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MATHEMATICAL PROBLEMS OF SEISMOLOGICAL MONITORING OF GEOTHERMAL AREAS

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ABSTRACT

Most of geothermal areas are located in seismically active regions. Because of an intensive tectonic regime, discontinuities of their lithosphere play the role of channels for powerful metallogenic heat and mass transfer processes, especially for intrusion of ultra-basic magmas with Fe, Mn etc. into the crust. Proceeding from the presence of substantial low resistivity structures in seismic lithosphere zones (in accordance with numerous geophysical data and the known explanation above), we derive the mathematical model of generation and propagation of seismic electromagnetic and temperature signals with emission into atmosphere. As a result of calculations, we give the recommendations for the seismological monitoring of geothermal areas.

1. INTRODUCTION.

Formation, evolution and operational properties of geothermal areas are determined by the interaction of geophysical fields of different nature: mechanical (deformations, hydrodynamics), temperature, electromagnetic and gravitational in tectonically active structures. Dynamic processes in these structures generate disturbances of the fields above. These signals from the earth depth were registered on the earth surface and above it many times (Gokhberg, M.B., Krylov, S.M. and Levshenko, V.T., 1991; Hayakawa, M. and Fujinawa, Y. (Editors), 1994; Parrot, M. and Johnston, M.J.S. (Editors), 1993; Mei Shirong., 1992). However, the mechanism of generation of these signals, their relation to the characteristics of a medium and its seismic excitation are not known well, especially from the numerical point of view, which is principal for seismological interpretation of the signals. The data on conductive structures in seismically active lithosphere zones were mainly obtained by magnetotelluric investigations during the last 25 years. These indicate existence of structures with conductivity 0.1÷0.5 Sm/m (and up to 1.0 Sm/m, characteristic size of cross section is 10÷50 km and depth at least 10 km) in most of well known seismically active lithosphere zones (Arora and Mahashabde, 1987; Bragin et al., 1993; Gough, D.I., 1974; Lilley, 1975). Geophysical data of these and other papers encourages one to believe that substantial low resistivity structures of the above characteristics are typical in seismic lithosphere zones.

We shall describe numerically origination and propagation (including emission in the atmosphere) of electromagnetic (em) and temperature (θ) signals in a model media with low resistivity structures. Thus the dependence of the non-mechanical signals near surface upon the characteristics of the medium and its gepogene seismic excitation will be investigated.

2. MATHEMATICAL MODEL.

Mathematical model of generation of seismogenic em- and θ-signals must include the non-stationary elastic, temperature and electromagnetic fields together, because according to observations, all of them can be disturbed during the earthquake preparation period. Generally, the behaviour of elastic displacements $\boldsymbol{u}(t,x)$ (t is time and $\mathbf{x}$ is spatial coordinate) obeys a hyperbolic equation, whose details depend on assumptions on the physical conditions of the process:

$$\mathcal{H}\boldsymbol{u} = \rho \boldsymbol{g}, \tag{2.1}$$

where $\mathcal{H}$ is some hyperbolic operator, ρ is the density and $\boldsymbol{g}$ acceleration of gravity.

Now let us come to the evolution of electromagnetic field. We shall consider the media with the electric conductivity $\sigma \geq 10^{-4}$ Sm/m and the processes with the main frequencies $f < 10$ **Hz.** In this case the displacement current is negligible as compared with the conductivity current $\boldsymbol{j}$ (density), thus due to the 1-st Maxwell equation $\boldsymbol{j} = \nabla\times\boldsymbol{H}$, where $\boldsymbol{H}$ is the magnetic field intensity. Using the **Ohm** law in the form $\boldsymbol{j} = \sigma\boldsymbol{E}$ ($\boldsymbol{E}$ is the electric field intensity), we derive: fiom the 2-nd Maxwell equation $\nabla\times\boldsymbol{E} = -\partial\boldsymbol{B}/\partial t$ the following parabolic equation describing diffusion of magnetic field:

$$\partial\boldsymbol{B}/\partial t = -\nabla\times(\sigma^{-1}\nabla\times\boldsymbol{H})$$

where $\boldsymbol{B} = \mu_e\boldsymbol{H}$ is the magnetic induction, μ_e the magnetic permeability. The above dynamics can be expressed as

$$\mathcal{P}_m\boldsymbol{H} = 0,$$

with the parabolic operator

$$\mathcal{P}_m \equiv \partial\boldsymbol{B}/\partial t + \nabla\times(\sigma^{-1}\nabla\times\boldsymbol{H}) \qquad (2.2)$$

