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RESEARCH NOTE

Seismic noise emission induced by seismic waves

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SUMMARY

The *in situ* rock undergoing different kinds of deformation accumulates elastic energy that can be released spontaneously or under artificial effect. Triggering of energy can also be performed by means of a dynamic excitation caused by elastic waves. We carried out special field investigations with the use of seismic vibrators (Vibroseis-like sources) to study the effect of the energy release under the influence of seismic waves. In the first experiment we conducted borehole observations of high-frequency seismic noise in two narrow frequency bands around 500 Hz and 1 kHz. The induced noise emission occurred in both frequency windows when the medium had been irradiated with the low-frequency seismic vibrations. Intensity of emission was proportional to the mechanical power of a vibrator. In the second experiment we carried out downhole measurements of a broad-band seismic noise. They showed a gradual increase of the noise energy in the frequency range 100–200 Hz during a series of monochromatic vibrations with frequency of 67 Hz. Facts observed give evidence that the elastic energy which accumulated during the rock deformation can be triggered by a relatively weak seismic excitation.

Key words: induced seismicity, seismic emission, seismic noise, seismic vibrations.

INTRODUCTION

Correlation of the properties of seismic noise emission and the processes of periodic deformation of rock has been extensively studied in Russia over the last 15 years. Rykunov, Khavroshkin & Tsyplakov (1978) were the first to establish a high sensitivity of seismic emission to the stress changes in the Earth's crust. They found a correlation between the level of high-frequency microseisms and the periodic deformation of the *in situ* rock caused by the solid Earth's tide. High-frequency noise emission in their work also correlated with the amplitudes of storm microseisms having periods of 4–8 s. This effect was called a 'modulation' of seismic emissions by the weak long-period deformations of the Earth.

Since that time other observations have been made in boreholes, mines, and the Earth's surface. Belyakov, Vereschchagina & Kuznetsov (1990) showed a high correlation of the seismic noise intensity in the frequency band of 30 ± 2 Hz with the rate of change of the moon- and sun-induced disturbances in the gravity force. In their opinion, the emissions were caused by the crust-stretching deformation produced by the Earth's tides. Rykunov, Khavroshkin & Tsyplakov (1980) found a similarity between the spectra of the envelope of high-frequency seismic noise and the spectra of the free oscillations of the Earth caused by strong earthquakes. Diakonov *et al.* (1990) reported a correlation between the level of low-frequency industrial noise and the intensity of high-frequency microseisms in Ashkhabad city (central Asia). Nikolaev & Troitskii (1987) and Diakonov *et al.* (1990) observed a seismic emission induced by *P* waves from the distant earthquakes in different areas of northern Kopet-Dag and Scandinavia. Simultaneous changes in the characteristics of short-period microseisms and hydrostatic pressure in the water reservoir in Tashkent area (central Asia) were noted by Nikolaev, Sultankhogjaev & Sharipov (1986). A review of the observations showing correlation between the processes of the Earth's crust deformation and the properties of high-frequency seismic noise was presented by Diakonov *et al.* (1990).

One interpretation of the experimental observations discussed above may be that the *in situ* rock is saturated with elastic energy and is characterized by a state of unstable equilibrium. Periodic deformations upset the equilibrium and cause the release of a portion of the accumulated energy in the form of induced noise. However, not all the observations show the existence of such a triggering effect. Galperin *et al.* (1990) call into question the inferences of some of the above-mentioned experiments and find no evidence of the modulation of short-period seismic

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noise in their own work. This indicates a complex nature to the effect and emphasizes the necessity of further studies.

In our field experiments we investigate the effect of vibrations on the level of seismic emissions in rock. Vibroseis-type sources were used to produce vibrations. Observations of high-frequency noise were carried out in boreholes.

FIELD EXPERIMENTS

A first series of experiments was conducted within the depleted oil field near the city of Poltava (Ukraine). It is known that the development of the oil field and injection of water into the reservoir are accompanied by the accumulation of stresses caused by the change in the internal reservoir pressure. We anticipated that such a system, largely disturbed from a natural equilibrium state, must be particularly responsive to the external excitation.

