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E_z-response as a monitor of a Baikal rift fault electrical resistivity: 3D modelling studies

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Abstract
3D numerical studies have shown that the vertical voltage above the Baikal deep-water fault is detectable and that respective transfer functions, E_z-responses, are sensitive to the electrical resistivity changes of the fault, *i.e.* these functions appear actually informative with respect to the resistivity «breath» of the fault. It means that if the fault resistivity changed, conventional electromagnetic instruments would be able to detect this fact by measurement of the vertical electric field, E_z, or the vertical electric voltage just above the fault as well as horizontal magnetic field on the shore. Other electromagnetic field components (E_x, E_y, H_z) do not seem to be sensitive to the resistivity changes in such a thin fault (as wide as 500 m). On the other hand, such changes are thought to be able to indicate a change of a stress state in the earthquake preparation zone. Besides, the vertical profile at the bottom of Lake Baikal is suitable for electromagnetic monitoring of the fault electrical resistivity changes. Altogether, the vertical voltage above the deep-water fault might be one of earthquake precursors.

Key words *Baikal rift zone – electromagnetic monitoring – transfer functions – resistivity changes of the fault*

1. Introduction

It is generally accepted that one of the possible precursors of earthquake in the seismically active Baikal region may be the change in the electrical resistivity of the saturated porous rock in deep-water rift faults. In accordance with the modern concept of the Baikal region geoelectrical structure (Merklin *et al.*, 1979), there is a narrow fault there that is galvanically connected with a deep-seated conductor. Berdichevsky *et al.* (1989) showed that for two-dimensional (2D) model of marine deep magnetotelluric investigations the vertical electric field at the ocean bottom is highly sensitive to the resistivity of the underlying cross-section. Besides, Berdichevsky *et al.* (1996) showed that certain 2D Earth models would generate considerable vertical electrical currents if the models include vertical faults of low resistivity. These authors used horizontal magnetotelluric field as an incident field. The latter work deals with magnetotellurics in the Lesser Caucasus but the first one deals with deep marine magnetotellurics. Meanwhile, Baikal water is fresh and much more resistive as compared with the oceanic water, however, Shneyer *et al.* (1998) proved that in 2D model of Southern Baikal the vertical electric field, E_z, is again sensitive to the presence of thin vertical fault of low resistivity. Though these results are valuable, we decided to explore the behaviour of E_z for a three-dimensional (3D) Baikal model, bearing in mind that the fault is a body of limited length but not of an infinite one. In this paper we build

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a simple 3D model of Southern Baikal and verify: 1) whether E_z is detectable over the fault, and 2) whether E_z-response is sensitive to the resistivity changes of the fault.

2. Model

Lake Baikal is located in the southern part of Eastern Siberia (see fig. 1). It is the oldest existing freshwater lake on Earth (20-25 million years old), being the deepest continental body of water. It is 636 km long and 48 km wide. Baikal lies in a deep structural hollow surrounded by rock. The fault that we are interested in, is located at the southern part of Lake Baikal, not far from the town of Slydyanka. A simplified 3D resistivity model of the Baikal deep fault is shown in figs. 2 and 3. The geometry of the model was taken mainly from seismic data by Merklin *et al.* (1979), whereas the resistivity data were taken from electromagnetic data by Popov (1977), and Kieselev and Popov (1992). In the model the 2 km thick, 40 Ω·m water layer is underlain by

