ISSN 1069-3513, Izvestiya, Physics of the Solid Earth, 2011, Vol. 47, No. 11, pp. 951–965. © Pleiades Publishing, Ltd., 2011.
Original Russian Text © V.Yu. Zaitsev, V.A. Saltykov, L.A. Matveev, 2011, published in Fizika Zemli, 2011, No. 11, pp. 3–17.

Modulation of High-Frequency Seismic Noise by Tidal Deformations: The Features of the Phenomenon before Strong Earthquakes and A Probable Physical Mechanism

V. Yu. Zaitsev[a], V. A. Saltykov[b], and L. A. Matveev[a]

[a] *Institute of Applied Physics, Russian Academy of Sciences, ul. Ul'yanova 46, Nizhnii Novgorod, 603950, Russia*

[b] *Geophysical Service, Kamchatka Branch of the Russian Academy of Sciences, bulv. Piip 9, Petropavlovsk-Kamchatsky, 683006 Russia*

Abstract—A probable physical mechanism of tidal modulation of intensity of the endogenous seismic noise is proposed. The mechanism associates this phenomenon with modulation of the size of the region over which the recorded noise is acquired due to nonhysteresis amplitude-dependent absorption in the Earth's rocks. The two most important cases, namely dry and fluid-saturated rocks, are considered. In both cases, internal elongated strip-like contacts (even in minor quantities) are found to be of fundamental importance. The proposed mechanism provides an explanation for a variety of features of high-frequency seismic noise modulated by tides, which were revealed in the long-term observations on the Kamchatka Peninsula: (i) the modulation depth on the order of the first few percent; (ii) stabilization of the modulation phase before a strong earthquake; (iii) a frequently observed near jump-like change in the phase to the opposite-sign phase after the earthquake; (iv) the subsequent period of a relatively unstable phase; and (v) temporary predominance of the modulation component on the second harmonic of the fundamental tidal frequency in the vicinity of the time when the earthquake occurred.

DOI: 10.1134/S1069351311100156

1. INTRODUCTION. KEY FEATURES IN THE OBSERVED MODULATION OF SEISMIC NOISE BY TIDAL STRAINS

The effect of the modulation of the intensity of endogenous high-frequency seismic noise (HFSN) by tidal strains of the Earth's crust has been known for over three decades. After its early observations (Rykunov, Khavroshkin, and Tsyplakov, 1980; Diakonov et al., 1990) which still left doubts on whether the observed HFSN variations are simply related to the daily periodicity in technogenic factors or winds, or fluctuations in the surface temperature, etc., the tidal origin of these variations has been reliably established by long-term careful measurements. This HFSN monitoring was carried out in areas remote from human activity (at the stations in Kamchatka, Kuril Islands, and Hokkaido Island) (see, e.g., (Saltykov, Sinitsyn, and Chebrov, 1997; Saltykov et al., 2002; Kugaenko et al., 2008)). The records were processed by coherent summation of envelopes of noise intensity within a moving window, with the aim to single out periodic variations corresponding to the known periods (Melchior, 1966) of waves of tidal deformations. The processing of temporal intervals several months in duration yielded statistically reliable variations in the intensity of HFSN, with the typical modulation depth on the order of several percent and the typical periods corresponding to different tidal components (see the examples in Fig. 1).

In spite of the long history of observations, there is no generally accepted explanation for the origin of the HFSN modulation by tides. The main obstacle for interpreting these data is the seemingly excessively large depth of the effect ($\sim 10^{-2}$–10^{-1}) compared to the level of tidal strains with a typical amplitude of 10^{-8}, which affect the state of the rock. Although the observed tidal variations in the velocities of seismoacoustic waves, which attain 10^{-5}–10^{-3} (De Fazio, Aki, and Alba, 1973; Reasenberg and Aki, 1974; Glinskii, Kovalevskii, and Khairetdinov, 1999; Bogolyubov et al., 2004), can be explained by the increased elastic nonlinearity of rocks, which is reliably established, this effect does not provide even a phenomenological description for tidal variations in the intensity of HFSN, which are by 2–4 orders of magnitude stronger.

Besides the level of tidal modulation of HFSN, some phase and spectral features of this phenomenon are also to be interpreted. For example, the data yielded by long-term HFSN monitoring show that over sufficiently large recording intervals, the modulation phase is not rigidly fixed to the tidal phase. Therefore, coherent accumulation of the modulation component which corresponds to the selected tidal wave first raises the signal-to-noise ratio and then, as the accumulation time further increases up to half a year and greater, reduces the depth of the observed modulation, i.e., the modulation features a long-term phase instability. It has been also noticed in many observa-

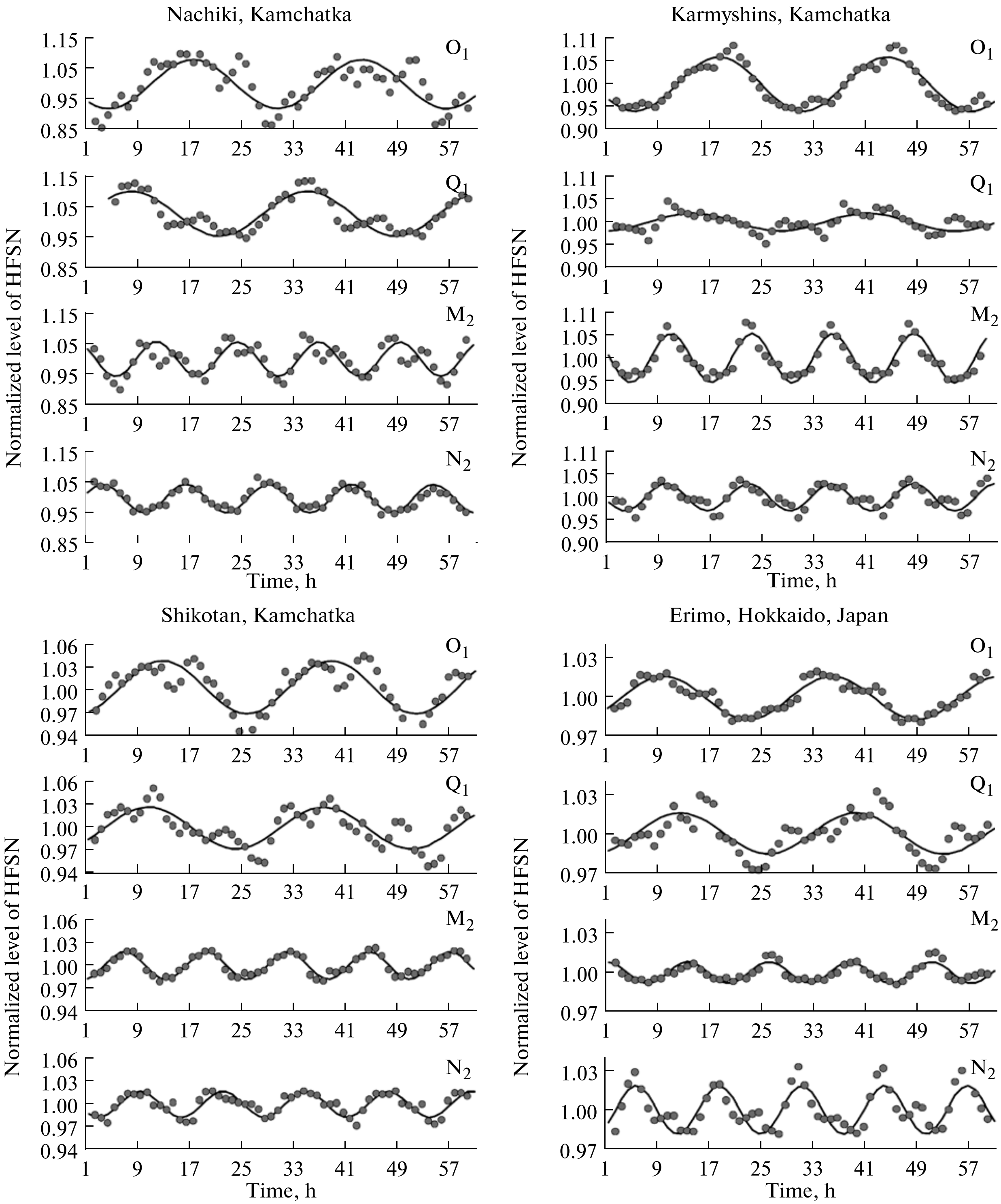

Fig. 1. Variations in the HFSN level with the periods corresponding to tidal harmonics O_1, Q_1, M_2, and N_2 at four stations of HFSN recording: Nachiki, Karmyshina, Shikotan, and Erimo. Solid line: least-square approximation of the points by the harmonic with the period of the corresponding tidal wave. In the experiments, noise with the strain amplitude of the order of 10^{-13}–10^{-11} (i.e., much smaller than the typical amplitudes of tidal deformations of 10^{-8}) was recorded. The narrow band seismic receivers with the central frequency of 30 Hz and the Q-factor $q = 100$ were used (the figure from (Zaitsev, Saltykov, and Matveev, 2008b)).

