Modulation of geoacoustic emission intensity by time-varying electric field

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The mechanism is suggested to account for the modulating effect of weak audio-frequency (a few hundred Hz) electromagnetic fields on the geoacoustic emission intensity in the case when liquid phase (aqueous solution) in the pore-fracture space of the noise zone controlled by the geophone is the incompressible Newtonian fluid with constant viscosity and permittivity beyond the slipping plane of the electrical double layer. *KEYWORDS:* Geoacoustic emission; borehole; electromagnetic radiation; electrical double layer; pore fluid.

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Introduction

The results of integrated logging measurements that have been conducted during many years at the Petropavlovsk-Kamchatsky geodynamical testing area indicate clearly promising outlook for monitoring the strain-stress state of the geological medium based on the modulating effects of the external electromagnetic fields on the intensity of geoacoustic emission (GAE) [*Gavrilov et al.*, 2014]. Understanding the probable physical mechanisms of this effect is one of the key prerequisites for correct interpretation of the results of these measurements. In the previous works in this direction, the modulating effect of the weak ELF electromagnetic fields (a few hundred Hz) on GAE intensity was accounted for by the changes in viscous friction between the mobile part of the fluid and the surface of the solid phase [*Gavrilov*, 2014; 2016]. In this model, a fluid was assumed to be viscoplastic and to have the shear resistance not entirely governed by viscosity but also controlled by static friction (the Bingham fluid). Meanwhile, the detailed analysis of the results of integrated logging measurements at the Petropavlovsk-Kamchatsky geodynamical testing area gives grounds to suggest that the model with Bingham fluid can correspond to the case of granular grained geological medium with capillaries having small diameters commensurate with the thickness of the electrical double layer (EDL), whereas GAE in the real geological medium should be much more related to the motion of the Newtonian fluid through microcracks with noticeably larger diameter than EDL thickness. Considering this, in the present paper we analyze the case when the fluid in the pore-fracture space controlled by the noise-zone geophone is an incompressible Newtonian fluid whose viscosity and permittivity beyond the slipping plane of EDL are constant.

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The Influence of Filtration Processes and Water Saturation of the Rock on the Characteristics of GAE

The data of the in situ experiments and long-term integrated monitoring in the boreholes at the Petropavlovsk-Kamchatsky geodynamical testing area suggest that the main GAE sources can be primarily associated with the motion of the liquid phase (a fluid) in the pore-fracture space of the noise zone controlled by the geophone. Here, when talking about fluid motion, we mean both the slow motion with flow velocities of at most a few mm/s and the relatively fast movements caused by the action of external alternating electric field in the frequency band up to 1 kHz.

A clear idea of the effect caused in the characteristics of GAE by the filtration processes in the pore-fracture space within the wellbore zone and the degree of fluid saturation of the pore-fracture space can be gained from the results of the in situ experiment conducted in the G-1 borehole at the Petropavlovsk-Kamchatsky geodynamical testing area in June 2014 [*Gavrilov and Panteleev*, 2016]. In this experiment, on June 4, 2014, ~ 50 l of water was pumped out from the borehole, which caused fluid inflow into the pore-fracture space of the noise zone of the geophone installed at a depth of 270 m. The results of geoacoustic measurements obtained in this experiment in the frequency band of 160 ± 20 Hz are illustrated in Figure 1. Figure 1a shows a fragment of the initial geoacoustic time series which demonstrates, firstly, the changes in the root mean square (RMS)

