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A Study in the Dynamics of the Geoelectrical Medium from Electrotelluric Field Data

Yu. F. Moroz and T. A. Moroz

Institute of Volcanology and Seismology, Far East Division, Russian Academy of Sciences, Petropavlovsk-Kamchatskii, 683006 Russia

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Abstract—The manner in which the dynamics of geoelectric earth inhomogeneities can be studied using receiving lines oriented in different directions at a single site is considered. It is shown that the presence of a local geoelectric inhomogeneity allows monitoring the state of electric conductivity in the earth by observation of the telluric tensor. We quote results from long-continued monitoring of the electrotelluric tensor in Kamchatka. The tensor's behavior showed an appreciable anomaly, which may have been related to great (magnitude 8.2 and 8.3) earthquakes in the Kuril–Kamchatka region.

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INTRODUCTION

The time variation of electric conductivity in geological media is studied by various electromagnetic methods based on the use of manmade and natural electromagnetic fields. Among the latter, attention is drawn to the magnetotelluric methods. The magnetotelluric field is known to contain information on the geoelectric inhomogeneity of the earth. This information can be used to study the time behavior of this inhomogeneity [6, 9]. Experience shows that the electrotelluric field possesses an increased sensitivity to local geoelectric inhomogeneities. This peculiarity of the field underlies the electrotelluric monitoring in Kamchatka conducted in the search for earthquake precursors [8]. The monitoring of the electrotelluric field is carried out simultaneously at sites 50–100 km apart. The behavior of the transfer function (the telluric tensor) between the horizontal components of the electrotelluric field was found to show anomalous effects, which are possibly related to large earthquakes [8]. These effects are due to changes in the earth conductivity at the observation sites. The present paper considers the possible monitoring of the earth conductivity from observations of the electrotelluric field at a single site using sets of orthogonal measuring lines oriented in different directions.

A BRIEF GEOELECTRIC CHARACTERISTIC OF THE AREA OF STUDY

The electrotelluric field is being observed at the Tundrovyi station situated on the coast of the Avacha Bay (part of the Pacific Ocean, Fig. 1). The area has a complex geologic structure [2]. Unlike the rest of Kamchatka, which is dominated by the linear zonality of northeast striking tectonic features, the area has transverse structures striking northwest. In this area, southwest of the Tundrovyi station, there are exposures of the oldest (Cenozoic and Proterozoic) metamorphic rocks, which are believed to compose the consolidated basement underlying a Cenozoic sedimentary–volcanogenic cover.

The geoelectric section of the area is as follows [7]. The upper part of the section is composed of Quaternary volcanogenic and sedimentary formations having resistivities of a few hundreds to a few thousands of ohm–meters or greater and thicknesses of a few hundreds of meters. Below this is a Cenozoic rock sequence having an average longitudinal resistivity of a few to a few tens of ohm-meters and a thickness of 0 to 4 km. This is underlain by a complex of Upper Cretaceous sedimentary volcanogenic formations having an average longitudinal resistivity of a few tens to a few hundreds of ohm-meters. The consolidated basement has a resistivity of a few thousand ohm–meters. The deeper part of the section contains a crustal and an asthenospheric conductive layer.

The behavior of the magnetotelluric field depends on the conductivity distribution in the earth. An idea of the conductivity in the sedimentary volcanogenic cover can be gathered from Fig. 2. One can see from this figure that the conductivity in question at the observation site is 20 S/m. There is a northeast transverse zone of increased conductivity. This is confined to a graben that is mostly filled with terrigenous deposits. The conductivity of this zone is as great as 600 S/m in the Avacha–Koryakskii group of volcanoes, which may be due to the presence of a liquid phase (solutions and magma melts). The conductivity in the Gulf of Avacha is about 100 S/m due to sea water. The conductivity of the upper layer (which contains the sea water) in the Avacha Bay is as great as 7000 S/m, increasing to reach 20 000 S m in the deep-sea trench area. The sharp conductivity con-

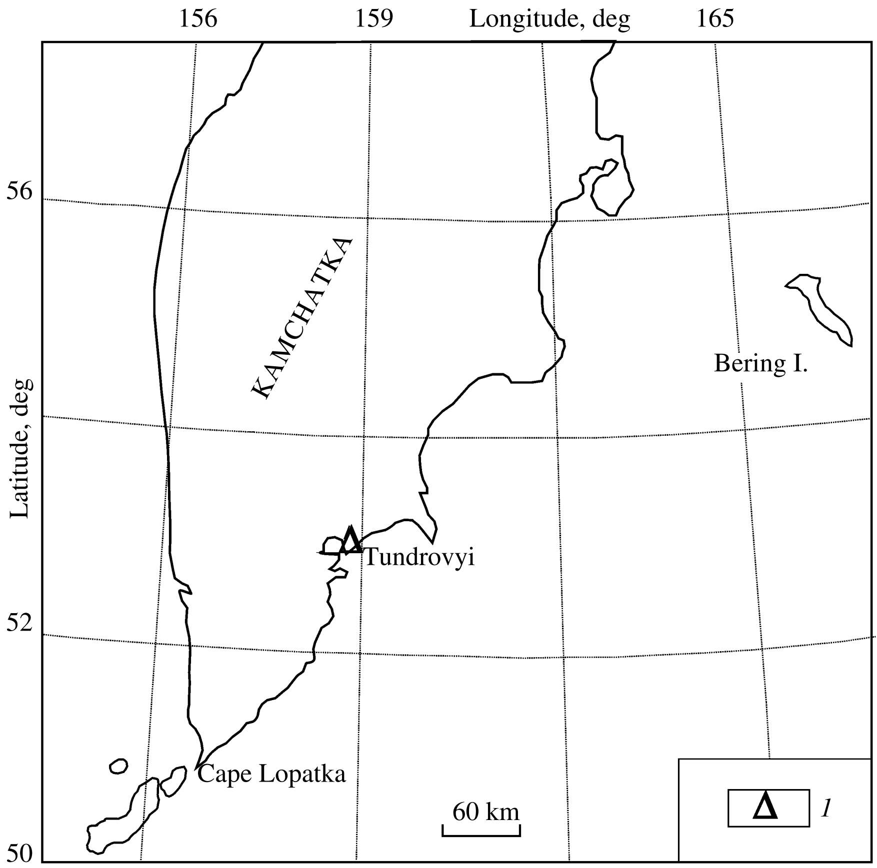

Fig. 1. A map showing the position of the Tundrovyi station where the electrotelluric field was measured: (*1*) Tundrovyi station.

