhote Alin sub-subduction belt, which marked the Asian continent edge in the Senomanian-Paleocene. Fragments of the oceanic plate of this belt that underwent subduction under the continent are now registered by seismic tomograph data at mantle depths as high-velocity objects [Bijwaard et al., 1998]. The Younger Cenozoic extension structures (including Tatar strait rift) upset the structures of continent margin and abutting perioceanic area formed before [Filatova, 2004] and are commonly accompanied by intense magmatic manifestations. Judging by heterogeneous composition of magmatic rocks, the latter are related to several levels of depth (lithospheric mantle, asthenosphere and lower mantle). In the East Sikhote Alin belt, magmatic activity went on from the Cretaceous until the Early Quaternary [Filatova, 1998]. The Paleogene-Quaternary basalt flows are the products of fissure eruptions; the thickness of basalt plateau sections reaches 800–1000 m. This effusive comprises tholeiites, sub-alkaline basalts and rocks of olivine-basalt series. Tholeiites are close to basalts of MORB type and apparently are associated with asthenospheric magmatic sources (Figure 13).

[37] The crust thickness varies from 30 km beneath volcanogenic belt to 38 km beneath Sikhote Alin [Rodnikov et al., 1996; Zverev and Tulina, 1971]. The results of magnetotelluric sounding in Sikhote Alin [Kaplun, 2002; Nikiforova et al., 1980] showed that electric conductivity layer considered as the asthenosphere is located in the upper mantle at a depth of approximately 100–120 km.

[38] The major part of Primor'e belongs to seismic zone of 5–6 intensity [Ulomov and Shumilina, 1999]. Several strong earthquakes with $M=6.0$ (1914), $M=5.6$ (1924), and $M=5.0$ (1968) were registered there that were associated with deep faults, along which terrains of different types forming Primor'e moved. Deep-focus earthquakes noted at depths in the range from 300 to 600 km are lower margins of two seismic focal zones the Kuril zone and Indzu Boninskaya zone subsiding under the continent.

[39] **Tatar Strait** (Figure 14) is a large rift structure, which is approximately 50-km wide and 4-km deep [Piip and Rodnikov, 2004]. It is composed of a thick bed up to 8–10 km of the Mesozoic-Cenozoic sedimentary formations [Khvedchuk, 1992; Tronov et al., 1987; Varnavskiy, 1994]. The rift is located between the Mesozoic structures of Sikhote Alin and West Sakhalin Mountains and is separated from them by deep faults. Sediments composing the trough from available geological and geophysical data are divided into four structural complexes separated from each other by regional stratigraphic disconformities and having different structural-compositional and physical characteristics: Upper Cretaceous, Paleogene, Oligocene-Lower Miocene and Middle Miocene-Quaternary. The trough basement is granite-metamorphic

layer with seismic boundary velocities in the range of 5.8–6.2 km s⁻¹ [Gnibidenko et al., 1995].

[40] The earth's crust is broken by faults. Recent tectonic activity is emphasized by high heat flow, magmatic activity and seismic manifestations. In this context, the thickness of the crust is lowered as compared to the bordering areas and decreases to 25 km, and velocities in M -boundary make 7.4–7.6 km s⁻¹. Deep faults revealed with the use of deep seismic sounding are corroborated by geological data. Thus in the area of West Sakhalin fault bordering Tatar Strait in the east, the Cenozoic sediments steeply tilt westwards (up to 50–80°) as compared to the rest of the trough and are intensely dislocated by faults and reversed faults. Displacements on faults vary within tens and hundreds of meters, reaching 4–5 km. Volcanic centers of the Lower and Upper Miocene and Pliocene are confined to the fault zone. Increased seismic activity and permeability (fluid conductivity) are characteristic of the faults [Rodnikov et al., 1996]. Calculations of deep temperatures showed that the sedimentary trough is associated with the rise of hot asthenospheric diapir causing the splitting of the earth's crust, rift structures formation in the trough basement, magmatic activity manifestations and sedimentary bed heating. The asthenospheric diapir may have been an additional source of hydrocarbons and fluidal flows providing intense hydrothermal activity and contributing to oil and gas deposits formation [Rodnikov et al., 2001]. The formation of Tatar Strait rift structure is associated with the upwelling of the asthenosphere to the earth's crust [Rodnikov, 1997]. The rift is the northern continuation of the spreading center located in the abyssal basin of the Sea of Japan, which was revealed from the studies of magnetic field anomalies profiles of the Sea of Japan [Isezaki et al., 1976]. It is believed that spreading processes went on there 15–25 million years ago and were accompanied by basalt lavas eruptions [Maruyama et al., 1997; Jolivet et al., 1995]. In the middle of the Oligocene the processes of the earth's crust extension started and in the Miocene they finished in Tatar Strait as a result of rift formation accompanied by area basalt volcanism manifested in Moneronskiy rise located in the central part of Tatar Strait. The chemical composition of effusive shows that the effusive belongs to tholeiitic and alkali olivine-basalt type [Piskunov, 1977]. Moneronskoe earthquake that occurred in Tatar Strait in 1971 is characterized by upthrust motions [Arefiev, 2003]. Earthquake hypocenters depth was on the average in the range from 5 to 20 km [Zlobin, 2005].

[41] In Figure 15 the deep structure of the lithosphere is shown beneath the sedimentary trough of Tatar Strait where Izylnmetievskoe gas field was discovered. Increased heat flow, magmatic activity and sedimentary bed heating caused by asthenospheric upwelling became an additional source of hydrocarbons and fluidal flows fostering hydrocarbon deposits formation in the sedimentary beds of Tatar Rift.

[42] **Sakhalin Island** is a fragment of Asian continental margin separated from it by the Cenozoic rift structure of Tatar Strait. In this context, the Paleozoic and Mesozoic – Early Paleogene structures can be followed in the island, which are abundant in Sikhote Alin, though they are considerably dislocated there by a system of faults drawn together

