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Deep Electrical Conductivity Features in the Transition Zone from the Pacific to Eurasia

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Abstract—Understanding the processes that occur in the transition from the Pacific Ocean to Eurasia is key to constructing the tectonic models of the Earth's shells and the convection models of the upper mantle. The electromagnetic methods permit estimating the temperature and fluid content (and/or carbon (graphite) content) in the Earth's interior. These estimates are independent of the traditionally used estimates based on seismic methods because the dependence of electrical conductivity on the physical properties of the rock is based on different principles than the behavior of the elastic waves. The region is characterized by a complicated geological structure with intense three-dimensional (3D) surface heterogeneities, which significantly aggravate the retrieval of the information about the deep horizons in the structure of the Earth's mantle from the observed electromagnetic (EM) fields. The detailed analysis of the nature of the deep electrical conductivity and structural features of the transition from the Pacific to Eurasia included numerical modeling of the typical two- and three-dimensional models has been carried out. Based on this analysis, the approaches that increase the reliability of the interpretation of the results of the EM studies are suggested.

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INTRODUCTION

The electromagnetic (EM) methods based on the skin effect, including the magnetotelluric (MT) and magnetovariational (MV) soundings, enable the study of electrical conductivity distribution in the crust and upper mantle of the Earth. In turn, the interpretation of the deep electrical conductivity data allows one to estimate the temperature and the content of the different conductivity-controlling impurities, primarily the fluid content and/or carbon (graphite) content. An important fact is that these estimates are independent of the traditionally used estimates obtained by the seismic methods since the dependence of the electrical conductivity on the physical properties of the rocks are based on physical principles that are different from the behavior of elastic waves.

The transition from the Pacific Ocean to Eurasia, which covers the northwestern Pacific and northeastern part of Asia (Fig. 1), is one of the most interesting regions from both the scientific and applied standpoints. This zone accommodates active convergent plate boundaries—the subduction zones; and understanding the processes that take place in this region provides the key for constructing the tectonic models of the Earth's envelopes and the convection models of the upper mantle.

It is the subduction zones where most of the catastrophic tsunamigenic earthquakes have their hypocenters. Studying the structure of the Earth's crust and upper mantle by the EM methods in these regions is fairly challenging because the surface heterogeneities, primarily the contrast in the surfaceelectrical conductivity between the land and ocean, as well as the complicated configuration of the coastline, induce intense anomalies in the EM field impeding the retrieval of the information about the deep structure. These anomalies in the EM field have been called the coast effect and have been studied by the geophysicists for more than fifty years (Rikitake, 1956; Parkinson, 1979; Schmucker, 1964; 1973; Dosso, 1973; Marderfeld, 1977).

The aim of the present paper is to critically estimate the resolution of the deep EM soundings in the transition from the Pacific Ocean to Eurasia and to consider different approaches to increase the efficiency of the interpretation of magnetotelluric (MT) and magnetovariational (MV) soundings in this region.

COAST EFFECT IN THE FAR EAST

Of course, the coast effect is most clearly pronounced in the coastal zone where the magnetovariational transfer function—the tipper—demonstrates anomalous behavior. The tipper's magnitude may exceed unity, i.e., the vertical component of the magnetic field is close to or even larger than the horizontal component (the length of the real induction vectors

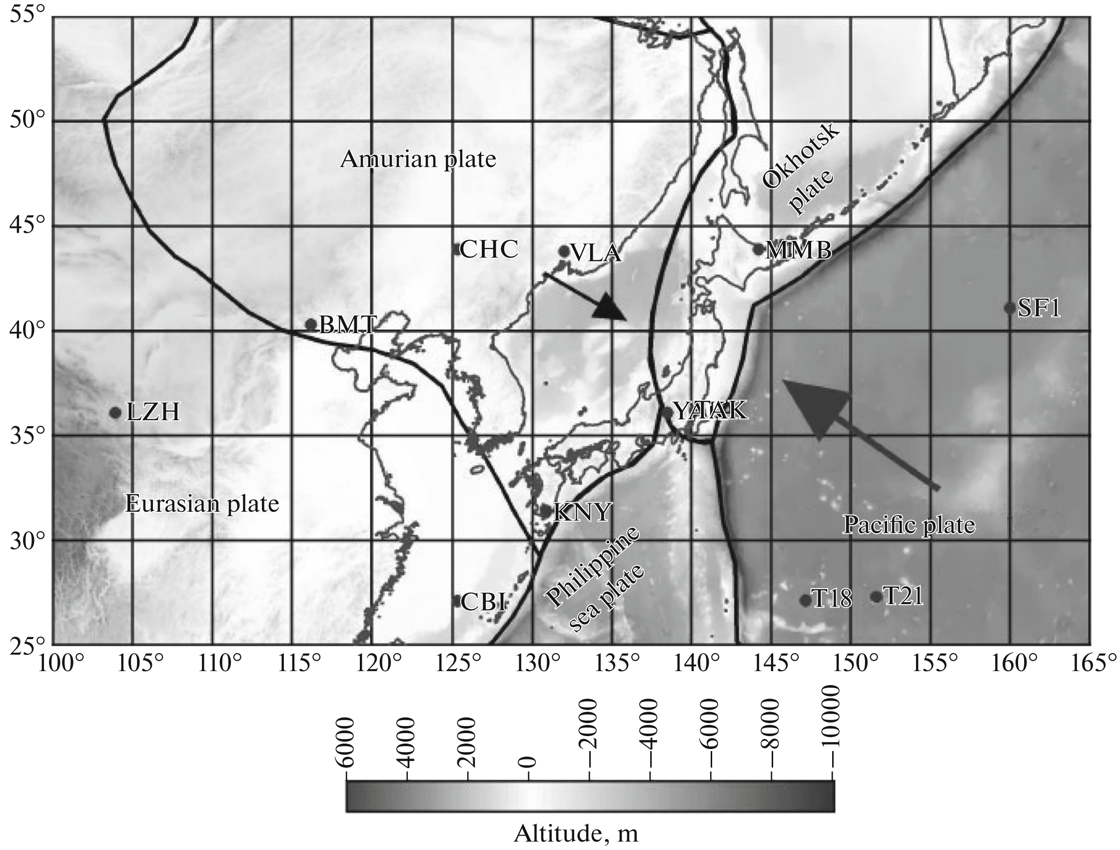

Fig. 1. The sketch of the lithospheric plate boundaries in the transition from the Pacific Ocean to Eurasia (after Zonenshain). The arrows show the direction of motion of the Pacific (10 cm per annum) and Eurasian plates (1 cm per annum). The main geomagnetic observatories and the seafloor MT points are shown.

reaches unity or longer). Besides, the coast effect not only largely determines the anisotropy of the impedance tensor in the coastal zone but also quite far from the coastline, both on land and in the sea. It has been believed for a long time that the analysis of the coast effect in the behavior of the EM transfer functions—impedance and tipper (induction vectors)—provides the information about the conductivity of the upper mantle, including the depth of the conductive layer in the upper mantle and/or integral resistivity of the lithosphere. Indeed, for the simplest two-dimensional (2D) three-layer model of the coast effect, where the upper layer simulates the land-sea boundary, the intermediate low-resistivity layer models the homogeneous lithosphere, and the third highly conductive layer mimics the homogeneous asthenosphere; it is possible to obtain a simple analytical formula in which the vertical electrical current leakage through the lithosphere which determines the behavior of the TM-mode depends on the galvanic constant $G = 1/\sqrt{S_1R_2}$, where S_1 is the conductance of the upper layer and R_2 is the transverse resistance of the lithosphere (Cox, 1980). Here, the amplitude of the jump in the TM-mode apparent resistivity (electric field) is determined by the conductance ratio between the land and sea in the first layer. From this it follows that the attenuation of the TM-mode coast effect is determined by the transverse resistance of the lithosphere (Vanyan and Palshin, 1990). The TE-mode anomaly (longitudinal component) in apparent resistivity relatively rapidly decays with distance from the coast (Vanyan and Palshin, 1990; Alekseev et al., 2009). Hence, the empirical estimates of the ratio of the longitudinal-to-transverse apparent resistivity are mainly determined by the TM-mode, which allows one to obtain the estimates of the transverse lithospheric resistivity based on this parameter. It is worth noting that the integral transverse resistivity for the oceanic lithosphere is mainly determined by the resistivity of the upper 20–40 km, in other words, by the parameters of the upper part of the lithospheric mantle (Palshin, 1988; 1996). These estimates were obtained for the northeastern Pacific (Chave and Cox, 1983), northwestern Pacific (Heinson et al., 1993a), Tasman Sea (Heinson and Lilley, 1993b; Vanyan et al., 1995), and Sea of Japan (Vanyan et al., 2000). Al the obtained estimates fall in the interval 10^7–10^8 Ω m^2.

