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**GEOPHYSICS**

# Deformation and Acoustic Precursors of Earthquakes

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Mechanisms of the generation of elastic oscillations in frequency range 0–10 kHz during the final stage of earthquake preparation are studied using geoacoustic methods and observations of deformations in near-surface sedimentary rocks. It is shown that acoustic noises appear as a result of deformation motions in the medium in a stressed state.

An increase in the intensity of high-frequency geoacoustic emission in near-surface sedimentary rocks during the final stage of earthquake preparation at a significant distance from their epicenters is caused by an increase in local stresses [1–3]. Variations in the stresses related to the effect mentioned above have not yet been studied. In the present paper, we consider peculiarities of local deformation at the final stage of the preparation of remote seismic events to study the mechanisms of geoacoustic noise generation in the kilohertz frequency range.

The methods of geoacoustic observations in small water reservoirs are described in detail in [1–3]. In our work, we use the receiving system of the Institute of Cosmophysical Research and Radiowave Propagation to record acoustic signals at the observation point located in the Karymshina River. The system consists of four coupled piesoceramic hydrophones oriented to the north, east, south, and vertically downward. The system was set in an artificial underground reservoir 2 × 2 × 2 m in size. Acoustic noises from all four directions were continuously recorded in the frequency range 0–10 kHz. In order to analyze the characteristics of the signals, they were filtered during processing in the following seven ranges: 0.1–10, 10–50, 50–200, 200–700, 700–1500, 3000–6000, and 8000–11 500 Hz.

A laser strainmeter of the unequal arm type developed at the Pacific Institute of Oceanology was set up according to the Michelson interferometer scheme at a distance of 50 m from the acoustic system in casings of two dry 5-m-long boreholes with a spacing of 18 m. One of the boreholes was equipped with an interference unit with an LHN-303 frequency-stabilized helium–neon laser placed in a box. The other borehole was equipped with a flasher placed in a container. The laser beam of the interferometer passed between the box and the container along an optical waveguide made up of steel pipes wrapped in insulation to decrease the external thermal influence. The measuring arm of the interferometer was oriented to the southeast perpendicularly to the fracture in the subduction zone. The laser and recording equipment were powered from the batteries recharged from a diesel generator or solar batteries. The sampling frequency of recording was equal to 800 Hz, and the sensitivity of the strainmeter was not less than $10^{-11}$. As will be shown below, the level of vibration noise and strain was significantly greater than this value. The total duration of observations was six months.

Approximately one day before most of the seismic events, we recorded an increase in the level of high-frequency geoacoustic noises and anisotropy of the signals, the direction to which coincides sufficiently well with the direction to the future earthquake source [1–3]. Such properties of the noises can be explained by the high sensitivity of geoacoustic emission to strains during the earthquake preparation period [1]. In order to study these phenomena, we carried out direct measurements of strains at the Earth's surface together with geoacoustic observations during the activation of seismic processes.

Figure 1 shows amplitudes of acoustic emission from the eastern direction in seven frequency ranges and records of the strainmeter in the period from February 13 to February 18, 2006. Arrows indicate the time moments of seismic events, whose parameters are given in Fig. 2. The character of acoustic signals from the northern, southern, and vertical directions was sim-