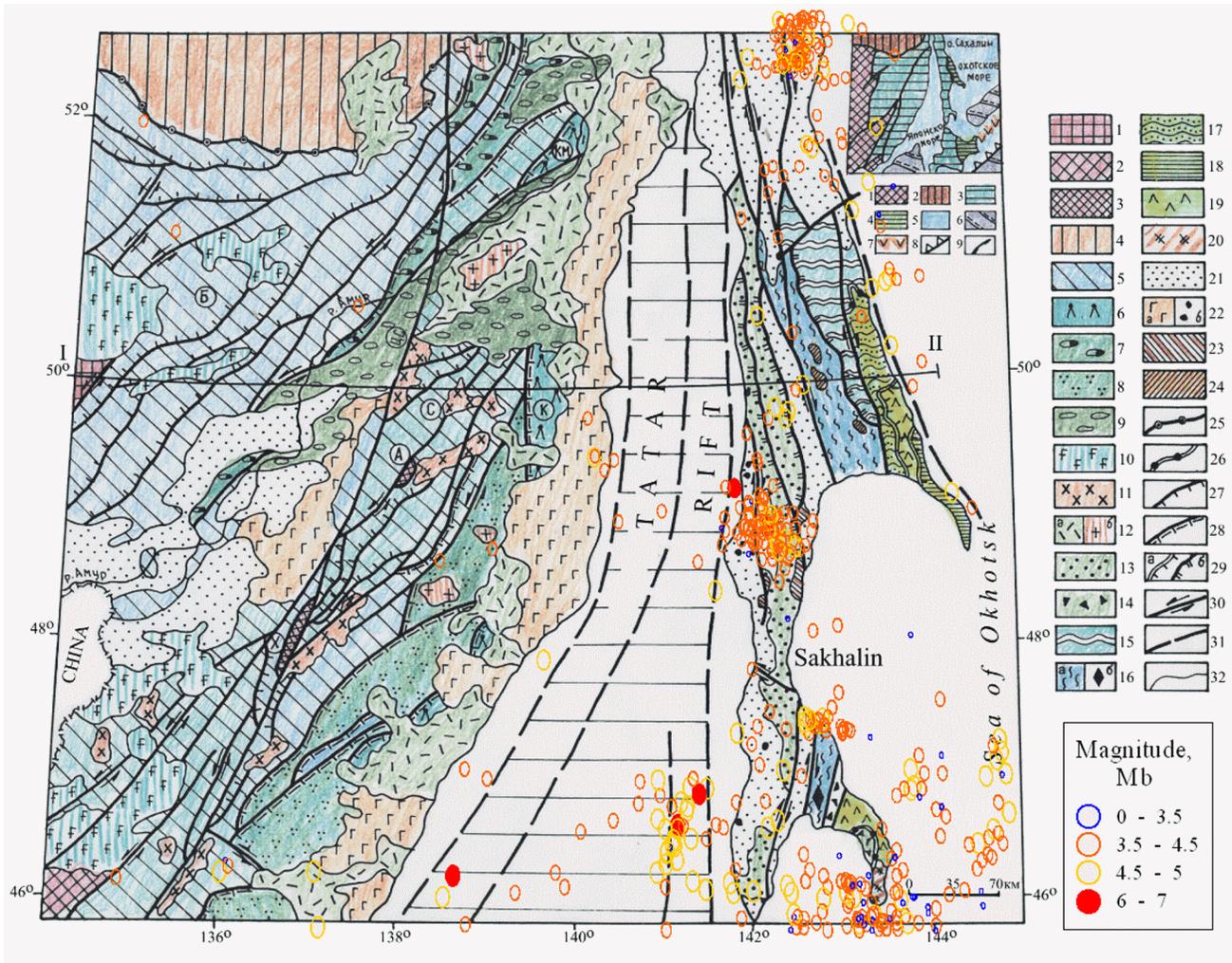


Figure 12. The scheme of tectonic structure of the Sikhote Alin region. 1–2 – continental micro plates: 1 – Bureinskaya, 2 – Khankaiskaya; 3 – blocks of presumed continental crust (Kh – Khorskii, A – Aniuiskii); 4 – Mongol-Okhotskii Paleozoic-Early Mesozoic orogenic belt (including Jurassic post-collision superimposed turbidite basins); 5–11 – Sikhote Alin-Sakhalin Middle Cretaceous orogenic belt: 5 – thrust nappe structures with tectonic coincidence of Paleozoic, Triassic, Jurassic and Neocomian oceanic, marginal-sea and island-arc structures that underwent local Paleozoic, Early Triassic and Middle Cretaceous amphibolite and green-shale matamorphism and granitization. (zones: B – Badzhalskaya, S – Samarkinskaya), 6 – Lower Cretaceous island-arc formations (zones: KM – Kiselevsko-Manominskaya, K – Kemsкая), 7–11 – strike slip Late Hauterivian–Early Cenomanian formations of the final stage of Middle Cretaceous orogenesis (collision-transform settings) 7–8 – Hauterivian–Middle Albian terrigenous structures of grabens and pull-apart basins: 7 – olistostrome and turbidite; 8 – turbidite, mainly arkose (Zhuravlevskii basin), 9 – Albian-Early Cenomanian terrigenous deposits, 10 – Aptian-Senomanian surface vulcanite (calc-alkali and alkaline series), 11 – Middle Cretaceous Khungariiskii collision granitoid complex; 12–14 – Sikhote Alin Cenomanian-Paleocene above-subduction continent-margin volcanic-plutonic belt: 12 – volcanogenic rocks (a) and intrusive rocks (b), 13 – Cenomanian-Paleocene turbidite of fore-arc trough, 14 – terrigenous-olistostromatic formations of the accretion prism of the inner part of the trench, 15 – tectonically combined Cenomanian-Turonian turbidite-olistostromatic formations of accretion prism and Jurassic-Lower Cretaceous oceanic formations considerably metamorphosed; 16 – metamorphic rocks (glaucophane schist, amphibolite) by oceanic rocks for the major part of Jurassic-Cretaceous (a), eclogite (b); 17–20 – East Sakhalin Middle Eocene orogenic belt: 17 – Campanian-Paleocene oceanic formations, 18 – Campanian-Paleocene oceanic and sea-margin un rugged formations, 19 – Campanian-Paleocene island-arc formations, 20 – Middle Eocene-Early Oligocene collision granitoid; 21–24 – Paleogene-Quaternary formations (settings of transform boundary of continental and oceanic plates): 21 – Late Paleogene-Quaternary terrigenous deposits in grabens and pull-apart basins, ⇒

← 22 – Eocene-Quaternary basalt locally bimodal and differentiated associations of vulcanite of alkali, tholeiitic and calc-alkali series (a), outcrops of those rocks regardless of scale (b), 23–24 – granitoid in zones of amphibolite metamorphism: 23 – Early Miocene, 24 – Late Paleocene-Eocene; 25–26 – collision sutures: 25 – Early-Middle Mesozoic, 26 – Middle Eocene; 27–29 – thrusts: 27 – Paleozoic-Mesozoic unrugged, 28 – Late Albian-Early Cenomanian, 29 – Middle Eocene (a) and Middle Miocene-Quaternary (b); 30 – faults (main faults are thickened), CS – Central Sikhote Alin shift; 31 – faults from geophysical data (for the major part shifts and faults); 32 – stratigraphic and intrusion boundary. Line I–II – geological profile (see Figure 13).

and having north-south extension. The western Sakhalin is occupied by thick (up to 10 km) the Cretaceous-Paleogene turbidites of the fore-arc trough of East Sikhote Alin magmatic belt and under it basement rocks like intensely dislocated the Jurassic-Neocomian and Paleozoic oceanic formations are buried. To the east those rocks of ancient oceanic plates, which underwent intense greenschist, glaucophanitic and locally eclogitic metamorphism, form the sublongitudinal zone bounded by faults of East Sakhalin mountains from where it can be followed to the south of Sakhalin Island to Susunaiskaya zone and farther to Kamuikotan zone of Hokkaido Island. The extreme east of Sakhalin Island is occupied by fragments of the Campanian-Paleocene island arc and they together with fragments of the Cretaceous oceanic plate are thrust on Sakhalin structures from the Okhotsk Sea plate. Basites-ultrabasites participating in the scaly-thrust structures and separated from the Cretaceous oceanic crust (earlier had belonged to the Okhotsk Sea plate), apparently create the linear magnetic anomaly along the eastern shoreline of Sakhalin Island. These ultrabasic rocks are apparently remnants of the Late Cretaceous–Early Paleogene zones of subduction. In deep seismic sounding profiles, listric faults sloping approximately at an angle of 15° are prominent that penetrate into the upper mantle from the sedimentary cover; discontinuities are noted in M -boundary and thickness variation of the upper layer of the crust and blocks of crust with high values of seismic velocities are noted [Piip and Rodnikov, 2004].