We used a vibrator having a peak force amplitude equal to 30 ton (1 ton = 9.8 kN). Seismic signals were recorded by a magneto-elastic seismometer assembled at the Institute of Physics of the Earth of the Russian Academy of Sciences, which measures a third time-derivative of the displacement in the wavefield. Its operation principle is that mechanical stresses induced by elastic waves change the permeance of a ferromagnetic material in the magneto-elastic transducer, which is detected by a transducer's measuring winding. The sensitivity of this sensor is proportional to the third power of frequency and has a growth rate of 60 dB decade^{-1} in the working frequency range of 30–10 000 Hz. Such a specific frequency response compensates for the fall-off in the amplitudes of the ambient acoustic field with increasing frequency. Unfortunately, the complex character of the frequency response of the seismometer made its calibration a rather difficult task, which is why the results presented below are consistently given in arbitrary units. The seismometer was emplaced at a depth of about 920 m in the borehole within the depleted oil reservoir. To exclude the effects of the imperfect coupling of the sensor to the borehole wall, which could result in its slippage with respect to the surroundings and then the production of a high-frequency noise, the sensor was firmly clamped to the wall by means of a steel spring. The vibrator was positioned at the surface near the well head. We made continuous analogue recordings of the envelope of the seismic signal using two narrow-band recording channels in the bands of 500 ± 10 and 1000 ± 20 Hz, as well as the digital recordings of the broad-band waveforms of the individual impulses of seismic emission on the PC-based station with a sampling frequency of 500 Hz.

After every 5 min of vibrations there was a pause for 5 min, and then the sources were vibrated again at another excitation frequency. The vibrator output was a pure monochromatic wave. To control the amplitude of a radiated signal, the reference seismometer was set up at the surface at the distance of 100 m from the source.

Figure 1 shows a fragment of the analogue recording of the envelope of seismic emission in both frequency bands made simultaneously by the downhole device before the onset of vibrations. The emissions have a pulsed nature. Peaks correspond to the single acts of emission that have a form of weak 'cracklings' occurring in rock. Note that two narrow-band traces may not temporally correlate. Because of the difference in the central frequency of channels and proportionality of the device sensitivity to the third power of frequency, the impulses that show up at traces 1 and 2 of Fig. 1 may belong to different micro-sources, especially if they have variable frequency content.

Figure 2 exemplifies the waveforms and Fourier power spectra of the individual impulses of seismic emission. These