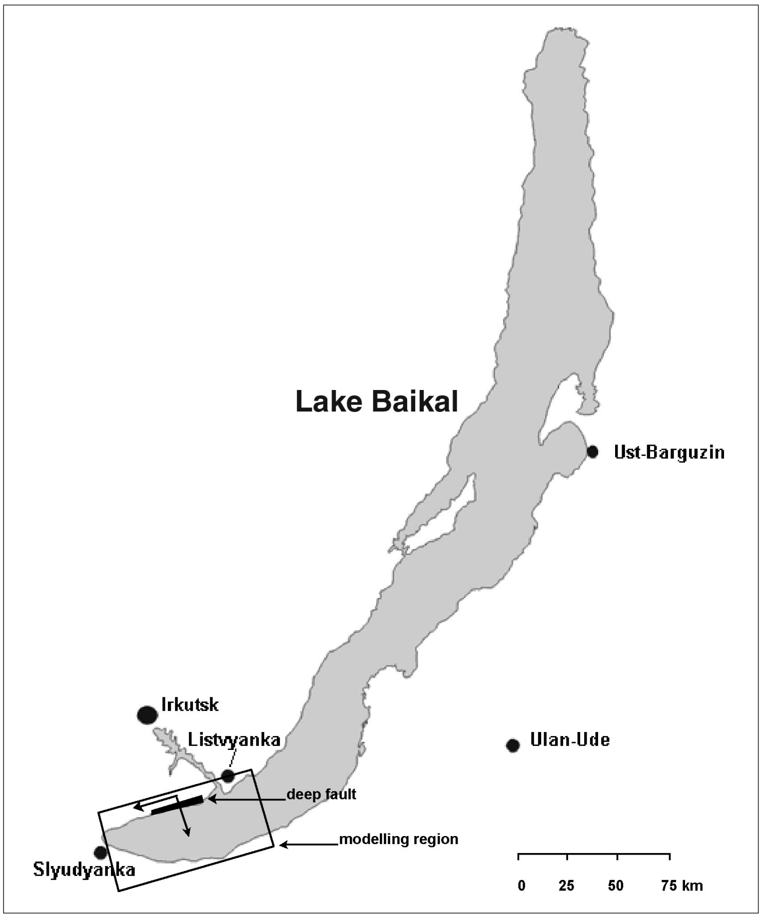

Fig. 1. Map of the region of Lake Baikal. Modelling region is marked with a rectangle. The fault is marked with a thick line.

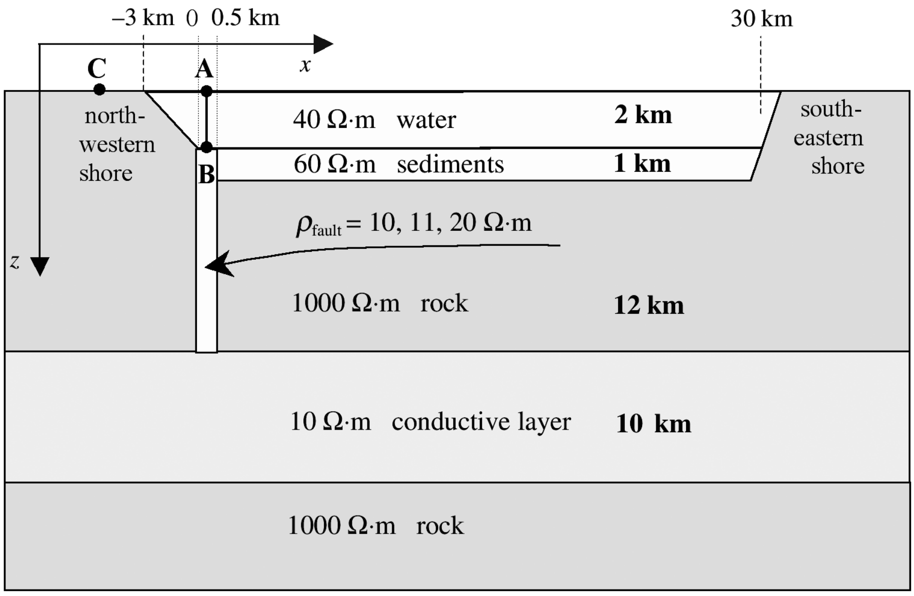

Fig. 2. 3D resistivity model of the Baikal Fault (side view). Line **A**-**B** is the profile where behaviour of E_z is studied. **C** is the coast site where components H_x and H_y are taken to obtain E_z response (see details in the text).