[43] The thickness of the earth's crust makes up 30–35 km. Velocities on M -boundary vary from 7.8 to 8.3 km s⁻¹. In Sakhalin, earthquakes are confined to the earth's crust and are related to deep faults extending along the whole island and serving boundaries of lithospheric plates. Geodetic observations of 1975–1983 showed regularities of horizontal movements in the zone of Central Sakhalin deep fault [Vasilenko and Bogdanov, 1986]. It was established that in 1975–1978 a right-lateral shift had been observed on the fault that had been replaced by compression by 1979. Subsequently in 1979–1980 in the fault zone expansion was observed that was replaced by attenuation in 1980–1983 [Vasilenko and Bogdanov, 1986]. Generally in Sakhalin, migration is noted of strong earthquakes sources from east to west and directed upwards from great depths to the surface [Zlobin, 2005]. Mud volcanoes eruptions are confined to deep faults as well [Melnikov et al., 2005].

[44] **Kuril Basin** of the Sea of Okhotsk belongs to back-arc depressions. In plan, it has a form of wedge narrowing northwards. It is outlined by isobath of 3000 m,

the average depths in the test site under investigation are 3200 m. Thick (more than 4000 m) sedimentary beds overlie “acoustic basement”, which evidently is a volcanogenic-sedimentary layer, and beneath it, the third layer of oceanic crust is observed with seismic velocities 6.4–6.8 km s⁻¹ and thickness of 5 km in the middle of the basin. High heat flow is characteristic of the basin [Smirnov and Sugrobov, 1980]. “The acoustic basement” is intensely rugged; scarps associated with faults are abundant on the slopes. From data obtained with the use of reflected wave method [Snegovskoi, 1974] the sedimentary cover is subdivided into two sedimentary complexes. The upper one, which is likely of Pliocene-Quaternary age, with thickness in the range from 800 m to 1000 m is characterized by thin layering. Sediments of the lower complex in the central part of the basin have thickness more than 3000 m and make transparent acoustic layer.

[45] Subsequent seismic research showed that seismic velocities range from 1.7 to 4.3 km s⁻¹ for sedimentary bed of thickness of approximately 5 km. It is underlain by a layer of thickness of 2.0–2.8 km with velocities of 4.8–5.2 km s⁻¹, which is apparently volcanogenic-sedimentary section of the oceanic crust [Baranov et al., 2002]. A layer with velocities 6.4–7.2 km s⁻¹ and thickness 4–5 km is located below; some researchers correlate it with oceanic layer 3 [Baranov et al., 2002]. M -boundary is noted at the depth of 11–13 km [Galperin and Kosminskaya, 1964]. Data on the basement composition and age are lacking. Insufficient data are only available on the basement structure in the basin edges. Samples dredged up from Akademii Nauk Elevation showed that the northern slope of the Kuril Basin is composed of magmatic rocks of calc-alkali series. K-Ar method testifies to their Cretaceous age [Gnibidenko et al., 1995]. According to [Baranov et al., 1999], isotopic analysis Sr-Nd-Pb of volcanic rocks testifies to the effect that the basement may be a thinned continental crust. Mean velocity of subsidence in the Pliocene-Quaternary apparently associated with back-arc basin extension ranges from 0.5 to 2.0 mm year⁻¹ [Baranov et al., 2002].

[46] Geophysical research of the basement shows that it is complicated with a number of dislocations with a break in continuity revealed in near-border areas and individual ledges of the basement that are commonly isometric in plan and conic in vertical section. Sediments overlap them and evidently they are buried volcanic constructions [Tuezov, 1975]. It is corroborated by characteristics of the magnetic and gravitational field anomalies [Krasnyi, 1990]. Rocks of “acoustic basement” are apparently composed of basic volcanics (basalts and their tuffs) alternat-

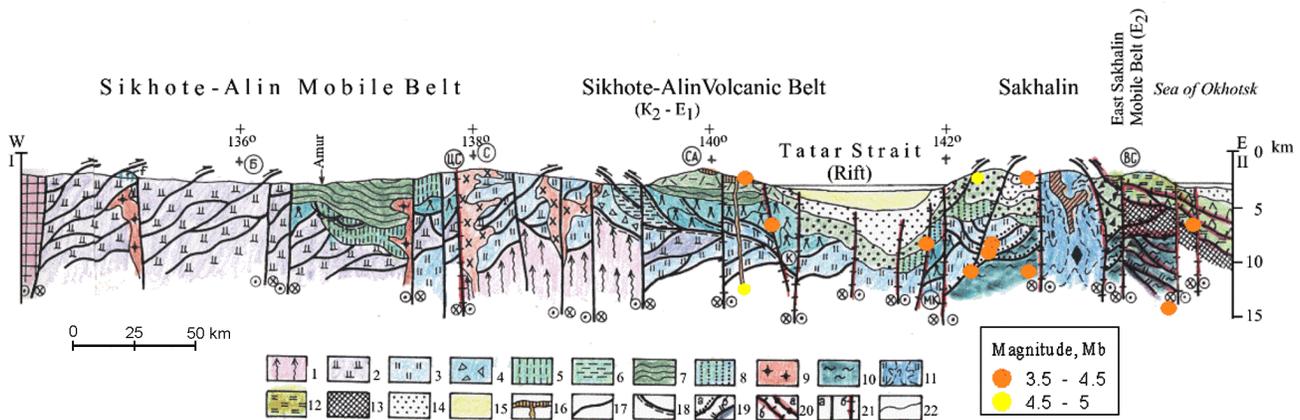


Figure 13. Geological section (by 50° N) across Sikhote Alin-Sakhalin region (section line is shown in Figure 12). 1 – blocks of assumed continental crust that underwent repeated metamorphism; 2–4 – Sikhote Alin-Sakhalin Middle Cretaceous orogenic belt: 2 – tectonically combined Paleozoic, Triassic, Jurassic, and Neocomian sea-margin and island-arc formations that underwent repeated orogeny and metamorphism (zones B – Badzhalskaya, S – Samarkinskaya), 3 – the same with prevailing Jurassic-Neocomian oceanic formations, 4 – Berriasian-Valanginian turbidite and olistostrome; 5–9 – Late Hauterivian-Early Cenomanian formations of the final stage of Middle Cretaceous orogenesis (collision-transform settings): 5–6 – Late Hauterivian-Middle Albian terrigenous formations of grabens and pull-apart basins: 5 – olistostrome and turbidite, 6 – turbidite for the major part arkose (Zhuravlevskii basin), 7 – Albian-Early Cenomanian terrigenous formations, 8 – Late Hauterivian-Early Cenomanian flyschoid formations, 9 – Barremian-Albian granitoid; 10 – assumed Late Cretaceous oceanic crust; 11 – metamorphic rocks mainly from Jurassic-Cretaceous ophiolite; 12–13 – East Sakhalin Middle Eocene orogenic belt: 12 – Campanian-Paleocene rocks of the first layer of the oceanic plate, 13 – assumed Cretaceous-Paleogene hyperbasite of the oceanic crust; 14–16 – Paleogene-Quaternary shift formations (settings of transform boundary of the continental and oceanic plates): 14–15 – terrigenous sediments in grabens and pull-apart basins: 14 – Late Eocene-Early Miocene, 15 – Late Miocene-Quaternary, 16 – Eocene-Quaternary basalt of alkali and locally calc-alkali series and delivery channels; 17 – thrusts in nappe structures of the Paleozoic and Middle Cretaceous, unrigged; 18 – Albian and Early Senomanian thrusts; 19 – Cretaceous-Paleogenic thrusts of accretion prisms of above-subduction belts: Sikhote Alin (a), East-Sakhalin-Hokkaido (b); 20 – frontal nappe thrust of East Sakhalin orogene belt (a), other Cenozoic thrusts (b); 21 – Middle Cretaceous shifts (a) and Cenozoic (b) (cross in a circle in the profile denotes movement from the observer; point denotes movement to the observer); 22 – stratigraphic and intrusive boundary. See the rest of designations in Figure 12. Additional letter designations: SA – Sikhote Alin above-subduction continental-margin volcanic-plutonic belt (Senomanian-Paleocene), K and MK are fragments (Kemskiy and Moneron-Kabato respectively) of Early Cretaceous island arc, ES is East Sakhalin Middle Eocene orogenic belt.