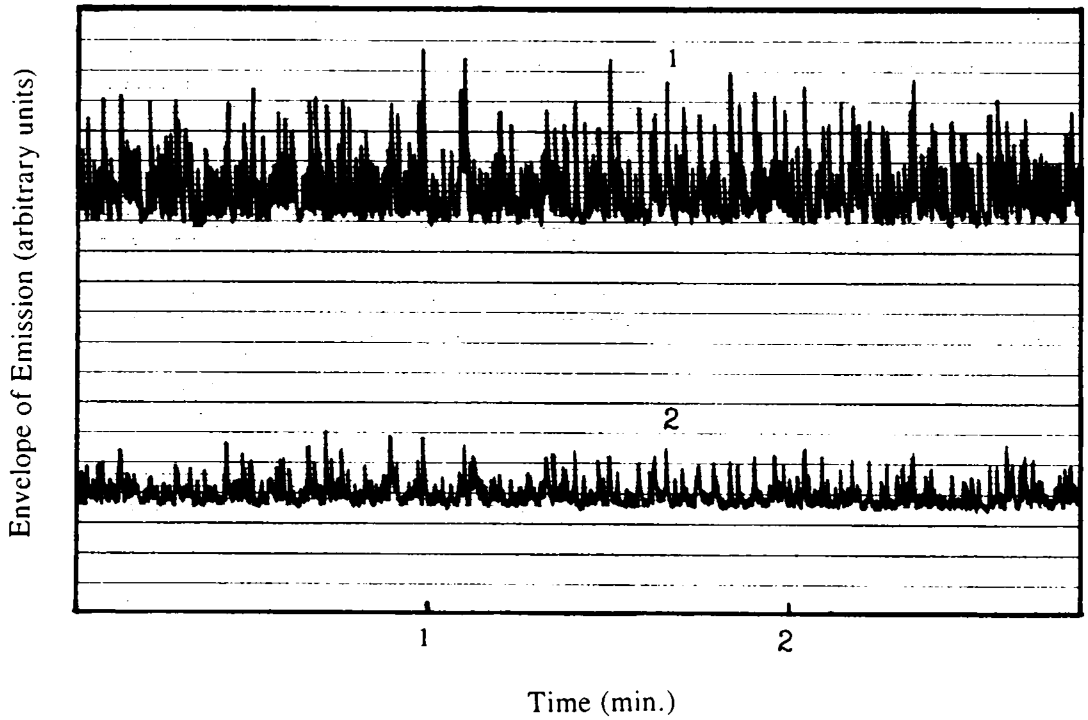

Figure 1. Recordings of the envelope of seismic emission at the frequencies of 500 Hz (1) and 1 kHz (2). Emission has a pulsed nature.

