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GEOPHYSICS

# Formation and Dynamics of Energoactive Zones in Geological Medium

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Traditional solutions of the problem of global geodynamics related to the theory of convective fluxes in the mantle are based on the modeling of the structure of viscoelastic flows of matter in the Earth's interior on a geological time scale. These models generally take into account the thermal effects and diffusive-convective method of energy transfer. They do not describe the mechanisms of the formation of energoactive zones in a geological medium. Problems of local geodynamics are dominated by cumulative processes, in which the internal energy of the geological medium is manifested in tectonic and geophysical processes. Solution of these problems requires physicomathematical models of nonlinear interactions in the system of physical fields, which exchange energy with the energy accumulated in the geological medium.

Endogenous energy fluxes lead to the formation of zones with energy excess. Mechanisms of energy accumulation in the geological medium can conventionally be divided into three groups: (1) restrained nonequilibrium states, which can be manifested in the dynamics of the geological medium if released from the restraining factors; (2) resonators as elements of its structure including analogs of microwave billiards; (3) structure of the peculiarities of chemical potential presented in the molecular spectra.

According to [1], molecular spectra in the 0–THz frequency range reflect cooperative fluctuations with the macroscopic range of duration. They become significant in geodynamics if they occur synchronously in the volumes of geological bodies. This is possible if the background equilibrium of the medium is achieved on the basis of the longwave fluctuating electromagnetic field [2]. Energy is accumulated in the structure of the chemical potential if two or more potential holes exist [1]. The transition of state from one hole to another is related to energy absorption or release. The results of emission Fourier spectroscopy in the THz frequency range demonstrate discreteness of the spectra in different substances [3]. Figure 1 shows molecular spectra of terrigenous and carbonate rocks in the frequency range of THz or higher.

Rock sample from a productive bed of the Orenburg oil-and-gas condensate deposit shows the maximum amplitude spectrum at 722 cm$^{-1}$. In samples from the same bed from other wells, the maximum is recorded at 720 to 725 cm$^{-1}$, i.e., within the expansion range of the common line of spectral emission over the entire productive bed area. During energetic impact, compositionally homogeneous volumes of the geological medium are transformed into a quasi-coherent state with the formation of narrow polarization channels around several resonance modes in the THz and GHz ranges. A line of 615 cm$^{-1}$ of the THz range is distinguished in similar spectra of terrigenous rocks.

In order to describe the medium dynamics, we shall consider a few lines of emission spectrum with maximal amplitudes $g_j(0)$. Let $A_j$ be integrals of spectral density peaks around these lines. They are proportional to the density of the corresponding pairs of THz-transitions between potential holes corresponding to the chosen frequency. The wavelengths in this range are 5–100 μm. In this case, energy is accumulated in the solid matrix of the medium and bound fluid. In the model of longitudinal perturbations of the geological medium along the direction of settled polarization, displacement $u$ is a scalar; $\frac{\partial u}{\partial x}$ is strain; and $P = \frac{\gamma \partial u}{\partial x}$ is pressure, where $\gamma$ is the local Young modulus, a value inversely proportional to the compressibility of the medium. It is assumed that the vector of electric field strength is directed along the displacements of the geological medium or its projection to this direction is considered.

Deformation of the medium in the THz frequency range influences the process of mixing between quantum states. For each $j$-line of the spectrum, the dipole moment between the excited $\psi_{aj}$ and nonexcited $\psi_{bj}$ states is

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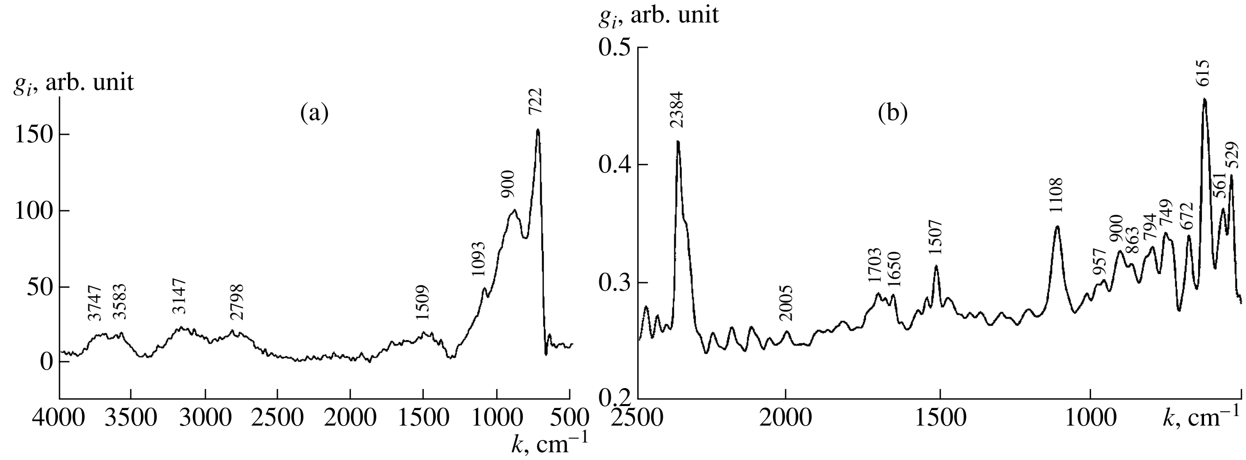