The equation for the non-stationary temperature field (stationary one is not a proper model for seismic media, especially in the case of a computation of temperature earthquake precursors, bellow) is the scalar parabolic equation whereas the magnetic field equation is the vector equation. The notations are usual: c_V is the heat capacity, κ the thermal conductivity, q is the density of the power of heat sources (chemical and lor radiogenic heat production of rocks), $\sigma^{-1}\boldsymbol{j}^2$ is the ohmic heat production.

Thus the temperature (θ) equation may be written using the parabolic ope-: tor $\mathcal{P}_H$ as regard to θ :

$$\mathcal{P}_H\theta = q, \qquad (2.3)$$

$$\mathcal{P}_H\theta \equiv \frac{\partial(c_V\rho\theta)}{\partial t} - \nabla\cdot(\kappa\nabla\theta) - \sigma^{-1}(\nabla\times\boldsymbol{H})^2$$

The operators $\mathcal{P}_m$ and $\mathcal{P}_H$ describe the evolution of magnetic and temperature fields, connected with the dissipative processes of the irreversible charge and heat transfer. Let us combine the parabolic equations (2.2) and (2.3) together:

$$\mathcal{P}w = q, \qquad (2.4)$$

where the parabolic operator $\mathcal{P}$ includes a **3D** vector part for magnetic and a scalar part for temperature field:

$$\mathcal{P}w \equiv \begin{pmatrix} \mathcal{P}_m\boldsymbol{H} \\ \mathcal{P}_H\theta \end{pmatrix},$$

and both the "state" variable $w \equiv (\boldsymbol{H}, \theta)^{tr}$ and the right hand side $q \equiv (\boldsymbol{0}, q)^{tr}$ include 3D vector component related to magnetic field and a scalar one for temperature field. Thus, using the classical models, i.e. without the field interaction, we have the hyperbolic system of equations (2.1), that describes deformations of the medium as a conservative process (the dissipation is neglected), and the parabolic system **of** equations (2.4), describing the dissipative processes (the deformations are neglected).

non-mechanical fields on the mechanical one and to include the source $\mathcal{A}(w)$ in **(2.1).** Besides, the effect

$$\mathcal{A}(\boldsymbol{u}, w)\xrightarrow{u\to 0} 0$$
$$\mathcal{B}(\boldsymbol{u}, w)\xrightarrow{w\to 0} 0 \qquad (2.6)$$

and the classical approach with the non-interacting fields (2.1), (2.4) is valid. Well-posedness of initial boundary value problems and their discretization for c.-d. systems was proved in the papers (Novik, **1969;** Novik, **1995** and other papers) on the basis of the methods developed by **O.A.** Ladyzhenskaya with collaborators (Ladyzhenskaya and Ural'tseva, **1968).**

Here we confine ourselves to the operators $\mathcal{H}$, $\mathcal{A}$, $\mathcal{P}$, $\mathcal{B}$ that correspond to ***non-uniform isotropic electrically uncharged media of differential type (without a "memory") in absence of displacement and thermoelectric currents, and marked processes of electric or magnetic polarisation*** Using then the theory of thermoelasticity for the thermomechanical interactions and electrodynamics of slowly moving media for the interaction of electromagnetic field with mechanical and temperature ones in accordance with the principles of the modem physical theory of magnetothermoelasticity (Knopoff, **1955;** Hutter and Ven, **1978;** Maugin, **1988),** we arrive at the following realisation of the interaction operators $\mathcal{A}$, $\mathcal{B}$ determining the c.-d. system as a modification of the classical equations (in the SI units):