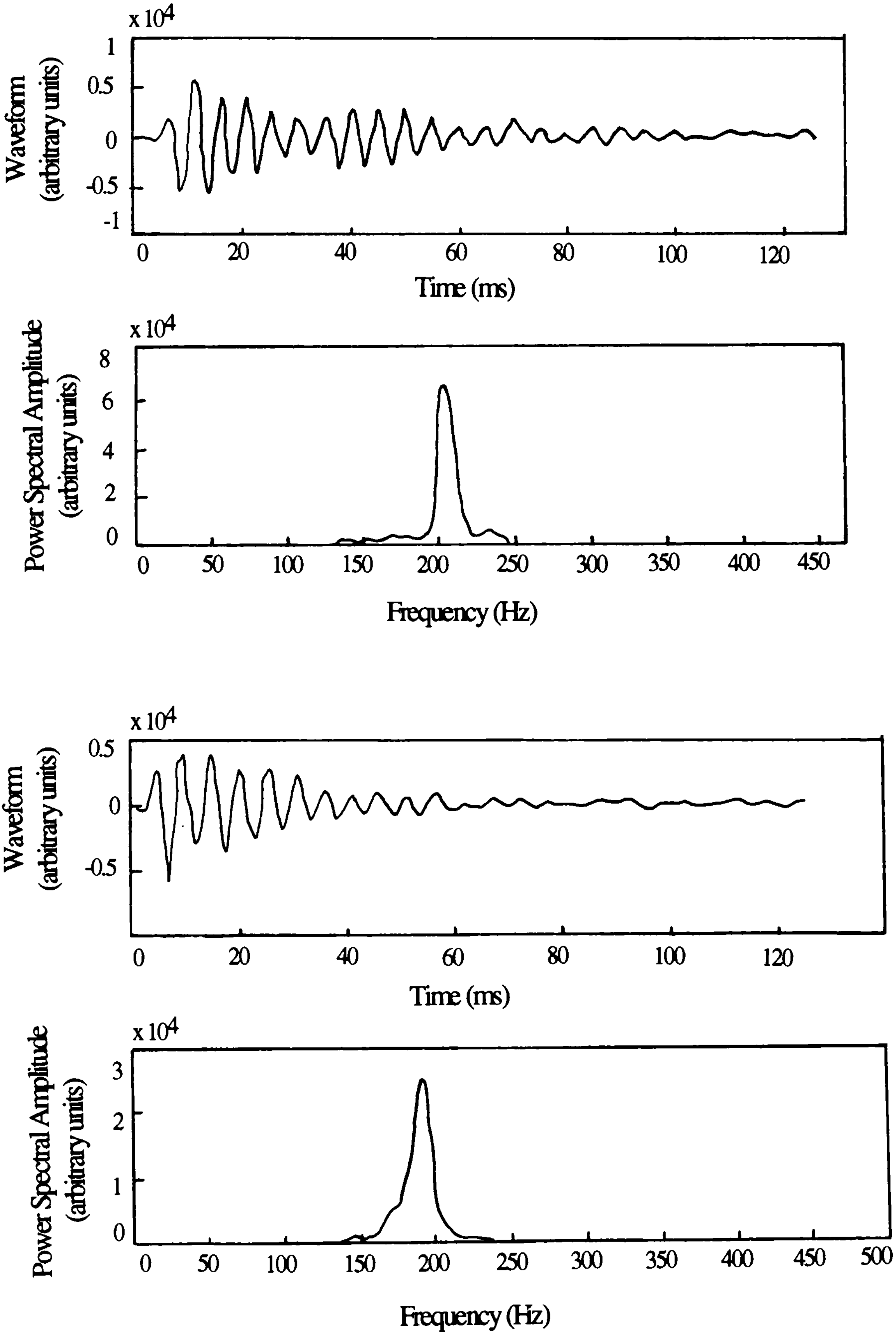

Figure 2. Waveforms and Fourier power spectra of the individual impulses of seismic emission (a) before and (b) after the activation of vibrations.

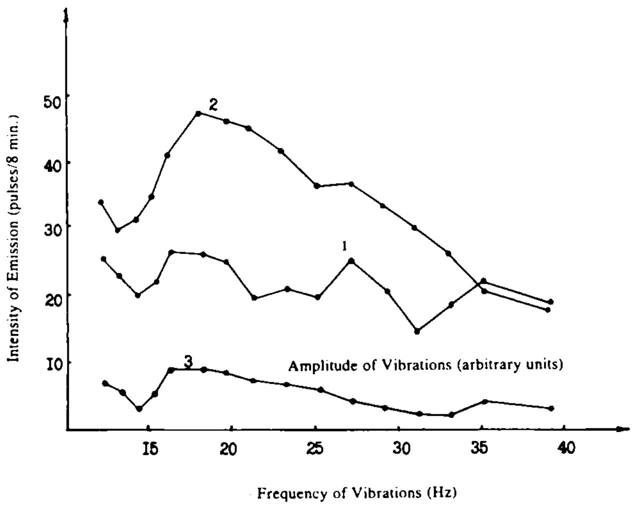

Figure 3. Dependence of the intensity of seismic emissions at the frequencies of 500 Hz (1) and 1 kHz (2) on the frequency of vibrations. Line 3 shows the amplitude of vibrations at the surface reference seismometer (out of scale in arbitrary units). A high correlation between the intensity of emissions and the vibration amplitude is observed.

waveforms were obtained using a sampling interval equal to 1 ms. Fig. 2(a) corresponds to the recording of emission before vibro-actions, while Fig. 2(b) applies to the recording after their beginning. The frequency of the maximum in the spectra shifts from 205 Hz to 193 Hz after vibrations start; however, such a variation apparently has a random nature. The well-defined characteristic frequencies of micro-events equal to approximately 200 Hz are not connected with the resonance of a magneto-elastic device, since its first resonance occurs at 1200 Hz, and may be attributed to the source effect. The dominant frequencies of different recorded micro-events vary within large limits. We are not concerned with the statistical study of the properties of individual impulses in this work; we are primarily interested in their integral characteristics such as the overall level of emissions per given time interval.

We calculated the intensity (rate of occurrence) of emissions by measuring the number of single pulses, whose amplitude exceeded some fixed 'threshold' value, per unit of time. In our case, this characteristic time was 8 min, comprising the last 4 min of vibrations and the first 4 min of pause. The 'threshold' amplitude chosen was high enough for the influence of the apparatus noise to be considered negligible.

Figure 3 shows the intensity of seismic emissions as well as the amplitude recorded by a reference seismometer versus the frequency of vibrations. The amplitude of the signal radiated by a vibrator is frequency dependent. There is an obvious correlation between the vibration amplitude and the intensity of seismic emissions recorded at the borehole. The correlation coefficients between curves 1 and 3, and 2 and 3 are 0.75 and 0.62, respectively. All the curves have a similar shape; the maximum amplitude produced by a vibrator corresponds to the maximum intensity of induced emissions. Our proposed interpretation of this result is that the high-frequency signals are generated in rock around the downhole seismometer. The stronger the amplitude of seismic waves radiated by a vibrator, the higher the number of single acts of emission.

Table 1. Velocity structure in the borehole used in experiment 2.