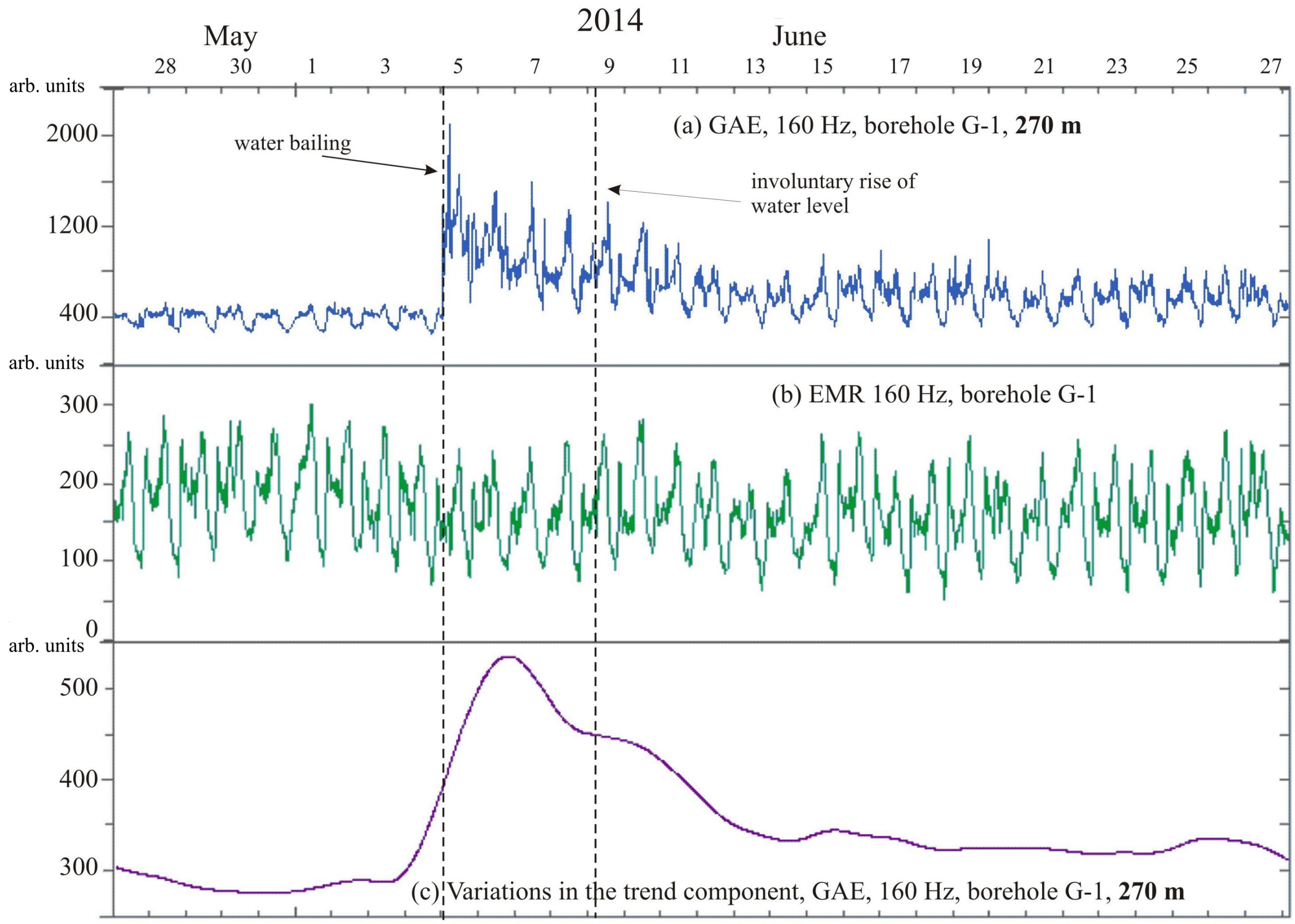

Figure 1. The changes in the character of GAE at a depth of 270 m for the vertical component Z in the frequency range 160 ± 20 Hz during the in situ experiment in the G-1 borehole in June 2014: (a) – initial GAE time series; (b) – daily variations in the external EMR in the frequency range 160 $\pm$ 20 Hz; (c) – variations in the trend component of the GAE time series.

values of daily GAE variations and, secondly, the changes in the trend component of GAE data, which envelopes the GAE time series from below. To explain, we note that according to the results of numerous works (e.g., [*Gavrilov et al.*, 2014]), the daily GAE variations for the zone of the G-1 borehole are responses to the daily variations of the external electromagnetic radiation (EMR) in the area of the G-1 borehole in the frequency band 160 $\pm$ 20 Hz (Figure 1b).

As can be seen from the presented data, at the initial time instant, after pumping out the water, the trend component of GAE time series (Figure 1c) has grown by $\sim$ 100% compared to the average level over the previous 10 days. The results of the long-term measurements at the Petropavlovsk-Kamchatsky geodynamical testing area suggest that at the reasonably high fluid saturation of the rock, the changes in the trend component of GAE time series up to the constant coefficients reflect the changes in the fluid filtration rate which is understood as the following quantity [*Mironenko*, 2005]:

$$V = \frac{Q}{\omega}$$

where Q is total fluid flow rate for the entire volume of the filtering rock and ω is the entire cross section of the filtering rock. In the case of the in situ experiment in the G-1 borehole, the growth of the fluid filtration rate in the noise zone of the geophone can be accounted for by the fluid inflow into the pore-fracture space of the wellbore area caused by the changes in the pore pressure due to pumping out water from the borehole [*Gavrilov and Panteleev*, 2016].

In the data presented in Figure 1a it can also be seen that simultaneously with the growth in the trend component of GAE, a significant increase (by 200%) is also observed in the root mean square (rms) values of daily GAE variations. Assuming that the changes in the trend component of GAE are associated with the changes in the fluid filtration rate, we may come to the conclusion that the growth in the rms values of daily GAE variations is also due to the fluid inflow into the pore-fracture space in the noise zone of the graph.

The results of long-term borehole logging studies at the Petropavlovsk-Kamchatsky geodynamical testing area, which were conducted in the mode of continuous monitoring, agree with the data of the in situ experiment described above. Besides, the long-term measurements of the stress-strain state of the geological medium at different stations