$$\mathcal{A}(\boldsymbol{u},\boldsymbol{w}) \equiv \nabla(\beta(\theta-\theta_0)) - \boldsymbol{j}\times\boldsymbol{B},$$
$$\mathcal{B}(\boldsymbol{u},\boldsymbol{w}) \equiv \begin{pmatrix} -\nabla\times(\boldsymbol{u}_t\times\boldsymbol{B}) \\ \beta\theta_0\nabla\cdot\boldsymbol{u}_t \end{pmatrix} \qquad (2.7)$$

where $\beta = (2\mu+3\lambda)\alpha$; μ and λ are the elastic constants of Lame, a is the coefficient of thermal linear expansion and θ_0 is the initial temperature.

The operator A i s determined as usually:

$$\mathcal{A}\boldsymbol{u} \equiv \rho\frac{\partial^2\boldsymbol{u}}{\partial t^2} - \mathrm{Div}\,\hat{\sigma},$$
$$(\mathrm{Div}\,\hat{\sigma})_i \equiv \sum_{k=1}^{3}\frac{\partial\sigma_{ik}}{\partial x_k}, \qquad (2.8)$$
$$\sigma_{ik} \equiv \mu\cdot\left(\frac{\partial u_i}{\partial x_k}+\frac{\partial u_k}{\partial x_i}\right) + \lambda\delta_{ik}\nabla\cdot\boldsymbol{u},$$

where $\hat{\sigma}$ is the stress tensor, δ_{ik} is 1 for $i=k$ and 0 otherwise, $i, k = 1, 2, 3$; μ and λ are Lame's elastic constants. Thus Hooke's strain-stress relation and Cauchy's strain tensor are considered, i.e. *the physical and geometrical nonlinearities are neglected* Characteristics of the medium ρ, μ, λ, μ_e, a, σ, c_V, and κ may depend on t and **x**.

Note, that in the c.-d. system **(2.2)–(..8)** the magnetic and temperature fields H and ϑ depend on $\partial \boldsymbol{u}/\partial t$, i.e. the displacement velocity. Therefore thermal and magnetic fields are disturbed under seismic activation of the medium.

Equations **(2.2)–(2.8)** are valid for the lithosphere; and the atmospheric dynamics is different. The *atmosphere near earth surface is supposed to be electric neutral, with $\sigma = 0$, and displacement current neglected,* because of frequencies of order of $1\div 10$ Hz considered. Such long electromagnetic waves in the atmosphere are not influenced considerably by the mechanical and thermal disturbances from the lithosphere. It follows thus 60m the Maxwell equations that in the atmosphere the magnetic field obeys Laplace equation:

$$\Delta\boldsymbol{H} = 0 \qquad (2.9)$$

But the magnetic field in the atmosphere is not stationary because it is conjugated with the lithosphere magnetic field depending on the seismic activation process. The usual conditions of the conjugation of the components the of electromagnetic field on the earth surface in the case **of** polarisation processes neglected are:

$$\boldsymbol{H}(t,x)\big|_{x\to+0} = \boldsymbol{H}(t,x)\big|_{x\to-0} \qquad \textbf{(2.10)}$$

where $\boldsymbol{x} = (x, y, z)$, x is the vertical coordinate (positive in the lithosphere, and negative in the atmosphere, so $x = 0$ is the earth surface), y and z are horizontal co-ordinates.

Thus, the mathematical model **(2.2)–(2.10)**, based on fundamental physical principles and mathematical investigations has the proper structure to describe the generation and propagation of seismic em- and θ-signals in a non-uniform lithosphere zone, including the em-emission into atmosphere.

3. INPUTDATA.

Let us suppose that the medium parameters and the fields do not depend on z coordinate, and the 3-rd components of $\boldsymbol{u}$ and H vanish. In this case, the model of Sect. **2** includes five PDEs instead of seven ones in the 3D case.