trast at the land–ocean boundary is seen in the magnetotelluric field in the form of the coast effect. This effect strongly affects the behavior of the electrotelluric field at the Tundrovyi station, as will be shown below. It is important to note that the intensity and polarization of the electrotelluric field also depends on the distribution of local near-surface geoelectric inhomogeneities. Since the geological medium is a hierarchy of rock blocks of varying dimensions, we are entitled to the assumption that the observation site area may contain geoelectric inhomogeneities with lengths comparable with those of the receiving lines. This is borne out by geological observations revealing geologic bodies and tectonic disturbances in the area, which vary in size between a few tens to a few hundred meters or greater [2]. Therefore, it is highly likely that the localities with the receiving lines contain geoelectric inhomogeneities, which may produce effects in the electrotelluric field.

OBSERVATIONAL TECHNIQUES

The arrangement for recording the potential difference of the electrotelluric field is shown in Fig. 3. It includes measuring lines 1 and 2 in the directions N–S and E–W, as well as lines 3 and 4 oriented at azimuths of 40° and 310°; these are along the axes of the earth geoelectric inhomogeneity as found from areal electric prospecting investigations the magnetotelluric sounding method. The lines have the following lengths: (1) 97, (2) 105, (3) 65, and (4) 90 m. We used earth lead electrodes sunk to depths of about 2–2.5 m. Automatic digital instruments are used to measure the potential difference of the electrotelluric field. Data are transmitted to a processing center in Petropavlovsk-Kamchatskii via radio channels. Each measuring line is sampled once a minute. The automatic observation stations are operated by the Kamchatka Branch of the Russ. Acad. Sci. Geophysical Service, with preliminary data processing carried out at the Service as well.

THE ANALYSIS OF ELECTROTELLURIC OBSERVATIONS

Figure 4 shows an example, a time series of electrotelluric field intensity measured on lines 1, 2, 3, and 4. The short period variations are seen as "noise." This is greater on line 3. The increased intensity of short-period variations is related to a transverse feature

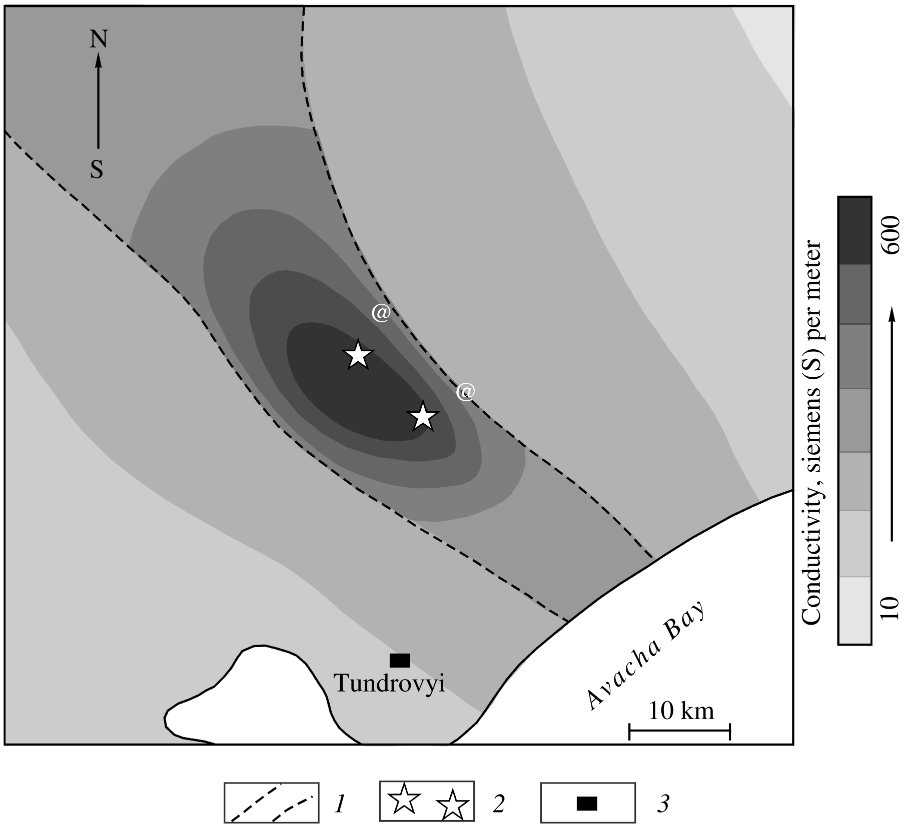

Fig. 2. A map of total conductivity in the volcanogenic sedimentary cover in the area of study: (*1*) lines of equal conductivity, (*2*) volcanoes, (*3*) Tundrovyi station.

(horst–anticlinorium) where the Tundrovyi station is situated. Daily variations with intensities up to 40–50 mV/km were observed on lines 1, 2, and 4. The daily variations are smaller on line 3, with their intensity being below 10 mV/km.

The time series 1 and 2 were converted to the directions of the azimuths of 40 and 320 degrees. This was done by rotating axes 1 and 2 by 40° counterclockwise, i.e., until coincidence with lines 4 and 3 was achieved. The conversion was based on the formulas [1]

$$x' = x\cos\alpha + y\sin\alpha$$

$$y' = -x\sin\alpha + y\cos\alpha,$$

where x, y and x', y' are the old and the new coordinates of the electrotelluric field intensity, and α is the angle of rotation.