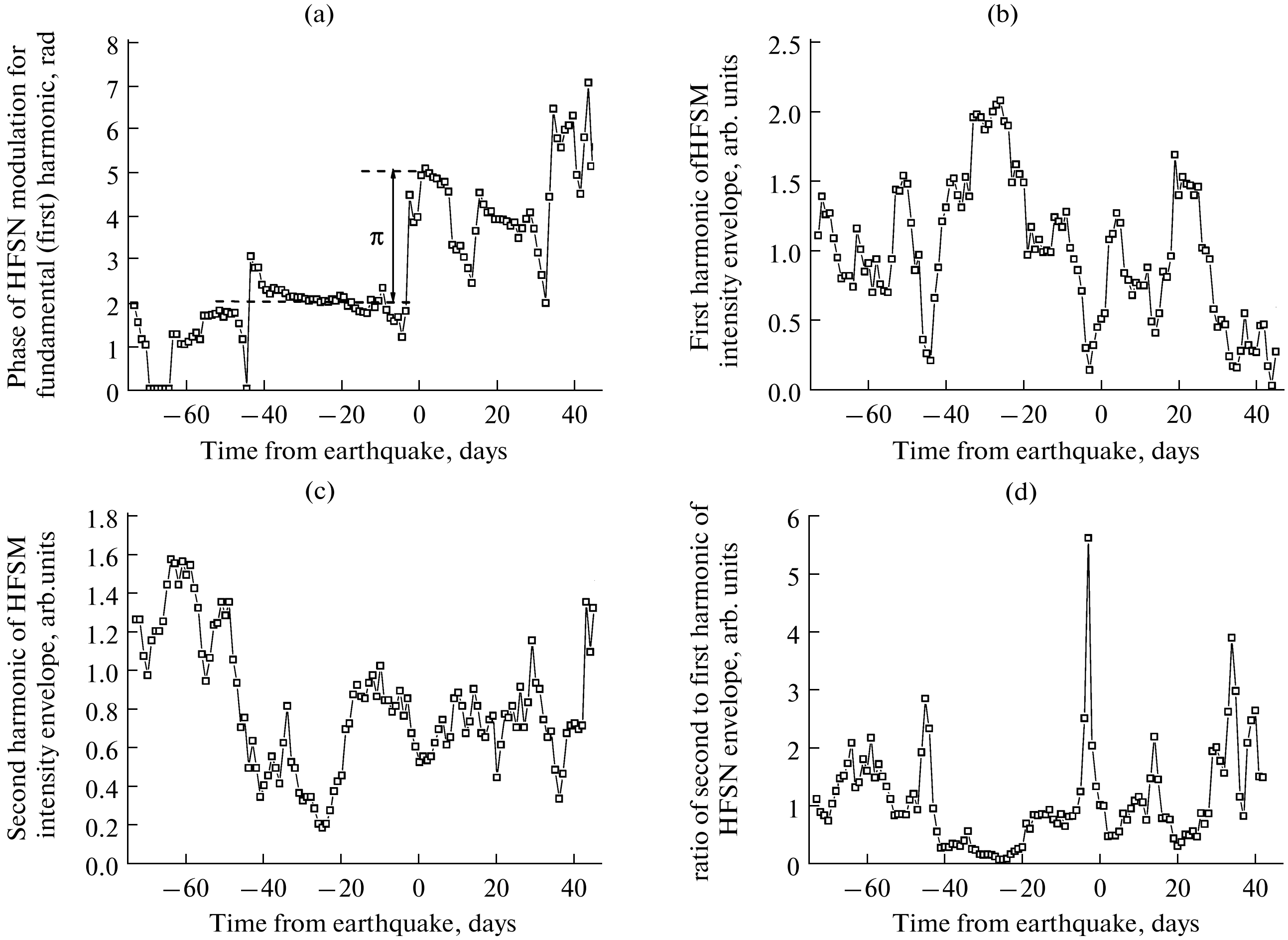

Fig. 2. Time dependences for (a) the phase and (b) amplitude of modulation of the intensity of endogenous seismic noise with the period of the tidal component O_1, (c) the amplitude of the second modulation harmonic, and (d) the ratios of the first and second harmonics. The time is measured from the moment of the earthquake on January 1, 1996. The averaging window is 28 days, the current time is referred to the window center.

tions that before strong earthquakes there is an interval of a pronounced stabilization of the modulation phase (within 1–2 months). Near the time of an earthquake, the phase typically swings by π radians, and then a period of unstable behavior of the phase follows until a new stabilization before the next earthquake. In addition, the ratio of the fundamental to the second harmonics of modulation induced by a nearly sinusoidal tidal-wave component is worth noting. The second harmonic is sharply predominant in the vicinity of the phase jump. The varying ratio of the harmonics and the swinging phase against a stable tidal impact itself unambiguously indicate that these variations are associated with the properties of the medium, and their analysis will probably provide additional information to elaborate the model of this effect.

Figure 2 illustrates the features of modulation of the intensity of HFSN at a frequency of 30 Hz by the O_1 component of the tidal deformation near the time of the earthquake of January 1, 1996 with magnitude $M = 6.9$, according to the data of Nachiki station (Saltykov et al., 2009). Here, the phase of the envelope, its first and second harmonics, and the ratio of these harmonics are shown. As seen from Fig. 2a, the phase of the wave changes by π radians in a nearly jump-like manner in the vicinity of the earthquake, when the tectonic stresses in the medium experience the strongest variations. In this case, the first harmonic exhibits a sharp minimum (Fig. 2b), while the second harmonic remains at an almost constant level (Fig. 2c). The ratio of the harmonics at this time has a distinct maximum (Fig. 2d).

Similar features were also revealed in other observations of this kind. The interval of a stable phase of modulation before the earthquake is likely the most remarkable and almost always persistent feature of this effect (for several dozens of earthquakes in the Kamchatka region since 1992) (Saltykov et al., 2008). In most cases (although not always), the modulation phase changes into the opposite phase after the earthquake (Saltykov, 1995).

2. MAIN REASONS FOR USING THE MECHANISM OF NONHYSTERESIS AMPLITUDE-DEPENDENT ABSORPTION FOR EXPLAINING THE MODULATION EFFECTS OF TIDES

At first sight, it seems quite natural to suppose that the microfracture of rocks and the accompanying acoustic emission are directly produced by weak tidal deformations, which might be hypothetically assumed for material which is in the immediate prefailure state. Without completely rejecting this possibility, we note, however, that this hypothesis does not seem quite justified as the only important factor to explain the large body of accumulated observations conducted in rather different conditions, in terms of the background stress state of rocks. Indeed, the observations of tidal modulation of the noise (like those described in (Saltykov, Sinitsyn, and Chebrov, 1997)) were carried out in seismically active regions where strong earthquakes are common. In these studies, pronounced HFSV modulation was observed at different phases of the seismic process (both before and after earthquakes) when the background stress in the rocks should have been drastically different. In view of this, a more universal and robust, in terms of the conditions for its existence, mechanism is required for interpretation of the data on tidal modulation obtained in such diverse conditions.

It was shown in (Zaitsev, Saltykov, and Matveev, 2008a; 2008b) that the existence of amplitude-dependent losses in the medium, which are sensitive enough to the weak tidal deformations of rocks, is the probable physical background behind this mechanism. Then, even if the noise emission does not practically depend on weak tidal deformations, variations in the losses in the medium caused by these deformations should induce modulation in the noise recorded by a seismograph, because the tidal modulation of absorption leads to the modulation of the effective size of the region from which HFSN comes to the receiver. It was also shown that, given the intensity of the sources in the medium whose elastic-dissipative properties are modulated by external factors, the relative variations in intensity, $I(\omega)$, of the received noise are primarily determined by the changes in dissipation (attenuation θ):

$$\frac{\Delta I(\omega)}{I(\omega)} \approx -\frac{\Delta\theta}{\theta}. \quad (1)$$

In (Zaitsev, Saltykov, and Matveev, 2008b), such a mechanism of HFSN modulation caused by the tide-induced variations in the attenuation was analyzed in terms of a rheological model assuming that there are soft defect inclusions in the medium, which correspond to the cracks in the rock. These defects are concentrators for dissipation (which is inherently linear, i.e., has no threshold in amplitude) and for elastic nonlinearity, whose coupled effect may appear as a pronounced amplitude-dependent absorption (Zaitsev and Matveev, 2006). According to estimates, this mechanism can provide good agreement with the observed amplitude of tidal modulation for both artificial sources (Glinskii, Kovalevskii, and Khairetdinov, 1999; Bogolyubov et al., 2004) and endogenous HFSN (Saltykov et al., 2002; 2006). In the context of the model proposed in (Zaitsev, Saltykov, and Matveev, 2008a; 2008b), it was shown also that, given the value of the quasi-static tidal strain, ε_0, the relative variations in the attenuation hardly depend on the concentration of defects and are only determined by their own nonlinearity and the parameter of their effective softness, $\zeta \ll 1$, relative to the ambient homogeneous matrix. In the model, for the typical tidal strain $\varepsilon_0 \sim 10^{-8}$, the consistence with the observed modulation depth (a few to a dozen percent) for both the amplitude of the fields of artificial seismoacoustic sources (Glinskii, Kovalevskii, and Khairetdinovv, 1999; Bogolyubov et al., 2004) and the variations in intensity of HFSN (see (Saltykov et al., 2002; 2006) and examples in Fig. 1) was achieved assuming the effective parameter of softness ζ of defects at least as small as 10^{-5}–10^{-6}. It is typically believed that the characteristic softness ζ of a crack, which is understood as the average strain in the material at which the crack completely closes, is approximately equal to the crack aspect ratio α (i.e., the ratio of characteristic opening of a crack to its diameter). Therefore, in order to achieve such small values of ζ, one must assume unrealistically thin cracks to exist in the medium. In addition, due to their high softness, such cracks should close by the overburden pressure at depths as shallow as a few meters. This problem has already been mentioned in (Reasenberg and Aki, 1974) when interpreting the huge elastic nonlinearity of rocks, which corresponded to the observed tidal modulation of elastic velocities.

In relation to this paradox, it was shown in (Zaitsev, Saltykov, and Matveev, 2008a) that variations in the elastic-dissipative properties of the crack, which are comparable in value with the case of complete closure of the crack, can also be due to the deformation on the internal contacts which exist in the real cracks whose state may substantially vary even if the crack opening has only insignificantly changed. In this case, in terms of variations in the elastic-dissipative properties, the effective values of the softness factor ζ on the order of 10^{-6}–10^{-7} can be attained for cracks with quite feasible aspect ratios $\alpha \sim 10^{-5}$–10^{-3}. Such average values of α allow the cracks to remain open at rather high average strains in the medium exceeding $\varepsilon \sim \zeta \sim 10^{-6}$–$10^{-7}$. In what follows, we will consider how to interpret not only the observed intensity of the modulation effect but also the mentioned features in the phase behavior and the spectral composition of this effect in the context of the dissipative mechanism of tidal modulation of HFSN, as proposed in (Zaitsev, Saltykov, and Matveev, 2008a). Instead of the rheological approach, we will apply in our analysis the physical models of dissipation expected to occur in the real corrugated cracks with internal contacts.

