ISSN 1069-3513, Izvestiya, Physics of the Solid Earth, 2012, Vol. 48, No. 4, pp. 287–296. © Pleiades Publishing, Ltd., 2012.
Original Russian Text © Yu.F. Moroz, T.A. Moroz, 2012, published in Fizika Zemli, 2012, No. 4, pp. 3–13.

Correlation of the Anomalies in the Electric Field and Electric Conductivity of the Lithosphere to Earthquakes in Kamchatka

Yu. F. Moroz and T. A. Moroz

Institute of Volcanology and Seismology, Far Eastern Branch, Russian Academy of Sciences, bul'v. Piip 9, Petropavlovsk–Kamchatskii, 683006 Russia

Received June 4, 2010; in final form, September 6, 2011

Abstract—The data of long-term electromagnetic monitoring are used for studying the dynamics of electric conductivity of the medium and the electric field of the terrestrial sources. The electric conductivity of the medium is estimated from the magnetotelluric transfer functions (impedance tensor and telluric tensor). The electric field of terrestrial sources is identified by filtering the variations of the observed electric field of the Earth. The magnetotelluric parameters and the electric field of terrestrial sources feature anomalous changes of supposedly earthquake-related origin. The anomalies associated with the same earthquake are not simultaneous. It is shown that these anomalies are generated by processes occurring at different depths. The strong earthquake is preceded by the appearance of surface anomalies several months before the event and accompanied by a deep coseismic anomaly. The probable nature of the recognized anomalies is discussed.

Keywords: electric conductivity, impedance tensor, geoelectric heterogeneity.

DOI: 10.1134/S1069351312010090

INTRODUCTION

The electric field of the Earth contains information about the electric conductivity of the geological medium and the terrestrial electric sources, which are associated with the electrochemical, piezoelectric, and many other processes. In order to retrieve this information, the variations generated in the electric field by the external (ionospheric and magnetospheric) should be separated from those caused by the terrestrial sources. The variations in the electrotelluric and geomagnetic fields induced by the external sources are used as the input data for determining the electric conductivity of the Earth's crust and the upper mantle. If we eliminate the variations of the electrotelluric field from the electric field of the Earth, we will obtain the electric field generated by the terrestrial sources alone.

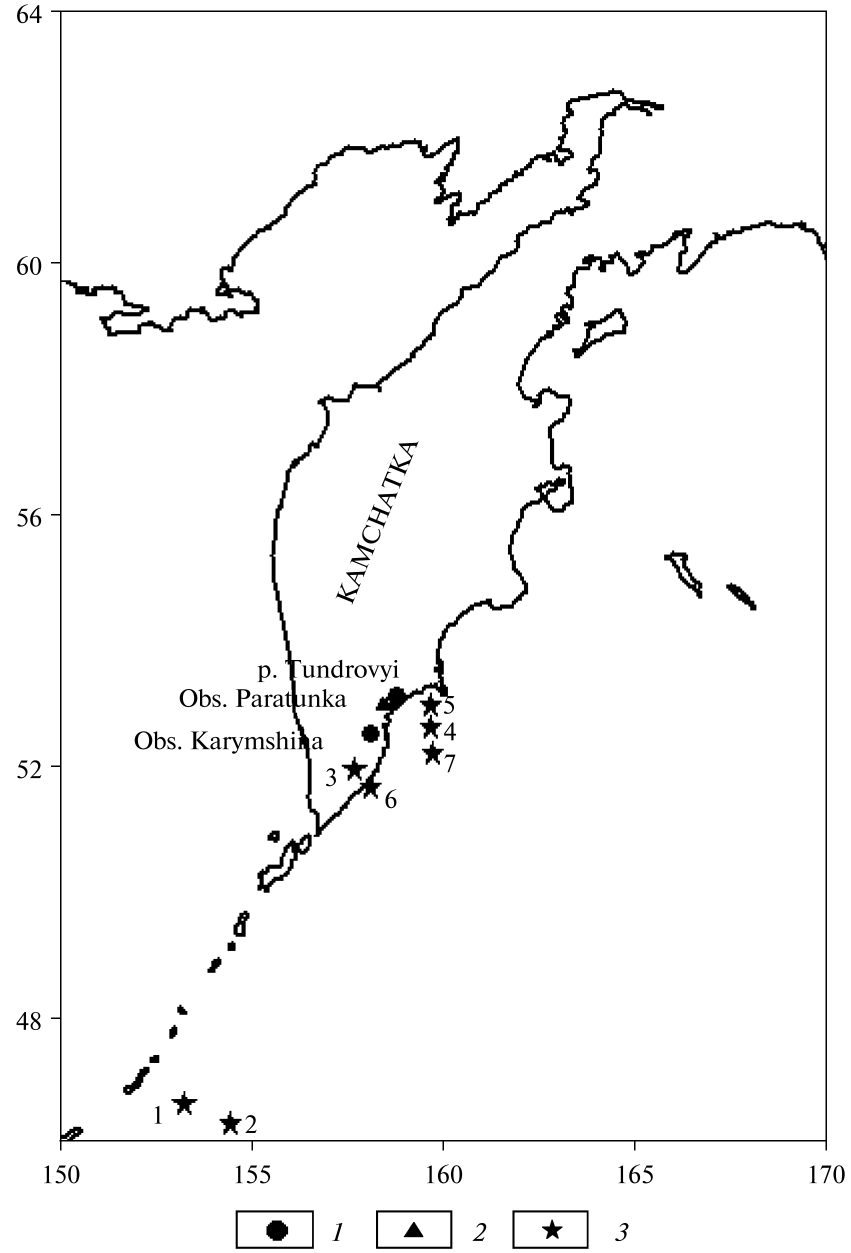
By applying this approach to the data measured at the Karymshina observatory and at the Tundrovyi observation point in Southern Kamchatka, we revealed anomalous changes in the behavior of the electric conductivity of the lithosphere and the electric field of terrestrial sources. These preseismic and coseismic anomalous changes are associated with the surface and deep processes that take place in the Earth's crust. The anomalies corresponding to the same seismic event are not synchronous; this question is studied in the present paper.

A BRIEF GEOELECTRIC OUTLINE OF THE REGION

The electromagnetic observations were carried out on the shore of the Avacha Bay (Fig. 1). This region is dominated by transverse northwest trending structures, which were named the Malko–Petropavlovsk dislocation zone (*Geologiya*..., 1964).