It is supposed that, if the geoelectric medium at the observation site does not involve local geoelectric inhomogeneities, then on conversion 1' and 2' would coincide with the time series of 4 and 3. However, this did not happen. Figure 5 compares the time series 1' and 4, 2' and 3 oriented in the same direction. It is seen that time series 1' differs from 4 and 2' from 3. These differences in the respective time series can be explained by the effect of local geoelectric inhomogeneities, which may be situated near the electrodes or be comparable with the length of the measuring lines.

ANALYSIS OF MAGNETOTELLURIC DATA

Magnetotelluric sounding curves give an idea of earth conductivity based on data measured on lines 1 and 2, 1' and 2', 4 and 3 (Fig. 6). The curves of apparent resistivity differ by more than an order of magnitude in resistivity level. Curves 1 and 2, which are oriented N–S and E–W, differ by nearly twice at shorter periods. The discrepancy increases toward lower frequencies. This behavior provides evidence of geoelectric inhomogeneities. It is important to note that curves 1' and 4, which are oriented in the same direction, are significantly different. The same applies to curves 2' and 3. For example, curves 1' and 4, which have similar shapes, differ in resistivity level by nearly an order of magnitude. Curves 2' and 3 differ between themselves both in shape and resistivity level. In the region of lower frequencies, curve 3 has a descending branch at an angle of nearly 65°. At the same time curve 2' is expressed by a nearly horizontal branch. We thus arrive at the conclusion that the MTS curves at the site are strongly affected by the earth geoelectric inhomogeneities.

Geoelectrical inhomogeneities may be regional or local. One regional inhomogeneity is the conductivity contrast on the coast of Kamchatka, at the boundary of the land and ocean. The specific electrical resistivity of rocks on land is a few to a few thousand ohm-meters, while that of sea water is a few tenths of an ohm-meter. This resistivity contrast by whole orders of magnitude is seen as a sharp anomaly in the Earth's electromagnetic field, termed the coast effect. The effect strongly distorts the magnetotelluric sounding curves [5].

The marine shoreline at the Tundrovyi site has a complicated outline because of the marine Gulf of Avacha and the Avacha Bay. For this reason the coast effect at this location has been studied using 3D numerical modeling of the MT field. The model involves the upper layer, which is a homogeneous sedimentary volcanogenic layer on land and an inhomogeneous sea mass of the seas and the ocean around Kamchatka. The upper layer conforms to the standard deep geoelectric section. Calculations yielded MTS curves along the directions corresponding to the trend along and across Kamchatka, as well as the locally normal MTS curve. The resulting curves are shown in Fig. 7. The transverse curve is represented by an ascending asymptotic branch that flattens in the range of periods 1600–10 000 s. This behavior is related to the coast effect. The MTS longitudinal curve in the region of lower frequencies is below (by resistivity level) the locally normal curve. The maximum of the longitudinal curve occurs at shorter periods. The curve gives the false idea that the deep section has higher conductivity. This distortion in the longitudinal curve is caused by the induction effect of electrical currents concentrated in the ocean. Comparative analysis of the modeled and experimental MTS curves shows that both longitudinal and transverse curves are similar among themselves (Figs. 6, 7). At the same time these curves are appreciably different among themselves both in resistivity level and in shape. This difference is related to the effects of local geoelectric inhomogeneities.

One gets a fuller idea of the geoelectric inhomogeneities on lines 1, 2, and 4, 3 from polar impedance diagrams. Figure 8 shows an example of the diagrams of the principal and diagonal impedance values at a period of 1000 s. The polar diagrams for lines 1 and 2 (Fig. 8a) are similar to those for the same lines when rotated by 40°, i.e., made coincident with the directions of lines 4 and 3 (Fig. 8b). The different orientations of the impedance diagrams are due to the different orientations of the coordinate axes. Diagrams of the principal and the diagonal impedance both image a 2D inhomogeneous geoelectric section. However, the diagrams for lines 1', 2' and 4, 3 oriented along the same directions are different in shape, compression, and orientation (Fig. 8b, 8c).

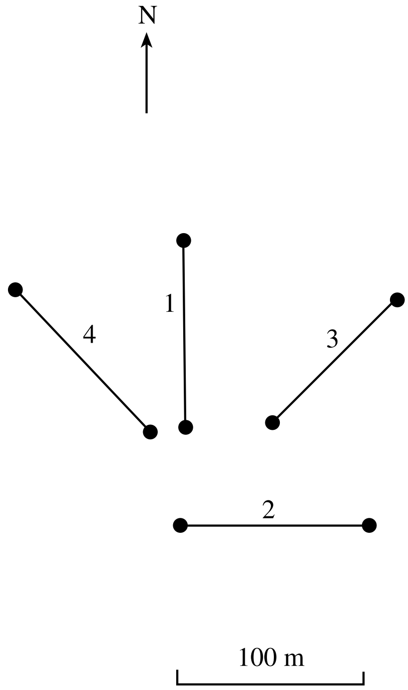

Fig. 3. A map showing the positions of measuring lines at the Tundrovyi site. 1, 2, 3, 4 are identification numbers of receiving lines. Azimuths of lines: 1 – 0°; 2 – 90°; 3 – 40°; 4 – 310°. The scale is shown for the measuring lines.

The diagrams of principal and diagonal impedance for lines 4 and 3 (Fig. 8c) thus image a 3D-varying section. The diagram of diagonal impedance for lines 4 and 3 has an oval shape. It has no directions along which the diagonal impedances would be close to zero values. It can thus be inferred that the geoelectric inhomogeneities manifest themselves differently on lines 1, 2 and 4, 3. This can be explained by the fact that the geoelectric inhomogeneities are local and may be comparable with the lengths of the measuring lines.

RESULTS OF ELECTROTELLURIC MONITORING

The monitoring of the electrotelluric field provides an opportunity to investigate the variation of a local geoelectric inhomogeneity over time. This goal is best served by the use of the telluric tensor [8]. The tensor can be found using Larsen's computer program [10]. The algorithm of that program is based on the well-known robust technique. Its advantage consists in its capability to effectively suppress noise, in addition to finding transfer functions.