We consider two cases that are most important for rocks, namely, dry cracks with internal contacts at which the elastic energy is efficiently dissipated due to the thermoelastic mechanism, and cracks with similar geometry saturated with a fluid. It will be shown how the allowance for these geometrical peculiarities of cracks suggests the possibility of strong variations in losses on such cracks. Besides, we will discuss how these variations can explain the above-mentioned features in the phase behavior and spectral composition of the tidal modulation of HFSN.

In order to find the attenuation θ of an elastic wave (related with the material quality-factor Q as $\theta = \pi/Q$), we make use of its well-known correlation with the density of the accumulated energy, W_{el}, and the energy dissipated in the medium during the period of fluctuation, W_{dis}:

$$\theta = W_{dis}/(2W_{el}). \qquad (2)$$

When determining W_{el}, we take into account that the elastic energy is accumulated, primarily, in the homogeneous matrix material, and the dissipation W_{dis} is predominantly contributed by microstructural defects; therefore, the losses in the homogeneous matrix are negligible.

2.1. The Expected Features of Modulation of Endogenous HFSN Caused by Thermoelastic Absorption on Internal Contacts in Dry Cracks

Following the works (Zaitsev, Gusev, and Castagnede, 2002; Zaitsev et al., 2005; Fillinger et al., 2006), we note that cracks are planar defects in a solid, which have a small aspect ratio $h/L \ll 1$ (the typical values are $h/L \sim 10^{-4}$–10^{-3}) and, thus, for a crack to fully close, the average strain in the material should be on the order of h/L. This estimate weakly depends on the details of the crack model (Mavko and Nur, 1978) and substantially (by 1–2 orders of magnitude) exceeds the typical amplitudes of elastic strains $\varepsilon \sim 10^{-7}$–10^{-5} at which nonlinear-elastic and dissipative effects become clearly distinct. In the further considerations, the fact that the cracks usually have wavy surfaces (i.e., the irregularities are shaped as extended rolls rather than as point asperities and notches) will be of crucial importance. This pattern of irregularity of the crack surfaces is confirmed by the crack images provided by the optical, electron, and atomic-force microscopy; and it agrees with the known models of crack formation. When a crack is formed, its wavy surfaces which initially coincided do not simply diverge along the normal retaining parallelism, but shift tangentially, thus facilitating the formation of internal contacts (or waists) which are predominantly shaped as extended stripes (as schematically shown in Fig. 3) rather than as point-like structures. In the vicinity of the contacts, the local distance between the crack

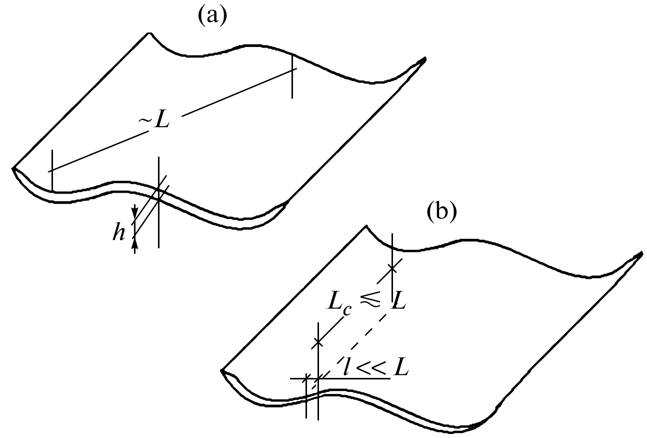

Fig. 3. A crack with wavy surfaces (a) without an internal contact and (b) with a stripe contact with the sizes $L_c \times l$. At $L_c \to l$, the stripe contact becomes a point contact.

faces (or their interpenetration) $\tilde{h}$ is much smaller than the average crack opening h. Therefore, the area near the contact is much more sensitive (approximately by a factor of $h/\tilde{h} \gg 1$) to the external stress than the crack as a whole. That is, the state of such contacts can be substantially changed by the action of average strains which are by the several orders of magnitude smaller than those required for a complete closure of the crack, e.g., $\varepsilon \sim h/L \sim 10^{-4}$.

The question arises, whether such small contacts (compared to the entire crack) can substantially affect the absorption of acoustic energy even when there is no complete opening/closure of the contact and, as a result, the adhesive-frictional losses do not yet effectively show up (Gordon and Davis, 1968; Sharma and Tutuncu, 1994). For the discussed small deformations typical for HFSN, the mechanism of effective dissipation due to thermoelastic losses locally increasing on a crack is well-known. Indeed, if there are stress and strain heterogeneities in the medium, the gradients of temperature variations are determined by the typical scale of heterogeneities, L_{het}, which are far smaller than the elastic wave length, or by the thermal wave length λ_{therm} (Landau and Lifshits, 1978). When the crack scales L_{het} and λ_{therm} coincide, global losses (i.e., those on the crack as a whole) of the elastic energy reach their maximum as shown in (Savage, 1966) by the exact solution for elliptical cracks. By applying the approach described in (Landau and Lifshits, 1978) to the losses in polycrystals, one can determine the thermoelastic losses without specifying in detail the crack model and estimating the temperature gradients both on the crack as a whole and on the internal contacts of the crack (Zaitsev, Gusev, and Castagnede, 2002; Zaitsev et al., 2005; Fillinger et al., 2006). The result for global losses on the crack found in this way agrees with (Savage, 1966); and we obtain the following approxi-

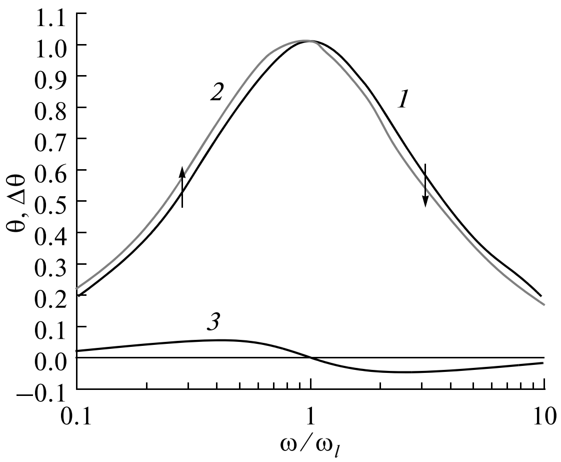

Fig. 4. The curves of relaxation absorption of type (3) in case of identical contacts: (*1*) the unperturbed curve at the background average strain ε_0 (corresponding to the first term in Eq. (10)); (*2*) the perturbed curve whose maximum is shifted by 10% along the frequency axis; (*3*) the frequency dependence of the correction to the initial curve.

mate expression for the attenuation $\tilde{\theta}^{therm}$, associated with thermoelastic losses on the internal stripe contacts (with width l and length L_c in a crack with the characteristic diameter L) for cracks with identical parameters and concentration $\tilde{n}_{cr}$ (Zaitsev and Matveev, 2010a):

$$\tilde{\theta}^{therm} = \frac{2\pi T_0 \mu_T^2 K L_c L^2}{\rho C} \frac{\omega/\omega_l}{1 + (\omega/\omega_l)^2} \tilde{n}_{cr}, \quad \omega_l \approx \kappa/(\rho C l^2), \tag{3}$$

where, ω is angular frequency, T_0 is temperature, μ_T is the coefficient of volumetric thermal expansion, K is the bulk modulus, ρ is the density of the medium, C is the specific heat (per unit mass), κ is the thermal conductivity, and ω_l is the characteristic frequency of thermal relaxation corresponding to the width of the contact, l.

It is instructive to compare this result with that obtained in (Savage, 1966) for thermoelastic losses in the region of stress concentration on the perimeter of the crack. In (Savage, 1966), the maximum is observed at a far lower frequency $\omega_L \approx \kappa/(\rho C L^2) \ll \omega_l$. The comparison shows that for a narrow ($l \ll L$) stripe contact with the length $L_c \sim L$, the losses near the maximum observed at $\omega \approx \omega_l$ are comparable with the maximum losses on the entire crack attained at $\omega \approx \omega_L$; they are determined by the cubed size of the entire crack, L, although the frequency values themselves (ω_L and ω_l) differ by several orders of magnitude.

The following important features of the obtained relaxation dependence (3) in the case of thermo-elastic absorption on the internal contact in a crack are worth highlighting. It follows from the structure of this expression that the amplitude of the relaxation maximum and its position on the frequency axis are determined by substantially different parameters; the amplitude and the position can turn out to be almost independent, and a relatively small variation in the average opening of a crack results in a change in the width of the stripe contact without substantially changing its length. Such changes of the relaxation frequency ω_l (due to variations in the width of the contact) cause the absorption maximum to shift almost without changing its height, as schematically shown in Fig. 4 (curves *1* and *2*). It is seen from the figure that with this shift of the peak, variations in the absorption for the waves with the frequencies $\omega > \omega_l$ and $\omega < \omega_l$ have opposite signs (curve 3 in Fig. 4). In other words, a minor, nearly sine-shaped change in the position of the maximum (e.g., caused by tidal deformations) for the waves with frequencies $\omega > \omega_l$ and $\omega < \omega_l$ should induce modulation of the absorption with opposite phases (shifted by π radians). While the selected observation frequency ω initially lies on one side of the maximum, in the case of a sufficiently strong shift in its average position (e.g., due to the action of stronger tectonic stresses), it may occur on the other side of the maximum. As the result, the initial phase of the tidal modulation of such a wave should change into the opposite one. The rheological models of the amplitude-dependent absorption considered earlier (Zaitsev et al., 2006; Zaitsev, Saltykov, and Matveev, 2008a) were unsuitable for a correct consideration of such features of absorption, although they still allowed one to estimate the level of the expected variations in absorption associated with the effect of tidal deformations.