The observation point at Tundrovyi is located in the region of the Ganal horst anticlynorium where the ancient metamorphic rocks of the Cretaceous and Proterozoic age outcrop. These rocks are associated with the consolidated basement that underlies the Cenozoic sedimentary-volcanic strata which have a thickness of 300 m at the observation point. The electric resistivity of these rocks is 60 Ω m. The Upper Cretaceous formations with a resistivity of a few hundred Ω m rest on a poorly conductive metamorphic basement characterized by the electric resistivity of several thousands of Ω m.

The Karymshina observatory pertains to the Nachika folded zone. Along the large, deep transverse fault, this zone contacts the Southern Kuril anticlynorium with the superimposed East Kamchatka volcanic belt. The increase in the intensity of the magnetic and gravity fields characteristic of this zone reflects the presence of denser rocks with higher magnetization. These are the older metamorphozed rocks of the Pre-Cretaceous age approaching the surface and outcropping at places in this region. The Karymshina observatory is located close to the neotectonic graben of the



No.	date	depth	magnitude
1	Nov. 15, 2006	29	8.3
2	Jan. 13, 2007	10	8.2
3	May 30, 2007	120	6.4
4	Nov. 17, 2007	17	5.7
5	Nov. 17, 2007	40	5.3
6	Nov. 17, 2008	82	5.5
7	Jan. 14, 2009	11	5.5

Fig. 1. The layout of the sites of electric and geomagnetic observations and the epicenters of the earthquakes. (*1*) the points of the electric field measurements; (*2*) the measurement points of geomagnetic variations; (*3*) the epicenters of the earthquakes with dates and magnitudes. The dates, the hypocentral depths, and the magnitudes of the earthquakes are indicated in the table.

Paratunka River. Here, the Cenozoic sedimentary-volcanic cover has a thickness of one kilometer and a resistivity of 30 Ω m. The crystalline basement with a resistivity amounting to several thousands of Ω m is recognized at a depth of 5 km.

According to the generalized electromagnetic evidence, the lithosphere of Southern Kamchatka includes a highly conductive layer in a depth interval from 20 to 40 km; the electric resistivity in this layer is a few tens of Ω m. The asthenospheric layer having an increased electric conductivity is identified at a depth of 100–200 km (Moroz, Laguta, and Moroz, 2008).

THE OBSERVATION SETUP AND PROCESSING TECHNIQUE

The Tundrovy observation point and the Karymshino observatory recorded the electric field with 10-s and 1-s sampling, respectively. The layout of the measurement lines MN is shown in Fig. 2. Measurements at the Tundrovyi observation point were carried out with lines 1 and 2 parallel and perpendicular to the meridian and the lines 3 and 4 oriented in the azimuths 40° and 310°, respectively. The lengths of lines 1, 2, 3, and 4 are 97, 105, 65, and 90 m, respectively. At the Karymshina observatory, the Γ-shaped setup with a central (zero) electrode is used. The receiving lines are arranged along the meridian and along the latitude. Lines 01 and 04 are 80 m long; lines 02 and 05 have a length of 240 m; and lines 03 and 06 have a length of 480 m. The lead electrodes placed to a depth of 2–3 m were used for grounding at both sites. The electric potential is measured by automated digital instruments. The data are transferred via radio channels to the data processing center in Petropavlovsk–Kamchatskii. The automated electric measurements and data preprocessing are operated by the Kamchatka division of the Geophysical Survey of the Russian Academy of Sciences.

The preprocessing of the time series of electric potential includes editing the data, identifying the failures in records, interpolating, averaging, scaling, and other procedures. The output results are compiled into a database that comprises yearly, monthly, and daily time series. For elaborate data processing, a specialized computer program was designed which calculates the magnetotelluric transfer functions (magnetotelluric impedance and telluric tensor) and variations of the electric field of terrestrial sources. This program outputs synchronous time series of the electric potential of the desired length. These time series were used for studying the dynamics of the electric conductivity of the lithosphere and identifying the electric field induced by terrestrial sources.

THE ANALYSIS OF THE MAGNETOTELLURIC TENSOR IMPEDANCE

Magnetotelluric variations in the middle and low latitudes are rather closely approximated by a plane wave model. This model implies a linear relation between the horizontal vectors of the electric and geomagnetic field at a point on the Earth's surface (Berdichevsky and Zhdanov, 1981):

$$\mathbf{E}_{\rm hor} = \hat{\mathbf{Z}}\mathbf{H}_{\rm hor}, \text{ where } \hat{\mathbf{Z}} = \begin{vmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{vmatrix},$$

or, in expanded form,

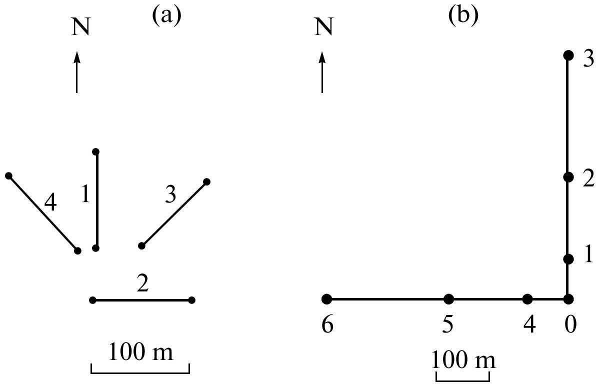


Fig. 2. The schematic setup of electric field measurements at (a) p. Tundovyi and (b) obs. Karymshina. The numerals indicate the numbers of the electrodes. The scale is shown for the measurement lines.

$$E_x = Z_{xx}H_x + Z_{xy}H_y;$$
$$E_y = Z_{yx}H_x + Z_{yy}H_y,$$

where $\hat{\mathbf{Z}}$ is the tensor impedance with the complex components Z_{xx}, Z_{xy}, Z_{yx}, and Z_{yy} which depend on the frequency, the distribution of electric resistivity in the Earth, and the orientation of coordinate axes.

The impedance tensor characterizes the complex resistance of the medium (capacitative, inductive, and resistive). The complex components of the impedance tensor can be cast in the following form:

$$Z_{xy} = |Z_{xy}|e^{i\varphi_{xy}};\ Z_{yx} = |Z_{yx}|e^{i\varphi_{yx}},$$

where $|Z_{xy}|$, $|Z_{yx}|$ and φ_{xy}, φ_{yx} are the moduli and the phases of the impedance.