At the same time, at the beginning of the 1980s, the results of measuring the resistivity of the oceanic lithospheric mantle by controlled-source EM (CSEM) frequency sounding have been obtained in the northeastern Pacific. Compared to the MT sounding, the penetration depth for this method is relatively shallow (at most 20–30 km (Vanyan and Palshin, 1993)); however, the electrical conductivity estimates for the oceanic crust and underlying lithospheric mantle were obtained by this method (Young and Cox, 1981; Webb et al., 1985; Cox et al., 1986).

The fact of reliably recording the electrical field at a frequency of 1 Hz at a distance of about 100 km from the source was most interesting. The interpretation of these results has shown that the relatively conductive oceanic crust is underlain by a poorly conductive lithospheric mantle forming sort of a waveguide with a thickness of 20–30 km which promotes horizontal propagation of EM wave with the minimal attenuation. The electrical conductivity of the lithospheric mantle is 10^{-5} S/m and its transverse integral resistivity is at least 10^9 Ω m^2 (Chave et al., 1990a; Chave, 1990). It should be noted that these estimates of electrical conductivity for the "dry" and "cold" lithospheric mantle correspond to the theoretical notions about the electrical conductivity of the dry mantle material (Constable et al., 1992; Constable, 2006).

Hence, there is significant (at least one order of magnitude) and systematic inconsistency in the estimates of the transverse integral resistivity R of the oceanic lithosphere. Indeed, if we estimate the galvanic constant G for the values inferred from the results of the seafloor soundings with a controlled source, we will see that the coast effect from the west coast of North America should operate almost throughout the entire Pacific. However, the seafloor MT soundings carried out in the Pacific 500–1000 km off the coast show the virtual absence of the anisotropy of the impedance tensor (Chave et al., 1990b). The detailed analysis of the anomalies in the MT field in the region of the Juan de Fuca Ridge which are induced by the 3D bathymetry features also indicate the absence of a significant coast effect even at shorter distances from the coastline (Heinson et al., 1993). A strong influence of the coast effect is also absent in the results of the seafloor MT soundings that were recently conducted in the northwest Pacific by Japanese geophysicists (Baba et al., 2010), as well as in the other numerous seafloor MT soundings carried out lately (e.g., (Kelly, 2011)).

It is clear that the cited estimates inferred from the attenuation of the TM-mode coast effect are, to all appearances, deflated. N.A. Palshin suggested explaining this contradiction based on the a priori geological-geophysical data and on the notions of the brittle-to-plastic transition of the oceanic upper mantle material (e.g., (White, 1990)). This explanation makes use of the fact that a brittle lithospheric mantle is characterized by anisotropy in electrical conductivity in which the conductivity is higher vertically than laterally. This anisotropy is associated with the block structure of the lithospheric mantle and with the existence of the system of faults providing a galvanic connection (current leakage paths) between the conductive water and deep, highly conductive layers of the upper mantle. Here, the degree of anisotropy of the lithospheric mantle is inversely proportional to the age of the oceanic crust (Palshin, 1988a; 1988b). According to this hypothesis, the EM anomalies induced by the water layer heterogeneities, including the coast effect, get normalized much faster (at shorter distances) than estimated from the simplest models with homogeneous lithosphere (Vanyan et al., 1992). Clearly, the role of the subvertical conductive zones is also played by the lithospheric plate boundaries, transform faults, and the zones of intraplate tectonic activation.

Thus, on one hand, the existing galvanic connection between the water layer and deep, conductive portions of the upper mantle significantly reduces the coast effect, making vast oceanic territories suitable for study by the EM sounding methods in the scope of 1D models. On the other hand, the integral resistivity estimates that have been obtained using the TM-mode in the coastal zone are apparent or effective; these estimates are not so much determined by the electrical conductivity of the rocks composing the lithospheric mantle as by imponderable parameters (the density, relative positions, and electrical conductivity of the vertically conductive zones).

Similar results were also obtained in the continental regions where the theoretical anomalies of the EM fields estimated for the models with a homogeneous lithosphere are larger than observed. For instance, based on scrutinizing these models, M.N. Berdichevsky has also come to the conclusion that an important normalizing role is played by the subvertical conductive zones (Berdichevsky et al., 1993; Berdichevsky and Kulikov, 1994).

For understanding the real coast effect, it is vital to allow for the complicated configuration of the coastline and the presence of islands, straits, and inland seas. Many peculiarities in the behavior of the EM field anomalies are accounted for by the 3D coast effect alone, without any additional structural features of the crust and/or upper mantle. For example, the results of numerically modeling the 3D coast effect in the Far East (Nikiforov et al., 2004), which were obtained for a 3D model allowing for the surface heterogeneities, alone show that the behavior of the induction vectors at the most of the observatories in Japan is reproduced fairly accurately. Here, the only parameter characterizing the upper mantle was its transverse integral resistivity making up the cited apparent 10^{-8} Ω m^2. Remarkably, in contrast to the induction vectors, this model fails to reproduce the behavior of the impedance (apparent resistivity and impedance phase curves).

More than 60 years ago, the noted Japanese geophysicist Tsuneji Rikitake, based on analyzing the shift of the solar daily variation maximum by 2 h toward the morning time at the geomagnetic observatories in northeastern Japan assumed that this phenomenon can be accounted for by the anomalous structure of the upper mantle—the existence of a poorly conductive inclined slab corresponding to the subducting Pacific plate (Rikitake et al., 1956). For a long time, this conclusion has been neither validated nor refuted by the modern mathematical methods. Recently, Aleksei Kuvshinov and Hisashi Utada have constructed a 3D model of the Far East region which takes into account the actual conductivity distribution in the surface layer, including the Pacific Plate subducting beneath the Eurasian Plate. They have shown that explaining the time shift of the maximum of the solar daily variation does not require the existence of peculiarities in the lithospheric structure beneath Japan but is rather accounted for by the 3D coast effect alone (Kuvshinov and Utada, 2010).

Hence, the recent studies clearly show that the anomalous EM fields induced by the 3D coast effect in the Far East can be virtually completely accounted for by 3D distribution of electrical conductivity in the surface layer, which includes the sedimentary basins and water layer. The significant normalizing influence is exerted by the subvertical conductive zones. The resolution of the anomalous EM fields, caused by the coast effect or island effect, with respect to the deep structures, is unlikely to be high.

ELECTRICAL CONDUCTIVITY OF THE UPPER MANTLE

For the purposes of studying the deep structure of the Earth, the distribution of the Earth's electrical conductivity in the first approximation can be represented by the sum of three components:

—background uniform conductivity distribution which only depends on depth;

—large anomalies, most frequently areas with high electrical conductivity values;

—electrical conductivity of the surface layer, which includes the Earth's crust with sedimentary basins, seas, and oceans.

What information about the deep structure of the Earth can be obtained by EM methods?

Let us consider the main regularities in the behavior of electrical conductivity with the increase in depth (thermodynamic, or PT-conditions) and the probable causes of the emergence of lateral inhomogeneities in the electrical conductivity of the upper mantle of the Earth.

The electrical conductivity of the upper mantle of the Earth increases with depth from 10^{-3}–10^{-4} S/m or even smaller in the uppermost "cold" part at a depth of up to 50–80 to a few S/m at the top of the lower mantle. The electrical properties of the mantle rock are mainly determined by the thermodynamic conditions. According to the most common pyrolytic mantle model, more than 60% of the composition of the upper mantle and its transition are made up by olivine and its polymorphs wadsleyite and ringwoodite. There rocks in their pure form (without impurities) are semiconductors and their electrical conductivity is described by the Arrhenius relationship, according to which conductivity is proportional to the product of the number of free charge carriers to their mobility. Electrical conductivity monotonically increases with temperature and weakly depends on pressure. The mechanism of conductivity is associated with the motion of polarons Fe^{3+} (polaron is a charged particle moving across the crystal, together with the lattice deformation caused by it). This mechanism has long been considered predominant in the temperature interval 700–1300°C, and the highly conductive layers in the upper mantle (frequently referred to as the asthenosphere) have been accounted for by the main and only factor—partial melting (e.g., (Vanyan and Shilovskii, 1983)). The lithologic composition of the mantle only slightly affects the electrical conductivity of the pure mantle rocks.

Since the temperature distribution at a depth below 300–400 km in the first approximation is close to spherically symmetric, the concepts of a normal MT sounding curve (Vanyan et al., 1980) and the kindred global curves of apparent resistivity based on the MV sounding data were advanced (Rokityanskii, 1972; 1981; Fainberg, 1977).

However, in 1990, the Japanese geophysicist Shun-Ichiro Karato (working in the U.S.) suggested an additional mechanism accounting for the high electrical conductivity of olivine by the diffusion of hydrogen ions (Karato, 1990). In this case, electrical conductivity is described by the Nernst–Einstein equation and significantly depends on the water content in the rock. Subsequently, this conclusion was validated by numerous studies (Huang et al., 2005; Wang et al., 2006; Yoshino, 2010). Despite the considerable scatter of the laboratory estimates, it can be stated that for the upper mantle olivine basalts this mechanism is predominant in the temperature interval from 600 to 1200°C. With the growth in temperature, the polaron mechanism additionally comes into play, and then the ionic mechanism is added (Fig. 2).