ing with volcanogenic-sedimentary and siliceous formations whose fragments were dredged up from the basin's slopes. T. A. Emelianova [Emelianova et al., 2003] studied the material composition of volcanogenic rocks obtained by dredging in the expeditions of research vessels “Pegas”, “Pervenets”, “Akademik Lavrentiev” [Biebow et al., 2000; Krasnyi et al., 1981; Tararin et al., 2000]. In the Kuril Basin they compose numerous volcanoes of the Pliocene-Pleistocene, which for the major part are located in the framing of the basin. They are in the southern slope of Akademii Nauk Elevation [Emelianova et al., 2003], in the rear zone of the Kuril Basin [Audeiko et al., 1992] and Geophysicist seamount volcano located in the northeastern Kuril Basin at a depth of approximately 3200 m [Baranov et al., 2002; Tararin et al., 2000]. In the southern slope of Akademii Nauk Elevation,

Pliocene volcanics are represented by andesite-basalt, andesite and locally basalts and andesite-dacite [Emelianova et al., 2003]. Similar rocks compose volcanic formations of the rear zone of the Kuril Basin and Geophysicist seamount volcano. K/Ar dating of whole rock samples shows the range from 0.9 to 1.6 million years. Volcanoes are located at intersections of transverse and longitudinal faults. The chemical composition of volcanic rocks composing volcanoes is more alkali as compared to effusive of calc-alkaline series of the Kuril Island Arc, which gives evidence in favour of their relation to the formation of Kuril back-arc basin [Emelianova et al., 2003].

[47] Palynological studies of rocks along seismic profiles allowed dating the sedimentary bed of the Kuril Basin [Bezverkhnyy et al., 2003]. It was established that the

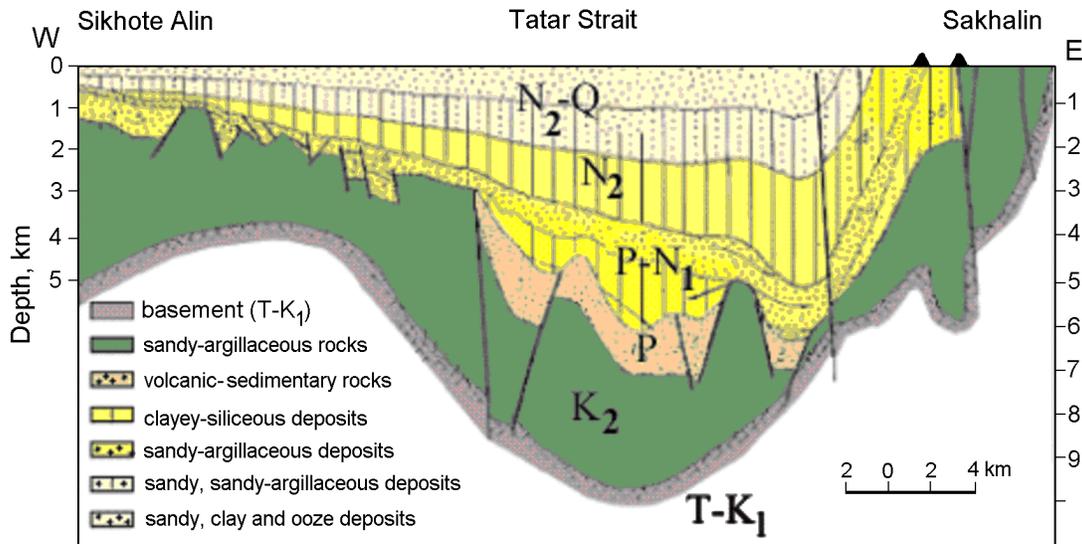


Figure 14. Geological section of the crust of Tatar Strait [Piip and Rodnikov, 2004].

basin formation started in the Late Paleogene – the Early Oligocene. Coastal and marine sediments with volcanogenic bands were deposited at that time.

[48] From seismic data, a rift or spreading structure is distinguished in the central part of the Kuril Basin [Piip and Rodnikov, 2004]. This structure is pronounced in the upper sedimentary layers. Faults forming it penetrate into the upper mantle where zones of anomalous low velocity ($7.0\text{--}7.5\text{ km s}^{-1}$) are likely to be the asthenospheric diapir containing magma-formation sources. Electromagnetic research testifies to a partial melting area in the upper mantle beneath the Kuril Basin [Lyapishchev et al., 1987].

[49] High heat flow is characteristic of the basin. The highest temperatures reaching 1200°C in the mantle are noted beneath the Kuril Basin at a depth of approximately 25 km, forming an area of partial melting [Smirnov and Sugrobov, 1980]. On the floor surface of the Kuril Basin, the rise of hot anomalous mantle corresponds to rift structures and basic magmatism. The Kuril Basin is a back-arc basin where we assume suboceanic crust associated with arc-rear spreading [Khain, 2001]. If this model is correct, we may expect layers of depleted tholeiite of composition close to MORB in combination with hyaloclastic rocks. The studies on the deep structure of the Kuril Basin show that the thickness of the crust reaches approximately 10 km. The asthenosphere forms diapir ledges immediately approaching the earth's crust. Rifts that are spreading centers are located in the basin's basement. The rise of asthenospheric diapirs to the crust caused high heat flow.

[50] Seismic activity in the Kuril Basin is considerably lower than in Kuril subduction zone. Shallow-focus earthquakes are only located there. Most of the earthquakes are located in the northwestern slope of the Kuril Island Arc and form a narrow belt running parallel to the arc. Seven focal mechanisms are known in the Kuril Basin. The focal mechanisms are of two types: reversed faults and strike-

slip faults. The epicenters of the former group are located near the continental rise of the Kuril Island Arc and in the northern slope of the Kuril Basin. Epicenters with strike-slip movements are located in the central part of the basin and near the continental rise of the arc [Baranov et al., 2002].