In the case we are considering, the connection between the electrotelluric fields on lines 1, 2 and 4, 3 can be written in the form

$$E_{1,2} = \hat{t}\, E_{4,3},$$

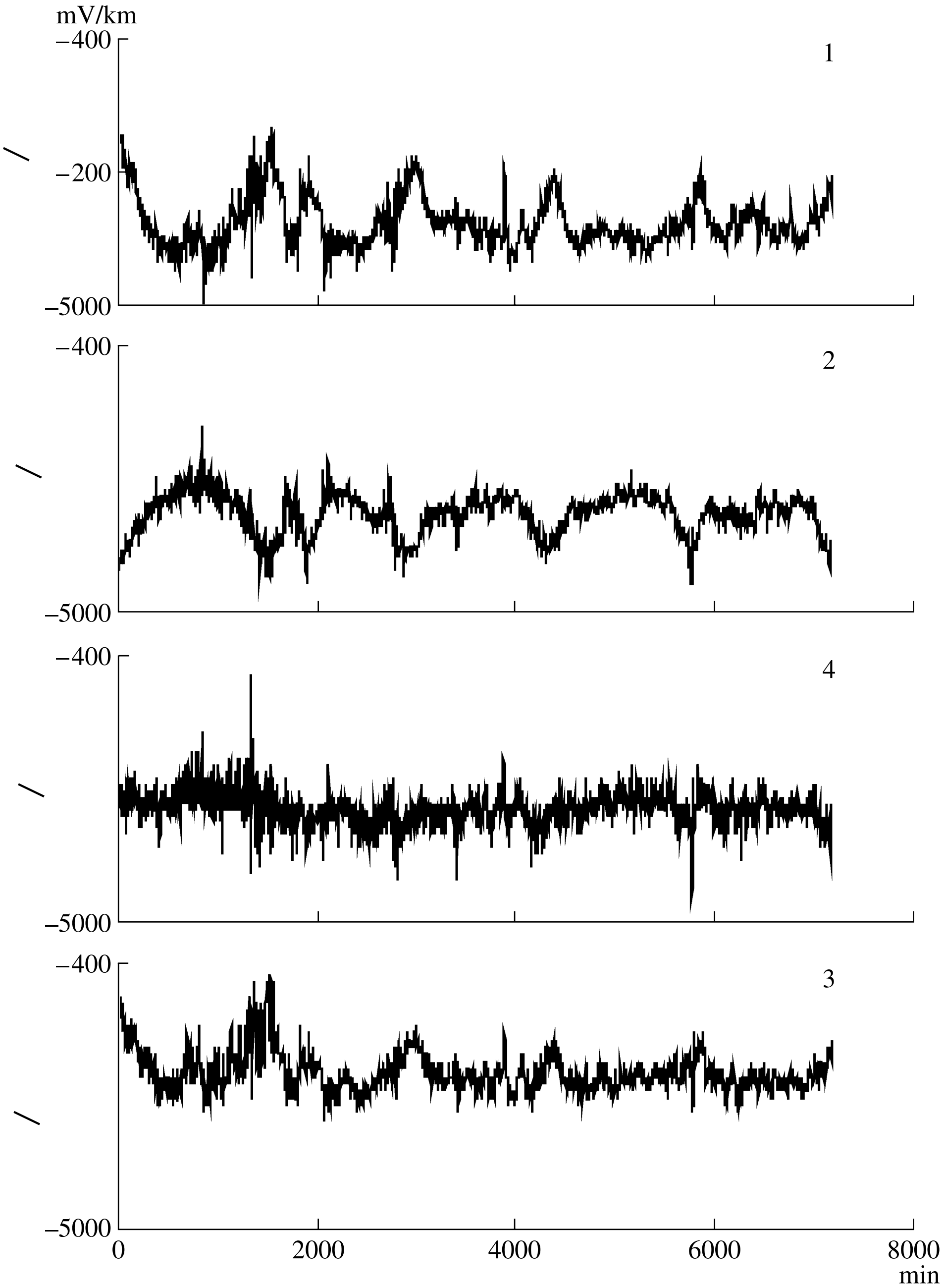

Fig. 4. Plots of electrotelluric field intensity. Numerals denote line numbers (see Fig. 3).

where $E_{1,2}$ and $E_{4,3}$ are horizontal vectors for channels 1, 2 and 4, 3, respectively, and $\hat{t}$ is the telluric tensor.

The relation connecting the vectors, when written out in explicit form, is

$E_1 = t_{YX}E_4 + t_{YY}E_3$, $E_2 = t_{XY}E_4 + t_{XX}E_3$, where E_1, E_2, E_4, and E_3 are components of the electrotelluric field and t_{XX}, t_{XY}, t_{YX}, t_{YY} are complex-valued components of the telluric tensor, which are functions of the frequency, orientation of the coordinate axes, and the distribution of specific electrical resistivities.

Let us now examine the observations of the electrotelluric field made at the Tundrovyi station. With the goal of studying the time-dependent behavior of the telluric tensor we developed a special computer program that can handle a data bank of long-continued observations to automatically retrieve data arrays for calculating components of the tensor. The important step is selecting the length of time intervals for sampling the electrotelluric field. The length of the interval chosen determines the range of periods where the tensor com-