The moduli of impedance can be recalculated into the values of apparent resistivity of the medium in the following way: $\rho_a^{xy} = 0.2T|Z_{xy}|^2 \rho_a^{yx} = 0.2T|Z_{yx}|^2$, where T is the period of variations.

Thus, using the variations of the magnetotelluric field, one may calculate the apparent resistivity and impedance phase in different directions as functions of the period of variations. It is worth noting that the impedance phase data largely improve and expand the information inferred from the apparent resistivity data. Below, we present some examples.

As is well known, compared to the magnetic field, the electric field is more sensitive to the geoelectric heterogeneity of the medium. Its increased sensitivity is associated with the galvanic effects which affect the amplitude curves leaving the phase curves undistorted. The example in Fig. 3 adopted from (Moroz, Laguta, and Moroz, 2008) shows the amplitude curves of apparent resistivity and the impedance phase curves for one region in Kamchatka. We see that the scatter in the resistivity level of the amplitude $\rho_{\rm a}$ curves attains about three orders of magnitude, whereas the phase curves are confined to approximately the same level.

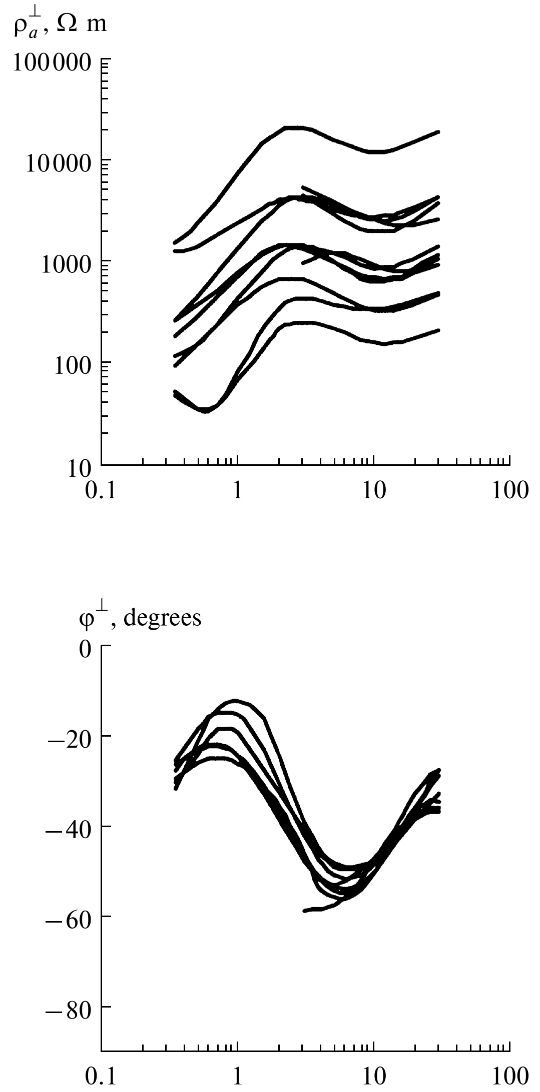


Fig. 3. The ensembles of the individual transverse MTS curves.

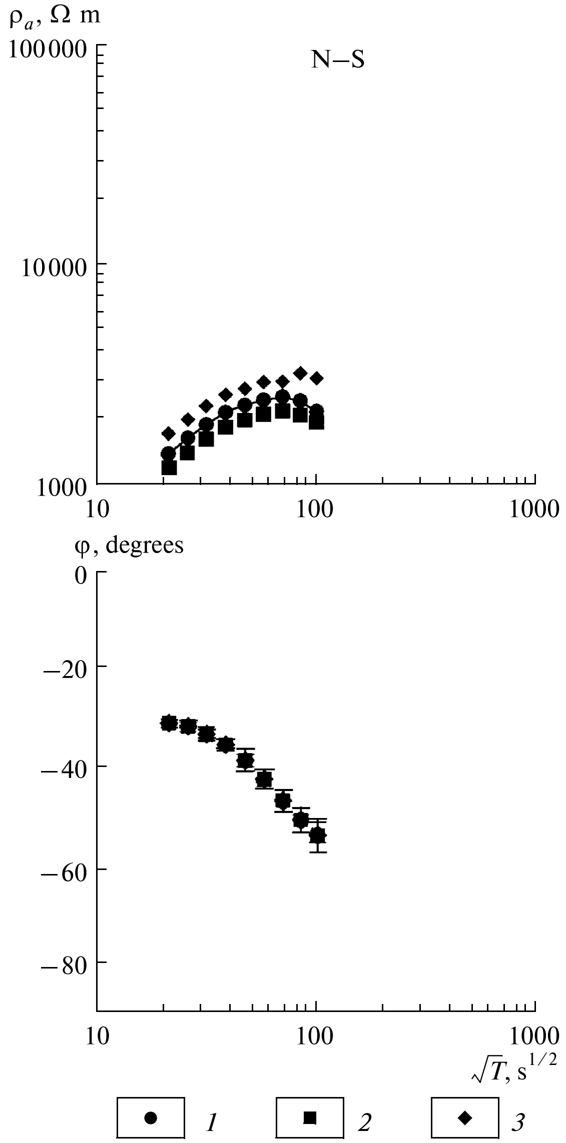


Fig. 4. The MTS curves at Karymshina for lines with various lengths. *1*, *2*, and *3* are the MTS curves for lines 03–06, 02–05, and 04–01, respectively (see Fig. 2b).

This phenomenon is called ρ effect. Another example in Fig. 4 shows the amplitude curves ρ_a and the impedance phase curves measured at the same observation point of the Karymshina observatory with the MN line having different lengths. It is clearly seen from these graphs that the effects of local geoelectrical heterogeneities commensurable in size with the length of the receiving line cause the amplitude curves of the apparent resistivity to diverge from each other while the corresponding impedance phase curves coincide, merging into one graph.

Thus, we arrive at an important conclusion which should be taken into account when analyzing the data of monitoring the magnetotelluric impedance. If the time series of the apparent electric resistivity (impedance) contain variations but these variations are not shown in the impedance phase, the studied cross section is dominated by the ρ effect associated with local geoelectric heterogeneities. If the time series of the impedance phase exhibit anomalous variations, they testify to the changes in the deep electric conductivity of the geological environment.