[51] **Kuril Island Arc** comprises the Greater island arc and the Lesser island arc separated by an inter-arc trough. The islands of the Greater island arc are composed of the Cenozoic volcanogenic and volcanogenic sedimentary rocks that, judging by xenoliths, overlie the basement composed of metamorphic rocks, crystalline schist, hornfels, gabbroid rocks, diorite and plagioclase granite. The crust thickness reaches 30–35 km. The thickness of the crust beneath the inter-arc trough decreases to 15 km. Submarine volcanoes confined to faults complicate the Okhotsk Sea slope of the island arc. They are composed of the Quaternary basalt, andesite-basalt and andesite lavas with layers of loose sediments. In dredged up fragments and blocks of effusive, impregnation of sulfide minerals was established: pyrite, marcasite, pyrrhotite, chalcopyrite, digenite and covellite [Kononov, 1989]. The Lesser island arc for the major part is composed of the Upper Cretaceous formations. Basement rocks are composed of banded gabbro, gabbro-norite, and serpentinous peridotite. They form allochthon plates, whose top part contains complexes of parallel dykes [Pushcharovskii and Melankholina, 1992]. The inter-arc trough is situated between the outer and inner island arcs and their contact is noted by the fault system. The trough width is 45–60 km. It is composed of the Neogene and Quaternary tufogenic sedimentary structures. The thickness of sediments in the axial zone is more than 3 km but seismic research in the sedimentary layer base has not been conducted. Evidently seismic research did not reveal the total section of sedimentary volcanogenic structures. On the basis of the calculation of the upper edges of anomaly-forming bodies the occur-

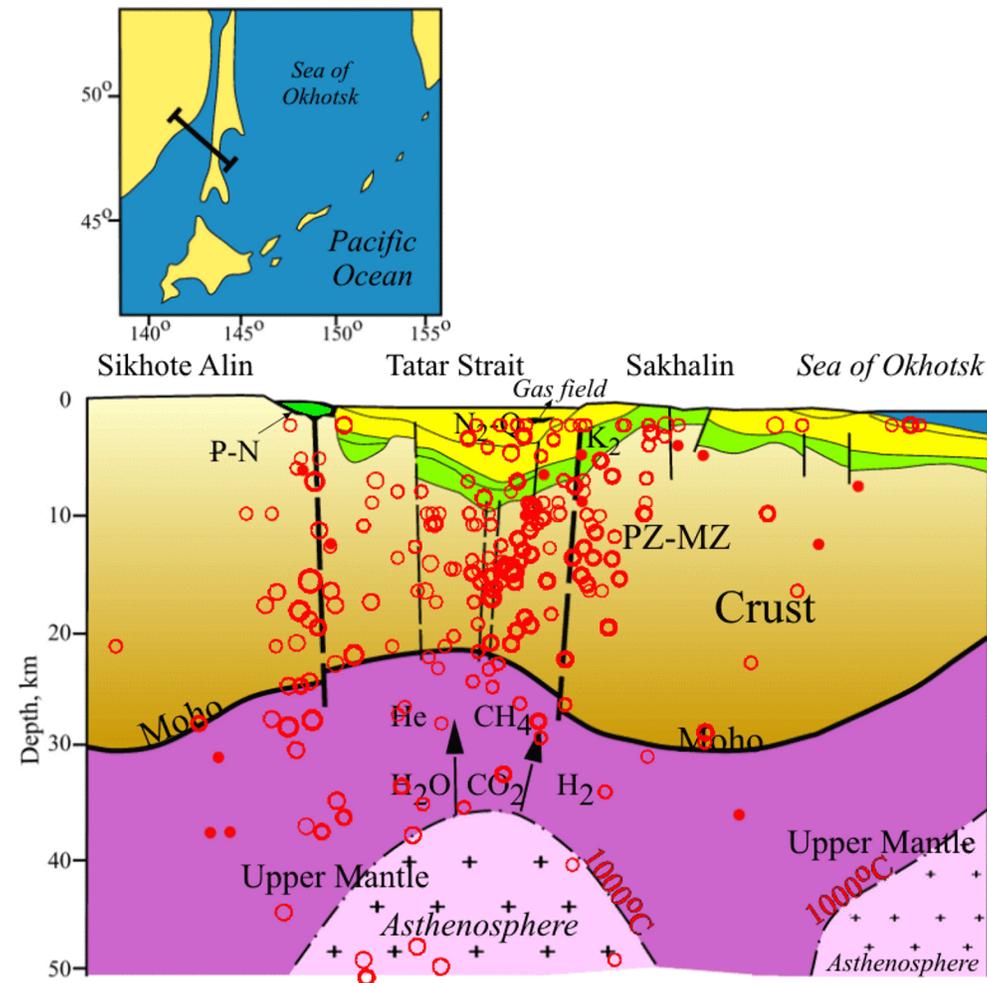


Figure 15. Deep structure of the sedimentary trough in Tatar Strait. Above is a schematic location of the profile. Geological age: PZ – Paleozoic, MZ – Mesozoic, K₂ – Upper Cretaceous, P – Paleogene, N – Neogene, Q – Quaternary. 1 – location of earthquake hypocenters, 2 – faults, 3 – geological layers; 4 – isotherm, °C, 5 – water mass.

rence of geological basement is likely in the most subsided parts of the trough at depths of 5–6 km. Abundance of volcanogenic rocks in the trough sediments is related to rifting with structures at present overlapped by thick loose sediments, intermediate effusive as well as tuff, tuff breccia and tuff sandstone.

[52] Andesite-basalt and andesite composing the volcanoes of the Kuril Island Arc belong to moderate potassic calc-alkaline series and basalt have chemical parameters close to rocks of tholeiitic series [Avdeiko, 1994]. In the Kuril Island Arc rear zone, depleted varieties disappear and calc-alkali volcanics have enriched composition at the expense of increased content of various incoherent and rare elements. In the same direction from front to rear zone, value $^{87}\text{Sr}/^{86}\text{Sr}$ increases in lavas and value $^{143}\text{Nd}/^{144}\text{Nd}$ decreases. The process of the Pacific plate subduction genetically determines volcanic rocks of the Kuril Island Arc. Their magmatic sources are located in the wedge above subduction in

the upper mantle and partially they may be located in the asthenosphere as well [Martynov *et al.*, 2005], which in the form of a mantle diapir immediately approaches the earth's crust of the inter-arc trough of the Kuril Island Arc [Rodnikov *et al.*, 2005].

[53] In the Kuril Island Arc earthquake sources form a distinct focal zone dipping at an angle of 40° from the Kuril Trench toward the continent to a depth of 700 km. The most of earthquake sources form a wedge narrowing at a depth of approximately 200 km [Yunga and Rogozhin, 2000]. The studies of earthquake focal mechanisms showed that generally in Kuril-Kamchatka island arc subhorizontal compression is noted oriented across the strike of the arc [Balakina *et al.*, 1996]. According to data on Kronotskoe earthquake focal mechanism in Kamchatka the major axis of compression gently subsides under the trench and is oriented from southeast to northwest. Extension axis steeply slopes to northeast. Repeated shocks encompassed the up-

per part of the lithosphere to a depth of 40 km. Earthquakes caused strike-slip motions accompanied by upthrust processes [Yunga and Rogozhin, 2000]. In the southern Kuril Islands, where oblique subduction is noted, Shikotan earthquake of 1994 caused upthrust motions [Arefiev, 2003]. The earthquakes were accompanied by vertical and horizontal movements that resulted in Shikotan subsidence for 0.5–0.6 m [Yunga and Rogozhin, 2000].

[54] Seismic focal zone in the Kuril-Kamchatka Island Arc is located in the area of increased values of seismic velocities [Tarakanov, 2005]. Separated areas of significant velocity gradients are characterized by strong earthquakes manifestations [Gontovaya et al., 2004] and the island arc areas characterized by considerable attenuation and low velocity of waves are located beneath the volcanic zone above subsiding slab [Fedotov and Chernyshev, 2002]. In the subsiding slab, a compression area is noted in the top part, which is replaced by expansion after the seismic focal zone bent at a depth of approximately 200 km [Balakina, 1981; Zlobin, 1987, 2002].