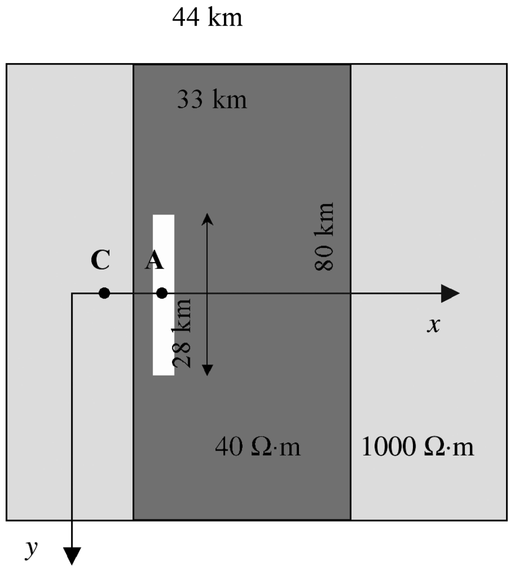

Fig. 3. 3D resistivity model (plane view).

the 1 km thick, 60 Ω·m sedimentary layer. Both layers are surrounded and underlain by 1000 Ω·m rock. Below, at a depth of 15 km, there is a 10 km thick conductive layer of 10 Ω·m. As for the fault in the model, it is 28 km long in y-direction (parallel to the shore) and 0.5 km wide in x-direction (perpendicular to the shore). The vertical size of the fault is 13 km. The fault outcrop is located at lake bottom exactly where the 35° steep slope of the north-western shore of the lake is ending. The shape of the south-eastern shore slope has been proved not to affect the electromagnetic (EM) field calculated in the vicinity of north-western shore. Thus, the fault appears to be galvanically connecting the deep conductive layer under the lake and the lake itself.

3. Numerical modelling

In the 3D resistivity model proposed we have performed a series of simulations of the vertical electric field, E_z, along vertical profile **A**-**B** as well as horizontal magnetic field on the shore. This 2 km long profile (from lake surface to the bottom) is located just over the center of the fault (see fig. 2). The amplitude of the incident plane wave electric field is chosen to be equal to 10 mV/km, resembling typical amplitudes of mid-latitude disturbances. Period of the incident field is taken to be 100 s and 1 h. While modelling, we varied the fault resistivity, ρ_{fault}, the values taken to be 10, 11 and 20 Ω·m. To perform the simulations we used X3D code which is based on the solution of modified scattering equation by the Krylov subspace iterations (Avdeev *et al.*, 1997, 2000). The modelling region of 44 km × 80 km × 15 km is divided into 440 × 100 × 14 cells.

Figure 4 presents the vertical electric field, E_z, along vertical profile **A**-**B** for E_x-polarized incident plane wave, with fault resistivity being 10 Ω·m. Left and right panels of the figure reveal the results for the periods of 100 s and 1 h respectively. The figure demonstrates that the values of $|E_z|$ are ranging, depending on depth, from zero (at the surface) up to 9 mV/km (at the bottom). In practice during the future experiment we are going to measure the vertical voltage, V(**A**, **B**), between points **A** and **B**. In our model, V(**A**, **B**) can be calculated as

$$V\,(\mathbf{A},\mathbf{B}) = \int_{\mathrm{A}}^{\mathrm{B}} E_z(z)\,dz..$$

The left plot in fig. 4 implies that the vertical voltage, V(**A**, **B**), should exceed 5 mV, which is very promising, since 5 mV could be readily detected by conventional EM instruments, their measurement precision accounting for 0.01 mV. In addition, it is also seen from the figure that