In order to illustrate this point by the example, we consider the results of monitoring the electric conductivity of the lithosphere at the Karymshina observatory in 2005–2008. The magnetotelluric impedance and its phase were measured at periods of 477, 700, 1050, 1570, 2340, 3460, and 5080 s. The time series are calculated from the electric field measurements at the Paratunka observatory with lines 0–3 and 0–6. In our

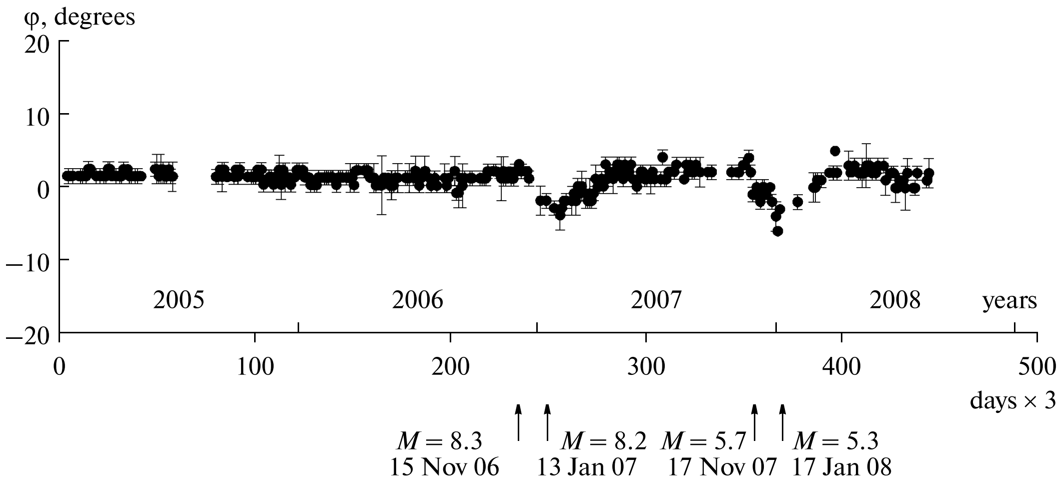


Fig. 5. The phase curve of the transverse impedance at a period of 700 s. The occurrence time and the magnitudes (*M*) of the earthquakes are shown by the arrows on the time axis.

present work, we only show the transverse impedance phase curve at a period of 700 s (Fig. 5). An important feature of this curve is the presence of bay-like variations whose magnitude attains 5–7 degrees, which is two to threefold above the accuracy of phase determination. The arrows on the time axis of the graph mark the moments of the strongest recent Kuril earthquakes in the Kamchatka-Koryak region, which had magnitudes $M = 8.3$ and $M = 8.2$ and occurred at the epicentral distances of 810 km and 820 km. Also indicated are the moments of the nearest (to the observatory) earthquakes with $M = 5.7$ and $M = 5.5$ that had epicentral distances of 75 and 80 km. These seismic events are supposed to be the sources of the anomalies apparent in the graph of the impedance phase. What is the probable origin of the anomaly in the impedance phase at a period of 700 s? The MT curve measured at the Karymshina observatory has a minimum at 700 s, which reflects the deep conductive zone in the lithosphere. The earthquakes might have changed the degree of mineral fluid saturation of this deep conductive zone, and the phase of transversal impedance has probably felt this change at a period of 700 s.

THE ANALYSIS OF THE TELLURIC TENSOR

The horizontal vectors of the electrotelluric field in two points on the Earth's surface are linked through the following relation (Berdichevsky and Zhdanov, 1981):

$E_1 = \hat{t}E_2$, where $\hat{t} = \begin{vmatrix} t_{xx} & t_{xy} \\ t_{yx} & t_{yy} \end{vmatrix}$ is telluric tensor whose complex components, t_{xx}, t_{xy}, t_{yx}, and t_{yy} depend on the frequency, the distribution of electric conductivity, and the orientation of the coordinate axes. These components can be represented in the following form: $t_{xx} = |t_{xx}|e^{i\varphi_{xx}}$, $t_{xy} = |t_{xy}|e^{i\varphi_{xy}}$, $t_{yx} = |t_{yx}|e^{i\varphi_{yx}}$, $t_{yy} = |t_{yy}|e^{i\varphi_{yy}}$, where $|t_{xx}|$, $|t_{xy}|$, $|t_{yx}|$, $|t_{yy}|$ and φ_{xx}, φ_{xy}, φ_{yx},φ_{yy} are the moduli and phases of the tensor components.

Here, again, as in the case with the impedance tensor, the moduli and the phases of the telluric tensor components contain information on the deep changes in the electric conductivity of a medium. This is clearly seen in the data of electrotelluric monitoring at p. Tundrovyi (Moroz and Moroz, 2009). In this experiment, the electrotelluric field was synchronously measured by two pairs of orthogonal lines oriented in different directions. The analysis showed that the components of the electrotelluric field recalculated to other directions by rotation of the coordinate system does not coincide with the values of the electrotelluric components measured in situ in these directions. This discrepancy is produced by the effects of local geoelectric irregularities commensurable in size with the length of the receiving lines.

We consider the results of monitoring the component t_{yy} at a period 4500 s (in a time interval of 10 days) for the period from January 1, 2001 to October 31, 2007. Figure 6 presents the time series of the modulus and phase of this tensor component. The moments of the strongest Kuril earthquakes with $M = 8.3$ and $M = 8.2$ are indicated by the arrows on the time axis. The modulus of t_{yy} features an anomaly attaining 40–50% of the average level. In contrast, the phase graph does not show an anomaly. This indicates that the anomalous variation in the modulus of t_{yy} is associated with the occurrence or the change in the local geoelectric heterogeneity in the region of the measurement lines, which is probably associated with the change in mineralization of the groundwater or other factors related to the geodynamical processes.