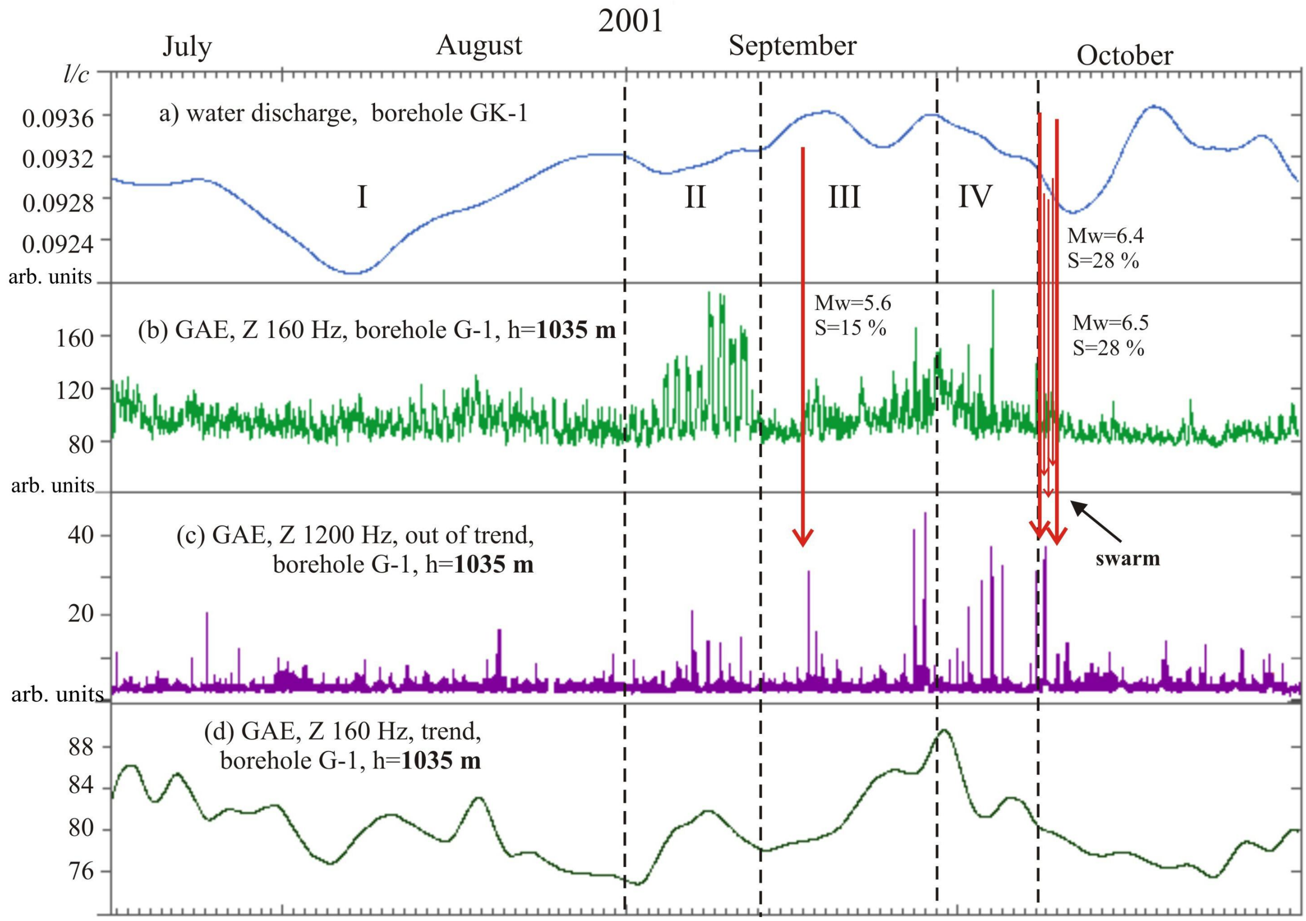

Figure 2. The results of geoacoustic measurements in different frequency channels in the time vicinity of the earthquake swarm in October 2001, the G-1 borehole, depth 1035 m, Z-component: (a) – time series of the water discharge of the GK-1 borehole; (b) – the rms GAE time series for the 160-Hz frequency channel; (c) – the rms GAE time series for the 1200-Hz channel; (d) – the variations in the GAE trend component for the 160 Hz channel. According to [*Gavrilov and Buss*, 2015].

established that in the case of extremely low water saturation of the rock, the growth in the GAE trend component is no longer associated with the fluid inflow into the pore-fracture space of the wellbore zone but caused by the increase of sliding friction between the grains of the rock and the walls of the existing cracks. In these cases, GAE responses to the variations in the external alternating EMR in the wellbore zone will be absent. As an example, in Figure 2 we present the results of the geoacoustic measurements in the G-1 borehole for the time vicinity of the swarm of the strong earthquakes in the Avacha Bay (on the eastern coast of Kamchatka) in October 2001.

The behavior of the geoacoustic data shown in Figure 2 suggests four stages within the considered time interval. For stages I and II, the multi-instrumental logging data have been fairly thoroughly analyzed in [*Gavrilov et al.*, 2014; *Ryabinin et al.*, 2011, 2012]. It was shown that the sharp and strong buildup of the amplitudes of GAE responses at stage II can be accounted for by the increase in fluid saturation within the noise zone of the geophone due to the fluid inflow from the deeper geological horizons and the enhancement of electrokinetic processes.

The beginning of stage III coincides with the commencement of the decay in the amplitudes of GAE responses. With the beginning of this stage, GAE responses to the variations in the external EMR have completely degraded. To the end of stage III, about 38 days before the strongest events in the swarm, the trend component of GAE in the 160-Hz channel has significantly increased (Figure 2d) in the absence of GAE responses to the variations in the external EMR. Besides, at the end of stage III, the GAE count rate has also increased both in the low-frequency (Figure 2b) and high-frequency (Figure 2c) channels. Note that in the high-frequency GAE channel, a sharp growth occurred in the number of the high-amplitude GAE events at that time.

As shown in [*Gavrilov and Buss*, 2015], this GAE behavior at stage III can be accounted for by the significant decrease in fluid saturation of the rocks in the borehole bore zone at this stage, which, inter alia, resulted in the degradation of GAE responses to the changes in the external EMR. The significant increase in the trend GAE components by the end of stage III in this case resulted from the noticeable growth of sliding friction between the particles of the rock and the sides of the existing cracks.

The Probable Mechanism of Electromagnetic Modulating Impact on the Intensity of Geoacoustic Emission

The described results show that the presence of the liquid phase in the pores and cracks of the rock is the necessary condition of the influence of external EMR on the intensity of GAE. Based on this conclusion, below we consider the probable mechanism rendering the modulating impact of the external EM factor on GAE intensity. We associate this mechanism with the action of the external alternating electric field on the pore fluid.