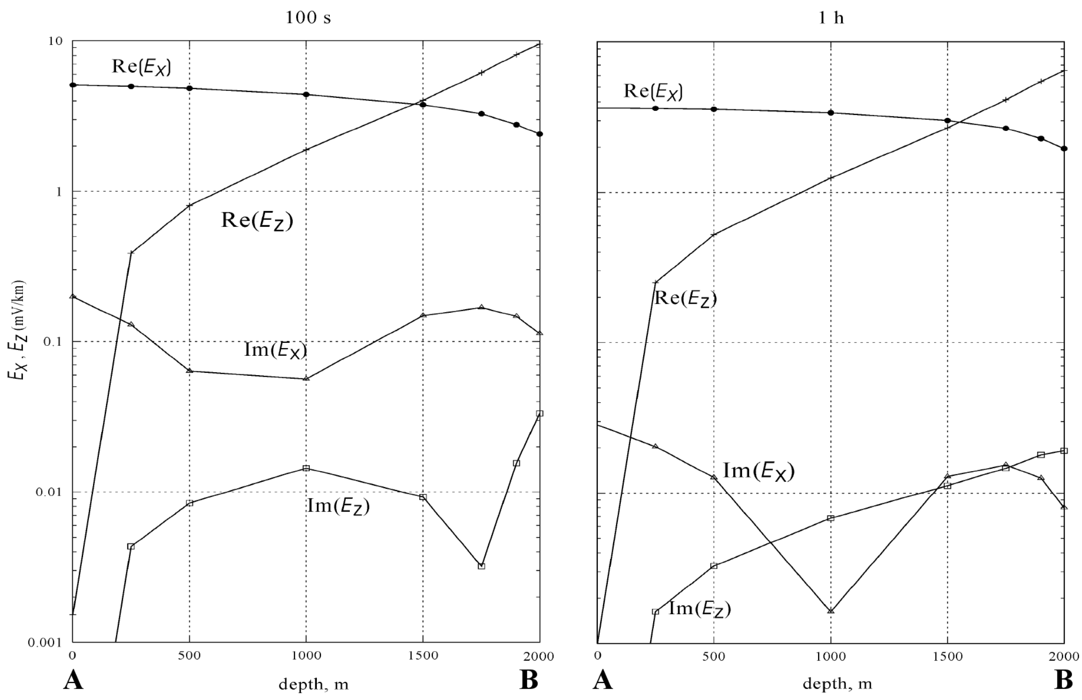

Fig. 4. Electric field components E_z and E_x along profile **A**-**B**. The source is E_x-polarized plane wave. The results are presented for periods 100 s (*left* panel) and for 1 h (*right* panel). The fault resistivity is 10 Ω·m.

near the fault outcrop, E_z-field even dominates the primary field E_x. Note that only real parts of the components are discussed, since imaginary parts are two orders of magnitude less.

It can be seen from fig. 4 $E_z(z)$ that can be approximated as follows:

$$E_z(z) \approx E_z(b)\, e^{(z-b)/h} \qquad (0 < z \le b) \tag{3.1}$$

when we evaluate integral

$$V(\mathbf{A},\mathbf{B}) = \int_{\mathrm{A}}^{\mathrm{B}} E_z(z)\, dz = \int_0^b E_z(z)\, dz.$$

Here b = 2 km is the bottom depth. Also, h = 621 m and h = 586 m for period of 100 s and 1 h respectively. As a consequence, the vertical voltage is directly proportional to the vertical electric field measured at the bottom

$$V(\mathbf{A},\mathbf{B}) = k \cdot E_z(b) \tag{3.2}$$

where proportionality coefficient is $k = h(1-e^{-b/h})$. We can show that coefficient k does not depend on the amplitude of the incident field.

The other consequence: higher values of the vertical electric field are accumulated near the bottom, so that it is not necessary to locate point **A** exactly at the surface. We can locate point **A**, say, 100 or 200 m deeper without significant change in the value of $V(\mathbf{A}, \mathbf{B})$.

As for the other polarization of the incident field (E_y-polarized plane wave), the vertical electric field is at least two orders of magnitude less than that for E_x-polarized incident field.

So far we demonstrated the amplitudes of the fields themselves. But it is known that while monitoring, the external field should be excluded from consideration. For this purpose, we introduce E_z-response as the expansion coefficients in

$$V(\mathbf{A},\mathbf{B}) = u_{zx} H_x^r + u_{zy} H_y^r \tag{3.3}$$

where H_x^r and H_y^r are the horizontal magnetic field components at the coastal reference site (site **C**, see figs. 2 and 3).

Expansion (3.3) can be used in the following way. Let $V^1(\mathbf{A}, \mathbf{B})$ and $V^2(\mathbf{A}, \mathbf{B})$ be the vertical voltage values measured for any two different polarizations of the incident field. Let (H_x^1, H_y^1) and (H_x^2, H_y^2) be the horizontal magnetic fields measured at the coastal reference site for the first and for the second polarization respectively. From expansion (3.3) it follows that:

$$\begin{aligned} V^1(\mathbf{A},\mathbf{B}) &= u_{zx} H_x^1 + u_{zy} H_y^1 \\ V^2(\mathbf{A},\mathbf{B}) &= u_{zx} H_x^2 + u_{zy} H_y^2. \end{aligned} \tag{3.4}$$