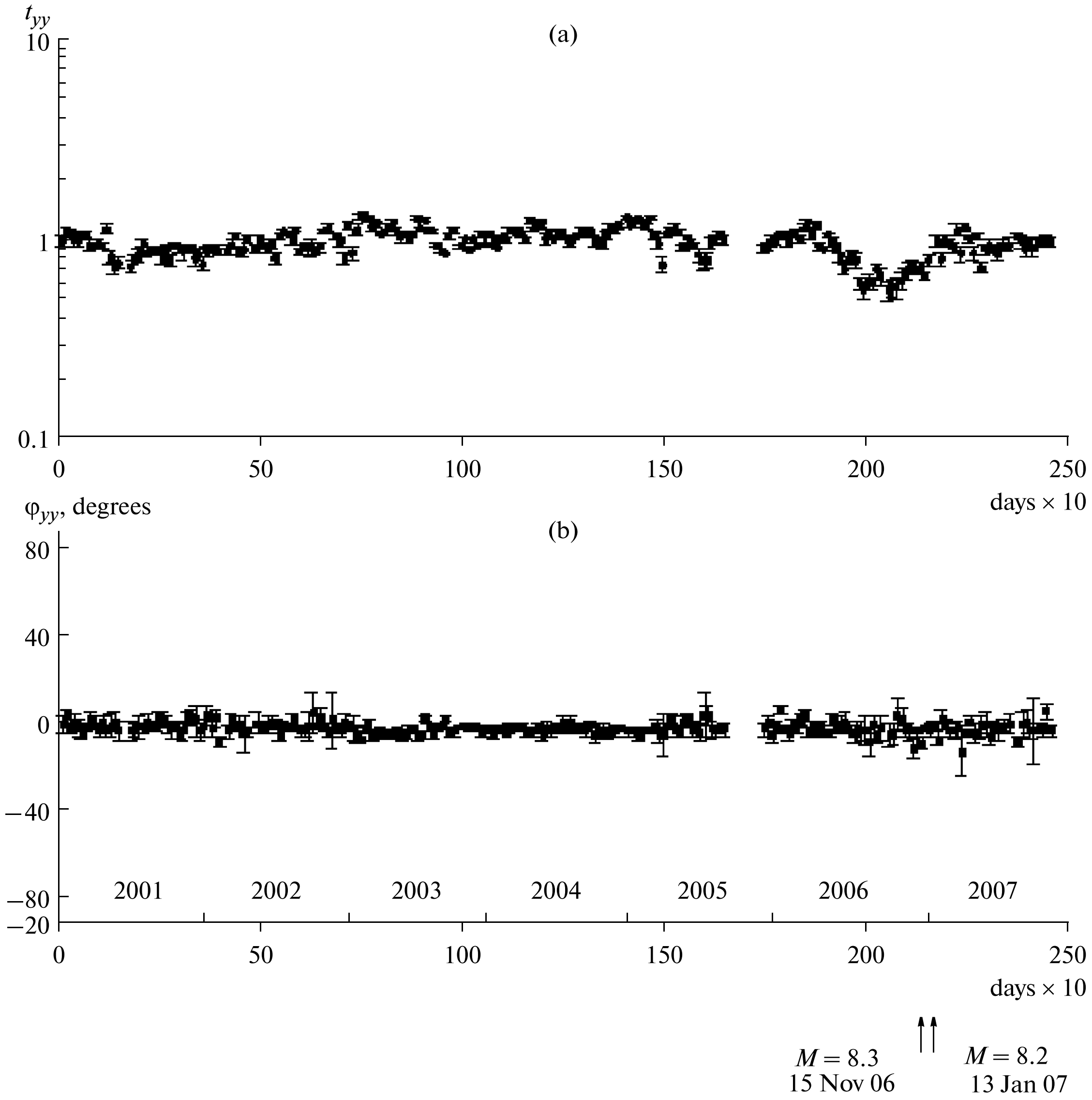


Fig. 6. (a) The modulus and (b) the phase of the telluric tensor component t_{yy}. The occurrence time of the strongest earthquakes ($M = 8.3$ and $M = 8.2$) that hit the Kuril–Kamchatka island arc over the past 30 years are shown by the arrows on the time axis.

THE ANALYSIS OF THE ELECTRIC FIELD OF TERRESTRIAL SOURCES

It is believed that the electric field of terrestrial sources is generated by the electrochemical, electrokinetic, piezoelectric, and other processes occurring in the lithosphere of seismically active regions. How can we separate the variations in the electric field of terrestrial origin from the total electric field of the Earth? The low-frequency electric field of the Earth seems to be a suitable object for this purpose, as the intensity of the external contribution (ionospheric and magnetospheric) to the electric field in this frequency band is low.

For a rough estimation of the intensity of the low-frequency electrotelluric field, we use the relationship $E_{\text{hor}} = ZH_{\text{hor}}$, which is valid for a horizontally uniform medium. Here, E and H are the intensities of the horizontal electric and magnetic fields, respectively, and Z is the impedance (the input complex resistance of the medium). We consider the electrotelluric field at periods longer than one day. This field contains variations with a period of 27 days and their harmonics with the periods of 13.5 and 9 days, as well as annual and semiannual periodic components (Moroz, Nazarets, and Moroz, 2005; Serson, 1973). The typical amplitudes of these variations in the horizontal component of the geomagnetic field in the middle latitudes do not exceed 10 nT (Serson, 1973), whereas during geomagnetic storms they may attain hundreds of nT. In the considered time interval from January 1, 2005 to March 31, 2009, the maximum amplitude of variations in the horizontal geomagnetic component during the strong storms was at most 450 nT. The impedance at periods longer than 9 days is less than 0.05 mV/km nT (Rokityanskii, 1975). Therefore, the intensity of the electrotelluric field during geomagnetic storms will not exceed 22.5 mV/km. According to (Moroz et al., 1999; Moroz, Moroz, and Mogi, 2007), the intensity of low-frequency variations ($T =$ 1.5–2 months) caused by terrestrial sources is several hundreds of mV/km; further, we will discuss such anomalies in the electric field, which have a duration of 1–2 months and an intensity of a few hundred nT. Therefore, when considering the low-frequency electric field of the Earth at periods longer than 9 days, we may ignore the variations caused by extraterrestrial sources.

Let us now analyze the low-frequency electric field monitored at the Karymshino observatory where the measurements are less contaminated by noise. Here, we have the time series of the electric field intensity for the period from January 1, 2005 to March 31, 2009. In our analysis, we used hourly average values of the electric field intensity. The high- and low-frequency variations were eliminated from the data by filtering the time series in the time windows with a width of 50 h and 1000 h, respectively. The resulting time series of the electric field intensity for lines 01, 02, 03, and 04, 05, 06 are presented in Fig. 7. For clarity, the time series are shown on the same vertical scale in mV/km. All the time series feature synchronous anomalous bay-like disturbances that last 1–2 months. The strong variations in the electric field occurred in a geomagnetically quiet period. The intensity of perturbations in the electric field is about a few hundreds of mV/km. The exception is the line 0–6, where the disturbances are weak or almost not pronounced. It is remarkable that higher-intensity disturbances in the electric field are observed with the shorter lines. This indicates that these disturbances are associated with the local subsurface effects in the area of the measurement lines. It is quite possible that these effects are confined to the vicinity of the electrodes and are due to the variations in the mineralization and the level of the groundwater near the electrodes.