The model cross-section includes the lithosphere zone **$(0<x<40)\times(0<y<80)$** and the atmosphere zone **$(-60<x<0)\times(0<y<80)$, km:**

1) the upper mantle conductive layer whith the sizes of $(35<x<40)\times(0<y<80)$;
2) the crust $(0<x<35)$, containing the sedimentary layer ("plate" $0<x<1$) and the conductive block (an ellipse with its centre at $x = 20$, $y = 50$ km and radii **5** and 10 km, respectively);
3) the atmosphere $(-60<x<0)$ up to the lower boundary of the ionosphere layer **D** was included to describe the em-emission caused by the deep (40 km) seismic excitation.

Let us remember that the vertical axis **Ox** is directed *downwards* (so $x<0$ in the atmosphere, Sect. **2**), y is the horizontal coordinate across the strike of the structures above, z is the horizontal coordinate along the strike. The physical parameters of the parts of the medium are shown in Table 1: ρ is the density; λ and μ are Lame's elastic constants; σ is electric conductivity. The parameters of low-resistivity structures (LRS) were chosen according to MTS-data (see references in Sect. 1). The values ρ, λ, μ, and σ are continuous across the boundaries of the structures. The remaining parameters: $c_V = 660$ J/(kg×K), $\alpha = 5\cdot 10^{-6}$ K^{-1}, $\theta_0 = 500$ K (see Sect. **2**) and the magnetic susceptibility $\chi = 0.001$ do not depend on coordinates.

Table **1**. Parameters of the medium.

parameters → *structures ↓*	ρ [kg/m³]	μ [Pa]	λ [Pa]	σ [S/m]
sediments	2700	$20\cdot 10^9$	$27.5\cdot 10^9$	0.005
crust	2800	$30\cdot 10^9$	$51.1\cdot 10^9$	0.0001

conductive block in the crust	4800	$90\cdot10^9$	$82.8\cdot10^9$	0.1
conductive layer of the upper mantle	4800	$25\cdot10^9$	$40\cdot10^9$	0.1

We consider the following model deep seismic excitation at the lower boundary due to the seismic source beneath it:

$$u_1(t,x,y)|_{x=40} = A(t)e^{-a\cdot(y-y_{0s})^2}$$

$$u_2(t,x,y)|_{x=40} = 0, \qquad (3.1)$$

$$A(t) = \begin{cases} A_1 \sin(2\pi f_1 t), & 0 \le t \le 3 \text{ s (pulse \#1)} \\ 0 & 3 \le t \le 5 \text{ s (pause)} \\ A_2 \sin(2\pi f_2 t), & 5 \le t \le 7 \text{ s (pulse \#2)} \\ 0 & t \ge 7 \text{ s (pause)} \end{cases}$$

The values of constants are: $A_1 = 1.5$ cm, $A_2 = 3$ cm, $f_1 = 1/6$ Hz, $f_2 = 1.5$ Hz; $a = 15\cdot10^{-10}$, $y_{0s} = 35$ km.

As one can see, this excitation consists of two pulses separated by a pause. The amplitude of excitation reaches its maximum at $y = y_{0s}$ and nearly vanishes at the edges $y = 0$ and $y = 80$ km.

Various initial and boundary conditions were considered as well as different (2÷3 times) values of the parameters of the medium. In all cases, the generation and propagation of the seismic signals and the connection between the deep seismic excitation and the surface signals were similar to those described bellow.

4. ORIGINATION OF THE ELECTROMAGNETIC AND TEMPERATURE SEISMIC SIGNALS.

The electromagnetic (em) and temperature (θ) disturbances originate near the bottom of the conductive layer. The evolution of the temperature field is rather simple: the θ-disturbances propagate together with the seismic wave. Thus, the beat transfer in seismically disturbed media is not similar to one in static media.