Depth (m)	V_P (m/s)
0-180	1360
180-390	2030
390-600	2420
600-790	1870
790-1000	2310
1000-1180	3030
1180-	3930

Another experiment was carried out in different geological conditions near the city of Gomel' (Byelorussia). We used a vibrator having a peak force amplitude of 10 ton. In this experiment we employed a standard borehole geophone (velocimeter) with a flat frequency response. It was emplaced at a depth of 600 m in the dry borehole within a zone composed of interlayered thin beds of clay, sand and sandstone. Table 1 gives a *P*-wave velocity profile from this borehole. The location of the geophone roughly corresponds to a velocity change from 2420 to 1870 m s^{-1}.

The surface vibrator produced a monochromatic signal with a frequency of 67 Hz. Fig. 4 shows an example of its amplitude spectrum at a depth of 600 m that contains harmonics and subharmonics of the fundamental frequency. Forty successive vibrations were produced, each of them having a duration of 1 min. Pauses between vibrations lasted for several seconds. The signal at the borehole was recorded for 8 s at the end of each vibration, and its Fourier spectra were calculated. In the spectra we filtered out the fundamental frequency at 67 Hz, as well as its harmonics and subharmonics at 33.5, 100.5, 134, 167.5 and 201 Hz. In addition, we removed the frequency of 50 Hz and its harmonics that might be attributed to the industrial electric interference. Then we calculated the value of the total noise energy in each spectrum by summing up the squared amplitudes of the spectral noise. Figs 5 and 6 show the energy of noise versus the number of excitations in four different ranges of frequencies. Experimental data were approximated by a parabola using a least-squares method. The energy of noise in the frequency range 100–200 Hz gradually increases with the total seismic energy pumped into the medium (Fig. 6). On the other hand, the energy does not depend statistically on the number of excitations in the frequency range of 10–100 Hz (Fig. 5). Beresnev & Nikolaev (1990) carried out a similar experiment with the same methodology using the surface-based geophones. They reported a stable build-up of noise emissions in the frequency interval of 64–128 Hz after the operation of a 50 ton vibrator at the frequency of 12 Hz, whereas there was no observed response at the frequencies between 16 Hz and 64 Hz. Our result is in good agreement with their data as to the frequency range in which the induced noise is detected.