The notions concerning the nature of the asthenosphere have also changed in the past years. The existence of a low-viscosity layer is not necessarily related to partial melting. An extensive partially molten layer can only exist beneath a young oceanic lithosphere. Under the thermodynamic conditions that are typical of most regions of the Earth, partial melting in the upper mantle is impossible in the absence of water (the dry solidus curve of olivine does not intersect the geotherm), whereas even the presence of a little water noticeably diminishes the solidus of olivine. This means that the formation of the zones of partial melting in the upper mantle is probably mainly due to the combined effect of temperature and excess water content resulting in the reduction of the melting point of the mantle material (e.g., (Yoshino et al., 2006; Karato, 2012; Utada and Baba, 2014)).

Hence, the presence or absence of water (free protons) in the upper mantle is the key factor determining the electrical conductivity. In other words, electrical conductivity is the key parameter permitting the estimation of the water content in the mantle because the seismic parameters (shear wave velocity, etc.) are not purely temperature dependent but are also simultaneously controlled by a few other parameters, primarily by the mineral composition, whereas their sensitivity to the effects of water is not as high (Jones et al., 2012, Jones et al., 2013)

Figure 3 shows the dependences of electrical conductivity of olivine on inverse temperature for different values of the water content according to the laboratory measurements (Wang et al., 2006). The graphs with different slope angles correspond to the different conductivity mechanisms: the polaron mechanism for the "dry" olivine and the proto mechanism for the "wet" olivine. The difference in conductivity between the dry and wet olivine reaching a few orders of magnitude is remarkable.

It should be however remembered that the characteristic scale of the laboratory measurements is a few mm, whereas the characteristic scale in the deep EM studies is dozens and hundreds of kilometers. Nevertheless, the approach has come into practice according to which the conductivity distribution derived from the MT and/or MV data and the depth dependence of conductivity obtained in the laboratory experiments for the dry mantle are used for estimating the temperature distribution. The obtained temperature estimates are compared to the similar estimates yielded by seismic tomography, which faintly depend on the water content. In the case when these two estimates are close, it can be accepted that the water content in a given depth interval is minimal and vice versa, when the temperature estimates from electrical conductivity are noticeably higher than those based on seismic tomography, the water content can be expected to be high (e.g., (Koyama et al., 2006; Utada et al., 2009)).

The fact that the phase transformations of olivine should be accompanied with jumps in electrical conductivity because the latter should increase with the compaction of the crystal lattice is another important consequence of the pyrolytic mantle composition. For instance, at a depth of ~410 km, the phase transformation of olivine into wadsleyite takes place (the alpha-phase is transformed into the beta-phase), and at a depth of ~520 km, wadsleyite is transformed into ringwoodite (from the beta-phase to the gamma-phase). At the top of the lower mantle below a depth of 660 km, it is believed that the mineral composition of the material is dominated by the petrovskite and magnesiowüstite mineral components (Katsura and Ito, 1989; Xu et al., 1998). Unfortunately, the geoelectrics also do not give an unambiguous answer about the existence of these jumps; however, at a depth of ~400 km, a jump in the electrical conductivity by one or two orders of magnitude is likely to be the case. In the lower part of the upper mantle, the conductivity is 3×10^{-3} to 10^{-2} S/m, whereas at depths from 700 to 900 km in the lower mantle, it is about 1 S/m (Fig. 4).

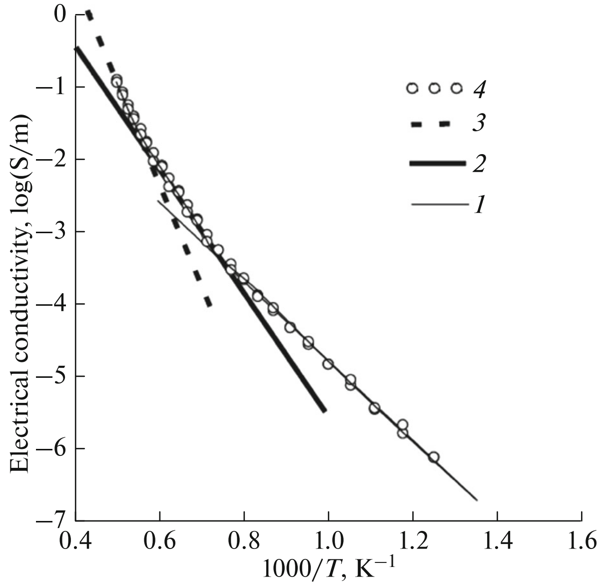

Fig. 2. The dependence of the electrical conductivity of the mantle rock on the inverse temperature. Three mechanisms of electrical conductivity are schematically shown: (*1*) proton mechanism; (*2*) polaron mechanism; (*3*) ionic mechanism (Xu et al., 1998; Yoshino, 2010); and (*4*) the resulting dependence of electrical conductivity on temperature.

The dependence of the hydrogen-ion diffusion rate on crystal orientation is yet another important peculiarity of olivine. To put it another way, if the crystal orientation has a predominant direction, the electrical conductivity of the upper mantle can be expected to be anisotropic (e.g., (Simpson and Tommasi, 2005; Baba et al., 2006)).

Hence, the recent studies suggest the water content as the key factor responsible for the observed lateral variability of electrical conductivity in the upper mantle because, in contrast to temperature and pressure, water content can vary within fairly wide limits.

Besides, a high water content significantly reduces the solidus of the mantle rocks which causes the "wet" partial melting.

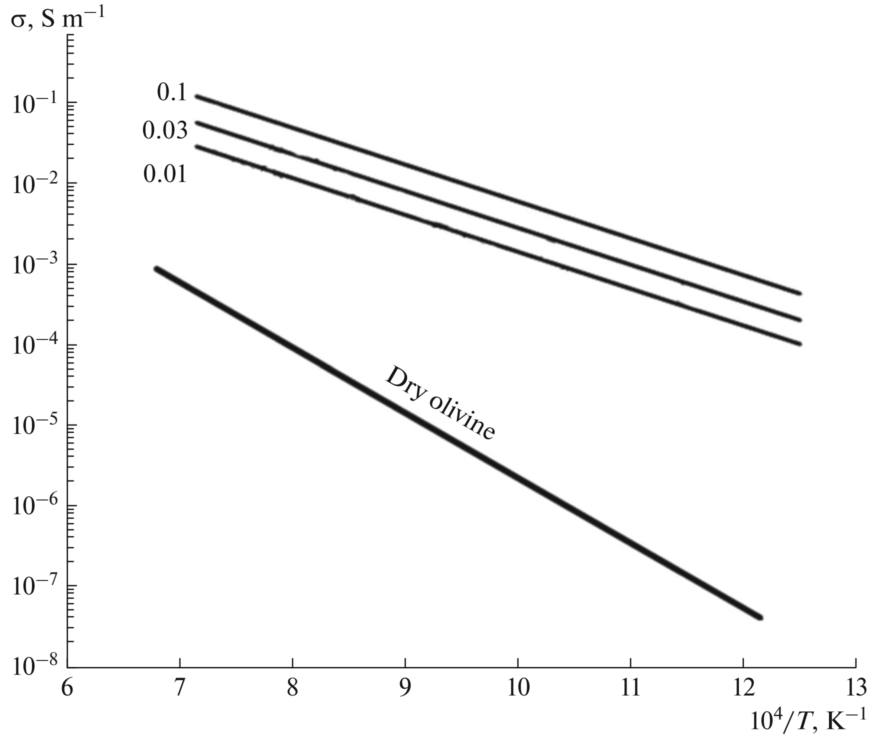

Fig. 3. The dependence of electrical conductivity of olivine on the water content according to the results of laboratory measurements. The numbers near the curves indicate the water content in wt % (Wang et al., 2006).