The evolution of electromagnetic field is more complicated. The em-signal outruns the 1-st seismic wave caused by the 1-st pulse (3.1) and arrives at the conductive block above the upper mantle conductive layer, but induction in this block is weak until the mechanical wave reaches it. Arrival of mechanical wave at the conductive body results (in presence of the stationary earth magnetic field) in generation of electromagnetic field in this block. At time $t = 5$ s the perturbation is strong enough to reach for the earth surface and emit in the atmosphere.

Later the elastic wave, going up to the surface, leaves the conductive block, and electromagnetic perturbations nearly vanish.

They are resumed after arrival of the second pulse, and are this time much stronger because of greater seismic energy contained in this pulse. Meanwhile, the first elastic pulse reaches for the earth surface and is reflected downwards. At time $t = 9.5$ s both pulses meet at the conductive block; and thus its seismic excitation reaches its maximum. As a results, the electromagnetic and thermal responses are also of their maximum value.

Because of the lack of place, we shall display spatial configuration of fields for this moment only, the more so that they are quite typical. These configurations are shown in Figs. 1–3 below. These figures display the litospheric part of the domain where the fields were simulated, and the lower part (10 km) of the atmosphere. Intensity is coded by shading; beneath the domain there is the horizontal "legend" with annotated shading scale. This scale covers only a part of the range of the field values so as to make the qualitative structure of the field more visible.

Note that the diffraction on the conductive block makes it clearly distinguishable from the crust, Fig. 1

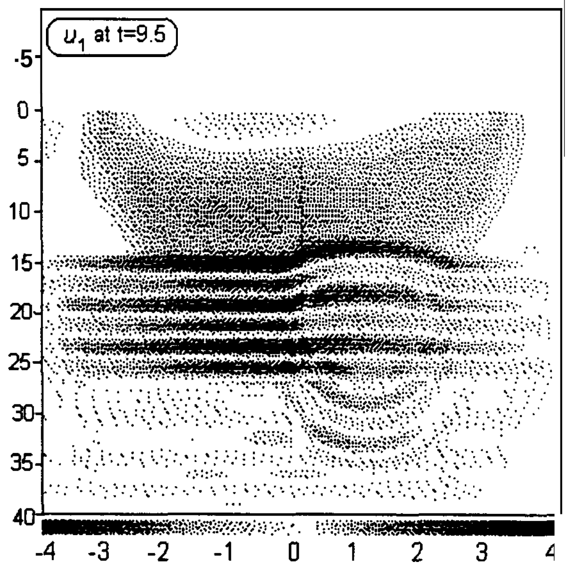

Fig. 1. Vertical component of displacement. The values on the shading scale are in cm; the whole range is –3.8 to 4.3 cm.

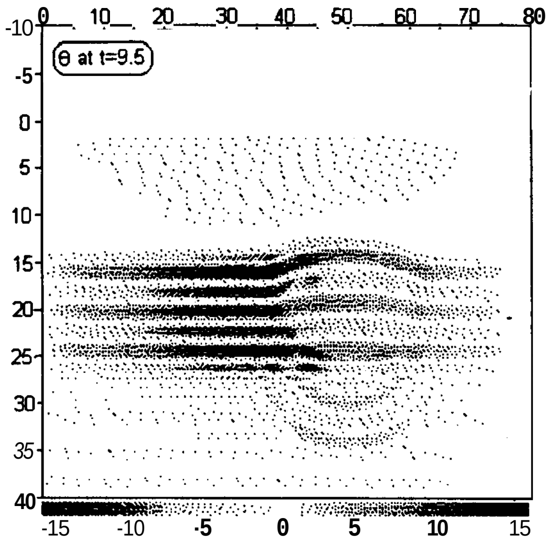

Fig. 2. Disturbance of the temperature field. The values on the shading scale are in thousandths of K; the whole range of θ is -0.017 to 0.019 K