Therefore, we obtain final formulae for transfer functions u_{zx} and u_{zy} as follows

$$\begin{pmatrix} u_{zx} \\ u_{zy} \end{pmatrix} = \frac{1}{\det H} \begin{pmatrix} H_y^2 & -H_y^1 \\ -H_x^2 & H_x^1 \end{pmatrix} \begin{pmatrix} V^1(\mathbf{A},\mathbf{B}) \\ V^2(\mathbf{A},\mathbf{B}) \end{pmatrix} \tag{3.5}$$

where $\det H = (H_x^1 H_x^2 - H_y^1 H_y^2)$. Then these transfer functions u_{zx} and u_{zy} are called the E_z-responses because bigger values of the vertical electric field, E_z, are accumulated near the bottom and because $V(\mathbf{A}, \mathbf{B})$ is proportional to $E_z(b)$ (eq. (3.2)).

Table I presents the absolute value of the E_z-response, $|u_{zy}|$, shown with respect to the fault resistivity and period. Table I shows $|u_{zy}|$ transfer function alone, since response u_{zx} appears to be negligibly small compared to u_{zy}. This is due to the fact that only TM-polarized incident field generates major vertical electrical current through the fault.

Although electromagnetic field components E_x, E_y, H_x, H_y, H_z appear to be insensitive to the

Table I. Absolute value of E_z-response, $|u_{zy}|$, with respect to the fault resistivity and period.

	E_z-response (mV/nT) 100 s	1 h
ρ_{fault}=10 Ω·m	$776\cdot10^{-9}$	$186\cdot10^{-9}$
ρ_{fault}=11 Ω·m	$743\cdot10^{-9}$	$180\cdot10^{-9}$
ρ_{fault}=20 Ω·m	$526\cdot10^{-9}$	$128\cdot10^{-9}$
precision of experimental E_z-response	$14\cdot10^{-9}$	$5\cdot10^{-9}$

resistivity of the fault, we still need components H_x and H_y on the shore in order to obtain transfer functions u_{zx} and u_{zy}. Indeed, transfer functions u_{zx} and u_{zy} do not depend on the polarization of the incident field but the vertical voltage does.

The second row of table I shows that for a 100 s period, an operator should measure the values of 776, 743, and 526 and distinguish them from each other having the measurement precision equal to 14. Obviously it is possible. For a 1 h period, the measurement precision is just enough to distinguish the 10 Ω·m fault from the 11 Ω·m fault; and it is far enough to distinguish the 11 Ω·m fault from the 20 Ω·m fault. Altogether, for both periods the changes in the fault resistivity lead to detectable changes in E_z-responses. More explicitly, 10% and 100% fault resistivity changes result in 4% and 30% E_z-response changes, respectively. It should be also stressed that traditional impedance responses (simulated but not shown here) have appeared to be practically insensitive to the changes of the fault resistivity. Further numerical modelling (performed but not shown here) reveals that the link between the E_z-responses and the fault resistivity holds valid for bigger resistivity values. Namely, for the values ρ_{fault}=10, 11, 12, 20, 40, 80, 160 and 320 Ω·m we calculated the E_z-responses and found that $|u_{zy}(\rho_{\text{fault}})|$ can be approximated as follows:

$$\left|u_{zy}(\rho_{\text{fault}})\right| \approx \nu \cdot \rho_{\text{fault}}^{\gamma} \qquad (3.6)$$

where $\gamma = \gamma(T)$ and $\nu = \nu(T)$ depend on the period, T, of the incident field. Approximation (3.6) now follows that though we could hardly distinguish the 10 Ω·m fault from the 11 Ω·m fault at 1 h period, the 10 Ω·m fault can easily be distinguished from the 14 Ω·m fault at this period.

Though our model is an estimate, we realize that the link between the E_z-responses and the fault resistivity is rough enough and it must be detected while *in situ* measurements.

4. Conclusions

3D numerical studies have shown that the vertical voltage is detectable above the Baikal deep fault, and that E_z-responses are sensitive to the resistivity changes of the fault, *i.e.* E_z-responses appear actually informative with respect to the resistivity «breath» of the fault. Further studies should include more detailed modelling and field operations. It should answer the question whether changes in E_z-responses (and ρ_{fault}) are connected with changes in a stress state in the fault vicinity and whether E_z-responses can be used as one of earthquake precursors.

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