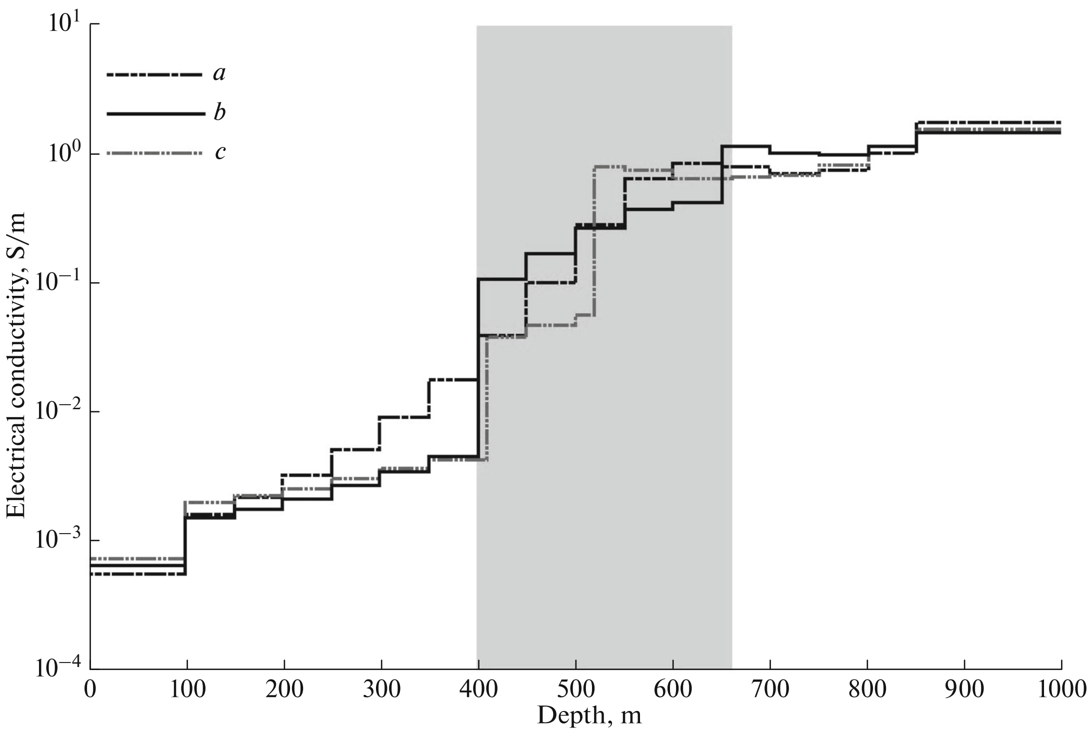

Fig. 4. The electrical conductivity distribution in the northern part of the Pacific according to the EM data (Utada et al., 2003). The transition of the mantle is shown in gray: *a* inversion for the maximally smooth distribution; *b* inversion with the allowed jump in conductivity at depths of 400 and 660 km; *c* inversion with the allowed jump in conductivity at depths of 400, 550, and 660 km (see text).

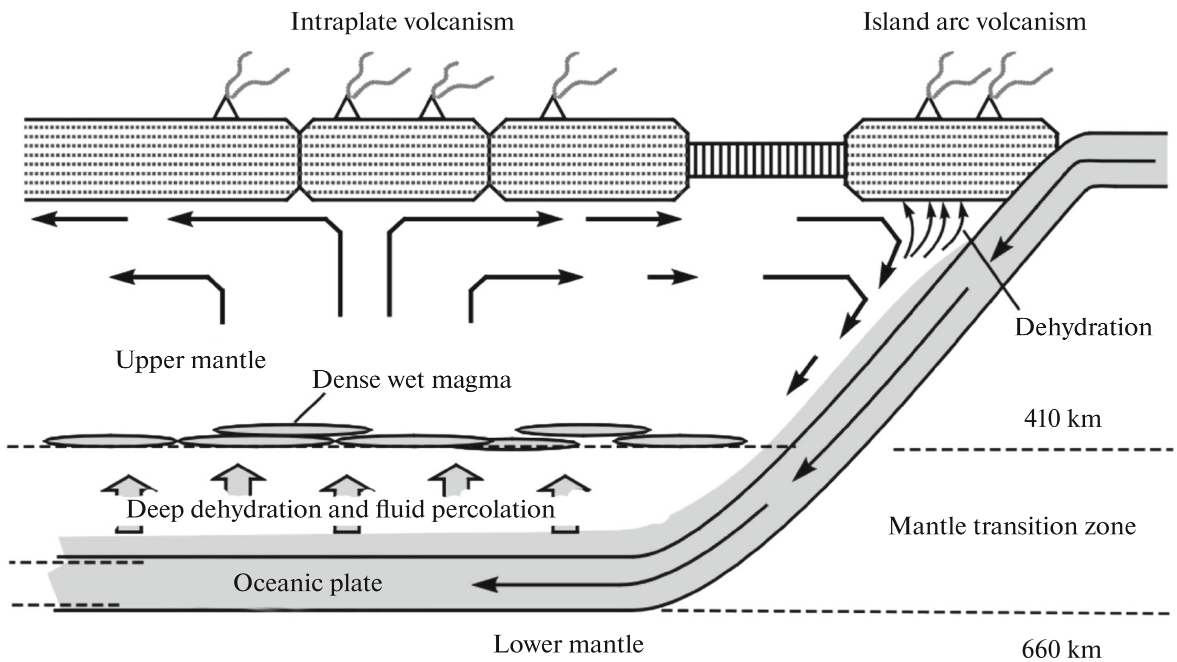

Fig. 5. The models of a large mantle wedge (Ohtani and Zhao, 2009).

The effect of the water content decays with the growth in temperature and pressure as the polaron and ionic mechanisms become predominant after the proton mechanism, which prevails in the temperature interval approximately from 600 to 1200°C.

It is presumed that the phase transformations of olivine in the mantle transition are responsible for the stepwise increase in the electrical conductivity, particularly at a depth of 410 km, corresponding to the phase transformation of olivine into wadsleyite.

STRUCTURAL PECULIARITIES OF SUBDUCTION ZONES IN THE FAR EAST

The transition from the Pacific to Eurasia, which includes northeastern Asia, the inland seas of the Far East, and the northeastern Pacific, pertains to the tectonically most active regions in the world. It is characterized by two key factors: subduction of the oceanic plates (the Pacific and Philippine Sea ones) underneath the Eurasian continent and the eastward divergence of the relatively small Amurian and Okhotsk microplates due to the collision of India and Eurasia, as suggested by L.P Zonenshain (Zonenshain and Savostin, 1981; Taira, 2001).

The mobility of the microplates suggests the presence of a well-developed asthenosphere in the upper mantle, where partial melting of the material should be expected. These tectonic features of the region are accounted for by the hypothetical process of the model large-scale water circulation whose dynamics is driven by the subduction of the oceanic plates beneath the Eurasian plate. The subduction mechanism maintains the process of permanent transportation of water from the oceanic lithosphere to beneath the Eurasian plate. Part of the water is squeezed in the accretionary prism, another part is involved in rock hydration at a depth of 30–40 km, yet another part provides the "wet" melting of the rock and island arc volcanism, and, finally, some water is brought to the mantle transition (Ichiki et al., 2006; Fukao et al., 2009).

According to the large mantle wedge model (Fig. 5), the high fluid (water) content in the upper mantle of the Amurian Plate accounts for the high intraplate seismicity and the presence of quaternary volcanism in the central part of the plate (Ohtani and Zhao, 2009).

The high mobility of the lithospheric plates, primarily the Pacific Plate which subducts under the Eurasian one by 8–10 cm per annum, entails high seismicity. The Kamchatka, Kuril, and Japan island arcs are seismically the most hazardous regions in the world; besides, due to the specific focal mechanism, the earthquakes in these regions frequently generate catastrophic tsunamis.

Based on the earthquakes distribution regularities in the island arcs, L.I. Lobkovskii and B.V. Baranov (1985) have developed the keyboard mechanical model of the interaction between the blocks of the lithospheric plates, which explains the characteristic features of the island-arc seismicity. In their model, the mantle lithospheric wedge (the hanging wall of the continental plate) is subdivided into separate key-blocks, each of which responds to the stresses induced by the subducting oceanic plate in its own individual way. The existence of these key-blocks in the forefront parts of the considered region is confirmed by the analysis of the seismicity distribution (e.g., (Avdeiko and Palueva, 2010)) and by the geophysical methods, primarily by the recent geomagnetic studies (Palshin et al., 2011; Brusilovskii et al., 2012). A system of the conductive fault zones is also revealed in the frontal zone of Kamchatka based on the MT sounding data (Moroz et al., 2008).

Many strong earthquakes occur in doublets: an earthquake caused by the underthrusting of the oceanic plate beneath the continental one is followed after a short while by an outer rise extensional earthquake in the oceanic plate (Lay, 2011). To all appearances, it is this type of earthquakes that are the predominant mechanism of the hydration of the subducting oceanic plate, providing the excessive amount of water which is required, in particular, for the serpentinization of the basalts (Kerrick, 2002). The formation of an elongated zone in the frontal part of the island arc, which is marked with a positive magnetic anomaly, a negative gravity anomaly, and low elastic velocities (Puruker and Clark, 2011) confirms the existence of the last process.