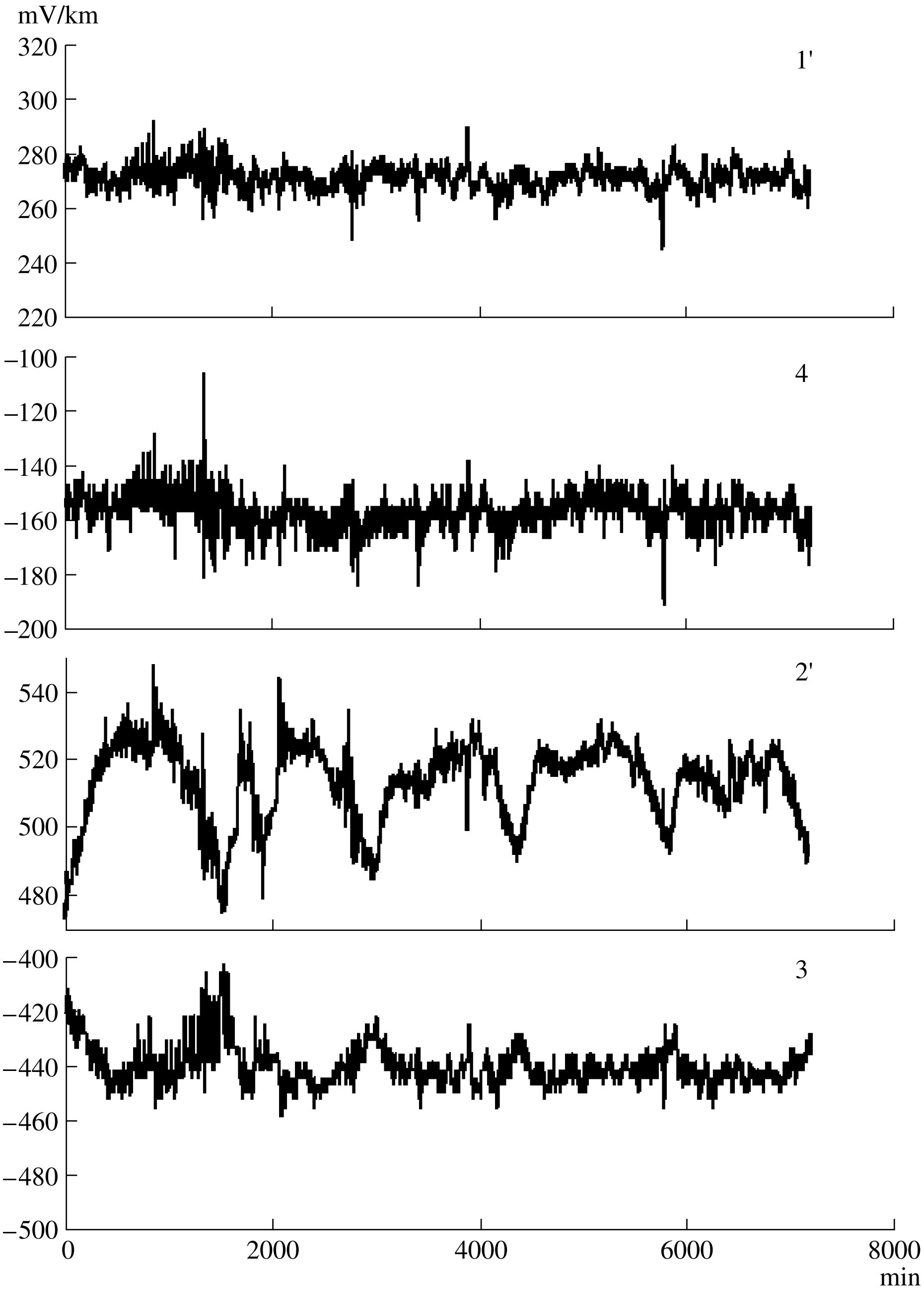

Fig. 5. Comparing the plots of electrotelluric field intensity. Numerals 1' and 2' denote the plots obtained by rotating the axes 1 and 2 by an angle of 40° in the counterclockwise direction, i.e., until they coincide with lines 3 and 4 (see Fig. 3).

ponents are calculated and the accuracy of the determinations. The components of the telluric tensor were calculated for time intervals equal to 1, 3, 5, 10, and 20 days. Analysis showed that the components are more stable for time intervals longer than 5 days.

Taking an example, we consider the monitoring results for t_{yy} during the period from January 1, 2001 to October 31, 2007 at a period of 4500 s (a time interval of 10 days). Figure 9 shows plots of the modulus of this telluric tensor component and its argument. The behavior of the absolute value of t_{yy} exhibited an anomaly of 40–50% during 2006. At the same time the anomaly is not seen in the behavior of the argument of this component. This provides evidence that the anomaly is related to the galvanic effect in the electrotelluric field [8]. This anomaly in the absolute value of the t_{yy} component preceded great earthquakes occurring in the Kuril–Kamchatka region: $M = 8.3$ (November 15, 2006, $\phi°$– 46. 62, $\lambda° = 153.22$) and $M = 8.2$ (January 13, 2007, $\phi°$– 46.29, $\lambda° = 154.45$). These events occurred in the Kuril Is.

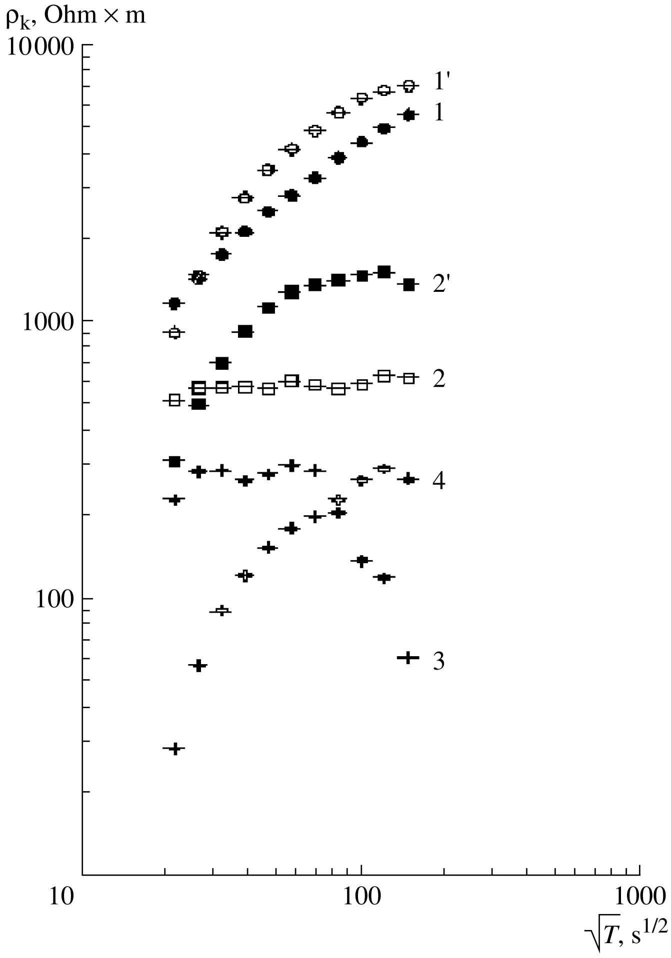

Fig. 6. MTS curves. Numerals 1, 2, 3, 4 denote the curves along the directions of the lines (Fig. 3). Numerals 1' and 2' denote the curves obtained by rotating the axes of lines 1 and 2 until they coincided with lines 4 and 3.