We have correlated the time series of the electric field intensity with the occurrences of the strong remote earthquakes ($M = 8.2$ and $M = 8.3$) and those with $M \geq 5.3$ that occurred within a 100-km epicentral distance (Figs. 1 and 7). There were seven such earthquakes overall during the considered time interval. It can be seen from Fig. 8 that most of the earthquakes are preceded by anomalous perturbations in the electric field approximately 1.5–2 months before the event. Similar effects were also observed at Lake Baikal (Moroz, Moroz, and Mogi, 2007), where bay-like variations attaining several hundreds mV/km were revealed in the electric field of terrestrial origin measured at the Tyrgan locality on the western shore of the lake. These variations were related to earthquakes with K > 12. The results obtained in the United States, former Soviet Union, and China, which testify to the changes in the electric potential of the Earth before earthquakes, are also worth noting (Sobolev, 1993; Corwin and Morrison, 1997; Mizutani, 1976; Myachkin, 1972; Noritomi, 1978; Zhu, 1976).

What is the origin of the anomalous variations in the electric field of the Earth? The analysis shows that the electric anomalies revealed in the Karymshina data are unrelated to the meteorological conditions. It is supposed that the changes in the tectonic stresses before earthquake can change the level and the mineralization of the ground water. This will cause an enhancement in the electrochemical, electrokinetic, and other effects in the upper crust, which will manifest itself in the anomalous changes in the electric potential. Based on the data on the diffusion of the ground water and the electrokinetic effect, Mizutani (1976) estimated the probable variations in the electric potential before earthquakes at hundreds of mV.

THE COMPLEX ANALYSIS OF THE ANOMALIES

Our interpretation of the data of electromagnetic monitoring revealed anomalous variations in the impedance phase, in the components of the telluric tensor, and in the electric field of terrestrial sources. As described above, we made an attempt to estimate the depth of the sources of these anomalies. It turned out that the anomaly in the impedance phase is due to the deep changes on the electric conductivity, whereas the anomalies in the telluric tensor and in the electric field of terrestrial sources are generated by the subsurface crustal processes. The surface and the deep anomalies related to the same earthquakes are not synchronous. Let us consider this situation in greater detail. Figure 8 presents the graphs of the impedance phases (φ), the telluric tensor components (t_{yy}), and the intensity of the electric field of terrestrial sources (E) at the Karymshina observatory. The anomaly in the impedance phase, which is associated with the deep variations in the electric conductivity of the rocks, generally, develops after strong earthquake with $M = 8.3$ and attains a maximum during the earthquake with $M =$ 8.2. The anomaly in the telluric tensor component appeared about 8 months before the earthquake with $M = 8.3$. The anomaly in the electric field of terrestrial sources emerged approximately 2 months prior to this event. Thus, the processes of preparation of strong earthquakes with $M = 8.3$ and $M = 8.2$ manifested themselves in the subsurface crustal layers and culminated in the anomalous increase in the electric conductivity of the lithosphere.

It should be mentioned that the Karymshina and Tundrovyi observation sites are located about 900 km off the epicenters of the Kuril earthquakes with $M =$ 8.3 and $M = 8.2$. According to (Reznitchenko, 1976), the processes of preparation of the strongest earthquakes involve crustal blocks as large as several hun-