A similar characteristic anomaly (Fig. 6), which was called a magnetic belt and which has long since been known in the frontal part of Japan (Ocubo et al., 1989), is also identified in the frontal zone of the Kuril island arc. This was convincingly demonstrated by the results of the latest studies conducted in the scientific oceanic cruises by the Institute of Oceanology of the Russian Academy of Sciences and the Pacific Oceanological Institute of the Far East Branch of the Russian Academy of Sciences (Brusilovskii et al., 2012). It can be hypothesized that the presence of a magnetic belt is a marker of the block structure of the frontal zone and the active processes of serpentinization in the upper mantle. A characteristic feature of these island arcs is the presence of strong doublet earthquakes which are capable of generating catastrophic tsunamis and whose mechanism can be described by Lobkovskii's keyboard model.

The multi-year studies of the upper mantle's electrical conductivity in the northwestern Pacific by the Japanese geophysicists (Shimizu et al., 2010) testify to the significant distinctions in the electrical conductivity of the upper mantle between the Pacific Plate and the continental (Okhotsk and Amurian) plates: the oceanic plate has far lower conductivity. Significantly higher conductivity is also characteristic of the Philippine Sea Plate (Baba et al., 2010).

However, for improving the reliability of the interpretation of the MT and MV soundings which form the basis of the models described above, it is necessary to learn to take into account the influence of the conductive zones of different scales and origins, which exist both in the crust and in the upper mantle of these regions.

NUMERICAL MODELING OF THE EM FIELDS FOR THE IDEALIZED ISLAND MODEL

For assessing the effects of a network of conductors presumably existing in the Earth's crust and/or upper mantle of the island arc systems of northeastern Asia, we constructed an idealized model of an island. The model has an elongated shape (450 × 150 km). The key features of the model are (1) the presence of two faults normal to the long side of the island; (2) the presence of a central fault cutting through the entire island along the axis; and (3) the presence of a crustal layer galvanically connecting the system of orthogonal faults (Fig. 7).

The normal faults have integral conductivity of 3000 S, the conductivity of the central fault is 5000 S, and the conductivity of the crustal layer is 2000 S. The calculations were conducted by a well-known program developed by Randy Mackie (Mackie and Madden, 1993) on a 99 × 129 × 33 grid for a set of periods in the interval from 100 s to one day. The hosting medium was modeled by the averaged one-dimensional (1D) section for the Pacific Plate (Fig. 8). The section was built based on the results of the seafloor MT soundings (Baba et al., 2013).

A large number of computations were carried out for different variants covering all the probable combinations of faults and the crustal layer for both the 3D and 2D versions of the model.

Let us initially consider the effects of three-dimensionality. Figure 9 shows the results in the form of apparent resistivity and impedance phase curves which illustrate the distinctions between the 3D and 2D versions of the model without faults but with a crustal layer. Figure 10 displays the behavior of the apparent resistivity along the profile for the model shown in Fig. 9. Evidently, the results obtained for the 3D (island effect) and 2D models (coast effect) differ significantly.

First of all, we note that both the longitudinal and transverse apparent resistivity components in the island for both the 2D and 3D models do not correspond to the locally normal (1D) curve, and the interpretation of the MT data here can only be conducted with allowance for the coast effect. Similar results were previously obtained by us in the analysis of the 3D coast effect in Primorie (Nikiforov et al., 2004).

Farther offshore from the island, the apparent resistivity approaches its locally one-dimensional values, i.e., normalization takes place. Remarkably, the apparent resistivities for the 3D model become normalized at shorter distances from the island than for the 2D model.

At a distance of 200–300 km from the coast, the transverse component for both the 2D and 3D models shows the known features that lead to the violation of the dispersion relation. These features were previously analyzed in a separate paper (Alekseev et al., 2009);

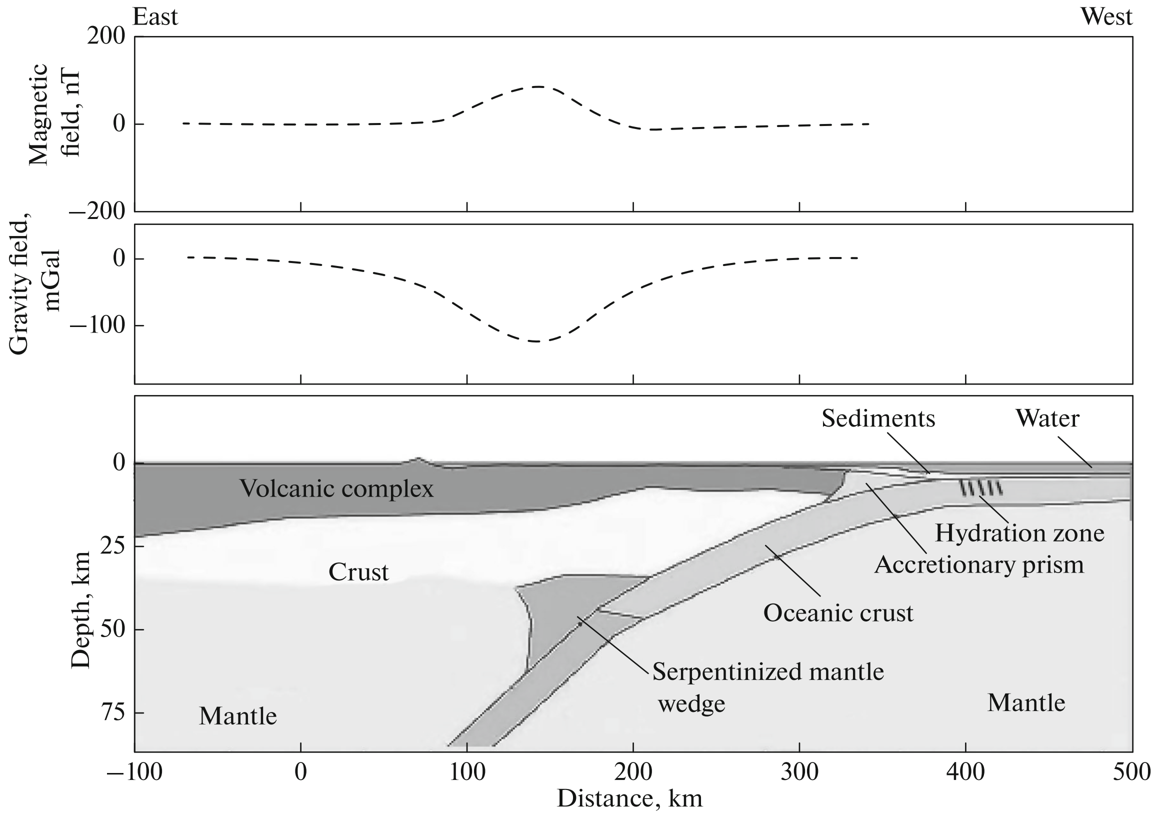

Fig. 6. The schematic model of the formation of a magnetic belt in the frontal part of the island arcs. Modified after (Puruker and Clark, 2011).

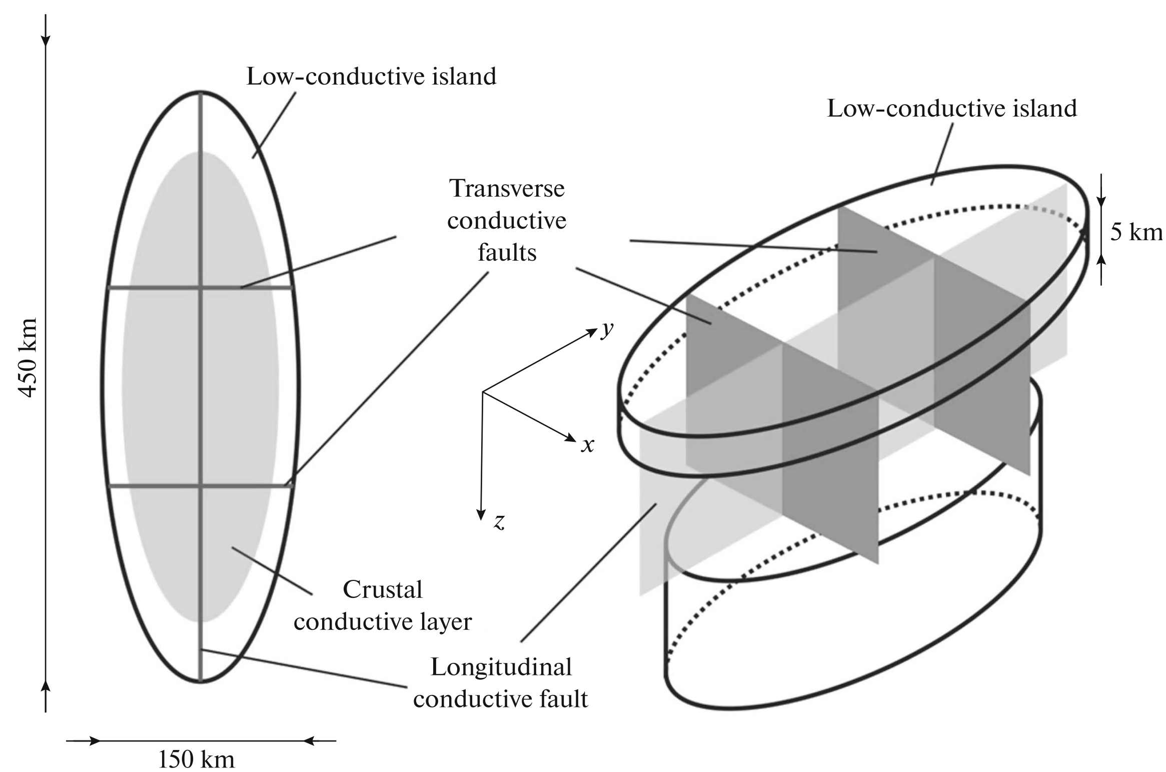

Fig. 7. The model of the idealized island of the island arc with a system of orthogonal faults and crustal layer.