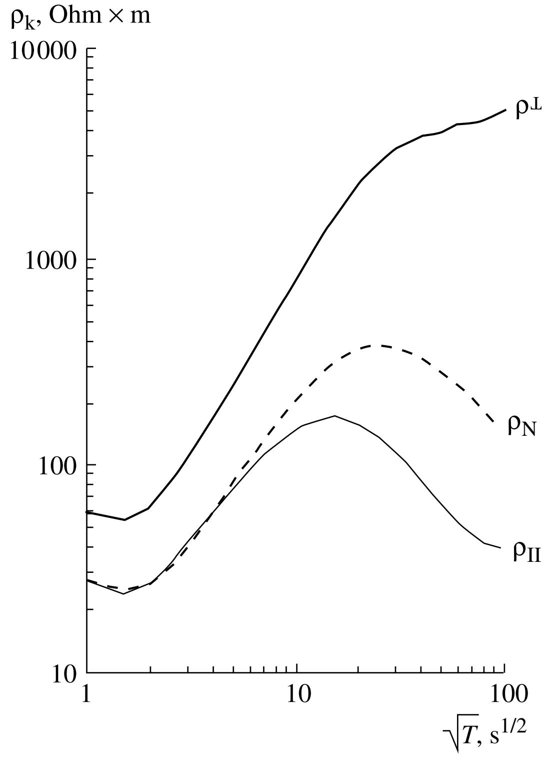

Fig. 7. Modeled MTS curves. ρ", $\rho^{\perp}$, and ρ_N are the MTS longitudinal, transverse, and locally normal curves.

area. It cannot be ruled out that the anomaly was related to the variation of a local geoelectric inhomogeneity, due to the geodynamic processes that preceded and accompanied these earthquakes.

What is the origin of this anomaly? To answer this question we consider the telluric tensor together with the magnetotelluric impedance, which is the transfer function between the electrical and the magnetic field. The relation between the intensity of the electrotelluric field and that of the magnetic field has the form [3]

$$\boldsymbol{E}_{\text{hor}} = \hat{Z}\boldsymbol{H}_{\text{hor}},$$

where $\hat{Z}$ is the magnetotelluric impedance.

In the general case, at a single observation site, we have $\boldsymbol{E}_{1,2} = \hat{Z}\boldsymbol{H}_{\text{hor}}$, $\boldsymbol{E}_{4,3} = \hat{Z}\boldsymbol{H}_{\text{hor}}$ and, because the right-hand sides of these equations are equal, we have $\boldsymbol{E}_{1,2} = \boldsymbol{E}_{4,3}$, hence $\hat{t} = 1$, which means that we possess the same information in the systems of channels 1, 2 and 4, 3. Our experience of many years shows that the magnetotelluric impedance is mostly affected by the influence of local near-surface geoelectric inhomogeneities. Magnetotelluric impedances observed at distances of a few hundred meters are frequently different by an order of magnitude [4]. Such changes in impedance are due to the increased sensitivity of the electric field, compared with the magnetic field, to local geoelectric inhomogeneities in the earth. It thus follows that, when monitoring the telluric tensor at a single site, we can expect changes in the tensor components due to the appearance or variations of local geoelectric inhomogeneities in the area of measuring lines 1, 2 or 4, 3. This situation may be due to geodynamic processes, e.g., earthquakes.

We now turn to consideration of the magnetotelluric sounding curves. These were obtained by recording the electrotelluric field for three months at the Tundrovyi station and variations of the geomagnetic field at the Paratunka Observatory. Figure 10 shows MTS curves observed before the appearance of the anomaly and during the period of the anomalous disturbance; it can also be seen that the apparent resistivity on receiving lines 1, 2 changed by a factor of nearly 10 during the anomaly and practically did not change at the same time on lines 4, 3. Analysis shows that the change is unrelated to weather conditions. This anomaly of the

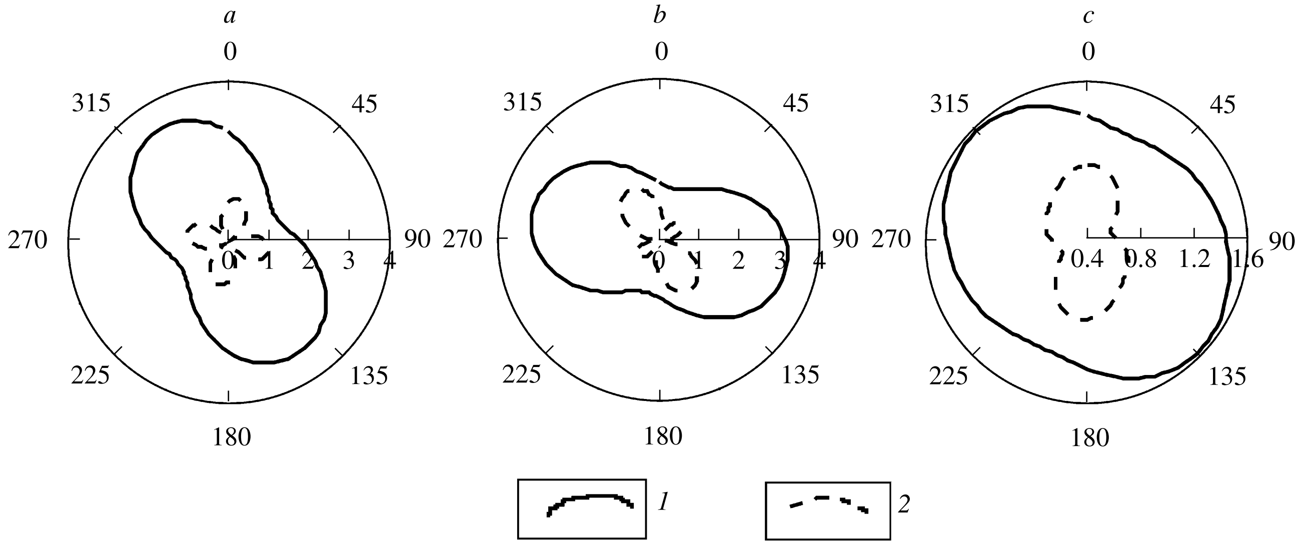

Fig. 8. Polar impedance diagrams. *a, b*, and *c* are for lines 1, 2; 4, 3; and 1', 2', respectively: (*1*) diagrams of the principal and (*2*) diagonal impedance.