[55] **Kuril-Kamchatka Trench** in the geotraverse test site is outlined with isobath of 7000 m and has an asymmetric profile. Near-island slope is steeper (7–10°, and locally up to 15°) than the ocean side (5–7°, in the top part 3–5°) [Vasiliev et al., 1979]. From the ocean side of the trench along the edge of the Pacific a gently sloping uplift of Zenkevich swell extends with elevation of 200–400 m above the ocean floor and width of 300 km. The major part of the trench is covered by the sedimentary bed of the first oceanic layer commonly overlapped by thin (tens of meters) turbidite structures or a landslide lens [Belousov and Udintsev, 1981; Rodnikov et al., 1996]. The oceanic slope is broken by numerous faults of strike-slip type; the majority of them only cut the second layer but some of them cut the first layer as well and manifest themselves in the relief as ledges 50–200 m high. Fault planes are commonly tilted with respect to the trench axis at an angle of 30–60°. The distance between faults ranges from 1 to 5 km [Vasiliev et al., 1979]. Low values of the heat flow are typical of the axial part of the trench. In the most of the seismic profiles [Belousov and Udintsev, 1981] in the axial part of the trench, the subsidence is observed of the roof of the second seismic layer of oceanic slope under the island slope for a distance traced for 12 km with inclination angle of 5–7°.

[56] **Northwest Pacific Basin.** The geotraverse runs within Zenkevich swell and a vast plain extending eastwards to Shatskii elevation with mean depths of 5000–5500 m. Zenkevich swell is a marginal oceanic elevation separated by isobath 5500 m of width of 300–350 km with the elevation above the ocean floor in the range from 200 to 400 m [Belousov and Udintsev, 1981]. The thickness of sediments is insignificant (300–350 m), and rocks of the second layer of the oceanic crust composed of basalts belonging to tholeiite are commonly exposed on the floor surface near the trench axial zone. Those rocks are commonly associated with horst ledges [Rodnikov, 1983]. Besides basalts, fragments of tuff, aleurolite, greywacke, argillite, siliceous rocks, hornfells, metaschist, andesite, diabase, felsitic porphyry, granodiorite, granite and aplite [Vasiliev et al., 1979]

were dredged up. K-Ar dating of basalts dredged up from acoustic basement outcrops of the boundary swell shows the age range from 80.1 to 32.6 million years (from the Late Cretaceous to Oligocene) and granodiorite dating is 103 million years (Early Cretaceous). Specialists, who studied the boundary swell, believe [Rodnikov, 1983] that such spread of dating bears evidence on duration of the final stage of magmatic activity in the swell. In the southeast, the swell smoothly gives way to the ocean floor forming a plain complicated by smaller and larger hills.

[57] Having the most ancient crust from geological and geophysical data (about 150 million years), the whole area of northwestern basin is covered through by sedimentary cover of thickness 300–400 m. Judging by boreholes DSDP 303 and 580 [Larson et al., 1975], the cover is composed of diatom and radiolarian ooze and laminated clays enriched with Late Miocene – Quaternary ash overlying zeolitic pelagic clays, clayey nanosilt and siliceous rocks. At a depth of 211 m, those sediments are underlain by the Lower Cretaceous pelagic zeolitic clays and in the bottom of the section with interlayers of flinty slate and nanoplankton limestone. At a depth of 284.75 m, sediments are underlain by pillow lavas of the Jurassic and Cretaceous basalts of MORB type accumulated with the activity of spreading axes of different orientation [Khain, 2001].

[58] **The upper mantle** beneath the Sea of Okhotsk is characterized by both horizontal and vertical heterogeneities. It is somewhat less packed as compared to the Pacific [Boldyrev et al., 1993].

[59] From seismic tomography data [Anderson and Dzhevonskiy, 1984; Bijwaard et al., 1998], we note decreased values of seismic velocities in the upper mantle beneath the Sea of Okhotsk as well as beneath the Sea of Japan and the Philippine Sea; in the Kuril Basin on the basis of electromagnetic research in the upper mantle in the depth range of 30–65 km a layer is distinguished of specific conductivity 0.3–0.5 S m⁻¹ and integral conductivity of approximately 15000 S [Lyapishev et al., 1987]. The nature of the layer is related to partial melting and it only occurs in the basin. At a depth of 100 km, the second conductivity layer may be separated. Obtained results are in agreement with deep temperatures in the upper mantle, seismic research and other geophysical data [Maruyama et al., 1997].

[60] The asthenosphere in the upper mantle is separated for the major part from geothermal data [Rodnikov et al., 1996]. The term asthenosphere is used in reference to the layer in the upper mantle where the matter is under temperature close to temperature of melting. Thus initial magmatic centers are located there, increased electric conductivity and drastic absorption of elastic waves is noted, decrease in their velocities and in rock density is observed. For the first time, B. Gutenberg substantiated the existence of the asthenosphere as a low-velocity layer on the basis of experimental data [Gutenberg, 1953]. The asthenosphere is separated with the use of various methods of research: seismic, geothermal, and electromagnetic. The notion of asthenosphere as the partial melting zone is very important for the studies of the geological evolution of sedimentary basins because besides heat the asthenosphere is the source of hydrocarbon flu-

ids. The upper boundary of the asthenosphere is assumed to be isothermal line of 1000–1200°. Under such temperatures the upper mantle rocks partially melt with account for deep fluid influence [Rodnikov *et al.*, 1996; Smirnov and Sugrobov, 1980]. From the calculations the asthenosphere is located in the upper mantle in the Sea of Okhotsk at a depth of 50–70 km and beneath Northwest Pacific Basin it is revealed at a depth of approximately 100 km. From the asthenosphere, diapirs of partially melted matter come off, which reach a depth of 20–30 km beneath the sedimentary trough of Tatar Strait, the Deryugin Basin and the Kuril Basin and cause active tectonic conditions manifested in volcanic, seismic and hydrothermal activity (Figure 16).

[61] Beneath the North Sakhalin sedimentary basin containing almost all oil and gas fields of Sakhalin, the asthenosphere is located at a depth of approximately 70 km. Besides, hydrocarbon deposits were noted above asthenospheric diapirs in the sedimentary cover of Tatar Strait and the Deryugin Basin, and sulfide mineralization was revealed in the Kuril Basin in submarine volcano peaks. Mantle fluids of asthenospheric diapirs determine the geodynamic evolution of sedimentary basins and the formation of hydrocarbon deposits in them.

[62] In Sakhalin, the asthenosphere conductivity layer occurs in the upper mantle beneath the whole island and Tatar Strait where it is noted at a depth of 80 km. Along the continent eastern margin in the upper mantle the junction is noted of the asthenosphere high-conductivity layers and the continent rigid high-resistance upper mantle. Besides, beneath Sakhalin in the depth range of 300–500 km anomalous high-resistance areas are noted, which may be related to the cold subsiding plate of subduction zone occurring there.

[63] Beneath South Kuril Islands in the geotraverse area, the depth down to conductivity layer in the upper mantle is 60–80 km [Alperovich *et al.*, 1978]. Geothermal observations corroborate the results of electromagnetic research. Highest temperatures are observed beneath the Kuril Basin where partial melting area is located at a depth of approximately 25 km. Lowest values are noted beneath the deep trench [Smirnov and Sugrobov, 1980]. On the sea-floor surface of the Kuril Basin anomalous mantle rise corresponds to rift structures and basic magmatism. Deep temperatures in Moho boundary vary from 100°C in the Pacific to 800°C beneath Tatar Strait and Kuril Basin.

[64] Thus maximum temperatures and minimum thickness of the lithosphere are characteristic of deep basins of the Sea of Okhotsk. In axial areas of the structures the asthenospheric layer rises to 15 km; in the sides it subsides to depths of 40–50 km and beneath the Pacific it goes down to a depth of 100 km.