Clearly, in this case the considered fluid should not be electrically neutral. It is known that the role of a charged fluid layer with a certain volume charge density is played by the pore fluid in the diffuse layer of the electrical double layer. The latter is the necessary element in the processes of the interaction between the solid and liquid phases at their interface boundary.

EDL is a layer with a thickness of $10^{-9} - 10^{-4}$ m, which is formed at the interface of two phases and composed of spatially separated opposite charges. EDL emerges in all cases when free charge carriers have existed before or appeared as a result of the interaction in at least one phase. The primary cause of EDL emergence lies in the difference of chemical potentials of the charged particles in the liquid and solid phases. Fluid ions can interact with the solid phase both due to the electrostatic forces (through Coulomb adsorption) and through the specific (chemical) adsorption.

According to the present-day notions of EDL structure, which rely on the Gouy-Chapman-Stern model, EDL consists of a layer of specifically adsorbed ions, which are relatively tightly bound to the surface of the solid phase, and a layer of ions that have been electrostatically attracted to the surface together with the hydration shells. The first form the so called inner Helmholtz plane (1 in Figure 3) and the second, the outer Helmholtz plane (2 in Figure 3). The potential drop within these planes is linear, just as in a parallel-plate capacitor. Next, the diffuse part of EDL follows. It consists of the ions of the both sign which are continuously distributed in the liquid phase. The ions compensating the charge of the solid phase are concentrated near the surface (positive Coulomb adsorption), whereas the counter-ions deplete the near-surface layers (negative Coulomb adsorption). At a sufficient distance from the surface, the potential of the diffuse part decays also exponentially.

Since the main rock-forming minerals are silicates and alumosilicates, solid phase typically carries negative charge and the liquid phase carries positive charge. This is implemented by several mechanisms of charge separation, namely, ion exchange between mobile cations

$$\mathrm{Na}^{+(\mathrm{solid})} \rightleftarrows \mathrm{Na}^{+(\mathrm{liquid})}$$

or

$$\mathrm{Ca}^{2+(\mathrm{solid})} + \mathrm{Na}^{+(\mathrm{liquid})} \rightleftarrows \mathrm{Na}^{+(\mathrm{solid})} + \mathrm{Ca}^{2+(\mathrm{liquid})}$$

and the possibility of ionization of surface groups, e.g.:

$$\equiv \mathrm{Si} - \mathrm{OH}^{(\mathrm{surf})} + \mathrm{H_2O} \rightleftarrows \equiv \mathrm{Si} - \mathrm{O}^{-(\mathrm{surf})} + \mathrm{H_3O}^{+}$$

In these cases, the role of the potential-forming agents is played by cations and the compact adsorption layer can be composed of anions. The similar structure is formed on the side of the solid phase in which the volume negative charges are bound whereas the mobile cations experience negative Coulomb adsorption (are attracted from the surface).

The diffuse layer in the fluid includes the immobile (fixed) and mobile parts which are separated by the slipping plane. Beyond this plane, fluid flow in the diffuse layer becomes impossible (3 in Figure 3). The potential in the slipping plane, which is referred to as electrokinetic or ζ-potential is the key parameter of EDL which is directly related to electrokinetic processes.

The geometry of EDL is typically described in terms of the effective thickness of EDL – the distance measured from the outer Helmholtz plane where the potential drops from the value φ_δ to 1/e of it (Figure 3). The calculated effective EDL thickness for fluid solution in the zone of the G-1 borehole at a depth of $\sim$ 1000 km is $\sim$ 0.7 nm. Considering the thickness of the adsorption layer of EDL ($\sim$ 0.3 nm), we obtain the total EDL thickness in this case at 1.0 nm.

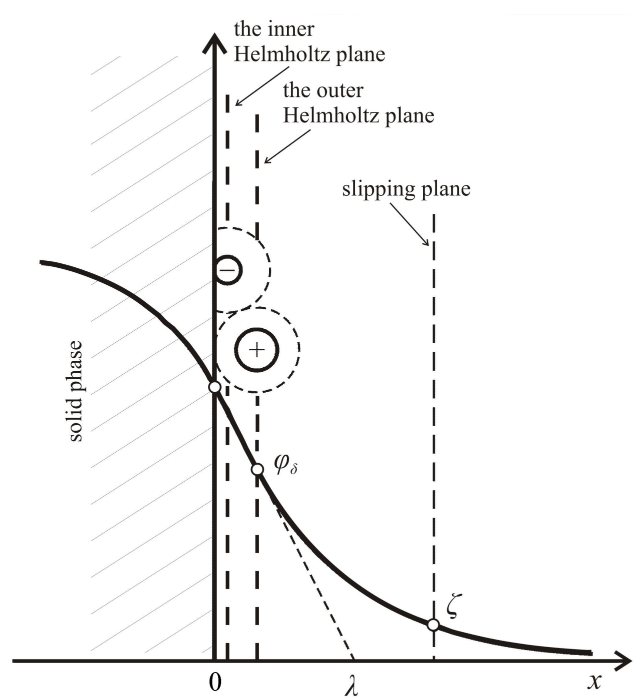

Figure 3. The structure of the electrical double layer and potential distribution in it: 1, the inner Helmholtz plane; 2, the outer Helmholtz plane; 3, the slipping plane. Distance x is measured from the boundary of the phases, and potential φ is measured from a certain depth level in the fluid.