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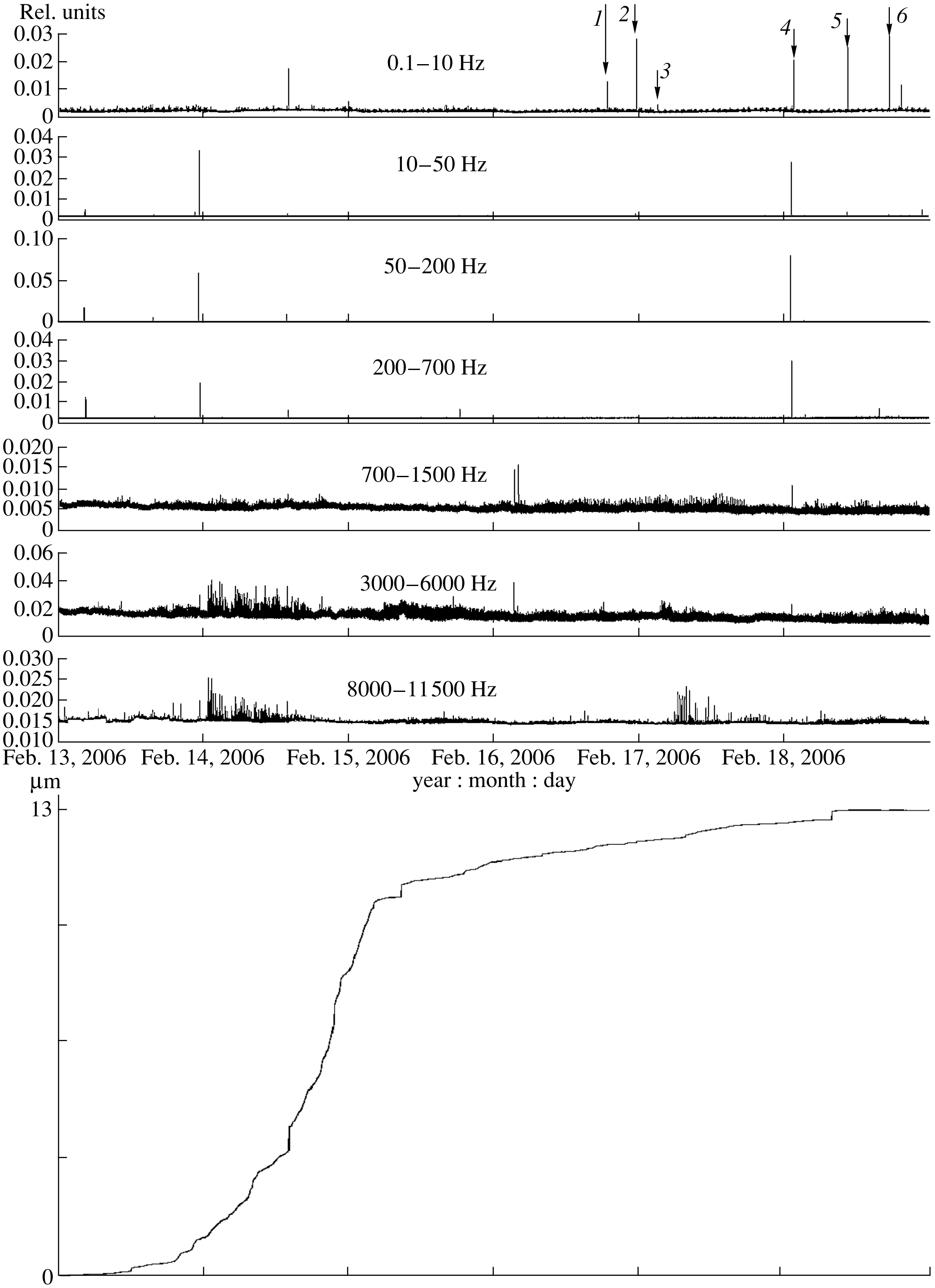

**Fig. 1.** Geoacoustic emission in the easterly direction in seven frequency ranges from February 13 to February 18, 2006, and records of the strainmeter during the same period. Arrows indicate time moments of earthquakes.

ilar. The direction of the signal was determined from the ratio of their amplitudes in the channels [1].

According to Fig. 1, a rapid increase in strain was observed on February 14, whose beginning was accompanied by a significant increase in acoustic emission during the day. On February 15, the strain growth rate dropped significantly, but acoustic noises intensified occasionally up to the events on February 16–18. For