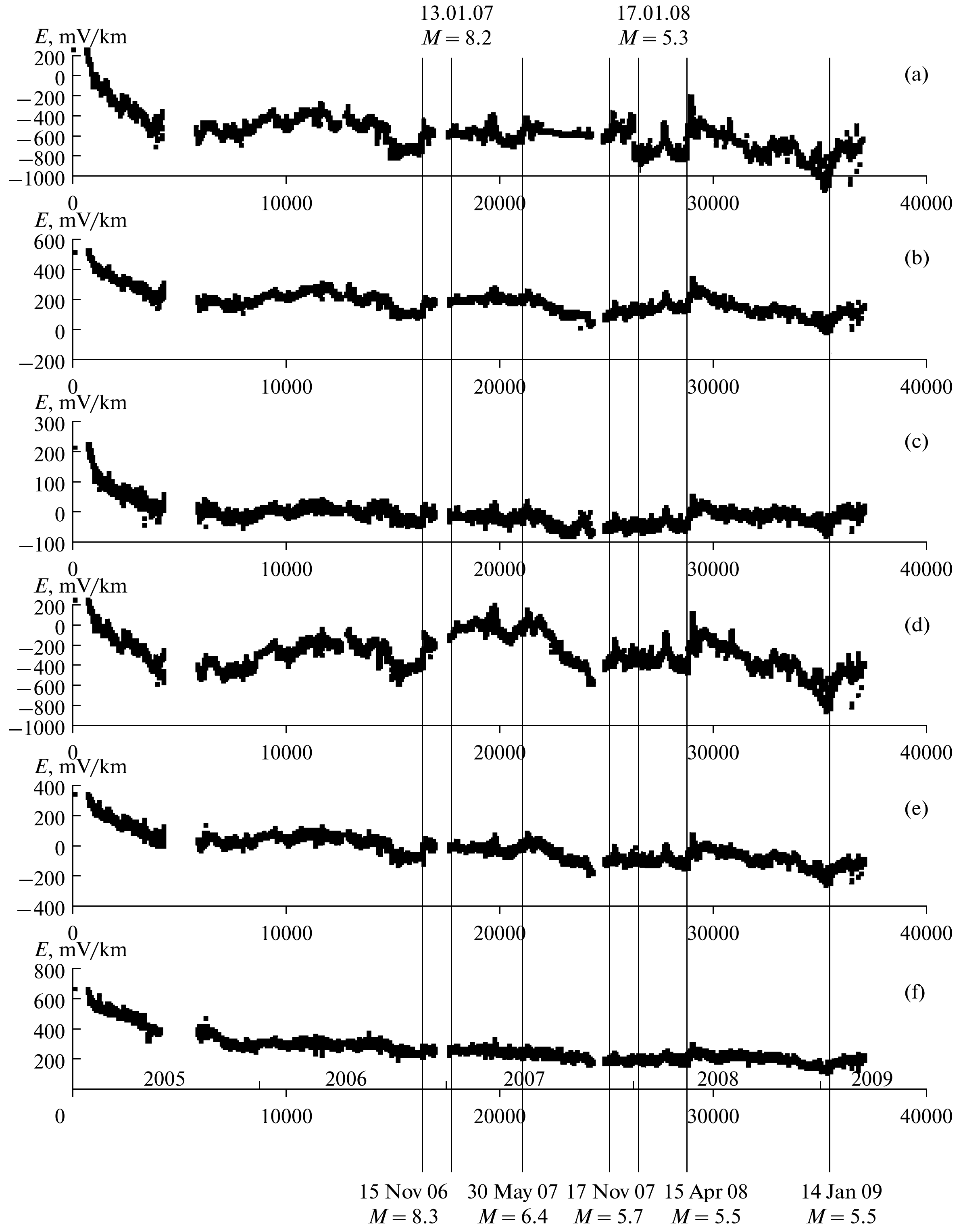


Fig. 7. The hourly mean intensity of the electric field at obs. Karymshina. The graphs (a), (b), (c), (d), (e), and (f) correspond to lines 0–1, 0–2, 0–3, 0–4, 0–5, and 0–6, respectively (see Fig. 2).

dreds of kilometers. It is important that the observation sites and the hypocenters of the earthquakes pertain to the same subduction zone. Due to this, it seems quite reasonable that the processes related to the Kuril earthquakes manifest themselves in Southern Kamchatka.

It is worth noting that not all earthquakes analyzed in the previous sections are associated with the pre-

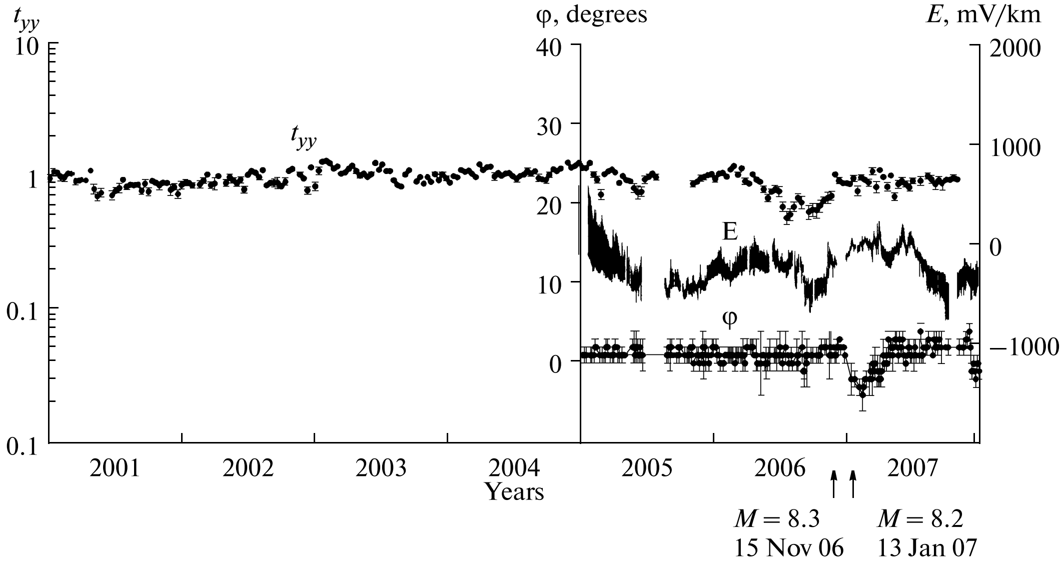


Fig. 8. The comparison of the impedance phase (φ_{yy}), the intensity of the electric field (E), and the modulus of the telluric tensor component (t_{yy}). The occurrence time, the magnitudes, and the dates of the strong earthquakes are shown by the arrows on the time axis.

seismic surface anomalies and coseismic deep anomalies. For example, the $M = 5.7$ and $M = 5.3$ earthquakes located in the near zone of the electromagnetic measurements are reflected in the impedance phase anomaly which is related to the increase in the deep electric conductivity (Fig. 5). However, these earthquakes were not preceded by any anomalies in the impedance tensor components and the intensity of the electric field of terrestrial sources, which might be induced shallow processes. This also relates to the earthquakes of 2007–2008 with magnitudes $M = 6.4$ and $M = 5.5$, which are preceded by electric anomalies, although they do not manifest themselves in the behavior of the impedance phase. The presented data show that only the strongest remote earthquakes and the events that occurred not far from the observation points led to the formation of the zone of increased electric conductivity in the lithosphere. It is remarkable that such zones can exist for about half a year after which the electric conductivity of the lithosphere recovers to its previous level. The development of positive anomalies in the electric conductivity can be accounted for by the formation of fractured crustal zones saturated with highly mineralized fluids which markedly reduce the electric resistivity of the rocks. Rough estimates show that for a variation by 5 degrees in the impedance phase to appear, the electric resistivity in an extended layer with a thickness of at least 10 km should be increased by several orders of magnitude. This procedure does not affect the modulus of the impedance, though.

We note that the behavior of the telluric tensor component only reflects the anomaly preceding the strong Kuril anomalies with $M = 8.3$ and $M = 8.2$. This anomaly is generated by the galvanic effects of the electrotelluric currents, which is due to the development of a strong geoelectric heterogeneity in the surface layers of the crust. This anomaly appeared about a year prior to the earthquakes with $M = 8.3$ and vanished after this event. This raises the question on why other earthquakes have no effect on the behavior of the telluric tensor. One probable reason is that before weaker seismic events, the geoelectric heterogeneities do not develop (or are less contrasting), therefore they do not affect the electrotelluric field. Other factors which are not known to us are also possible.

Thus, our results reveal a complex distribution of anomalies associated with earthquakes. In some cases, the surface anomalies appear, and in other cases, deep anomalies develop. There is also an example of the strongest Kuril earthquakes when both shallow and deep anomalies were present. Thus, in order to infer thorough information about the earthquakes, we should employ a set of methods intended for studying the surface and the deep anomalies from the electromagnetic and other geophysical data. This approach would much help developing the methods for predicting strong earthquakes.