Tectonic and Magmatic Evolution of Cenozoic Extension Structures of Continental Margins

[65] The origin of the Tatar and Kuril Basins crossed by the geotraverse is related to the general geodynamic settings

that were formed there by the end of the Paleocene. Under the effect of Indo-Eurasian collision the continental framing of the western Pacific including the Amur and Okhotsk Sea micro plates underwent destruction by sublongitudinal zones of right-lateral shifts with the formation of pull-apart type basins of different intensity of extension, which for the major part falls on the Early and Middle Miocene [Filatova, 2006]. Bounded by shifts the single pull-apart structure including the Japan and Tatar deep basins was a continent-marginal rift in the Eocene and in the first half of the Miocene, maximum extension resulted in the separation from Asian continent of Japan micro continent owing to spreading that appeared in the Japan Basin and marginal crust that formed there. In Tatar Rift, this episode corresponds to further thinning of the continental crust.

[66] The Kuril Basin most likely has a similar nature. Its opening resulted from southward migration of eastern Hokkaido and the Kuril Island Arc along the Sakhalin-Hokkaido dextral strike-slip fault zone. Thus the origin of the Kuril Basin is related to shifts within continental crust and in this context it is similar to Japan pull-apart basin. With this model it appears reasonable that maximum extension of continental crust took place in southwestern area of the basin abutting structure-formation Sakhalin-Hokkaido shift zone and it was there that in the Early – beginning of the Late Miocene spreading went on with the formation of marine-margin crust, whereas northeastern “edge” of the basin is underlain by extended continental crust though there, judging by isotopic parameters of rocks of Geophysicist seamount volcano, diffuse spreading processes may have taken place.

[67] Data on the geotraverse testify to correlation between tension intensity and the composition of the structures under investigation on crustal and subcrustal levels. Maximum intensity of tension (Kuril Basin) corresponds to continental crust rupture, formation of marine-margin crust associated with spreading and asthenospheric upwelling up to near-surface levels accompanied by maximum heat flow. Tatar Rift where only continental crust thinning took place corresponds to asthenospheric diapir located at much greater depths; heat flow is far less intense there.

[68] The same type of magmatism dynamics in extension zones emphasized above, which correlates with stages of basin formation and their deep structure, allowed us to reveal levels of magma formation and their changing with time. The most complete data on basins with different types of the crust suggest that the Eocene-Oligocene basalts of the initial stage of rifting with characteristics of calc-alkali series are related to activation of relict (Mesozoic) above-subduction sources of the lithosphere mantle. The stage of the Early-Middle Miocene maximum extension characterized by maximum asthenospheric upwelling corresponds to tholeiite of Pacific MORB type related to asthenospheric source. Therefore from the initial rifting stage to the maximum extension stage the change of sources takes place from the upper-mantle source to the asthenospheric one. At the same time, even marginal-sea lavas of maximum extension stage that are most close to Pacific MORB (in the Sea of Japan they are rocks of borehole 797 upper part) show signs of the upper continental mantle that underwent hydrother-

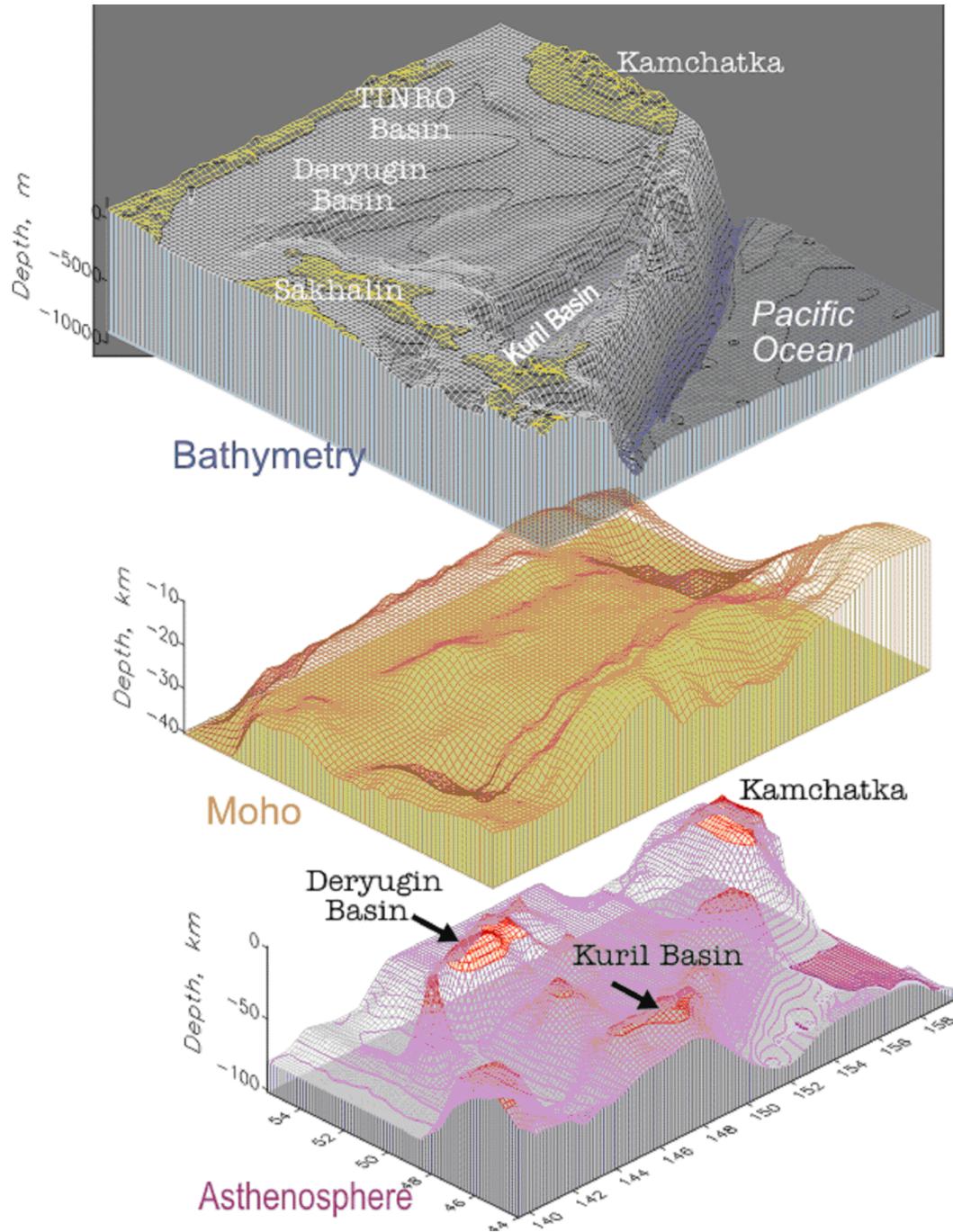


Figure 16. 3D Model of the lithosphere structure of the Sea of Okhotsk. Upper – the Okhotsk Sea floor relief. Middle – Moho relief. Lower – relief of the asthenosphere. The asthenosphere in the upper mantle of the Sea of Okhotsk is located at a depth of 50–70 km and beneath the Northwestern Pacific Basin it is revealed at a depth of 100 km. Diapirs of partial melting come off the asthenosphere, reaching a depth of 25–30 km beneath the Tatar Strait Trough, Deryugin Basin and Kuril Basin and causing active tectonic regime manifested in volcanic, seismic and hydrothermal activity. Red color in the asthenosphere shows area of magma formation beneath the sedimentary basins.

mal change (amphibolite-phlogopite content). Such mixture of isotopic and geochemical features of basalts of the major stage of basins formation testifies to the interaction of prevailing asthenospheric source and metasomatized litho-

spheric mantle. Alkaline basalts of post-rifting and post-spreading stage of the end of the Miocene – Holocene that is similar in isotopic-geochemical characteristics to OIB composition and of EMI sources and locally EMII sources may

have been genetically related to lower-mantle matter by model although lithospheric source must not be ruled out either.