For the mentioned features of absorption on internal contacts in the cracks to be used for the interpretation of the tidal effect, it is of crucial importance to estimate to what extent the tidal and background tectonic stresses and strains will affect the position $\omega_l \approx \kappa/(\rho C l^2)$ of the relaxation maximum of thermoelastic absorption. To do this, we consider how the width of the internal stripe contact in a crack varies under the action of the average strain in the host material. We use the solution provided in (Landau and Lifshits, 1987) for the width of the contact area between two aligned cylinders with the radii R and R' made of the same material, which touch each other:

$$l \approx 2\left(\frac{16DF}{3\pi} \frac{RR'}{R + R'}\right)^{1/2}, \tag{4}$$

where, $D = (3/2)(1 - \sigma^2)/E$, σ is Poisson's ratio, E is the elastic modulus of the material of the cylinders, and F is the compressive force per unit length of the contact. Taking into account that $\sigma^2 \ll 1$, it can be assumed with the same accuracy at which Eq. (3) was obtained that $D \approx 3/(2E)$, $R \approx R'$, and the linear force F is related with the length of the stripe contact L_c and the force F_c acting on the internal contact in the crack by the formula $F = F_c/L_c$. Then, it follows from Eq. (4) that

$$l^2 \approx \frac{16}{\pi}\frac{F_c}{E}\frac{R}{L_c}. \quad (5)$$

Fillinger et al. (2006) obtained the approximate equation for force F_c acting on the internal contact in the crack: $F_c \approx \frac{L_c}{L + L_c}\varepsilon E L^2$, where ε is the average strain in the host material. Hence, taking into account Eq. (5), the following approximate equation is derived:

$$l^2 \approx \frac{16}{\pi}\frac{L}{L + L_c}\varepsilon RL \sim \varepsilon RL. \quad (6)$$

In Eq. (6), it is taken into account that $1/2 \le L/(L + L_c) \le 1$, so that the term before εRL is on the order of unity and weakly depends on the length of the contact, L_c. Hence, the relative variation in $\Delta(l^2)/l^2$ (or $\Delta\omega_l/\omega_l$) is related to the variation $\Delta\varepsilon$ of the average strain by the following formula:

$$\left|\frac{\Delta\omega_l}{\omega_l}\right| = \frac{\Delta(l^2)}{l^2} \sim \Delta\varepsilon\frac{RL}{l^2}. \quad (7)$$

In order to quantitatively estimate the strain sensitivity of relative variations in l^2 (and, correspondingly, $\omega_l \approx \kappa/(\rho C l^2)$), we take into account that the asperities on the crack faces often have a radius comparable with the characteristic size of the entire crack $R \sim L$, and the width, l, of the appearing contact does not typically exceed the average opening of the crack, h. Therefore, with the characteristic values of the aspect ratio for thin cracks $h/L \sim 10^{-3}$–10^{-4} , as discussed above, the term RL/l^2 in Eq. (7) can attain 10^6–10^8. Therefore, tidal strains as small as 10^{-8} may change the position of the relaxation maximum for the contacts (and, correspondingly, the value of the attenuation for the selected frequency component) by a few (and even tens) of percent.

Even greater (by several orders of magnitude) variations in the state of the contacts should be expected to be produced by tectonic stresses and strains that develop near the source of the earthquake. According to (Dobrovol'sky, 1991), the tectonic strain in the vicinity of the source region of the impending earthquake is linked with the magnitude of the event $M > 5$ by the following approximate relation:

$$\varepsilon = 10^{1.299M - 8.19}R^{-3}, \quad (8)$$

where the distance R is measured in kilometers. The estimates based on Eq. (8) show that the tectonic strains attain 10^{-6}–10^{-5} for the sources of earthquake with magnitude $5 \le M \le 7$ at a distance of 100–200 km from the source. Thus, if, due to the earthquake, the average strain changes by such a value, this could be sufficient even to almost completely open/close the internal contacts and, thus, to change the relaxation frequency $\omega_l \approx \kappa/(\rho C l^2)$) severalfold and greater. As a result, the observed frequency component of the HFSN, which initially lay on one side of the maximum, after the earthquake, could be shifted on the other flank of the absorption curve, which will change the phase of tidal modulation into the opposite phase.

For comparison with observations, it is important to estimate the range of the expected positions of the relaxation maximum $\omega_l \approx \kappa/(\rho C l^2)$) on the frequency axis. To do this, we use the parameters for quartz which is a typical component of many rocks. In this case, $\kappa = 0.015$ W/cm/K, $\rho = 2.6$ g/cm^3, and $C =$ 0.7 J/g/K. For various widths of contacts, the corresponding frequencies will be $\omega_c \sim 1$ rad/s, 10^2 rad/s, and 10^4 rad/s at $l \sim 10^{-1}$ cm, 10^{-2} cm, and 10^{-3} cm, respectively. Thus, the internal contacts with a width of the order of hundreds of micrometers (which seems to be reasonable value for the discussed situation) can indeed provide a contribution to the amplitude-dependent absorption, which is sufficient for relative variations in the attenuation caused by tidal deformations to attain the level of several percent. In this case, the tectonic stresses can cause the relaxation maximum to occur in the frequency range of the order of several tens of hertz and to broadly vary relative to the 30 Hz frequency that was used in the discussed observations like those described in (Saltykov, Sinitsyn, and Chebrov, 1997; Saltykov et al., 2002; 2006; 2008).

Another important problem is as follows: whether the conclusions concerning the opposite-sign variations in the absorption on different sides of the relaxation maximum during its shift, which were obtained for a single contact, are valid for an ensemble of the contacts distributed in the parameters, which should be the case in real rocks. Assuming that the distribution of contacts over the length L_c and the width l in the cracks with diameter L is described by the function $n(L, L_c, l)$, in order to determine the total attenuation due to thermoelastic losses, we obtain from Eq. (3):

$$\theta = \frac{2\pi T_0 \mu_T^2 K}{\rho C}\int L_c L^2 \frac{\omega/\omega_l}{1 + (\omega/\omega_l)^2} n(L, L_c, l)\, dL dL_c dl. \quad (9)$$

As already noted, tidal deformations should primarily affect the width, i.e., the characteristic frequencies $\omega_l \approx \kappa/(\rho C l^2)$), rather than the size of the crack as a whole and, correspondingly, the length of the stripe contacts. Therefore, the width of the contacts l should be essentially independent of L and L_c, so that the function of the distribution of the contacts in the parameters should be factorized, $n(L, L_c, l) = n(L, L_c)n(l)$. In this case, integration with respect to the crack size and to the length of a contact yields the effective height of the relaxation maximum, which turns out to be almost independent of tidal deformations. The width of the relaxation maximum and the character of variations in the position of the absorption curve (either with or without self-intersection), which are associated with the changes in the average strain, are determined by the distribution of contacts in width l, i.e., by the distribution in the characteristic frequency ω_l of the maximum. Further, it is convenient to use the quantity inverse to ω_l, i.e., the relaxation time $\tau = 1/\omega_l \approx \rho C l^2/\kappa \propto l^2$ proportional to the squared width of contacts, and to characterize the contacts by the distribution $n(\tau)$ over the relaxation times.

For the weak tidal variations discussed, it can be assumed that the distribution function describes a certain initial state of the ensemble of the relaxators—contacts (i.e., it is assumed to be deformation-independent), while the parameters of the individual relaxators (in the case considered, their relaxation times) depend on the deformation of the medium but do not change very much. In this case, parameters L and L_c of the relaxators can be assumed constant, and the strain dependence can be taken into account in terms of the dependence of ω_l (or $\tau = 1/\omega_l \approx \rho C l^2/\kappa$) on the variations in the average strain relative to the initial value ε_0. Thus, taking into account Eq. (3) in combination with Eqs. (7) and (6), we obtain the following expression:

$$\left.\frac{\omega\tau}{1+(\omega\tau)^2}\right|_{\varepsilon} \approx \left.\frac{\omega\tau}{1+(\omega\tau)^2}\right|_{\varepsilon_0} + \left.\frac{d}{d\varepsilon}\frac{\omega\tau}{1+(\omega\tau)^2}\right|_{\varepsilon_0}\Delta\varepsilon$$
$$= \left.\frac{\omega\tau}{1+\omega^2\tau^2}\right|_{\varepsilon_0} + \left.\frac{\omega(1-\omega^2\tau^2)}{\left[1+\omega^2\tau^2\right]^2}\right|_{\varepsilon_0}\frac{d\tau}{d\varepsilon}\Delta\varepsilon \quad (10)$$
$$= \left.\frac{\omega\tau}{1+\omega^2\tau^2}\right|_{\varepsilon_0} + \left.\frac{\omega(1-\omega^2\tau^2)}{\left[1+\omega^2\tau^2\right]^2}\right|_{\varepsilon_0}\frac{\rho C}{\kappa}RL\Delta\varepsilon.$$

Finally, taking into account the above-mentioned possibility of factorization of the distribution, we obtain

$$\theta = \frac{2\pi T_0\mu_T^2 K}{\rho C}\int L_c L^2\frac{\omega\tau}{1+(\omega\tau)^2}n(L,L_c)n(\tau)\,dL\,dL_c\,d\tau$$
$$+\frac{2\pi T_0\mu_T^2 K}{\rho C}\int L_c L^2\frac{\omega\tau(1-\omega^2\tau^2)}{(1+\omega^2\tau^2)^2}\left(\frac{RL}{l^2}\right) \quad (11)$$
$$\times\,\Delta\varepsilon\, n(L,L_c)n(\tau)\,dL\,dL_c\,d\tau,$$

where the distribution in the relaxation times $n(l)$ is used instead of the distribution in the width of the contacts $n(\tau)$.