**Fig. 1.** Molecular spectra of surfaces of the samples. (a) Emission spectrum of carbonate rocks from a productive bed of the Orenburg oil-and-gas condensate deposit; (b) absorption spectrum of the terrigenous rock sample (b).

$$\frac{Pr_{0j}}{\gamma} = -e\int\psi_{aj}r\psi_{bj}dr,$$

where $r_{0j}$ is the corresponding dipole moment in the undeformed state and $r$ is the radius-vector. Emission of each line of the THz-spectrum is polarized [2]. Therefore, a consistent orientation of all transitions between levels and potential holes is assumed. Each transition specifies a shift of charges, which is equivalent to the introduction of a dipole with $\psi_{aj}$ and $\psi_{bj}$ distributions of charges with different signs into the medium. The potential field beyond the dipole decreases exponentially with distance. In a small volume $V$ within the dipole, it specifies the increment of the chemical potential, which is additive if several dipoles are present in the microvolume. It is assumed that the dipole equilibrium center is characterized by the mean value of the increment of potential energy ($r_{1j}$) in volume $V$ and its value is constant for all such dipoles owing to the polarization of the spectral line.

During deformation of the medium $\frac{P}{\gamma}$, the $r_{1j}$ value is transformed into $\frac{\gamma r_{1j}}{P}$. Excited states of electrons related to energy accumulation make up volume forces in the medium: grad$\left[\frac{\gamma r_{1j}}{P}N_{jt}\right]$, where $N_j$ is the occupancy number (probability of the existence of polarized $j$-excited state at a given point). The Maxwell–Bloch equation system [4] is used to describe interactions between the electric field strength $E$ and the resonance excitation field taking into account the strain field and equation for this field with the sources in the form of volume forces described above:

$$\frac{\partial N_j}{\partial t} = -\frac{2r_{0j}}{\gamma h\omega_j}PE\frac{\partial R_j}{\partial t},$$

$$\frac{\partial^2 R_j}{\partial t^2} + \omega_j^2 R_j = \omega_j\frac{2r_{0j}}{\gamma h}PEN_j, \quad (1)$$

$$c^2\frac{\partial^2 E}{\partial x^2} - \frac{\partial^2 E}{\partial t^2} = -\sum_j\frac{4\pi n_j r_{0j}}{\gamma}\frac{\partial^2(PR_j)}{\partial t^2},$$

$$v^2\frac{\partial^2 P}{\partial x^2} - \frac{\partial^2 P}{\partial t^2} = -\sum_j\frac{\partial\left(\frac{2n_j r_{0j}r_{1j}}{h\omega}E\frac{\partial R_j}{\partial t}\right)}{\partial x}, \quad j = 1, 2, \ldots, s.$$

Here, $n_j$ is the mean density of two-level subsystems with transition frequency $\omega_j$, which is proportional to $A_j$; $Q_j$, $R_j$ is polarization of the medium in the background equilibrium state; and $c$ and $v$ are velocities of electromagnetic and acoustic waves, respectively, in the medium.

Different spectral harmonics do not interact in the first order of the theory of perturbations. Therefore, we consider the processes generated by one harmonic and its contribution to the dynamics of the geological medium is proportional to its amplitude in the emission spectrum. Equations for the mode of the maximal amplitude are sufficient for the applications.