[69] High heat flow, magmatic activity and sedimentary bed heating caused by asthenospheric upwelling became an additional source of hydrocarbon and fluidal flows fostering oil and gas fields formation in Tatar Rift sedimentary beds.

[70] Thus extension structures on the Okhotsk Sea geotraverse (Tatar and Kuril structures) are pull-apart basins that started formation with predominant structural control caused by the interaction of lithospheric plates. The both structures appeared within continental crust and in the course of their evolution they differed in the degree of extension showing continental crust thinning or its rupture with spreading and the formation of marine-margin crust. The similarity of the Tatar and Kuril Basins is in synchronous change, magmatism dynamics of the same type and similar structure of subcrustal areas. Both basins correspond to asthenospheric upwelling caused by the lithosphere tension and in this case the level of asthenospheric diapir rise shows positive correlation with the degree of crustal extension. It is this feature that determines magmatism dynamics: early stages of rift formation were accompanied by basalts associated with areas of the upper mantle that underwent hydrothermal change, whereas maximum extension is correlated with tholeiite of asthenospheric sources [Filatova and Rodnikov, 2006].

[71] The composition of mantle fluids having a leading part in the formation of continental margin structures, sedimentary basins of marginal seas and island arcs is determined from gas-geochemical survey in recent rift structures and analysis of gas inclusions in the upper mantle rocks from kimberlite pipes. Thus in underwater mid-oceanic ridges and rifts of marginal seas the studies revealed high content of helium, hydrogen, methane and carbon dioxide [Craig et al., 1987; Hussong et al., 1981]. The studies of liquid and gaseous inclusions in diamonds and in kimberlite pipe rocks showed that besides the above-mentioned gases a high content of liquid hydrocarbons is noted as well [Zubkov, 2001]. Major components of mantle fluids are carbon dioxide, methane, hydrogen, fluorine, chlorine, selenium, arsenic, iridium, mercury, antimony and other elements. From data by A. F. Grachev [Grachev, 2002] one million km³ of lava contains no less than 10¹⁴ tons of methane and the same amount of carbon dioxide. Research conducted [Riabchikov et al., 2004] showed that in the eruption of basalt lavas of Siberia trappean province formed approximately 230 million years ago, more than 10¹³ tons of carbon dioxide was released in 1 million years. The emission of such amount of carbon dioxide in so short a period of geological time was a real course of disastrous global change in the boundary of the Permian and Triassic periods and corroboration of magma saturation with gaseous components.

Discussion and Conclusions

[72] Research in the deep structure of the Far East continental margins was conducted on the basis of combined

interpretation of geological and geophysical data. To construct geodynamic models we used the results of geological, seismic, petrological, geothermal, magnetic, electromagnetic and gravimetric research. Geophysical fields, geological structure of sedimentary cover, the structure of the earth's crust and the upper mantle, location of deep faults, volcanoes and their magmatic sources, earthquake sources distribution, depths of occurrence of the asthenosphere and individual diapirs, paleo- and modern subduction zones, deep temperatures distribution are shown on geodynamic models.

[73] A feature of the deep structure of the transition zone from the Eurasian continent to the Pacific is the occurrence of asthenospheric layer in the upper mantle, from which anomalous mantle diapirs run off and the processes going on in them determine the formation of the earth's crust structures. The increase of asthenosphere thickness is revealed beneath all deep-sea basins of the transition zone from the Eurasian continent to the Pacific. Young and active spreading basins are areas of generation of new oceanic crust and the lithosphere; such basins correspond to the asthenosphere roof emergence immediately at the foot of the crust.

[74] The nature of continental margins geoid, apparently similar to the Earth on the whole, is determined by deep density heterogeneities, which may be either static or dynamic and are related to the mantle convection. Thus of structures of transition zone from Eurasian continent to the Pacific is characteristic linear relation between residual heights of geoid and the age of the beginning of back-arc areas formation. Since tectonic magmatic activity is caused by the asthenosphere conditions and its effects on the earth's crust (the higher is the level of asthenosphere bedding, the younger is tectonic magmatic activity), it is reasonable to relate geoid height variation to the features of asthenosphere structure.

[75] Correlation is noted between geological structures, tectonic and magmatic activity and the upper mantle structure. Thick and most pronounced asthenosphere corresponds to tectonically active areas like island arcs and rift structures of marginal seas. On the surface, asthenosphere rises correspond to rift structures and eruptions of mostly tholeiitic magmas. They are located in extension zones and are manifested against lithosphere thickness decrease and high heat flow. With the asthenosphere upwelling to the earth's crust, the lithosphere breaks, rift structures start to form, basalt (mostly tholeiitic) magma erupts, active hydrothermal processes with sulfide deposits formation go on and avalanche sedimentation is underway. Asthenosphere diapirs are channels by which hot fluids including hydrocarbons penetrate into sedimentary basins and other structures of the transition zone.

[76] The relation between heat flow, tectonic and magmatic activity is corroborated. It manifests itself in the heat flow increase with tectogenesis rejuvenation age. Increase in heat flow density is caused by the intrusion of asthenosphere diapirs into the lithosphere, which caused tectonic magmatic reworking of the crust and volcanism development. The higher is the level of asthenosphere position and the higher is the heat flow values, the younger is tholeiitic basalt eruption age. With the asthenosphere position level reaching 10-20 km, the lithosphere breaks, inter-arc troughs are formed and rift structures with tholeiitic basalt eruption

are formed along their axial lines. Data on the geotraverse testify to the correlation between extension intensity and the structure of the formations under investigation in crustal and sub-crustal levels. Maximum intensity of extension (Kuril Basin) corresponds to continental crust rupture, marginal sea crust formation (associated with spreading) and asthenosphere upwelling up to near-surface level accompanied by maximum heat flow. Tatar rift, where only thinning of continental crust was underway, corresponds to asthenosphere diapir as well, but it is located at greater depths and heat flow is far less intense there. Extension structures in the geotraverse of the Okhotsk Sea region (Tatar Rift and Kuril Basin) are pull-apart basins; structural control caused by lithospheric plates interaction prevailed at their formation. Both structures were formed within continental crust and in the course of evolution they differed in the degree of extension: either with continental crust thinning or its rupture (with spreading) and marginal-sea crust formation. The similarity of rocks is in synchronous change, magmatism dynamics of the same type and similar structure of sub-crustal areas. Asthenosphere upwelling caused by lithosphere extension corresponds to both basins; in this case the level of asthenosphere diapir rise shows positive correlation with the degree of crustal extension. The latter feature determines magmatism dynamics: early stages of rift formation were accompanied by basalts associated with upper mantle areas that underwent hydrothermal changes, whereas maximum extension correlates with tholeiite of asthenosphere sources.

[77] The origin of volcanic rocks of the the Kuril Island Arc is related to subduction of oceanic lithosphere. Their magmatic sources are located in the above-subduction wedge within the upper mantle and locally in the asthenosphere.

[78] Thus the construction of active continental margin models on the basis of combined interpretation of geological and geophysical data allows us to reveal the epochs of highest rates of activation (including degassing) of asthenosphere diapirs and to study the geodynamic evolution of the processes going on in the transition zone from continent to the ocean.

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