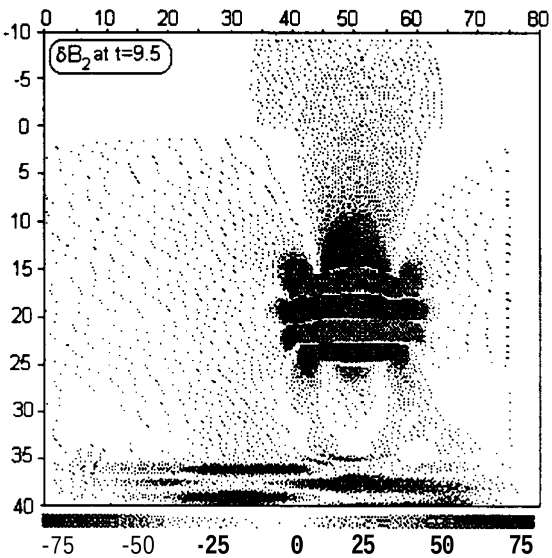

Fig. 3. Disturbance of the horizontal component of magnetic field (plotted is the deviation from the stationary field). The values on the shading scale are in pT; the whole range **of** δB_2 is -965 to **760** pT.

In these figures, one see overlapping of two waves: a longer one caused by the 1st pulse in (3.1), and the shorter one caused by the 2nd pulse in (3.1). The latter is mainly located in the vicinity of conductive block, while the former is mainly above it. Besides, "secondary" waves resulting due to reflections and refractions fill nearly the whole domain.

Thus we conclude that conductive block transforms the seismic excitation (3.1), coming from the depth of 40 km, into electromagnetic disturbances. They reach for the earth surface, and emit into the atmosphere. Such generation is only possible in presence **of** the static earth magnetic field.

Besides electromagnetic signal, propagation of seismic excitation results in generation **of** temperature disturbances. Unlike the electromagnetic ones, they are generated everywhere (i.e. outside the conductive body). Emission of heat into the atmosphere is not taken into account in the model described.

5. TIME SERIES OF THE TEMPERATURE AND ELECTROMAGNETIC SIGNALS.

Fig. **4** shows time series of the seismic temperature deviation $\theta - \theta_0$ (8-signal) in the sedimentary layer. The oscillations resemble those of the 2nd exciting seismic pulse (3.10), delayed by some **7** seconds which is just the travel time of the seismic wave. There is nearly no response to the 1st seismic pulse because the latter has too low frequency.

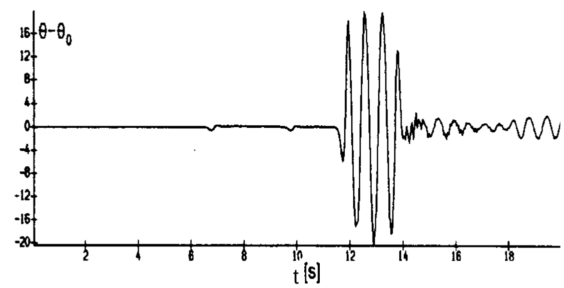

Fig. 4. Seismic temperature signal at the point $x = 500, y = 25$ km (sediments). The deviation $\theta - \theta_0$ (θ_0 is the temperature before excitation) is in 10^{-3} K.

In Figs. **5** and **6,** the seismic magnetic signal B_2 (deviation from the stationary field) is plotted *vs.* time t at the earth surface and 30 km above it, i.e. at $x = 0$, $y = 50$ km and at $x = -30$, $y = 50$. One can see that magnetic signal at the earth surface arises at $t = 4$ s, some *5* seconds before arrival of the seismic wave. Immediately it can be registered in the atmosphere; the shape of the signal is much the same as at the surface but the amplitude is much smaller. The shape of both of the pulses of seismic excitation (3.1) is reproduced quite closely:

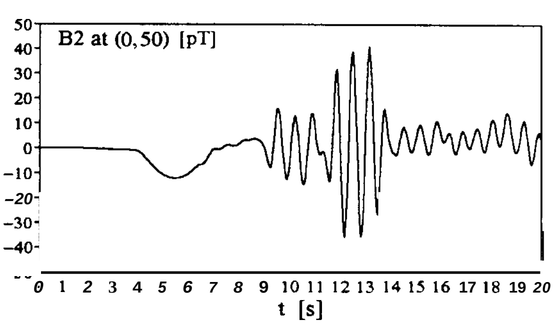

Fig. 5. The seismic magnetic signal at the earth surface, $x = 0, y = 50$ km.