Let $\varepsilon_j$ be expressed as $\varepsilon_j = 2\frac{E^*}{\gamma}\frac{|r_{0j}|}{h\omega_j}$, where $E^*$ is the measure of electric field strength; $\frac{E^*}{\gamma} = O(1)$ and $\frac{|r_{0j}|}{h\omega_j} \ll 1$, since $n_j h\omega_j = A_j = O(1)$ and $n_j|r_{0j}| \ll 1$ due to the low density of distribution in the medium of 2-level systems. Next, $E = \frac{eE}{E^*}$, $2\pi n_j \frac{|r_{0j}|}{\gamma E^*} = \varepsilon_j \alpha_j$, where $\alpha_j = \frac{\pi n_j h \omega_j}{(E^*)^2} = O(1)$. The ratio of the potential energy of the dipole to the energy quantum of its radiation is $k = \frac{r_{1j}}{h\omega_j} = O(1)$. Hence, $\alpha_j \gamma\left(\frac{r_{1j}}{h\omega_j}\right) = \beta_j = O(1)$. Substitutions in (1) lead to a system of equations:

$$\frac{\partial N_j}{\partial t} = -\varepsilon_j PE\frac{\partial R_j}{\partial t}, \quad \frac{\partial^2 R_j}{\partial t^2} + \omega_j^2 R_j = \omega_j \varepsilon_j PEN_j,$$

$$c^2\frac{\partial^2 E}{\partial x^2} - \frac{\partial^2 E}{\partial t^2} = -\sum_j \alpha_j \varepsilon_j \frac{\partial^2 (PR_j)}{\partial t^2}, \tag{2}$$

$$v^2\frac{\partial^2 P}{\partial x^2} - \frac{\partial^2 P}{\partial t^2} = -\sum_j \frac{\partial\left(\beta_j \varepsilon_j E\frac{\partial R_j}{\partial t}\right)}{\partial x}, \quad j = 1, 2, \ldots, s.$$

System of Eqs. (2) is written with respect to slow variables and functions $X = \varepsilon_j x$, $T = \varepsilon_j t$, $N = N_{0j} + \varepsilon_j N_{1j}$, $R = R_{0j} + \varepsilon_j R_{1j}$, $E = E_0 + \varepsilon_j E_1$, $P = P_0 + \varepsilon_j P_1$ for zero order with respect to ε:

$$O(\varepsilon^0)\colon \frac{\partial N_j}{\partial t} = 0, \quad \frac{\partial^2 R_j}{\partial t^2} + \omega_j^2 R_j = 0,$$

$$c^2\frac{\partial^2 E_0}{\partial x^2} - \frac{\partial^2 E_0}{\partial t^2} = 0, \tag{3}$$

$$v^2\frac{\partial^2 P_0}{\partial x^2} - \frac{\partial^2 P_0}{\partial t^2} = 0, \quad j = 1, 2, \ldots, s.$$

Solutions of Eq. (3) are substituted into equations of the first order $O(\varepsilon^1)$ with $\delta = \frac{\Omega_j}{\omega_j} = \frac{v}{c}$ and coordinates $X = \frac{\omega_j X}{v}$, $T = \omega_j T$. An obstacle to the formation of modulated waves stable over time $\frac{1}{\varepsilon}$ are resonance terms from partial pressures $P_{0j}$ (with frequencies $\Omega_j$) and frequencies of spectrum lines $\omega_j$ of the electric field with stresses $E_{0j}$:

$$\begin{aligned} &N_{0j}(x, X, T), \quad R_{0j}(x, t, X, T) = R_j(X, T)\exp i\omega_j t, \\ &E_{0j}(x, t, X, T) = E_j(X, T)\exp i(k_j x - \omega_j t), \\ &P_{0j}(x, t, X, T) = P_j(X, T)\exp i(k_j x - \Omega_j t), \end{aligned} \tag{4}$$

$$j = 1, 2, \ldots, s, \quad \frac{\omega_j}{k_j} = c, \quad \frac{\Omega_j}{k_j} = v.$$

Zero resonant terms in $O(\varepsilon^1)$ with account for $\delta \ll 1$ lead to

$$\frac{\partial \Phi_j}{\partial T} = P_j E_j, \quad N_j = \pm\cos\Phi_j, \quad R_j = \pm\sin\Phi_j, \quad \frac{\partial E_j}{\partial X} = 0;$$

$$\frac{\partial E_j}{\partial T} = \pm\alpha_j P_j \sin\Phi_j, \tag{5}$$

$$\frac{\partial P_j}{\partial X} + \frac{\partial P_j}{\partial T} = \pm\beta_j E_j \sin\Phi_j, \quad j = 1, 2, \ldots, s.$$

Three physically different approximations of system (5) are considered.