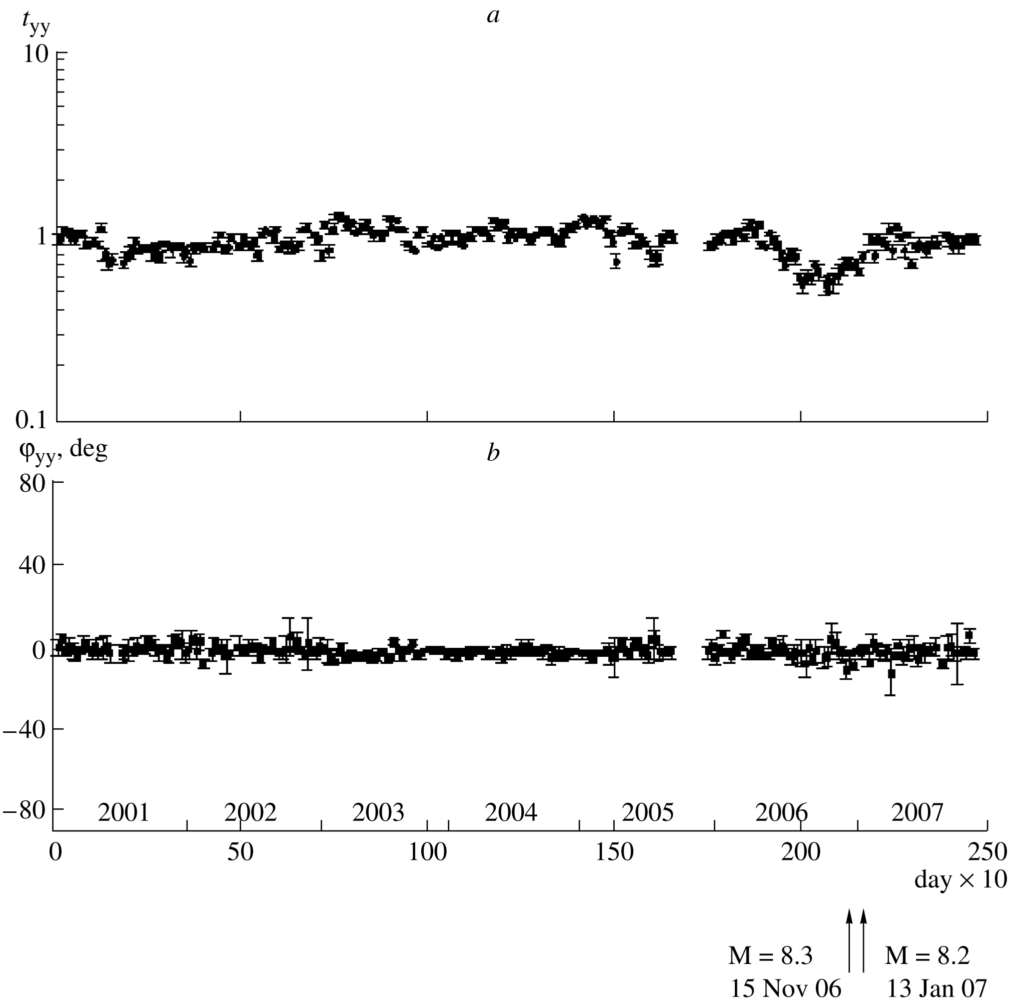

Fig. 9. Plots of the absolute value of the telluric tensor component t_{yy} (*a*) and its argument φ_{yy} (*b*). The dates of great earthquakes (M = 8.3 and 8.2) occurring in the Kuril–Kamchatka island arc area during the past 30 years are marked on the time axis.