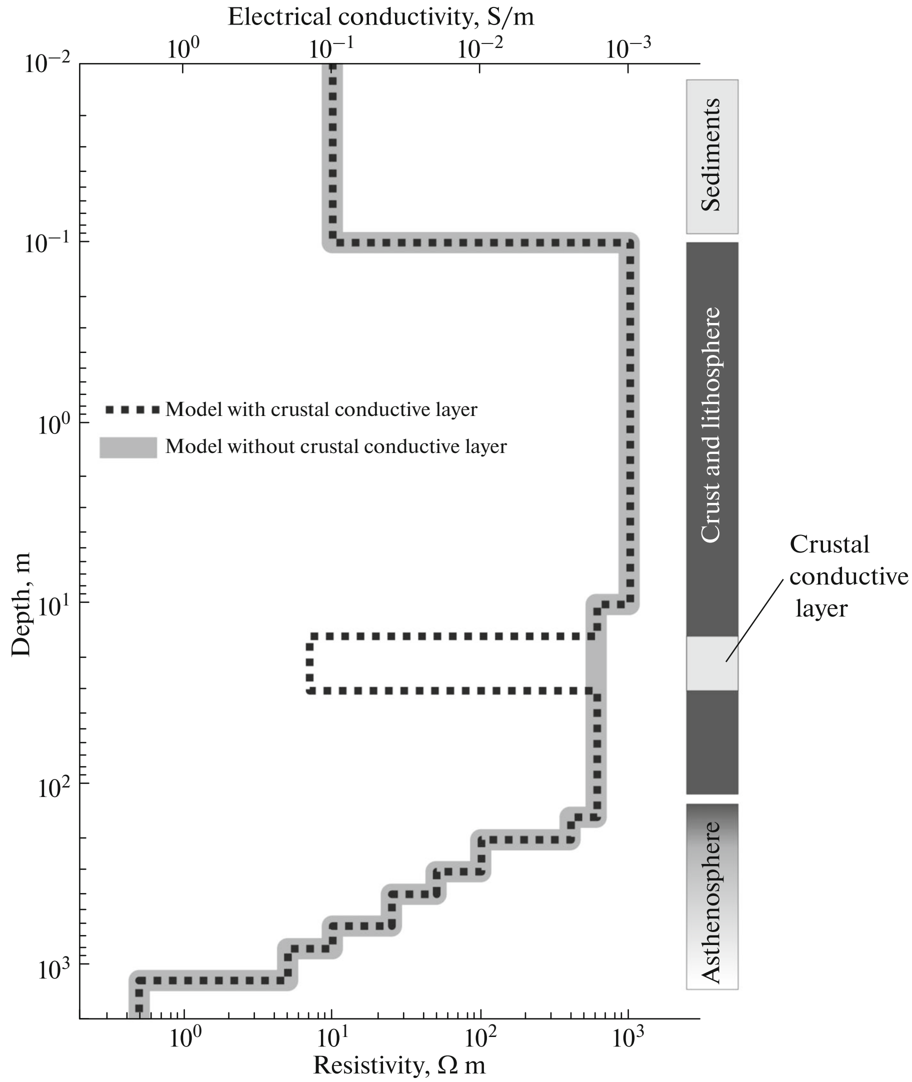

Fig. 8. The background 1D section (see text).

therefore, we do not discuss them here. The anomalies in the longitudinal component of apparent resistivity (and the impedance phase) are much smaller than in the transverse component (e.g., (Vanyan and Palshin, 1990)). At the same time, the normalizing effect of three-dimensionality on the transverse component is much stronger than on the longitudinal component: for the latter, the normalization for the 2D and 3D models differs little.

Below, for analyzing the model parameters determining the normalization of the values of apparent resistivity, we mainly limit the analysis to considering the behavior of the transverse component of the apparent resistivity and impedance phase since this component determines the anisotropy of the impedance tensor.

Figure 11 illustrates the behavior of the transverse component of apparent resistivity for different variants of the island model. The most important characteristic for understanding the coast effect in the ocean is the rate of its decay with the distance from the island (coast). The calculations show that the slowest decay is observed in the apparent resistivity in the model without the faults and with the normal faults alone. Introducing the orthogonal fault system into the model noticeably speeds up the attenuation, and adding the crustal layer leads to even faster normalization of the transverse component. The fact that introducing the system of orthogonal faults leads to a mixing of the longitudinal and transverse apparent resistivity components within the island is yet another conclusion from the analysis of the results for all the probable variants of the model. For instance, this effect was revealed on the eastern coast of Kamchatka (Moroz et al., 2008).

Generally, computing the models that contain faults (or fault zones) by the classical grid methods

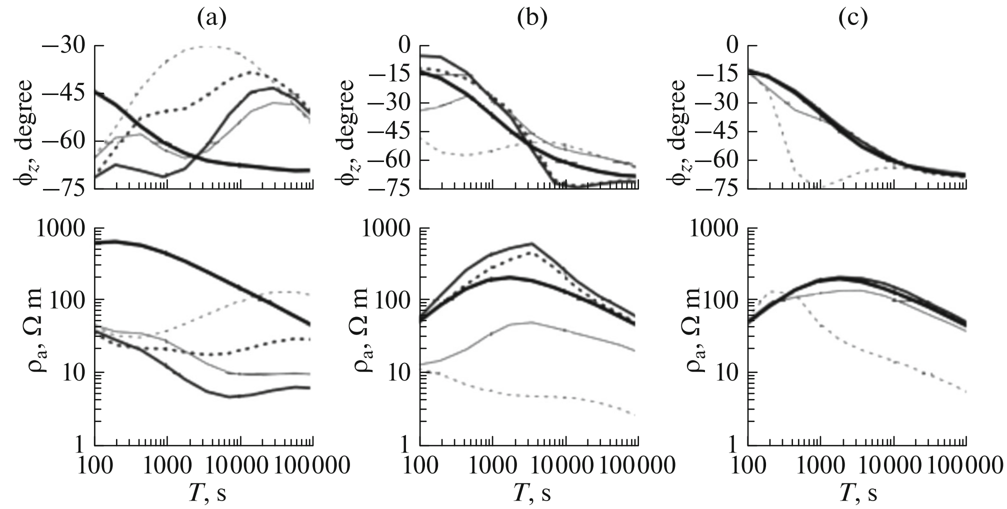

Fig. 9. The comparison of the MT curves above the island for the 2D and 3D models with a crustal conductor: (a) above the middle of the island; (b) 200 km offshore; (c) 500 km offshore. The dashed and solid lines show the curves for 2D and 3D model, respectively. The thin and medium lines are the transverse and longitudinal curves, respectively. The thick solid lines are the local 1D curves. The values beyond the island are the apparent resistivities and impedance phases on the seafloor.