Curve *3* in Fig. 4 shows that the variation in the attenuation described by the second term in Eq. (11) has different signs on the different sides of the maximum for the case of identical contacts (i.e., for a Dirac delta distribution in all parameters). Let us show that this character of the variation in absorption is stable enough with respect to the law of distribution of the contacts in the parameters. It is seen from the structure of the factorized integral (11) that the shape of the distribution $n(L,L_c)$ does not affect the frequency behavior of the attenuation. The latter is controlled by the shapes of individual absorption curves for each relaxator—contact and by the form of distribution $n(\tau)$ (we note that since $\tau \propto l^2$, there is a simple relation with the distribution in the width of the contacts: $n(l) = n(l^2)2l \propto n(\tau)\tau^{1/2}$). Unfortunately, as of now, there seem to be no direct data on the size distribution of contacts in cracks, although the sizes of the cracks themselves and the scales of asperities on the surfaces obtained by cleaving the rock samples are known to obey a power law (Bonnet et al., 2001; Scholz, 2002). Therefore, it seems reasonable to assume the distribution function $n(l)$ of the width of contacts to follow apower law, too. Thus, $n(\tau)$ will also have the power-law distribution. A power-law distributions should be bounded from above and from below. The minimal size of the contacts should be constrained due to the action of short-range intermolecular forces, as discussed in many works addressing the investigations of elastic properties of granular rocks (Murphy, Winkler, and Kleinberg, 1986). This scale limit is likely to be of the order of a few micrometers. The maximum width of the contacts is assumed to be far smaller than the size of the entire crack. To illustrate the robustness of the discussed sign-alternation feature of the correction to the absorption, we consider the power-law distributions in the form $n(\tau) \propto \tau^p$ for essentially different $p =$ 2, 1, –1, –2, –3, –4. In the examples shown in Fig. 5 (normalized in the ordinate), the integration was carried out within $\omega\tau \in [0.1, 10]$, i.e., the width of the distribution covered two orders of magnitude. As seen in Fig. 5, similarly to the case shown in Fig. 4 for the Dirac delta distribution, the character of the correction, which depends on the average strain, remains sign-alternating in all these distributions, which are very diverse and rather wide.

Thus, the above-discussed frequency properties of the thermoelastic absorption on the internal contacts in cracks are rather robust and do not require any special type of size distribution of the contacts. Here, the fact that the height of the maximum of relaxation absorption on a contact (determined by the size of the entire crack and the contact length) is independent of the position of this maximum on the frequency axis (determined by the width of the internal contact varying under control of the average strain) is of key importance. Of course, other cracks that do not have contacts must also contribute to the total absorption, so that the total absorption must experience somewhat weaker changes than the contribution of the soft contacts themselves. The required share of cracks with the favorable peculiarities will be further estimated after the discussion of another important case of structural defects, namely the fluid-saturated cracks.

2.2. The Expected Features of Modulation of Endogenous HFSN Due to Viscous Absorption on Fluid-Saturated Cracks with Irregular Surfaces

We focus on one more mechanism relevant for the discussed issue, namely, the local squirt-type losses in cracks containing a viscous fluid (Walsh, 1969;

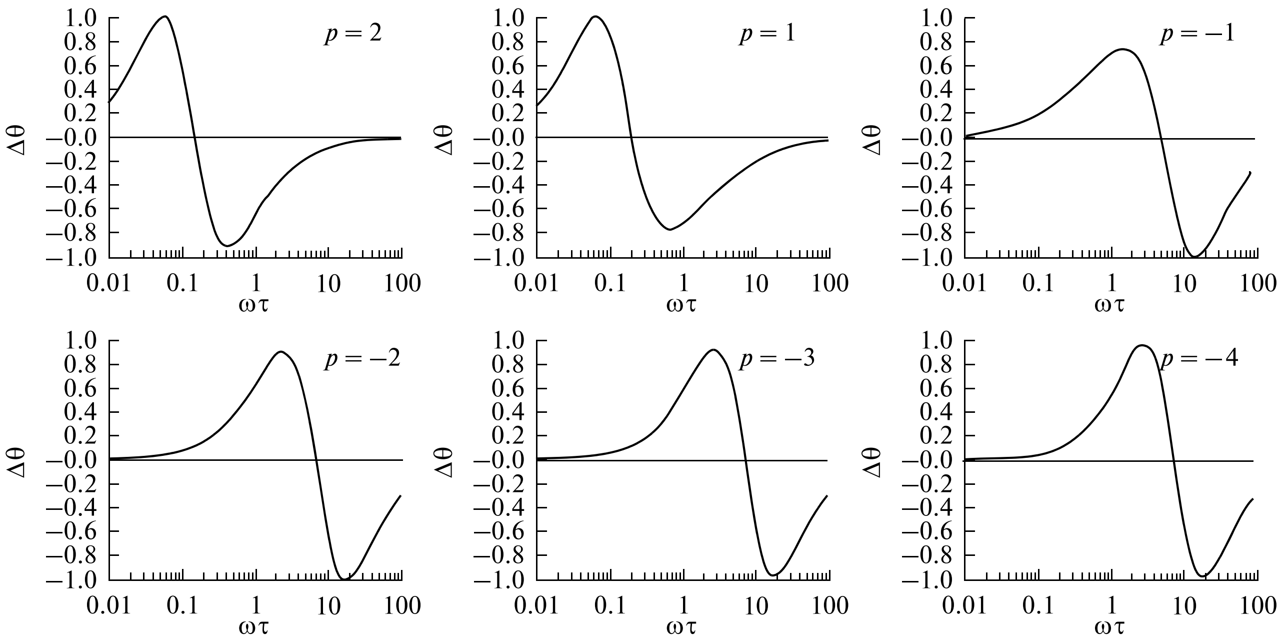

Fig. 5. Normalized frequency dependences of the correction to the attenuation for different distributions of $n(\tau) \propto \tau^p$.

O'Connell and Budiansky, 1977; Johnston, Toksoz, and Timur, 1979; Mavko and Nur, 1979; Murphy, Winkler, and Kleinberg, 1986; Pride, Berryman, and Harris, 2004). These losses can be expected to be sufficiently highly sensitive to the average stresses, as distinct from the other, often-discussed, viscous losses associated with the global flows in a porous medium (the Biot–Frenkel mechanism) with the pore channels that almost do not change their shapes. Those viscous losses due to global flows are unlikely to strongly depend on the weak average strains in the medium.

When estimating the squirt losses for sufficiently low oscillation frequencies, the fluid motion can be approximated in terms of the model of incompressible fluid; thus, as frequency increases, the velocity gradients in the flow and the viscous losses will also increase. At sufficiently high frequencies, the change in the fluid volume due to compressibility becomes substantial, which cause the velocity gradients in the flow and the corresponding viscous losses to decrease again. Due to this, for viscous losses, a characteristic relaxation maximum is formed at some frequency determined by the geometrical parameters of the channel (the crack), as well as by the viscous properties and compressibility of the fluid (Johnston, Toksoz, and Timur, 1979). Here, the assumption of the compressibility of the fluid to be far lower than that of the host rock is typically, valid. For example, based on such kind considerations, a rather cumbersome expression was obtained in (Johnston, Toksoz, and Timur, 1979) for the losses in the case of a squirt-type flow of pore fluids from thin cracks to the ambient porous channels. In the vicinity of the above-mentioned maximum (in the frequency range lower than MHz), this expression is well approximated by the standard relaxation dependence which is functionally identical to that considered above for thermoelastic losses:

$$\theta \sim \frac{\omega/\omega_r}{1+(\omega/\omega_r)^2}. \tag{12}$$

The corresponding relaxation time $\omega_r = 1/\tau$ is determined by the following equation (Johnston, Toksoz, and Timur, 1979):

$$\tau \approx \frac{8\eta}{\alpha^2 K_f} \propto \frac{L^2}{h^2}, \tag{13}$$

where K_f is the bulk modulus of a fluid, η is viscosity, and $\alpha \approx h/L$ is the aspect ratio of a crack. Just as in the case of thermoelastic losses on the crack as a whole, in order to cause the parameters of the relaxation maximum to change noticeably, one should substantially change the average opening of the crack. This requires the average strains of the order of $\varepsilon \sim \alpha$, which means that even very thin cracks with $\alpha \sim 10^{-3}$–10^{-4} are still too rigid to substantially change the value of viscous absorption under the action of tidal strains of the order of $\varepsilon \sim 10^{-8}$. In addition, for the characteristic value of the relaxation maximum, it follows from Eq. (13) that with $K_f = 2.25 \times 10^9$ N/m² and $\eta = 10^{-3}$ Pa s, which are typical values for water, $\omega_r \sim \alpha^2 10^{11}$ rad/s. Even for very thin cracks with $\alpha = 3 \times 10^{-4}$, we obtain the characteristic frequencies $\omega_r \sim 10^4$ rad/s, which is signifi-

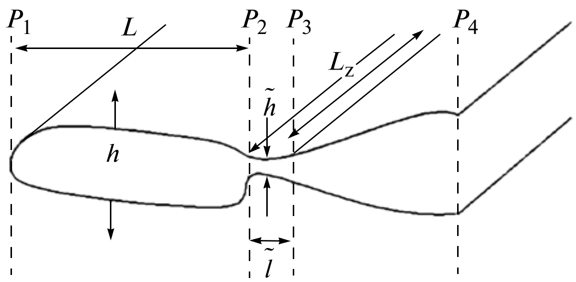

Fig. 6. The crack with a local narrowing (waist) in the vicinity of which the velocity and pressure gradients of the filling fluid are concentrated. The opening of the waist is $\tilde{h}$,, which is much smaller than the average crack opening h; the length of the waist in the direction of the flow is $\tilde{l} \ll L$. In the calculations it is assumed that $\tilde{l}/L \sim \tilde{h}/h$ and $L_z \sim L$.

cantly higher than the frequency of 30 Hz used in the discussed observations of HFSN.