CONCLUSIONS

The dynamics of the electric conductivity of the lithosphere and the electric field generated by the terrestrial sources is studied using the data measured at the Karymshina observatory and the observation point at Tundrovyi in Southern Kamchatka. The dynamics of the lithosphere are estimated from the magnetotelluric transfer functions. The anomalies supposedly related to the earthquakes are revealed in the time series of the magnetotelluric impedance, the telluric tensor, and the electric field of the terrestrial sources.

In the Karymshina data, the anomaly in the behavior of the impedance tensor components is most prominent in the impedance phase at a period of 700 s, indicating the changes in the deep electric conductivity related to the conductive zone in the lithosphere. This anomaly in conductivity is probably generated by the change in saturation of the conductive lithospheric zone by mineralized fluids.

The data measured at Tundrovyi exhibit the anomaly in the telluric tensor component, which has an intensity of 40–50% above the average level and is correlated to the strongest Kuril earthquakes with $M = 8.3$ and $M = 8.2$. However, the phase of this component does not show any anomaly. This indicates that the anomaly in the modulus of the telluric tensor component is associated with the occurrence or change of local geoelectric heterogeneity in the vicinity of the measurement lines. This anomaly is probably induced by the changes in the fluid mineralization and variations in the water level, although other mechanisms related to the geodynamical processes are possible as well.

In the Karymshina data series, we revealed anomalies in the behavior of the electric field generated by the terrestrial sources, which have a duration of 1 to 2 months. The intensity of these perturbations is a few hundred mV/km. They appeared 1.5 to 2 months before earthquakes with the magnitudes $M = 5.4–8.3$. A remarkable fact is that the perturbations in the electric field are stronger in case of shorter lines, which indicates that they are associated with the local surface effects close to the measurement lines. These effects are likely near-electrode and probably induced by the physicochemical processes occurring during the preparation of the earthquakes.

The complex analysis of the identified anomalies shows that the surface and the deep anomalies correlated to the same earthquake do not appear simultaneously. We revealed the following features in the behavior of the anomalies associated with the strongest events with $M = 8.2–8.3$. The anomaly in the telluric tensor component emerges approximately 8 months before the earthquake; the anomaly in the electric field of the terrestrial sources appears 2 months before the event, and the anomaly in the impedance phase develops after the earthquake with $M = 8.3$ and attains a maximum during the earthquake with $M = 8.2$. This indicates that the anomalies preceding strong earthquakes with $M = 8.2$ and $M = 8.3$ are associated with the top layers of the Earth's crust. The coseismic anomalies have deep sources. Our results suggest that the data on the electromagnetic field of the Earth provide information about the shallow and deep variations in the electric properties of the geological environment related to strong earthquakes.

REFERENCES

Berdichevsky, M.N. and Zhdanov, M.S., *Interpretatsiya anomalii peremennogo elektromagnitnogo polya Zemli* (Interpretation of the Anomalies in the Alternating Electromagnetic Field of the Earth), Moscow: Nedra, 1981.

Corwin, R.F. and Morrison, H.F., Self-Potential Variations Preceding Earthquakes in Central California, *Geophys. Res. Lett.*, 1977, vol. 4, pp. 171–174.

Geologiya SSSR. T. 31. Kamchatka, Kuril'skie i Komandorskie ostrova. Geologicheskoe opisanie (Geology of the USSR. Vol. 31: Kamchatka, Kuril and Komandor Islands. Geological Description), Moscow: Nedra, 1964.

Mizutani, H., Ishido T., Yokokura, and Ohnishi, S., Elektrokinetic Phenomena Associated with Earthquakes, *Geophys. Res. Lett.*, 1976, vol. 3, pp. 365–368.

Moroz, Yu.F., Popruzhenko, S.V., Trubnikov, V.M., Kuznetsova, V.P., and Moroz, T.A., Telluric Current Effects Preceding Earthquakes on the Kamchatka Peninsula, *Izv. Phys. Earth*, 1999, vol. 35, no. 3, pp. 237–245.

Moroz, Yu.F., Nazarets, V.P., and Moroz, T.A., Comparative Characteristics of Geomagnetic Field Variations in the Kamchatka and Lake Baikal Regions, *Izv. Phys. Earth,* 2005, vol. 41, no. 9, pp. 718–726.

Moroz, Yu.F., Moroz, T.A., and Mogi, T., Methods and Results of Monitoring of the Natural Telluric Field in the Baikal Rift Zone, *Izv. Phys. Earth*, 2007, vol. 43, no. 11, pp. 938–950.

Moroz, Yu.F., Laguta, N.A., and Moroz, T.A., Magnetotelluric Sounding of Kamchatka, *J. Volcanol. Seismol.*, 2008, vol. 2, no. 2, pp. 83–93.

Moroz, Yu.F. and Moroz, T.A., A Study in the Dynamics of the Geoelectrical Medium from Electrotelluric Field Data, *J. Volcanol. Seismol.*, 2009, vol. 3, no. 1, pp. 34–43.

Myachkin, V.I., Sobolev, G.A., Dolbikina, N.A., Morozow, V.N., and Preobrazensky, V.B., The Study of Variations in Geophysical Fields near Focal Zones of Kamchatka, *Tectonophysics*, 1972, vol. 14, pp. 287–293.

Noritomi, K., 1978, Application of Precursory Geoelectric and Geomagnetic Phenomena to Earthquake Prediction in China, *Chinese Geophys.*, 1978, vol. 1, no. 2, pp. 377–391.

Rokityanskii, I.I., *Issledovanie anomalii elektroprovodnosti metodom magnitovariatsionnogo profilirovaniya* (Study of the Conductivity Anomaly by Magnetovariational Profiling), Kiev: Naukova Dumka, 1975.

Reznichenko, Yu.V., The Source Size of the Crustal Earthquake and the Seismic Moment, in *Issledovaniya po fizike zemletryasenii* (Investigations in the Physics of Earthquakes), Moscow: Nauka, 1976, pp. 9–26.

Serson, P.H., Instrumentation for Induction Studies on Land, *Phys. Earth Planet. Inter.*, 1973, VOL. 7, pp. 313–322.

Sobolev, G.A., *Osnovy prognoza zemletryasenii* (Basics in the Prediction of Earthquakes), Moscow: Nauka, 1993.

Zhu F. M., Prediction, Warning, and Disaster Prevention to the Haicheng Earthquake of Magnitude 7.3, in *Proc. Lectures by the Seismological Delegation of the People's Republic of China*, Seismol. Soc. Japan Special Publication, 1976, pp. 15–26.