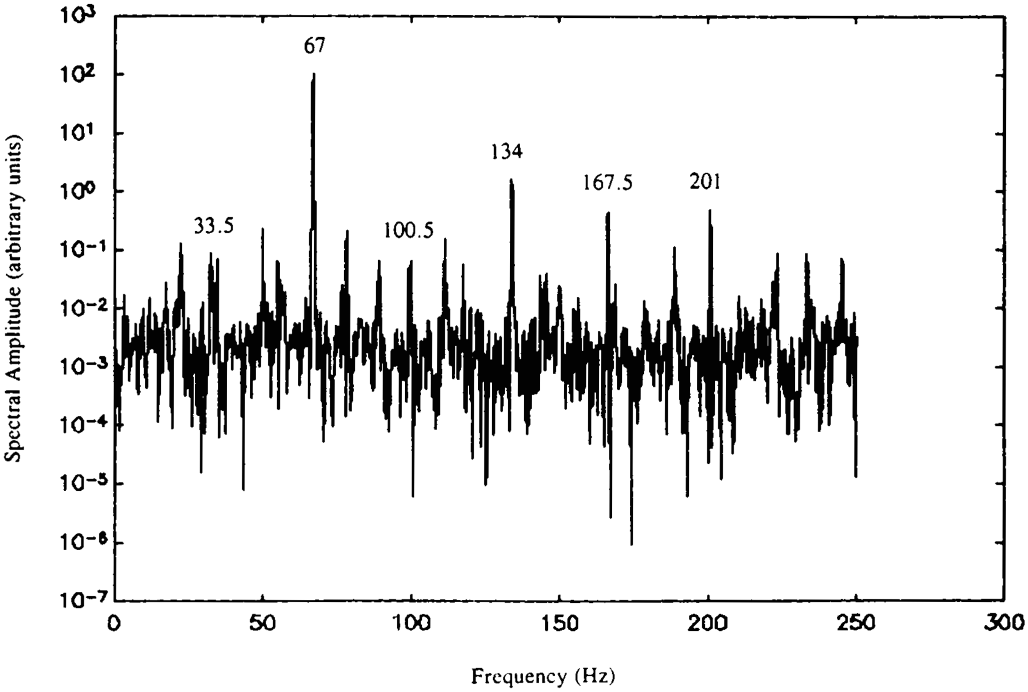

Figure 4. Amplitude spectrum of a vibratory signal with a frequency of 67 Hz at a depth of 600 m. The spectrum contains harmonics and subharmonics of the excitation frequency.

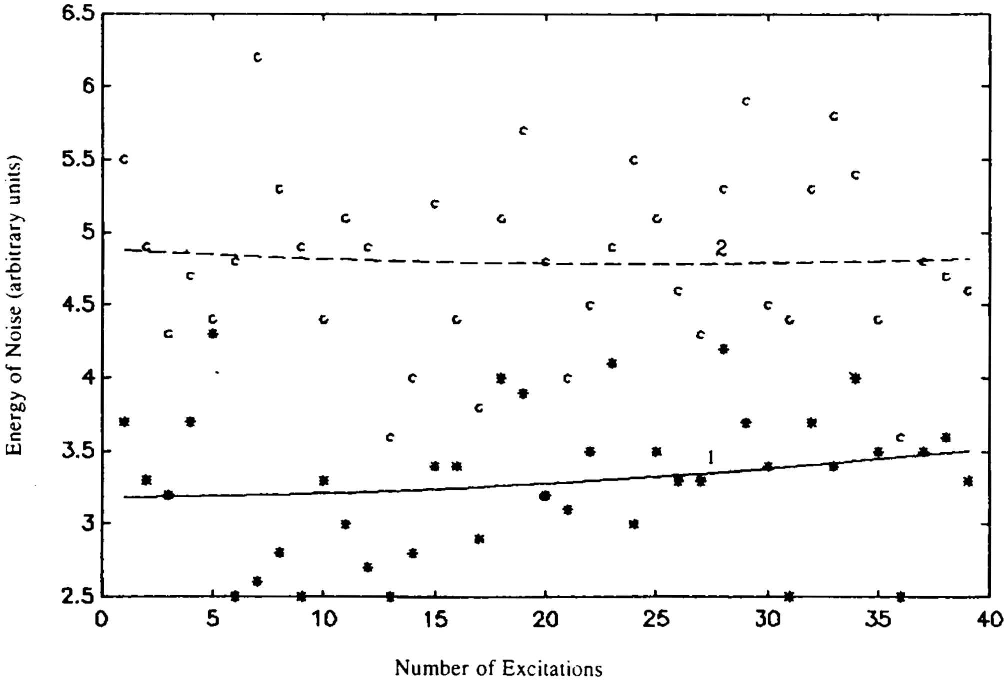

Figure 5. Spectral energy of noise versus number of vibratory excitations in the frequency range of 10–50 Hz (1) and 50–100 Hz (2). Energy does not depend on the number of excitations.

DISCUSSION AND CONCLUSIONS

The results of the two experiments described above need careful interpretation. Namely, alternative explanations for the observations should be considered. Such an explanation that first comes to mind is that the noise measured in the borehole may be a surface disturbance caused by a vibrator itself. Indeed, the downhole spectrum shown in Fig. 4 exhibits rather strong harmonics of the initial signal up to 200 Hz. In the first experiment we measured the noise level at the frequencies of 500 and 1000 Hz. Let us assume that the wave attenuation coefficient is proportional to the first