Thus, neither the traditionally considered squirt-type viscous losses on the crack as a whole nor the traditional global model of thermoelastic losses (Savage, 1966) possesses the properties necessary for explaining the effects of tidal modulation. Now, we take into account the same geometrical peculiarities of the real cracks which have been mentioned above when analyzing the modified mechanism of thermoelastic losses. We consider how these peculiarities modify the viscous dissipation due to local flows inside cracks. The key role here is again played by the above-discussed wavy asperities on the faces of real cracks, which can form waists that almost cover the entire cross section of a crack. If there is such a thin waist in the crack, in its vicinity the viscous losses associated with the locally increased gradients of velocity and pressure in the flow are localized and, as a result, the characteristic relaxation frequency of viscous origin drastically changes. Similar to the contraction of contacts in the case of thermoelastic losses, the opening of a crack in the vicinity of the thin waist can be far more sensitive (by 2–3 orders of magnitude) to the average strain of the host material. Therefore, tidal deformations with $\varepsilon \sim 10^{-8}$ are capable of drastically changing the parameters of the flow near the waist, although the variations in the average crack opening are still negligible.

A crack with a local narrowing almost completely covered by a strip contact is schematically shown in Fig. 6. The notations for the geometrical characteristics are evident from the figure. The values P_i characterize the pressure in the corresponding cross sections. Using an approach similar to that described in (Johnston, Toksoz, and Timur, 1979) and modifying it so as to allow for the variations in the character of the fluid flow, which are introduced by the stripe contact almost completely spanning the crack, one easily obtains the modified approximate equation for the relaxation time $\tilde{\tau} \approx 1/\tilde{\omega}_r$ (Zaitsev and Matveev, 2010b):

$$\tilde{\tau} \approx \frac{12\eta}{\alpha^2 K_f}\left(\frac{h}{\tilde{h}}\right)^3\left(\frac{\tilde{l}}{L}\right). \tag{14}$$

Here, the aspect ratio $\alpha = h/L$ is explicitly factored out for comparison with Eq. (13). It follows from Eq. (14) that, if there is no waist in the crack (which corresponds to $\tilde{l} \sim L$ and $\tilde{h} \sim h$, so that $((h/\tilde{h})^3(\tilde{l}/L) \sim 1)$, this equation yields $\tau = 12\eta/\alpha^2 K_f$, which, within the used approximations (accurate within the terms on the order of unity) can be considered coinciding with Eq. (13).

The presence of a thin waist corresponds to the case $(h/\tilde{h})^3(\tilde{l}/L) \gg 1$, thus, the relaxation frequency corresponding to Eq. (14) significantly decreases compared to the value (13) for cracks without a waist and passes from the ultrasonic range to the range of 1–100 Hz which is of interest for us. Evidently, the position of the relaxation maximum (14) is also much more sensitive to the average strains in the host material since it depends primarily on the local opening $\tilde{h}$, in the region of the waist rather than on the average opening $h \gg \tilde{h}$. of the crack.

In order to more accurately analyze the changes in the curve of relaxation absorption (in particular, to find out whether a self-intersection occurs here as in the case of thermoelastic absorption on the contacts), one should consider the modified equation for attenuation for the discussed mechanism of viscous losses in cracks with stripe contacts. Assuming the the Poiseuille flow (which is not necessarily the case for insufficiently thin cracks (Mavko and Nur, 1979) but holds much better in the region of a thin waist) and by conducting direct summation of viscous losses throughout the volume of the flow, one easily finds the asymptotic equations for losses for the frequencies far above and far below the characteristic frequency of relaxation, which is associated with compressibility of the fluid (Zaitsev and Matveev, 2010b). Then, by matching the obtained low- and high-frequency asymptotic equations, one obtains the relaxation dependences similar to the thermoelastic curve (3) for the attenuation θ and $\tilde{\theta}$, caused by viscous losses in cracks without and with a waist, respectively:

$$\theta = \frac{\pi}{2}\frac{K_f L^3}{K\alpha} n_{cr} \frac{\omega\tau}{1+(\omega\tau)^2}, \tag{15}$$

$$\tilde{\theta} = \frac{\pi}{2}\frac{K_f L^3}{K\alpha} \tilde{n}_{cr} \frac{\omega\tilde{\tau}}{1+(\omega\tilde{\tau})^2}, \tag{16}$$

where $\tau = 1/\omega_r$ for the cracks without a waist and $\tilde{\tau} = 1/\tilde{\omega}_r$ for the cracks with a waist are defined by Eqs. (13) and (14); $\tilde{n}_{cr}$ and n_{cr} correspond to the concentrations of cracks with and without a waist, respectively. It should be emphasized that, just as in the case of thermoelastic losses on a stripe contact intersecting the entire crack ($L_c \approx L$), the maximum value of losses localized near the waist coincides with the maximum value of global losses on the entire crack without a waist; and it is determined by the total crack's size cubed. At the same time, the positions of the maxima on the frequency axis strongly differ. As in the case of thermoelastic losses on a narrow contact, the position of the maximum in the case of a crack with an waist is much more sensitive to the average strain. Bearing in mind that the absolute variations are equal, $\Delta\tilde{h} = \Delta h$, and taking into account at for crack strain $\varepsilon_{cr} = \varepsilon/\alpha = \varepsilon L/h$, for own crack strain, we find that in the presence of a waist, the relative variations in the position of the maximum caused by the changes in the average strains are as follows:

$$\frac{\Delta\tilde{\omega}_r}{\tilde{\omega}_r} = \frac{1}{\tilde{\omega}_r}\frac{d\tilde{\omega}_r}{d\varepsilon}\Delta\varepsilon \approx \frac{3h}{\tilde{h}}\frac{L}{h}\Delta\varepsilon \approx \frac{3h}{\tilde{h}}\frac{1}{\alpha}\Delta\varepsilon. \quad (17)$$

This equation is a counterpart of Eq. (7) for thermoelastic losses in dry cracks. From Eq. (17), we again see that minor variations in the average strains can bring about noticeable changes in the position of the relaxation maximum since $3(h/\tilde{h})\alpha^{-1} \gg 1$. For example, $3(h/\tilde{h})\alpha^{-1} \sim 3 \times 10^6$ for $1/\alpha \sim 10^4$ and $h/\tilde{h} \sim 100$ therefore, the tidal deformations with the amplitude $\varepsilon = 10^{-8}$ should generate variations in $\Delta\tilde{\omega}_r/\tilde{\omega}_r$ on the order of 3% and, as a result, a peak-to-peak variation of 6%.

All conclusions that follow from the significantly different role of the parameters L and l in the case of thermoelastic losses are also valid for the relaxation maximum in Eq. (16), the height of which is controlled by the size L of the entire crack, while the frequency is determined by the local opening $\tilde{h}$ in the vicinity of the waist. In particular, the conclusion on the different-sign variations in the attenuation on different sides of the maximum of the relaxation curve in the case of shifting the position of the maximum under the effect of average strains also holds true. In addition, due to the functional analogy between Eq. (16) for the local viscous absorption in the region of the waist and Eq. (3) for local thermoelastic losses on a stripe contact, all considerations (with the width l of the contact replaced by the value of the local opening $\tilde{h}$) regarding a weak influence of the distribution in $\tilde{h}$ on the character of variations in attenuation remain valid. This means that the alternating-sign variations in the attenuation depending on the mutual position of the frequency of the relaxation maximum and the observed harmonic component of the signal takes place for fluid-saturated cracks as well. Thus, strong variations in the background tectonic stress can lead to a shift in their relative positions and change the phase of the tidal modulation into the opposite phase.

Now, we turn back to the questions on importance of the role of the background (almost independent of tidal deformations) absorption introduced by the cracks without a waist, and how big should be the share of cracks with favorable internal contacts for their influence to be sufficient to explain the observed tidal effects. To find the answers, one should compare the background contribution to the attenuation from the cracks without narrowings, which have the concentration n_{cr}, in the frequency interval close to the relaxation frequency of the favorable cracks with narrowings, which have the concentration $\tilde{n}_{cr}$. Here, we allow for the fact that for equal-sized cracks with and without narrowings, the heights of the relaxation maxima almost coincide (see Eqs. (15) and (16)), although the maximum corresponding to the cracks without a narrowing occurs at a much higher frequency. Thus, at the observation frequency $\omega \sim \tilde{\omega}_r \ll \omega_r$, we can use the low-frequency asymptotic form of Eq. (15) for the attenuation in cracks without a waist:

$$\theta \approx \frac{\pi}{2}\frac{K_f L^3}{K\alpha}\frac{\omega}{\omega_r}n_{cr}. \quad (18)$$

It follows from Eqs. (18) and (16) that at $\omega \sim \tilde{\omega}_r$, the ratio of the contributions to the attenuation from equal-sized cracks with and without waists are determined by the expression

$$\frac{\tilde{\theta}(\omega = \tilde{\omega}_r)}{\theta(\omega = \tilde{\omega}_r)} \sim \frac{\tilde{n}_{cr}}{n_{cr}}\frac{\omega_r}{\tilde{\omega}_r}, \quad (19)$$

where $\omega_r/\tilde{\omega}_r \gg 1$ (and the typical value of this frequency ratio may exceed two orders of magnitude). Thus, even a small fraction of cracks $\tilde{n}_{cr} \sim n_{cr}\tilde{\omega}_r/\omega_r \ll n_{cr}$, with a waist should be sufficient for their contribution to dominate and provide a high degree of sensitivity of absorption in the vicinity of the frequency $\tilde{\omega}_r$ to very weak variations in the average strain in the rock.