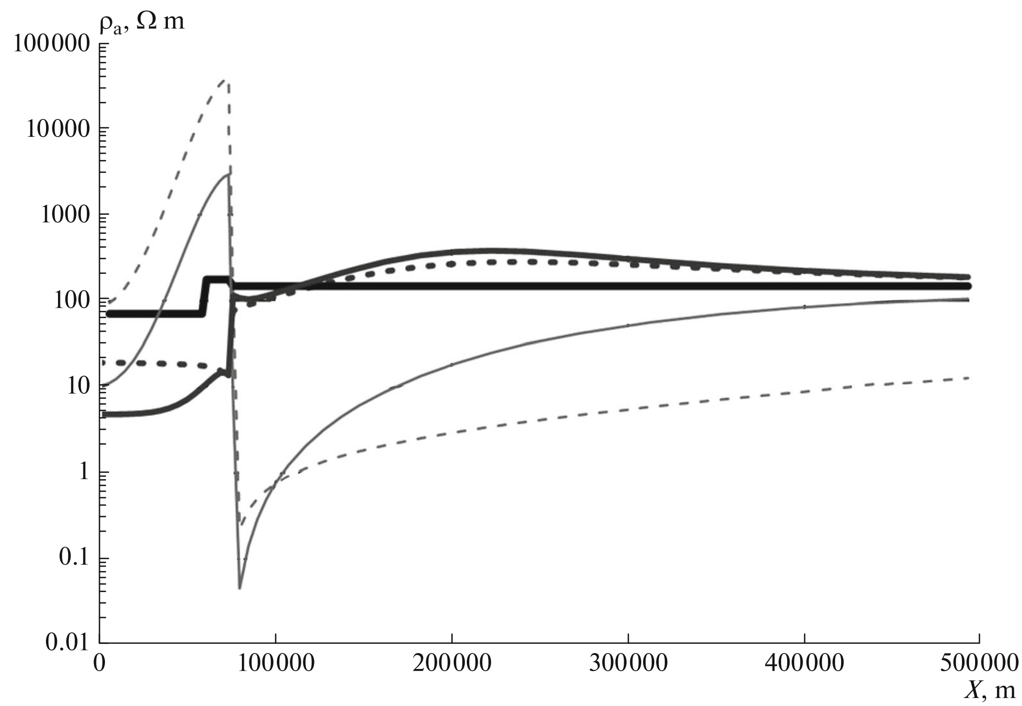

Fig. 10. A comparison of the 2D (coast) and 3D (island) effect in the values of the longitudinal and transverse components of apparent resistivity. The values of apparent resistivity are shown at a period of 2 h on the central profile passing through the center of the island. *X* is the distance from the center of the island in m; the coast is located at a distance of 75000 m. The dashed and solid lines are the apparent resistivities for the 2D and 3D models, respectively. The thin and medium lines are the transverse and longitudinal apparent resistivities. The thick solid line shows the locally normal values of apparent resistivity. The numbers beyond the island indicate the values of apparent resistivity on the seafloor.

(finite difference or finite element) is burdensome. The faults have a fairly small width; in fact, they are geological singularities which have practically only two dimensions. For specifying the faults, one has to strongly refine the grid, which leads to the unreasonable growth of the matrix size. The adequate grid approximation of the 3D models with the fault zones is particularly difficult, and to mitigate this difficulty, one has to significantly coarsen the description of fault tectonics.

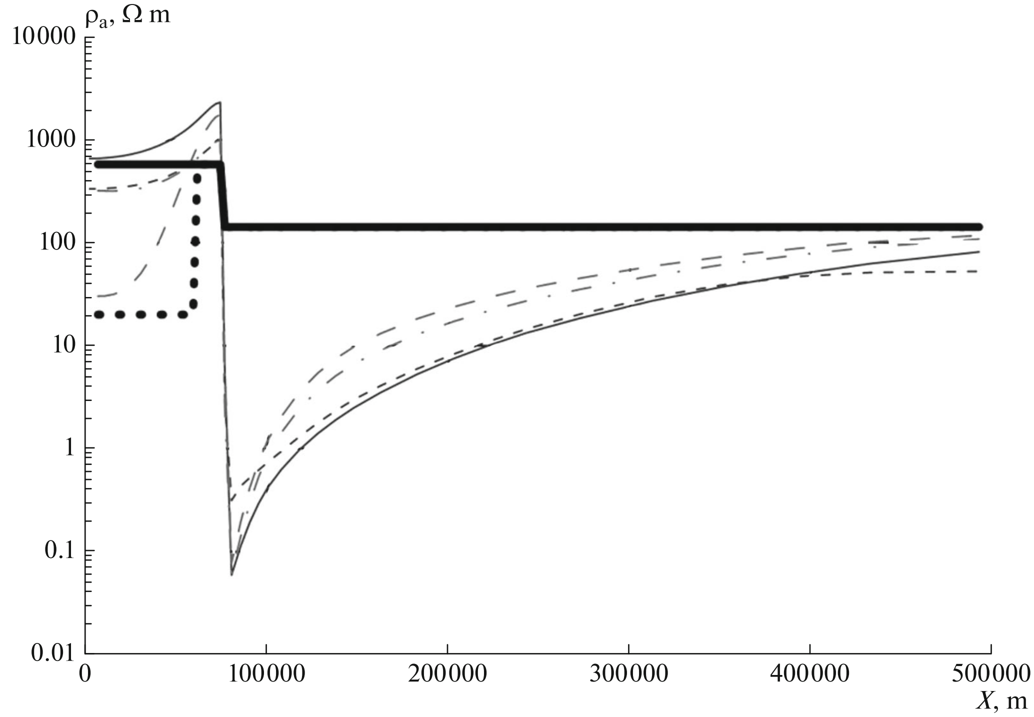

Fig. 11. The influence of the system of conductive faults on the island effect. The values of the transverse apparent resistivity are shown in the period of 450 s on the central profile passing through the middle of the island. *X* is the distance from the center of the island in m; the coast is located at a distance of 75000 m. The thin solid line corresponds to the variant without conductive faults and a crustal conductive layer. The thin dashed line with short dashes corresponds to the variant with transverse faults. The thin dashed-dotted line corresponds to the variant with the transverse and central faults. The thin line with long dashes corresponds to the variant with all faults and a crustal conductive layer. The thick solid line shows the locally normal values of apparent resistivity for the variant without a crustal conductive layer. The thick dashed line shows the locally normal values of apparent resistivity for the variant with a crustal conductive layer. The numbers beyond the island indicate the values of apparent resistivity on the seafloor.

A straightforward way to describing the fault tectonics lies in specifying the anisotropy of the electrical conductivity. We constructed the 2D anisotropic model based on the central cross section of the cited 3D model of the idealized island which was previously used for calculating the isotropic model with faults. This model was added by three anisotropic blocks (Fig. 12). The calculations were conducted by the program designed by Joseph Pek (Pek and Toh, 2000).

The first block emulates the central conducting fault zone; it is described by the sharply reduced vertical and transverse resistivity compared to the longitudinal resistivity (1, 1000, 1). We note that modeling the influence of narrow fault zones on the regional EM field with the use of grid methods is a difficult task, and introducing the anisotropy is likely to be an efficient way of parameterization of the conductive fault zones.

The second anisotropic block corresponds to the frontal zone of the island arc, which is moderately anisotropic: the electrical conductivity is high in the longitudinal and vertical directions (1000, 10, 10). Thus, we simulate the system of the faults that are orthogonal to the strike of the subduction zone, typical of the frontal zones of the island arcs (see above).

The third anisotropic block was introduced for testing the hypothesis concerning the presence of vertical anisotropy in the subducting plate. The existence of anisotropy in a young lithosphere is evident, whereas in the old subducting lithosphere, the anisotropy can emerge due to the high deep-seated seismicity (see above). The anisotropic parameters for the subducting lithosphere were specified by the same values as for the frontal zone of the island arc but with the predominance of the transverse and vertical conductivity components (10, 1000, 10).

The island had a width of 150 km; the ocean had a depth of 5 km; and in the depth interval from 15 to 25 km beneath the island arc, there was a conductive (1500 S) crustal layer galvanically connected with the surface through the central fault (anisotropic block 1). On the surface of the island and on the seafloor there were conductive sediments. The parameters of the background 1D cross section were taken by us from the 3D model (see above).

The parameters of the anisotropic model were selected fairly arbitrarily because obtaining the anisotropy estimates is barely possible. At this stage, we did not intend to construct a realistic model of electrical conductivity; our purpose was rather to evaluate the