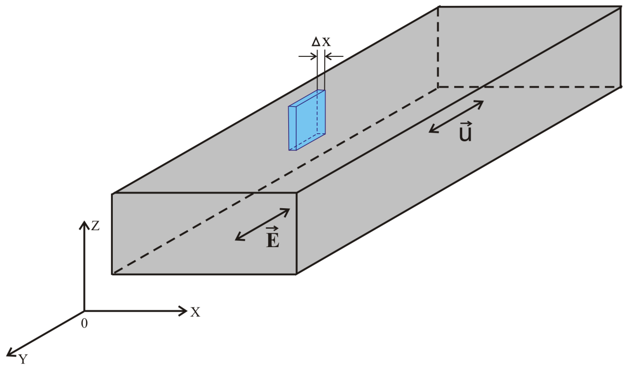

Figure 4. Simplified model of permeable channel. See text for explanations.

Taking into account the structure of EDL, we may try to qualitatively analyze the probable physical mechanism that accounts for the modulating effect of the external alternating electric field in the frequency band up to a few kHz on GAE intensity.

The liquid phase located in the pore-fracture space of the geophone-controlled noise zone is assumed to be incompressible Newtonian fluid with constant viscosity and permittivity beyond the slipping plane of EDL.

As a simplified mesoscale model of the pore-fracture space in the zone of the borehole we consider a heterogeneous dual-porosity system composed of the weakly permeable blocks and grains which are split by the more permeable wide (compared to EDL thickness) channels. This model fairly well agrees with the results of drilling for the G-1 borehole in the Petropavlovsk-Kamchatsky geodynamical testing area below a depth of 108 m (the beginning of the Upper Cretaceous sequence [*Zabarny et al.*, 1990].

We consider a separate permeable channel (Figure 4). We assume that this channel is wide compared to the EDL thickness. This allows us to disregard the influence of the opposite wall of the channel on the fluid motion. As noted above, the pore fluid in the diffuse layer of EDL in the rocks is electrically not neutral, i.e. the external part of EDL can be thought of as a charged fluid layer with a certain volume charge density. In this case, in the presence of the external electric field in the geological medium, each arbitrary element of the pore fluid with volume dV will be acted by the force $d\mathbf{F} = \mathbf{E}\rho(x)dV$, where $\mathbf{E}$ is the intensity of the electric field and $\rho(x)$ is volume charge density for the considered element of volume. We assume that the electric field acting on the pore fluid is a plane electromagnetic wave propagating along the normal to the channel's wall, i.e. parallel to the X-axis. Let us consider the relationships that will help us to establish the dependences of the pore fluid flow velocity on the characteristics of the external EMR. To this end, we use the approach presented in [*Simanova*, 2004].

Let the considered fluid volume be located in the vicinity of the channel's wall (Figure 4) in the EDL diffuse layer beyond the slipping plane (Figure 3) were fluid motion is possible. For simplicity, we analyze one-dimensional (1D) problem where this element of the fluid has an infinitely small thickness dx and unit areas of its side faces. The mean charge density $\rho(x)$ for the considered element of the volume is in this case a function of the coordinate x and is determined by the 1D Poisson equation:

$$\frac{d^2\varphi(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon_0\varepsilon} \tag{1}$$

where ε_0 is electric constant, ε is permittivity of the pore fluid; and $\varphi(x)$ is the electrical potential at point x.

With the allowance for the fact that for the considered volume $dV = dx$, the Navier-Stokes equation which describes fluid motion in the channel, is in this case reduced to the following equation:

$$d\tau(x) + E\rho(x)dx = 0 \tag{2}$$

where $d\tau(x)$ is the difference of friction forces on the far (in accordance with x, see Figure 4) and near wall of the dx.

Combining (1) and (2) and integrating the result from x to ∞, we obtain:

$$\tau(x) = -\varepsilon\varepsilon_0 E\int_x^\infty \frac{d^2\varphi}{dx^2}dx = \varepsilon\varepsilon_0 E\frac{d\varphi}{dx}|_x$$

since $d\varphi/dx|_\infty = 0$.

According to the Newton's law of internal friction,

$$\tau(x) = \mu\frac{du}{dx}|_x$$

where μ is dynamic viscosity of pore fluid and u flow velocity of the pore fluid. Then

$$\mu\frac{du}{dx} = \varepsilon\varepsilon_0 E\frac{d\varphi}{dx}$$

or

$$du = \frac{\varepsilon\varepsilon_0 E}{\mu}d\varphi$$

Since the viscosity and permittivity of pore fluid in this case are assumed to be constant, the last equation can be easily integrated. In the integration, we take into account the fact that on the slipping plane, the flow velocity of the pore fluid is zero and the potential φ is equal to ζ-potential. The integration leads to the Helmholtz-Smoluchowski equation [*Frolov*, 1982]:

$$\int_0^{u(x)} du = \frac{\varepsilon\varepsilon_0 E}{\mu}\int_\zeta^{\varphi(x)} d\varphi$$

or

$$u(x) = \frac{\varepsilon\varepsilon_0 E}{\mu}(\varphi(x) - \zeta) \tag{3}$$

Far from the interface boundary, the potential exponentially drops: $\varphi(x) = \varphi_\delta e^{-x/\lambda}$. From formula (3) it follows that given constant viscosity and permittivity of the pore fluid beyond the EDL slipping plane, the variations in the flow velocity for a fixed coordinate x are determined by the variations in the intensity of the electric field.