Similar estimates can also be obtained for the thermoelstic absorption. In this case, for the cracks with the size $L \gg l$ without contacts, one should use the high-frequency asymptotic approximation because $\omega_L \ll \omega_l$. Then, for such global thermoelastic losses on a crack with the size L the approximate equation for $\omega \gg \omega_L$ has the following form (Zaitsev, Gusev, and

Castagnede, 2002; Zaitsev et al., 2005; Fillinger et al., 2006):

$$\theta_{glob}^{therm} = \frac{2\pi T_0 \mu_T^2 K^2}{E\rho C} L^3 (\omega/\omega_L)^{-1/2} n_{cr}, \quad (20)$$

where n_{cr} is the concentration of cracks without contacts. This contribution should be compared with Eq. (3) in the vicinity of the relaxation frequency for the contacts $\omega \sim \omega_l$. Evidently, for the stripe contacts with $L_c \approx L$, the contributions of the background absorption due to global losses on the crack as a whole and the losses on the contacts become comparable as early as when the relative fraction of cracks with contacts $\tilde{n}_{cr} \sim n_{cr}(l/L) \ll n_{cr}$. For $L/l \sim 10^2$, which seems quite realistic, the conclusion follows that the attenuation is largely dependent on the average strains in the vicinity of the discussed frequencies when the share of the favorable cracks with internal contacts is as small as a few percent of the total number of cracks.

3. DISCUSSION

We have considered two dissipation mechanisms, most important for cracks, which do not have amplitude thresholds and are therefore fully applicable to the NFSN with small strains of 10^{-13}–10^{-11}. Our analysis, in which the stripe irregularities (contacts and waists) existing in real cracks are taken into account, suggests that tidal deformations can induce variations in the attenuation from a few to tens of percent. This can ensure similar-level modulation of the intensity of the received HFSN, which is associated with variations in the size of the effective area from which noise is acquired by the receiver. A very small fraction of cracks with favorable characteristics of the total number of cracks is sufficient to provide the intensity of the effect typically observed in the range of dozens of hertz. In case of the thermoelastic mechanism, a few percent of such cracks is sufficient, and an even smaller fraction is necessary in the case of fluid-saturated cracks.

The similar qualitative (functional) features of thermolelastic and viscous relaxation indicate that the phase shifts by π radian are probable in the phase of modulation, depending on the relative position of the relaxation maximum and the selected frequency of observations. These features are sufficiently robust to the shape of the crack distribution over the parameters.

Thus, the changes in the phase of modulation by π radians observed in the vicinity of many earthquakes can probably be explained by a substantial shift of the relaxation maximum (relative to the fixed frequency of observations) caused by the strong changes in the stressed state of the medium after the earthquake.

The effect of stabilization in the phase of HFSN modulation, which is commonly observed before all strong earthquakes, can be attributed to the fact that the pre-earthquake accumulation of strong stresses which do not change their sign ensures stable (relative to the observed signal component) position of the relaxation maximum on the frequency axis. On the contrary, after the accumulated stresses are released by the earthquake, the residual background stresses and strains, although they significantly exceed the tidal deformations, remain unstable for some time and can substantially change not only in value but in sign as well. This should lead to the unstable position of the relaxation maximum and result in the instability of the phase of modulation, as explained above. The effect of antiphase modulation of the attenuation at different slopes of the relaxation curve is schematically illustrated in Fig. 7.

Finally, we note that the pronounced temporal predominance of the HFSN modulation at the second harmonic of the tidal impact, which is observed about the moments of many earthquakes (see the example of observations in Fig. 2), also agrees with the proposed dissipative model. Indeed, by changing the relative positions of the observed HFSN frequency component and the relaxation maximum (where the slope of the tangent line is zero, see Fig. 7) in the vicinity of an earthquake, one should expect a substantial temporal decrease in the modulation depth at the fundamental harmonic and, as a result, an essential predominance of modulation at the double frequency (as in Fig. 2d). In order to illustrate this explanation, the normalized relaxation curve of type (3) or (16) whose position is sine modulated with a 7% amplitude, and the calculated amplitudes of the first and the second modulation harmonics as functions of the position of the HFSN observation frequency on the relaxation curve are shown in Fig. 8. The variations in the intensity of the received noise are proportional to the variations in the effective size of the area from which the noise comes to the receiver (i.e., to the variations in attenuation, see Eq. (1)). Therefore, in order to calculate the level of modulation harmonics, it is sufficient to separate these harmonics in the variations of attenuation at the frequency of observations. The latter is convenient to represent in the normalized form ω/ω_r and to assume sinusoidal modulation of the position of the relaxation maximum with the selected swing. It is seen that for $\omega/\omega_r = 1$, i.e., in the vicinity of the maximum of the relaxation curve, there is a local minimum in the first harmonic and inflection an $\theta/\theta_{\max}$ at $\omega/\omega_r = 1.6$, for which the second harmonic vanishes although the modulation in the first harmonic remains substantial. The situations when the amplitude of the second harmonic has a distinct minimum while the level of the fundamental harmonic modulation component remains high are also experimentally observed (e.g., the minimum in the second harmonic is seen in Fig. 2b in the vicinity of the day no. –25, where the amplitude of the first harmonic in Fig. 2c remains rather high).

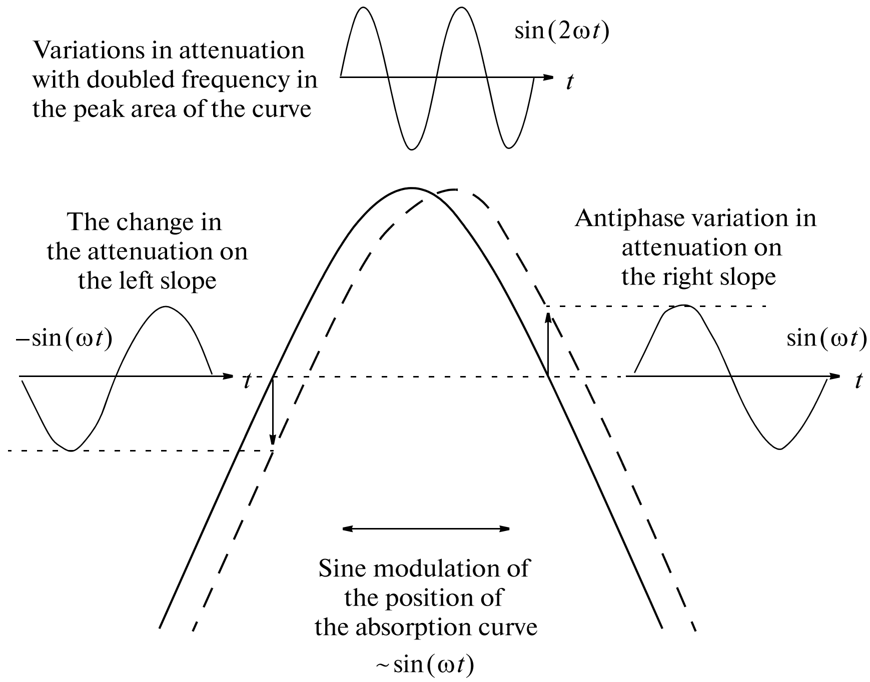

Fig. 7. Schematic explanation of the antiphase changes in attenuation on different sides of the maximum of the relaxation curve during its periodic shift caused by tidal deformations. Due to almost zero derivative in the vicinity of the maximum, the sign of variations in the attenuation is the same for any direction of its shift; thus, in this region, the second harmonic predominates in the modulation of absorption.

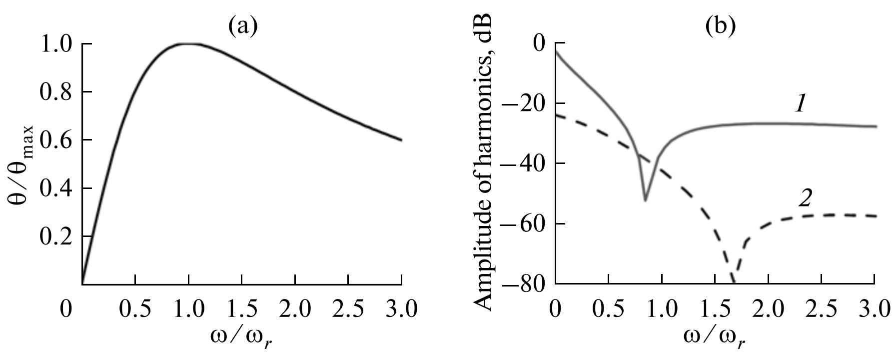

Fig. 8. (a) The normalized curve of relaxation and (b) the amplitudes of generation of the first and the second modulation harmonics as functions of the position of the observation frequency on this curve. The solid line in figure (b) shows the first harmonic; the dashed line, the second harmonic. In the simulation it was assumed that the position of the relaxation maximum varies by ±7%. The ratios of the harmonics (panel (b)) agree with the typical observed ratio (see Fig. 2).

CONCLUSIONS

In summary, we emphasize that the dissipative model discussed in the present work considers the combined action of losses (inherently linear in the physical origin) and increased elastic nonlinearity both of which are localized on the soft defects of the rock. This model suggests an explanation for the effect of tidal modulation of the endogenous seismic noise, for which there was no generally accepted interpretation for about 30 years. In the context of the dissipative mechanism proposed for this effect, we have analyzed the dissipation mechanisms for two characteristic cases of dry and fluid-saturated cracks. For the two discussed cases, the proposed dissipation mechanisms took into account the same key features of roughness of crack surfaces typical of real cracks. The analysis showed that the proposed mechanism of tidal modulation is rather robust to the distribution of crack parameters, and a very small (about one per cent and even less) share of cracks with favorable geometrical features is sufficient for its workability. Slow relaxation processes (related to fluid filtration, gradual breaking/rebinding of adhesion bonds, etc.) which knowingly take place in the rock do not change the main conclusions although they will likely smooth the sharp phase jumps predicted by the considered model, which agree with the observations, see, e.g., Fig. 2.