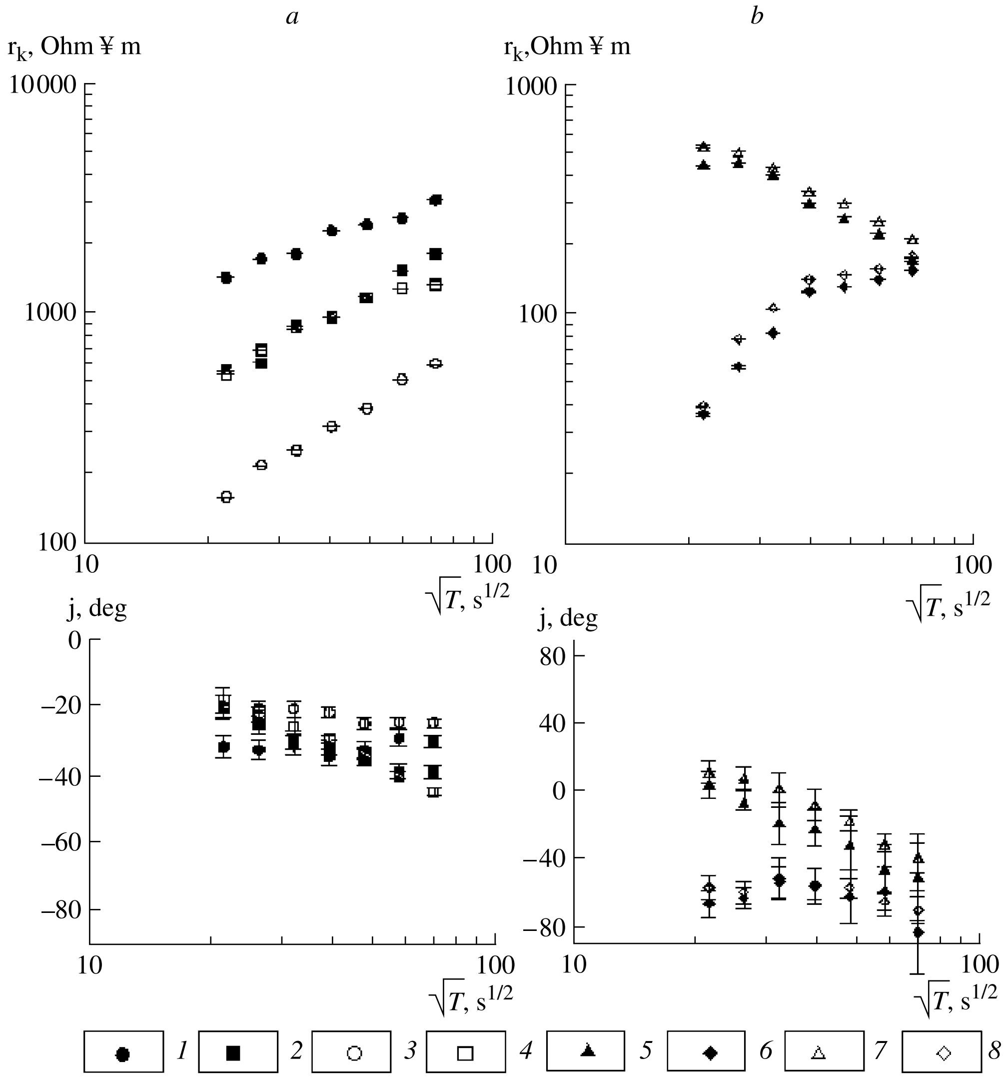

Fig. 10. Comparing the MTS curves before and during the period of anomalous variation in the telluric tensor, *a* and *b* denote the MTS curves along N–S (line 1), E–W (line 2) and NW (line 4), NE (line 3), see Fig. 3. Numerals correspond to the identification numbers of receiving lines in Fig. 3: *1* – 1; *2* – 2; *3* – 1; *4* – 2; *5* – 3; *6* – 4; *7* – 3; *8* – 4. The filled symbols show values of apparent electrical resistivity before the anomalous change of the electrical field, the open ones are for the period of anomalous variation.

telluric tensor was most likely due to a change in the local geoelectric inhomogeneity in the area of receiving channels 1, 2 in connection with a change in salinity or the level of ground water, or with other causes due to geodynamic processes.

CONCLUSIONS

(1). Components of the electrotelluric field, when converted to other directions by rotating their axes, do not invariably coincide with the components of the electrotelluric field obtained along the same directions in the field. The discrepancy may be due to the effects of local geoelectric inhomogeneities comparable with the length of the receiving lines.

(2) The presence of a local geoelectric inhomogeneity at an observation site provides an opportunity, by observing the telluric tensor, to monitor the geodynamic processes that produce the variation in the earth conductivity.

(3) A bay-shaped anomaly in the behavior of the telluric tensor component has been identified at the Tundrovyi station based on the results of long-continued monitoring of the electrotelluric field along different directions, with the anomaly preceding great earthquakes ($M = 8.3$ and 8.2) in the Kuril Is. area. The conductivity anomaly may have been related to a change in salinity or the level of the ground water or to other causes due to the geodynamic processes preceding great earthquakes.

REFERENCES

1 1. Vygodskii, M.Ya., *Spravochnik po vysshei matematike* (A Handbook of Higher Mathematics), Moscow: Fizmatgiz, 1963.

2. *Geologiya SSSR. Kamchatka, Kuril'skie I Komandorskie ostrova. Geologicheskoe opisanie* (The Geology of the USSR. Kamchatka, Kuril Is., and the Commander Is.: A Geological Description), vol. 31, Moscow: Nedra, 1964.

3. Berdichevskii, M.N., *Elektricheskaya razvedka metodom magnitotelluricheskogo profilirovaniya* (Electrical Prospecting Using the Method of Magnetotelluric Profiling), Moscow: Nauka, 1968.

4. Moroz, Yu.F. and Nurmukhamedov, A.G., Magnetotelluric Sounding of the Petropavlovsk Geodynamic Test Site, Kamchatka, *Vulkanol. Seismol.*, 1998, no. 2, pp. 77–84.

5. Moroz, Yu.F., Kobzova, V.M., and Ladanivskii, B.T., Physical Modeling of the Magnetotelluric Field in the Petropavlovsk Geodynamic Test Site, Kamchatka, *Vulkanol. Seismol.*, 2000, no. 3, pp. 50–56.

6. Moroz, Yu.F. and Vershinin, E.F., Magnetotelluric Monitoring of a Seismic Region: Kamchatka, *Fizika Zemli*, 2001, no. 10, pp. 63–70.

7. Moroz, Yu.F., Nurmukhamedov, A.G., and Moroz, T.A., A Deep Geoelectric Model for the Interior of the Petropavlovsk Geodynamic Test Site, Kamchatka, *Fizika Zemli*, 2001, no. 6, pp. 58–66.

8. Moroz, Yu.F. and Moroz, T.A., Results from an Electrotelluric Monitoring in Kamchatka: The Search for Precursors of Large Earthquakes, *Fizika Zemli*, 2005, no. 3, pp. 47–55.

9. Moroz, Yu.F., Moroz, T.A., and Smirnov, S.E., The Electrical Conductivity of the Geologic Medium Based on Data of Magnetotelluric Monitoring in Kamchatka, *Vulkanol. Seismol.*, 2006, no. 6, pp. 34–43.

10. Larsen, I.S., Noise Reduction in Electromagnetic Time Series to Improve Detection of Seismic Induced Signals, *J. Geomagn. Geoelectr.*, 1997, vol. 49, pp. 1257–1265.

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