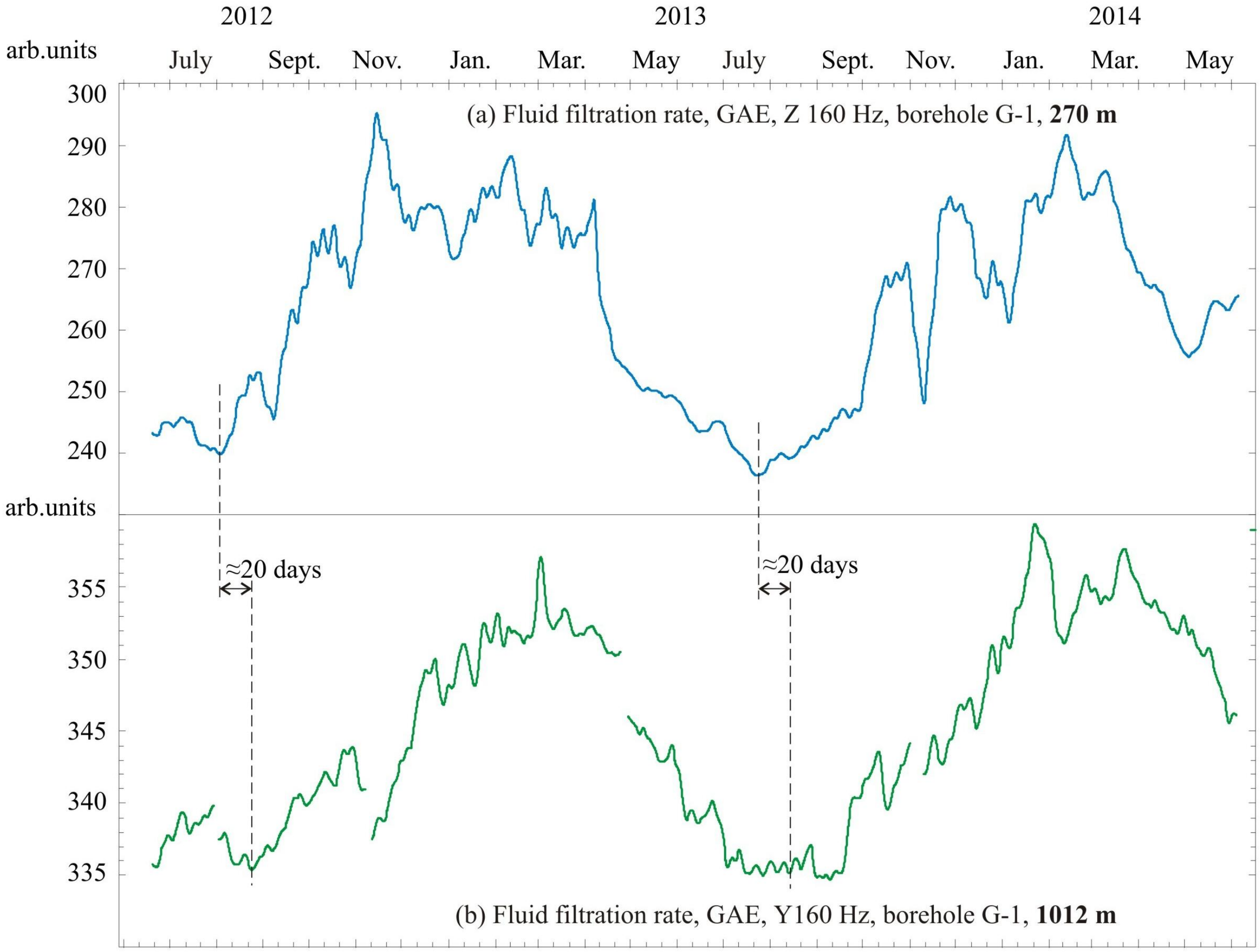

Figure 5. The results of simultaneous measurement by two geophones installed in the G-1 borehole at the depths (a) 270 m and (b) 1012 m.

Under the external stationary tangential electric field, beyond the range of action of the stationary EDL field (beyond the distance of twice or thrice the effective EDL thickness), potential φ will be close to zero and the flow velocity of pore fluid will be maximal:

$$u = -\frac{\varepsilon\varepsilon_0 E}{\mu}\zeta$$

In the case when the medium is affected by weak alternating varying electric fields with the intensities of a few mV/km, the highest sensitivity to their impact will be observed in the fluid layer located in the tail zone of the potential of the diffuse part of EDL (Figure 3) where the stationary EDL field is commensurate with the external alternating varying electric field.

Let us now focus on the questions about the dependence of GAE parameters on the flow velocity of the pore fluid. On the qualitative level, this dependence can be supposed from the described results of the in situ experiment in the G-1 borehole and the data of the long-term multi-instrumental logging measurements at the Petropavlovsk-Kamchatsky geodynamical testing area.

The results obtained in the numerous laboratory and in situ studies on fluid and gas filtration processes show that at low flow velocities ($v \ll c_s$, where c_s is the speed of sound in the fluid), the amplitudes of the filtration noise are proportional to the fluid flow velocities [*Afanas'ev et al.*, 1987; *Marfin*, 2012; *Nikolaev and Ovchinnikov*, 1992; *Nikolaev et al.*, 1992].