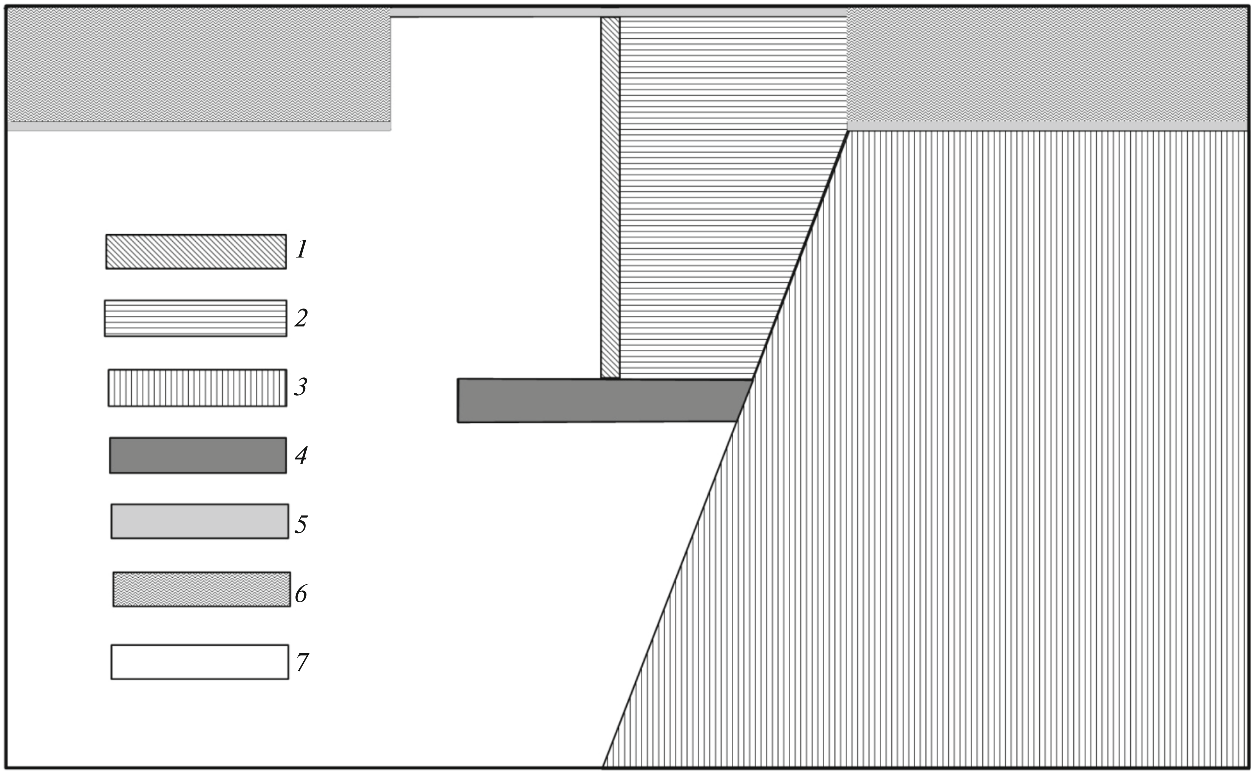

Fig. 12. A 2D anisotropic hypothetical model of island arc: (*1*) the first anisotropic block, (*2*) the second anisotropic block; (*3*) the third anisotropic block; (*4*) a crustal conductive layer; (*5*) conductive sediments; (*6*) sea water; (*7*) background 1D section. See also the text.

influence of the hypothetical anisotropic model, which was postulated based on the a priori data, on the behavior of the apparent resistivity. The results of the calculations for a period of 450 s are presented in Fig. 13. Quite expectedly for our model, anisotropy does not affect the results for the TE mode, whereas the TM-mode coast effect dies out as steeply as 200–300 km off the shore. Thus, we managed to select the anisotropic parameters at which the calculated coast effect basically corresponds to the observed one.

The use of the anisotropy of electrical conductivity as a means for parameterization of the fault tectonics is an evident solution of the problem of increasing the reliability of the solution of direct and inverse problems in the deep regional EM studies. Parameterization is a process of structuring the properties and characteristics of the model, and reducing them to the common (unified) classes of the initial data. In our case, we will specify the anisotropic conductivity in fairly large cells in such a way as to adequately describe the existence of the conductive faults with the widths that are far smaller than the cell size.

CONCLUSIONS

Deep electrical conductivity is an important parameter which permits estimating the temperature in the upper mantle and the content of various conductivity-controlling impurities in the mantle material. These estimates are independent of the traditional estimates obtained by the seismic methods because the dependence of electrical conductivity on the physical properties of the rock is based on different principles than the behavior of elastic waves.

In general, the electrical conductivity of the upper mantle monotonically increases with depth due to the growing temperature and pressure. The lateral variability observed in the electrical conductivity of the upper mantle is due to the water content because, in contrast to temperature and pressure, this parameter can vary widely. Besides, the high water content significantly lowers the solidus of the mantle rocks which causes the wet partial melting. The influence of the water content decreases with the growth in temperature and pressure as the polaron and ionic mechanisms become predominant over the proton mechanisms which prevails in the temperature interval from 600 to 1200°C.

For the subduction zones overall and, especially, for the subduction zones of the Far East considered in the present paper, it is characteristic that they contain the subvertical fault zones. The existence of the fault zones is verified by a variety of geophysical methods. These fault zones exist within the frontal parts of the

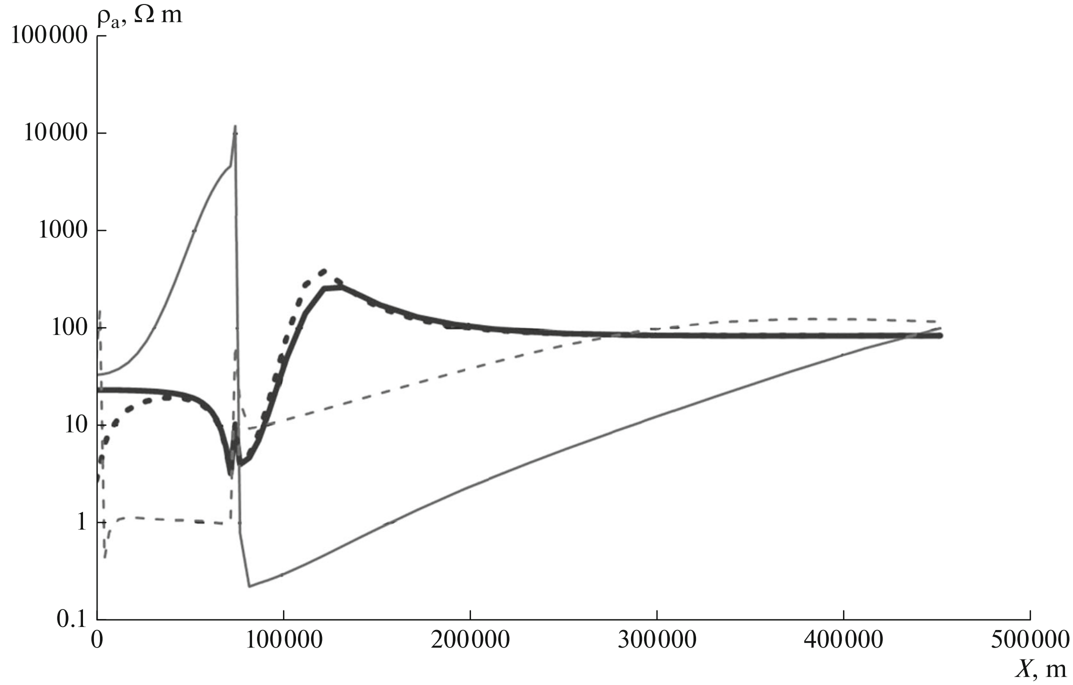

Fig. 13. The influence of the system of conductive faults specified by the anisotropy of electrical conductivity on the coast effect. The values of the transverse component of apparent resistivity are shown in the period of 450 s on the central profile passing through the middle of the island. *X* is the distance from the center of the island in m; the coast is located at a distance of 75000 m. The thin lines show TM mode (the solid line corresponds to the isotropic model and the dashed line corresponds to the anisotropic model). The thick lines show the TE mode (the solid line corresponds to the isotropic model and the dashed line corresponds to the anisotropic model). The numbers beyond the island indicate the values of apparent resistivity on the seafloor.

island arcs and in the zone of the oceanic plate subduction (outer rise). The process of the formation of deep faults parallel to the island arcs plays a key role in the fluid conveyor, permitting the oceanic water penetration deep into the subducting plate, where the fluids become chemically bounded by the hosting rocks. These fluids then descend to large depths where dehydration processes take place. Part of these fluids is likely to reach the mantle transition and determine the intraplate activation of the continental margin of Eurasia. These factors are also responsible for the significant lateral variability of the electrical conductivity of the mantle caused by the proton conductivity mechanism.

The study of the deep electrical conductivity is complicated by the presence of surface heterogeneities: island arcs and deep-sea trenches, the complicated configuration of the coastline, the presence of marginal back-arc seas, and the existence of a system of mutually perpendicular deep faults.

The coast (island) effect in the EM fields, which is caused by these heterogeneities, typically cannot be used for obtaining information about the deep structure of the subduction zone. The anomalous EM fields are virtually fully determined by the configuration of the coastline, the bathymetry of the coastal areas, and the geoelectrical structure of the narrow coastal zone controlling the leakage of electrical currents from the water layer to the deeper conductive continental layers through the subvertical conductive zones.

The complicated structure of the region largely determines the specific features of the EM field:

—due to the presence of the system of orthogonal faults in the island arcs and oceanic crust, the anomalies in the EM field become significantly normalized, thus reducing the intensity and range of action of the coast (island) effect. This normalization in some cases allows us to use the 1D approach for obtaining the information about the distribution of electrical conductivity in the upper mantle;

—two polarizations become intermixed, which virtually excludes the possibility of using the traditional bimodal 2D approach in the interpretation of the EM data.

The deep structure of the region can be studied in the scope of 3D models or 2D anisotropic models. The use of the anisotropy of electrical conductivity (macro-anisotropy) as a means for parameterization of the fault tectonics appears to be an efficient instrument.

Increasing the efficiency of the EM data interpretation is impossible without obtaining the new empirical data, primarily in the poorly studied regions of the Sea of Japan and the Sea of Okhotsk.

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