1. *$E_j$ is constant over a small time interval $\Delta t \ll \frac{1}{\varepsilon}$.* After transformation of coordinates $X \to (T - 2X)$, $T \to T$ in (5), we obtain the sinus-Gordon equation:

$$\Phi_{j\,XX} - \Phi_{j\,TT} = \pm\beta_j E_j^2 \sin\Phi_j. \tag{6}$$

Pulse width in the automodel case for partial pressure is written as

$$\int E_j P_j dX = \gamma E_j \int \frac{\partial u_j}{\partial X} dX$$

$$= \gamma E_j u_j(+\infty) - \gamma E_j u_j(-\infty) = \gamma E_j U_j(X), \tag{7}$$

where $U_j(X) = u_j(X, +\infty)$ is the accumulated value of shear caused by localized perturbation. The following equation follows from the theorem for areas [4]:

$$\frac{\partial U_j}{\partial X} = \pm 2\pi\beta_j E_j g_j(0)\gamma^{-1}\sin\gamma E_j U_j, \tag{8}$$

where $g_j(0)$ is the amplitude of the corresponding spectral line. Localized perturbation of the geological medium governs the shear when $U_j$ is constant. Compression of the medium occurs at $\frac{\partial U_j}{\partial X} < 0$, and extension occurs at $\frac{\partial U_j}{\partial X} > 0$. At small $\gamma E_j U_j$, Eq. (8) describes electrostriction forces depending on the field energy $E_j^2$:

$$\frac{\partial U_j}{\partial X} = \pm 2\pi\alpha_j k E_j^2 g_j(0) U_j. \tag{9}$$

Pulses are generated by the nonequilibrium state of the geological medium, for example, in weakened zones, where fixed instabilities are formed as a result of natural processes. They exert a cumulative impact on the medium under the action of a triggering mechanism, resulting in the accumulation of effect depending on conditions of the realization of Eq. (8): compression (or compaction); extension (or dilatation); and tectonic shear. The formation of tectonic shear requires the presence of a specified direction, i.e., stable polarization properties of the geological medium, which can appear, for example, in lithospheric zones confined to fractures (generators of perturbations).

The right-hand part of Eq. (8) changes sign at $\gamma E_j U_j = \pi m$; i.e., the regime of extension–compression can change with the change in the electric field strength in the geological medium. Different signs in Eq. (8) correspond to the levels of accumulated energy higher or lower than the critical level. In order to determine this level, system (1) is linearized near the stationary solution of equilibrium values of physical parameters: partial component of pressure $P_j = P_{j0}$, mean field [2] $E_j = E_{j0}$, $Q = R = 0$, and density of background energy of the system specified by occupancy number $N_j = N_{j0}$. The dispersion relation yields a quadratic equation for frequency $\omega$ as a function of wave number $k$. The critical level of accumulated energy is the zero point of its discriminant. In the supercritical region, the wave packet would absorb energy from the potential energy resources, producing the effect of self-induced transparency (SIT).

The SIT phenomenon makes possible propagation without attenuation of seiche pulses (solitons), which are stable to small perturbations. Their width determines the constant shear value at each point of the medium by $\frac{2\pi\lambda}{\varepsilon}$, where $\lambda$ is the wavelength of the carrier mode in the submillimeter range. Each pulse first approaches the configuration of a soliton [8]. Owing to the SIT phenomenon, the pulse then spreads without attenuation along the zone of homogeneous background equilibrium and specifies the shear of the geological medium by a few millimeters. Periodically spreading pulses induce accumulated shear in the lithospheric region.

Changes in the compression–extension regimes caused by variations in the level of background energy of electric field stress were observed in the Sosnovskii geodynamic test site [5] within the Pripyat depression. The measurements showed that changes in the compression–extension regime occur near the Rechitskii regional fault with a frequency of 2.5 yr. According to the data of measurements, the average amplitude of horizontal shear in the Earth's crust caused by compression and extension is equal to 2 mm/yr over 1 km. The length of the main mode of the carrier wave in the THz range is ~0.1 mm. The number of compressing pulses is $\sim 120\alpha_j g_j(0)$, which is approximately equal to the number of days in the year. Daily tidal perturbations can act as a triggering mechanism for releasing the energy of fixed instabilities.

The mean velocity of horizontal motions in the Earth's crust recorded over 15 yr for the Yuzhnaya triangulation network, which crosses the Krivoi Rog–Kremenchug deep fault [6], is equal to 3 mm/yr, which also falls within the estimates given above. The faults generate flat pulses, which induce submillimeter-range shear waves. Their propagation due to the SIT effect provokes horizontal displacements. Investigation of the Terskii profile in the Terskii and Sunzhenskii zones of the Terskii–Caspian depression showed the existence of compressive horizontal tectonic motions, which are also equal to 2 mm/yr over 1 km of the profile on average [5].