The mean actual velocity of the fluid flows emerging in the G-1 borehole under the action of gravity can be estimated from the results of the simultaneous geoacoustic measurements by two geophones installed in the G-1 borehole at the depths 270 and 1012 m (Figure 5). The presented data reflect seasonal water inflow from the active soil layer into the noise zones of the geophones (at a depth of 270 m in Figure 5a and at a depth of 1012 m in Figure 5b).

From the data shown in Figure 5 it can be seen that the variations in the flow velocity recorded by the both geophones are virtually identical. At the same time, variations at a depth of 1012 m are delayed by ~ 20 days relative to those at 270 m. Correspondingly, the mean actual flow velocity of the filtrating fluid in the zone of the G-1 borehole in this case can be estimated at $\sim 4 \times 10^{-4}$ m/s. Incidentally, this value by the order of magnitude coincides with the fluid flow velocities at the stage of the short-term precursors of the earthquakes [*Dobrovol'skii*, 2009]. Clearly, at these low velocities, the intensity of the GAE associated with the filtration processes can be assumed to be proportional to the flow velocity.

According to the calculations by formula (3), linear velocities of the flow of the pore fluid due to the action of electric field with the intensity of 10 mV/m is estimated at 10^{-9} m/s. In these calculations, for the pore fluid it was assumed that dynamic viscosity $\mu = 10^{-3}$ Pa s; permittivity $\varepsilon = 80$; electrokinetic potential $\zeta = 150$ mV; potential $\varphi = 50$ mV. Hence, the amplitudes of GAE associated with the motion of the pore fluid due to the action of the alternating electric field can also be thought of as proportional to flow velocity.

For the geophone located at a certain distance from the moving volume of the pore fluid, the amplitude of the noise recorded during this process, with the allowance for formula (3), can be recorded in the following way:

$$A(t)_{\mathrm{GAE}} = a\mathbf{E}(t) \tag{4}$$

where

$$a = \frac{\varepsilon\varepsilon_0(\zeta - \varphi(x))}{\mu}$$

Given the external harmonic electric field $E(t)_{\mathrm{ext}} = E_m \sin \omega t$ with the intensity vector directed along the permeable channel, the amplitude of the noise of filtration according to (4) will increase on the intervals of the growth of the external field and decrease on the intervals of its diminution. Concerning the conditions of the logging measurements, we note that in these cases, the geological medium is typically affected by the alternating electric fields which have low amplitudes. For example, in the area of the G-1 borehole in the Petropavlovsk-Kamchatsky geodynamical testing area, the intensity of the electric field for the frequencies 160 ± 20 Hz at a depth of 1000 m is about 1.0 mV/m. At such low intensities, the superimposition of the external alternating EMR on the background electric field of a different origin which exists in the geological medium does not cause periodical variations in the vector direction of the total electric field acting on the medium, and neither does it produce the corresponding variations in the flow direction of the pore fluid. (The influence of the intense harmonic fields can change the flow direction of the pore fluid every half-period). The weak electric harmonic fields only accelerate/decelerate the motion of the pore fluid. This hypothesis is supported by the results of the measurements in the boreholes which demonstrate the absence of the second harmonic component of the external EMR signal in the GAE spectra.

We also note that the characteristic time of the evolution of electro-osmotic flow under the electric impact for the channels with the cross section of $10^{-6} \div 10^{-5}$ m falls in the interval $10^{-6} \div 10^{-4}$ s [*Kadet and Koryuzlov*, 2009]. Considering the fact that these values are by several orders of magnitude lower than the length of the periods of EMR signals in the frequency band of a few hundred Hz, the inertia of the processes of electric transfer in the pore fluid should also be taken into account in this case.

The Effects of Permittivity of the Pore Fluid and Electrokinetic Potential of EDL

Formula (4) shows that at constant viscosity, besides the variations in the electric field, the amplitude of GAE is also controlled by the permittivity of the pore fluid and electrokinetic potential of EDL. Let us estimate the severity of the probable influence of the both these factors on the pattern of GAE.

According to [*Antropov*, 1984; *Sukhotin*, 1981], the dependence of permittivity ε of electrolyte solution on its molar volume concentration is described by the following formula:

$$\varepsilon = \varepsilon_0 + a \sqrt[m]{C} \tag{5}$$

where ε_0 is permittivity of pure solvent (in the considered case, for free water $\varepsilon_0 = 81$); a is the constant; index m here can be 1 or 2. For the dilute aqueous electrolytic solutions such as NaCl it is assumed that $a = -3.8$ and $m = 2$.

The typical range of variations in water salinity in the G-1 and GK-1 boreholes whose data are used in the multi-instrumental measurements in the Petropavlovsk-Kamchatsky geodynamical testing area is a few percent [*Khatkevich and Ryabinin*, 2006]. It can be hypothesized that variations in water salinity in the microcracks and capillaries of the rocks in the G-1 and GK-1 boreholes at a depth of ~ 1000 m have the same order of magnitude. If so, according to (5), probable variations in ε will not be more intense than a few percent.

According to the results of phase analysis carried out by A. V. Naumov and A. V. Sergeeva, the rocks pertaining to the depths of about 1000 m in the zone of the G-1 borehole include α-quartz, plagioclase from the area of albite compositions, and montmorillonite. These aluminosilicates are the cation-exchange phases, and the Na^+ (K^+) ion transport through the solid phase/aqueous solution phase boundary ensures charge separation. In this respect, the considered mineral phases are close to sodium silicate glass, which fact allows us to use the graphs of the dependence of the ζ-potential on the concentration of KCl solution (Figure 6.)