Unfortunately, as of now, there are insufficient experimental data to verify some implications of the proposed mechanism. The relevant observations are very labor-consuming and require long (of the order of several years) recording to provide a statistically reliable interpretation. Primarily, it seems important to carry out additional multi-frequency measurements (parallel in time and place) and to verify the model prediction of probable antiphase modulation of the sufficiently distant frequency components that fall on different sides of the relaxation maximum. However, the proposed mechanism even in its present form is capable of explaining the observed level of the HFSH modulation and a variety of its important qualitative features, such as phase stabilization before strong earthquakes, phase jumps by π radians often observed after earthquakes, and variations in the amplitude ratio of the fundamental to second harmonic in the vicinity of the time of earthquake. Although there still remains a hypothetic possibility of direct influence of tidal deformations on the HFSN emission, the existing data on the tidal modulation of HFSN well agree with the predictions of the proposed model. Moreover, the proposed dissipative mechanism is supported by independent observations of the phase–amplitude tidal modulation of the radiation from artificial seismoacoustic sources (Glinskii, Kovalevskii, and Khairetdinov 1999; Bogolyubov et al., 2004), for which the hypothetic effect of tides on seismoacoustic emission is definitely not relevant.

ACKNOWLEDGMENTS

The work was supported by the Russian Foundation for Basic Research (projects nos. 11-05-01003, 09-02-91071-CNRS-a and 11-05-00303).

REFERENCES

Bogolyubov, B.N., Lobanov, V.N., Nazarov, V.E., Rylov, V.I., Stromkov, A.A., and Talanov, V.I., Phase-Amplitude Modulation of a Seismoacoustic Wave under Diurnal Tides, *Rus. Geol. Geophys.*, 2004, vol. 45, no. 8, pp. 996–1000.

Bonnet, E., Bour, O., Odling, N.E., Davy, P., and Main, I., Scaling of Fracture Systems in Geological Media, *Rev. Geophys.*, 2001, vol. 39, pp. 347–382.

De Fazio, T.L., Aki, K., and Alba, J., Solid Earth Tide and Observed Change in the in Situ Seismic Velocity, *J. Geophys. Res.*, 1973, vol. 78, pp. 1319–1323.

Diakonov, B.P., Karryev, B.S., Khavroshkin, O.B., Nikolaev, A.V., Rykunov, L.N., Seroglasov, R.R., Trojanov, A.K., and Tsyplakov, V.V., Manifestation of Earth Deformation Processes by High-Frequency Seismic Noise Characteristics, *Phys. Earth Planet. Inter.,* 1990, vol. 63, pp. 151–162.

Dobrovol'skii, I.P., *Teoriya podgotovki tektonicheskogo zemletryaseniya* (Theory of Preparation of a Tectonic Earthquake), Moscow: IFZ AN SSSR, 1991.

Fillinger, L., Zaitsev, V., Gusev, V., and Castagnede, B., Nonlinear Relaxational Absorption/Transparency for Acoustic Waves Due to Thermoelastic Effect, *Acust. Acta Acust.*, 2006, vol. 92, pp. 24–34.

Gordon, R.B. and Davis, L.A., Velocity and Attenuation of Seismic Waves in Imperfectly Elastic Rock, *J. Geophys. Res.*, 1968, vol. 73, p. 3917.

Glinskii, B.M., Kovalevskii, V.V., and Khairetdinov, M.S., Vibroseismic Monitoring of Seismically dangerous Zones, *Vulkanol. Seismol.,* 1999, no. 6, pp. 60–64.

Johnston, D.H., Toksoz, M.N., and Timur, A., Attenuation of Seismic Waves in Dry and Saturated Rocks: II. Mechanisms, *Geophysics*, 1979, vol. 44, pp. 691–711.

Kugaenko, Yu.A., Saltykov, V.A., Sinitsyn, V.I., and Shishkin, A.A., The First Results of Investigation of Seismic Noises on Shikotan Island Based on Long-Term Observation Data, *Tikhookean. Geol.*, 2008, vol. 27, no. 3, pp. 33–43.

Landau, L.D. and Lifshits, E., *Course of Theoretical Physics: A Textbook for Universities, vol. 7: Theory of Elasticity,* Oxford: Butterworth–Heineman, 1999.

Mavko, G.M. and Nur, A., The Effect of Non-Elliptical Cracks on the Compressibility of Rocks, *J. Geophys. Res.*, 1978, vol. 83, pp. 4459–4468.

Mavko, G.M. and Nur, A., Wave Attenuation in Partially Saturated Rocks, *Geophysics*, 1979, vol. 44, pp. 161–178.

Melchior, P., *The Earth Tides*, Oxford: Pergamon Press, 1966.

Murphy, W.F., Winkler, K.W., and Kleinberg, R.L., Acoustic Relaxation in Sedimentary Rocks: Dependence on Grain Contacts and Fluid Saturation, *Geophysics*, 1986, vol. 51, pp. 757–766.

O'Connell, R.J. and Budiansky, B., Viscoelastic Properties of Fluid-Saturated Cracked Solids, *J. geophys. Res*, 1977, vol. 82, pp. 5719–5735.

Pride, S.R., Berryman, J.G., and Harris, J.M., Seismic Attenuation due to Wave-Induced Flow, *J. Geophys. Res.*, 2004, vol. 109, p. B01201.

Reasenberg, P. and Aki, K., A Precise Continuous Measurement of Seismic Velocity for Monitoring in Situ Stress, *J. Geophys. Res.*, 1974, vol. 79, pp. 399–406.

Rykunov, L.N., Khavroshkin, O.B., and Tsyplakov, V.V., Moon–Sun Tidal Periodicity in Spectral Lines of Time Variations in High-Frequency Microseisms, *Dokl. Akad. Nauk SSSR*, 1980, vol. 252, pp. 577–580.

Saltykov, V.A., Possible Mechanisms of the Effect of Terrestrial Tides on High-Frequency Seismic Noise, *Vulkanol. Seismol.,* 1995, no. 3, pp. 81–90.

Saltykov, V.A., Sinitsyn, V.I., and Chebrov, V.N., High-Frequency Seismic Noise from Monitoring in Kamchatka, *Izv. Phys. Earth,* 1997, vol. 33, no. 3, pp. 205–212.

Saltykov, V.A., Kasakhara, M., Gordeev, E.I., Okayama, M., Sinitsyn, V.I., Takada, M., and Chebrov, V.N., High-Frequency Seismic Noise Components Observed on Cape Erimo, Hokkaido Island, Japan, *Izv. Phys. Earth,* 2002, vol. 38, no. 2, pp. 165–172.

Saltykov, V., Chebrov, V., Kugaenko, Y., and Sinitsyn, V., High-Frequency Seismic Noise: Results of Investigation in Kamchatka, *Phys. Chem. Earth*, 2006, vol. 31, p. 132.

Saltykov, V.A., Kugaenko, Yu.A., Sinitsyn, V.I., and Chebrov, V.N., Precursors of Large Kamchatka Earthquakes Based on Monitoring of Seismic Noise, *J. Volcanol. Seismol.*, 2008, vol. 2, no. 2, pp. 94–107.

Saltykov, V.A., Sinitsyn, V.I., Chebrov, V.N., and Kugaenko, Yu.A., "Nachiki" Specialized Station for Seismic Noise Recording in the System of Geophysical Monitoring at Kamchatka, *Seism. Pribory,* 2009, vol. 45, no. 2, pp. 24–41.

Savage, J., Thermoelastic Attenuation of Elastic Waves by Cracks, *J. Geophys. Res.*, 1966, vol. 71, pp. 3929–3938.

Scholz, C.H., *The Mechanics of Earthquakes and Faulting,* Cambridge: Univ. Press., 2-nd edition, 2002.

Sharma, M.M. and Tutuncu, A.N., Grain Contact Adhesion Hysteresis: a Mechanism for Attenuation of Seismic Waves, *Geophys. Res. Lett.*, 1994, vol. 21, pp. 2323–2326.

Walsh, J.B., New Analysis of Attenuation in Partially Melted Rock, *J. Geophys. Res.*, 1969, vol. 74, pp. 4333–4337.

Zaitsev, V., Gusev, V., and Castagnede, B., Luxemburg-Gorky Effect Retooled for Elastic Waves: a Mechanism and Experimental Evidence, *Phys. Rev. Lett.*, 2002, vol. 89, p. 105502(1-4).

Zaitsev, V.Yu., Gusev, V.E., Nazarov, V.E., and Castagnède, B., Interaction of Acoustic Waves with Cracks: Elastic and Inelastic Nonlinearity Mechanisms on Different Time Scales, *Acoust. Phys., Suppl. Issue "Geoacoustics"*, 2005, vol. 51. pp. S67vS67

Zaitsev, V.Yu. and Matveev, L.A., Strain-Amplitude Dependent Dissipation In Linearly Dissipative And Nonlinear Elastic Microinhomogeneous Media, *Rus. Geol. Geophys.*, 2006, vol. 47, no. 5, pp. 694–709.

Zaitsev, V.Yu., Saltykov, V.A., and Matveev, L.A., The Model of Seismic Noise Modulation by Tidal Deformations, in *Geofizicheskii monitoring i problemy seismicheskoi bezopasnosti Dal'nego Vostoka Rossii* (Geophysical Monitoring and Problems of Seismic Safety of the Far East Russia), Petropavlovsk-Kamchatskii: GS RAN, 2008a, vol. 2.

Zaitsev, V.Yu., Saltykov, V.A., and Matveev, L.A., Relation between the Tidal Modulation of Seismic Noise and the Amplitude-Dependent Loss in Rock, *Acoust. Phys.*, 2008b, vol. 54, no. 4, pp. 538–544.

Zaitsev, V.Yu. and Matveev, L.A., High Sensitivity of Acoustic Dissipation to Small-strain Deformations in Elastic Material Containing Fluid-Saturated Cracks with Wavy Surfaces, *Sbornik Trudov XXII Sessii Rossiiskogo Akusticheskogo Obshchestva* (Proc. XXII Session. Rus. Acoust. Soc.), 2010a, vol. 1, pp. 175–179.

Zaitsev, V.Yu. and Matveev, L.A., High Sensitivity of Acoustic Dissipation to Small-strain Deformations in Elastic Material Containing Dry Cracks with Wavy Surfaces, *Sbornik Trudov XXII Sessii Rossiiskogo Akusticheskogo Obshchestva* (Proc. XXII Session. Rus. Acoust. Soc.), 2010b, vol. 1, pp. 179–183.