In the zones of active fluid-dynamics with ion conductivity, the current strength, which generates the magnetic field, is proportional to $E_j$. Therefore, the maximal values of the magnetic field along the Terskii profile (up to 10 nT) is confined to the Terskii petroliferous zone (Eldarov oil field). Thus, the combination of horizontal motions of the crust with the effects of extension–compression and variations in the magnetic field allow us to make conclusions about conductivity and fluid saturation of the geological medium.

The analysis of fluid-dynamic regimes in active faults [7] showed that the degree of watering is high in compression zones of the profile. This leads to a decrease in the proportion of bound fluid in the volume, distorts the structure of the chemical potential, and decreases the energy of the main lines of the emission spectrum. The level of background energy decreases to the state lower than the critical one, resulting in compression according to the theorem for areas. Compressive pulses in this zone block the fluid rather than extract it from the zone. On the contrary, low flooding in extension zones fosters the binding of fluid, increase in the number of two-level states, creation of supercritical level of the mean field, and initiation of extension. Widening pulses pump out the fluid from this zone, resulting in the reduction of flooding.

2. *Pressure $P = P_{0j}$ is constant accurate to $O(\varepsilon)$ over a short time interval $\Delta t \ll \frac{1}{\varepsilon}$*. In this case, the following equation follows from (8):

$$\frac{\partial^2 \Phi_j}{\partial T^2} = \pm\alpha_j P_{0j}^2 \sin\Phi_j. \qquad (10)$$

According to (10), in the approximation of small initial amplitudes of the field, the pulse-generating exponential instability of electric field strength appears in a medium with background energy exceeding the critical energy. If the background energy is lower than the critical one, a harmonic of the electromagnetic field is formed with a frequency proportional to pressure:

$$E = E_0 + \alpha_j^{-1}\sin(\alpha_j^{-1} P_{0j} T),$$

which allows us to determine the level of the background energy of the medium in the kHz range.

3. *E- and P are variable.* In the approximation of a small deviation from the constant, values of the accumulated pulse in the medium caused by acoustic energy $\left(\int \frac{\partial P^2}{\partial X} dT = I_{ac} + \varepsilon f(X, T)\right)$ in the concomitant coordinates of Eq. (5) are reduced to the double sinus-Gordon equation:

$$\Phi_{j\,XX} - \Phi_{j\,TT} = \pm[\beta_j(W_j + W_{j1}) - \alpha_j I_{\rm ac}]\sin\Phi_j - 2\alpha_j\beta_j\sin 2\Phi_j, \quad (11)$$

where $W_j$ and $W_{j1}$ is energy of the $j$-component of electromagnetic and acoustic fields, respectively, in the initial time moment. The conclusions of Eq. (6) in section 1 related to geodynamic regimes remain valid for Eq. (11). However, it describes a more complex dynamics. Equation (6) describes only the sequences of kink-pulses, whereas Eq. (11) describes interactions between pulses [8]. If the level of total energy of acoustic and electromagnetic oscillations in a geological medium does not exceed the $(\gamma^{-1}I_{\rm ac} + 4\alpha_j)$ value, the following nontrivial dynamic regimes are possible [8].

3.1. In the swinging regime, two linked shear pulses alternately overtake each other. The first pulse slows down and leaves part of its energy in the medium. The next pulse accelerates using this energy and overtakes the first pulse. Then, the process is repeated. In this case, the pulses are linked by the alternating electromagnetic field. Generation of seismic waves in the range up to 100 Hz can be recorded.

3.2. Oscillating kink–antikink links of the breather type appear, the width of which corresponds to zero shear. They do not cause geodynamic effects. However, kHz-scale acoustic waves and mHz-scale electromagnetic waves are radiated. Low-frequency pulses synchronize breather modes [8], amplifying the links and amplitudes of these lines in spectra.

Thus, processes of shear, extension, and compression are realized at a high level of field energy. If the energy of physical fields does not exceed the critical level, generation of electromagnetic and acoustic perturbation in the kHz and Hz ranges are recorded during the passive complex geodynamic–geophysical monitoring. The proposed theoretical model opens new capabilities for the joint interpretation of different geophysical–geodynamic data, establishes new important parameters of the energetic structure of the lithosphere, and outlines methods for their determination based on various geophysical methods.

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