The pore fluids in the zones of the G-1 and GK-1 boreholes are the NaCl solutions with average concentrations of about 0.21 mol/l and 0.16 mol/l, respectively. The typical range of the variations in the solution concentrations in this case is within a few percent. The data presented in Figure 6 show that in this case the variations in zeta-potential associated with salinity variations in the water of the G1 and GK-1 boreholes will be at most 0.1%. According to (3) and (4), the corresponding variations will be in the linear velocity of electro-osmotic flow and amplitudes of GAE.

It is also worth noting that since the permittivity variations of the pore fluid and the variations in zeta-potential of EDL have much slower rates of change than the variations

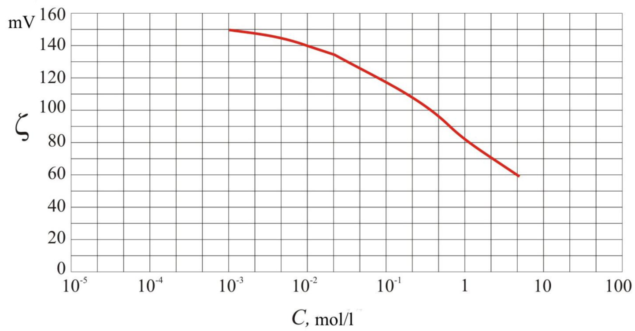

Figure 6. The dependence of the electrokinetic potential of glass on the concentration of KCl solution. According to [*Simanova*, 2004].

in the intensity of the alternating electric field, the changes in the first two mentioned quantities will only be reflected in the changes of the trend components of GAE time series.

Variations in the Amplitudes of GAE Responses to the Influence of Harmonic Electric Field with Slowly Varying Intensity

We consider the situation when the amplitude of the external harmonic electric field $E_{\text{ext}}(t) = E_m \sin \omega t$ slowly varies with time as $E_m = E_s \sin \Omega t$, $\Omega \ll \omega$. For example, this behavior corresponds to the EMR in the zone of the G-1 borehole of the Petropavlovsk-Kamchatsky geodynamical testing area where the amplitude of the electric field variations in the 150-Hz component contains clearly pronounced daily fluctuations. In this case, the GAE amplitude for water-saturated geological medium, which varies in accordance with (5), will also have the corresponding variations, e.g., daily.

The influence of water saturation of the rock. Vital importance of water saturation of the geological medium for the emergence of the effect of modulation of GAE intensity by the external EMR should be underscored. The change of the total contact area of the liquid and solid phases in the pore-fracture space of the noise zone controlled by the geophone is the most significant factor affecting the variations in the amplitudes of GAE responses. For instance, this conclusion is suggested by the results of the in situ experiments in the G-1 borehole. The modulating effect of the external EMR on GAE intensity is impossible in dry rock (Figure 2.) As noted above, in the conditions of the observations in the boreholes, the external EM impact is caused bt the alternating electric currents with low values of their intensities (at most, a few mV/v). Clearly, the gain in the flow velocity of the pore fluid and, correspondingly, in the amplitudes of GAE responses under the action of these weak electric fields will be extremely small for a separate unit volume of the fluid. At the same time, on the scale of the noise zone controlled by the geophone, GAE intensity will depend on the number of the potential point sources of GAE events, which is determined by the total area of the surface of the rocks contacting with liquid phase and forming EDL. As demonstrated in [*Gavrilov and Panteleev*, 2016), according to the most conservative estimates, the area of the fractured space of the noise zone controlled by the geophone is at least 10^8 m^2. With such a large area of the pore-fracture space and with sufficiently high fluid saturation of the geophone controlled noise zone, the geoacoustic emission associated with the interaction between the fluid and the surface of the solid phase is the superimposition of the emissions from a huge number of separate point sources of GAE acting simultaneously at the different points of the noise zone. Due to this, the signal-to-noise ratio increases up to the level when it becomes possible to observe the manifestations of the modulating effect of the continuous weak external EMR on GAE intensity. It is perhaps also worth noting that, considering the very large volume of the pore-fracture space of the noise zone, the question concerning the required orientation of the acting electric field vector relative to the permeable channels is cancelled because within the volume of the noise zone there is a branched network of differently oriented channels.

Conclusions

1. The generalization of the results that have been obtained so far leads to the conclusion that the main sources of GAE in the in situ rocks can be primarily associated with the motion of liquid fluid in the pore-fracture space of the noise zone of the geophone. The motion includes both the slow flow with the velocity of a fluid of a few mm/s and lower and the relatively fast flow under the action of the external alternating electric field with a frequency up to 1 kHz.

2. It is shown that the influence of the weak audio frequency EM fields on GAE intensity can be accounted for by the presence of electrically charged volume of the fluid within the diffuse layer of EDL. In this layer, the volume electric force associated with the intensity of the external alternating electric field can affect the flow velocity of the pore fluid causing its increase on the intervals of the buildup of the field intensity and the decrease during the decline of the amplitude of electric field. These variations in flow velocity of the pore fluid on the scale of the geophone controlled noise zone will lead to the corresponding changes in GAE amplitudes.

When water saturation of the rock is sufficiently high, the action by of the harmonic electric field with slowly varying amplitude on this rock will cause the corresponding variations in GAE amplitude. In this case, for instance, daily variations in the amplitude of the affecting electric field will induce daily variations in the rms GAE values.

3. The total area of the contact of liquid and solid phases in the pore-fracture space of the geophone is the most significant parameter controlling the amplitude of GAE responses in the rock affected by the external alternating electric field with varying amplitude.

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