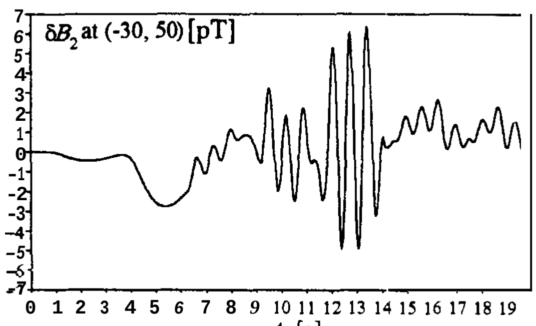

Fig. 6. The magnetic signal at the height of **30 km** above the earth surface, $x = -30, y = 50$ **km.**

According to our computations, the power spectra of em- and θ-signals near the earth surface are similar to those of the seismic excitation at the depth. Both spectra and amplitudes of the non-mechanical signals near surface change as one varies the corresponding characteristics of the seismic excitation.

Similarly, if the seismic excitation consists of several pulses with different amplitudes and spectra, the em-response at the surface also consists of a series of pulses, ***so*** a change of spectral characteristics of em-signal clearly indicates arrival of a new seismic pulse. The changes of the em-signal arise ***before*** the arrival of the seismic wave at the surface.

Such "information transfer" from depth to surface by non-mechanical signals was the same under different initial and boundary (external) conditions, as well as for different values of the parameters of the model structures. Numerical characteristics of the signals (amplitudes, spectra, velocities) correspond to known ones.

6. CONCLUSION.

1. Proceeding from the physical theory of magneto-thermoelasticity, a mathematical model is developed that describes the interaction of ultra low-frequency elastic, electromagnetic and temperature fields in lithosphere and emission of the electromagnetic component into the atmosphere. This is an extension of the approach (Novik et al., **1996)** to the case of nonuniform medium that can now include insulating parts (atmosphere), sediments etc.

3. Geometry and the value of electroconductivity of the low-resistivity structures **(LRS)** were chosen ***so*** as to match ***typical*** characteristics measured in geophysical field investigations in seismic regions.

4. Numerical simulation of our model with the above data revealed origination and propagation of electromagnetic and temperature signals in response to seismic excitation in the upper mantle (40 km).

5. The em-signal computed substantially outruns the seismic wave whose typical travel time is some **10** seconds in our case. The θ-signal propagates together with the seismic wave and reproduces its shape.

6. The dependence of the em- and θ-signals near the earth surface upon the structure of the medium and its seismic excitation was investigated numerically. The em- and θ-signals near the earth surface (and em-signals at the height up **to 30 km)** transfer information on the seismic excitation at the earth's depth: the amplitudes and spectra of these signals change, in response to the change of excitation, before the seismicwave arrival at the surface.

7. Qualitative characteristics of information transfer from depth to surface by em-perturbation are much similar to those for the case of a uniform conductive block excited from its bottom (Novik et al., **1996).**

8. Proceeding from the results above, we conclude that, for a seismological monitoring, em-signals in the frequency band **0.1** to **10** Hz should be measured at the earth surface and in the atmosphere at heights of **10** to **30 km** along with θ-signals (amplitudes **0.001÷0.05** K can be detected with quartz thermoresistors) at some 500 m (bore-holes) to distinguish the lithosphere em-signals from the ionospheric ones and to eliminate the temperature noise **from** the earth surface. The corresponding equipment, measurements and interpretation of seismic em- and θ-signals based on the relation between them and dynamic processes in the earth's depth, enables to perform seismological monitoring of geothermal areas because most of them, due to their geodynamic nature, are seismically active.

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