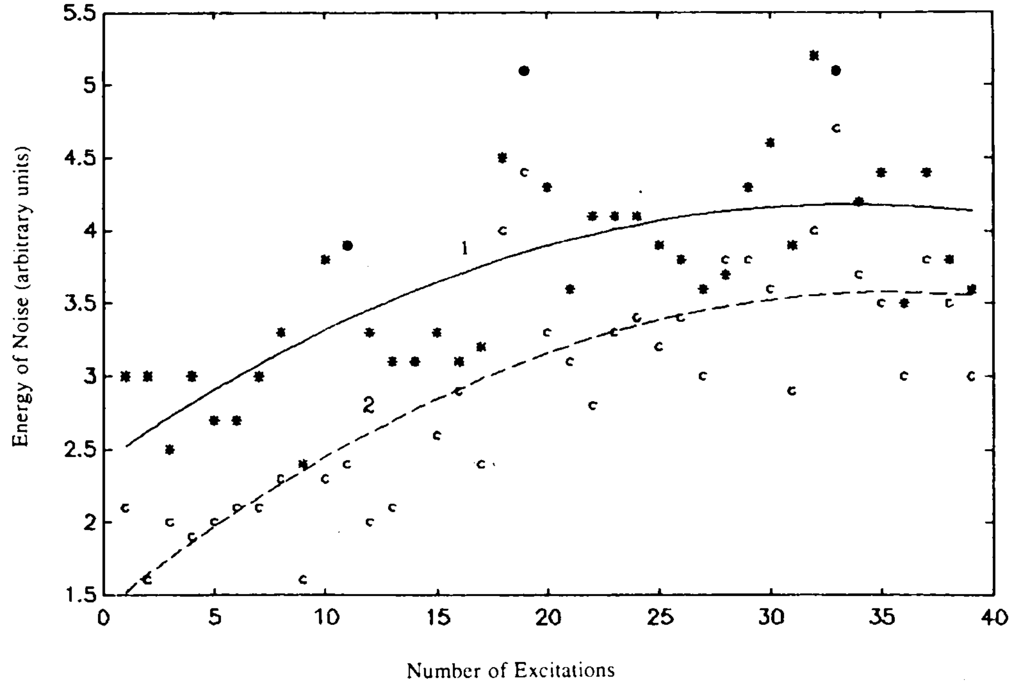

Figure 6. Spectral energy of noise versus number of vibratory excitations in the frequency range of 100–150 Hz (1) and 150–200 Hz (2). Noise energy gradually increases as the total amount of radiated seismic energy increases.

power of frequency. Then the amplitude of the surface-originated signal at 1000 Hz is $e^5 \approx 150$ times weaker than the amplitude of the harmonic at 201 Hz at the equal depth. The signal-to-noise ratio for this harmonic at a depth of 600 m is of the same order of magnitude (Fig. 4). Thus, a 1000 Hz vibrator-sourced signal at this depth would have an amplitude comparable to the noise. Curves in Fig. 3 correspond to a depth of 920 m, so that this amplitude would be even smaller. We also assumed in this calculation that the amplitude of the 1000 Hz signal at the surface was equal to the amplitude of the harmonic. Actually, the vibrator engine does not produce such high-frequency oscillations, or they are negligibly small compared with the strength of vibration and its harmonics. Consequently, the amplitude of the signal with a frequency of 1000 Hz transmitted from the surface to a depth of 920 m would be much lower than the general noise level. It cannot be responsible for a high correlation of this frequency component with the amplitude of low-frequency vibrations shown in Fig. 3.

One can suppose that the high-frequency surface noise could be transmitted to the transducer via control cables. Such waves do not attenuate nearly as rapidly. However, the borehole is never vertical, and the deviations of its axis from a vertical line may be as large as ±10°. The cable in these conditions lies on the borehole wall and damps the mechanical waves very effectively.

In the second experiment we demonstrated the gradual increase of the noise level in the frequency range of 100–200 Hz with the cumulative time of vibrations. Vibrators can theoretically produce weak disturbances in this frequency range apart from harmonics of the sinusoidal signal. However, this artificial noise *never* shows such a regular temporal build-up as the one observed.

We conclude therefore that the passage of seismic waves stimulates 'crackling' processes in the rock which release the accumulated stresses on a microscopic level. These processes cause the emission of high-frequency signals recorded by a downhole geophone. Intensity of emissions depends on the amplitude of seismic excitation and also increases with a total amount of radiated seismic energy. As inferred from these experiments, the *in situ* rock has a property of an active energy-saturated medium being close to the threshold of the natural equilibrium. The more energy pumped up into it, the more energy is released in the form of emissions.

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