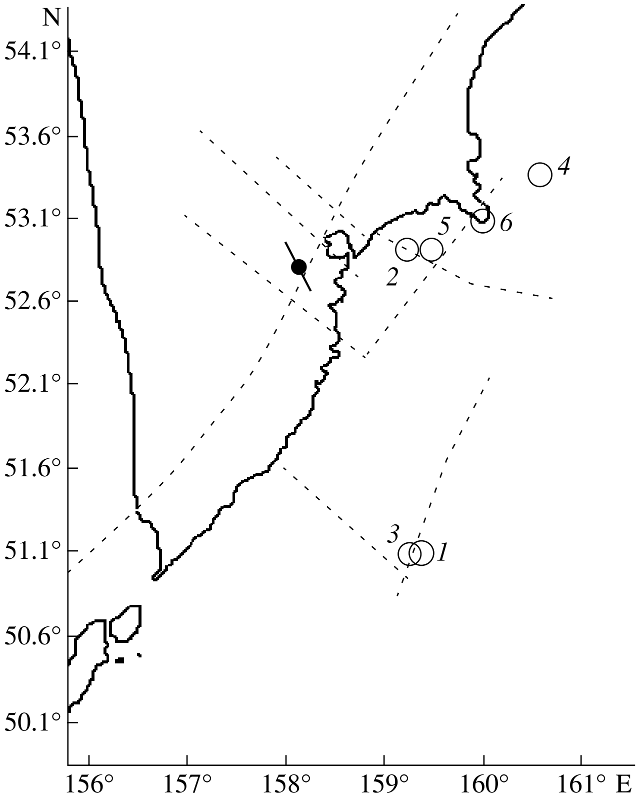

**Fig. 2.** Chart of earthquake epicenters: (*1*) Feb. 16, 2006, 18:41:20 UT, 51.12° N, 159.4° E, depth 15 km, class 11.5, azimuth 155°, distance 209 km; (*2*) Feb. 16, 2006, 23:31:14 UT, 52.92° N, 159.25° E, depth 86 km, class 10.6, azimuth 82°, distance 75 km; (*3*) Feb. 17, 2006, 03:00:01 UT, 51.11° N, 159.29° E, depth 15 km, class 10.8, azimuth 157°, distance 206 km; (*4*) Feb. 18, 2006, 01:30:57 UT, 53.37° N, 160.61° E, depth 57 km, class 11.3, azimuth 70°, distance 175 km; (*5*) Feb. 18, 2006, 10:34:29 UT, 52.92° N, 159.5° E, depth 68 km, class 10.1, azimuth 83°, distance 92 km; (*6*) Feb. 18, 2006, 17:21:46 UT, 53.10° N, 160.02° E, depth 50 km, class 11.0, azimuth 76°, distance 129 km. Black dot indicates the location of the strainmeter, while the line shows its orientation. Dashed line denotes fractures.

six days, the total deformation in loose sedimentary rocks in the observation region reached 13 μm. The relative strain over the 18-m-long base of the strainmeter was equal to $7 \cdot 10^{-7}$. A more detailed consideration of variations in the strain revealed that they consist of a sequence of different amplitude displacements, the so-called slips (Figs. 3, 4). Shear deformations correspond to the peaks of acoustic emission (Fig. 3), whose frequency range depends on the velocity of displacements. The form and characteristics of geoacoustic pulses appearing in this process are considered in [1]. The frequency of the recurrence of shears has a negative correlation with their amplitude. The slips and corresponding acoustic signals have fractal properties. The relative deformations of individual displacements are not large. For example, even if their amplitude is relatively large (Fig. 3), their value is equal to $4 \cdot 10^{-8}$. However, strains can accumulate for approximately a month without change in the sign of the derivative of the trend. It should be noted that strong earthquakes are observed in Kamchatka with this periodicity.

In general, slips occur spontaneously, but induced displacements (Fig. 4) frequently appear during the arrival of seismic signals from remote earthquakes if the medium is in a stressed state.

The events belonging to two spatially separated groups (Fig. 2) alternated in time and had simultaneous deformation influence on the observation region. In such a situation, the direction of the signals manifests strong variability [1, 3], while the directional diagram averaged over the observation period has two maxima oriented to the earthquake epicenters.

The direction of acoustic emission is provided by polarization of slips in shear deformations [1]. The consequent deformations of omnidirectional compressions have no effect because the strength of the rocks with respect to these compressions is significantly greater.

The obtained results indicate that the preparation of remote earthquakes promotes the stressed state of the medium in near-surface sedimentary rocks under the influence of strains propagating from the epicenter. Slips appear in the rocks due to the loss of cohesion. The consequent friction-induced intense geoacoustic emission can serve as a sensitive indicator of the activation of strains preceding earthquakes over a few days.

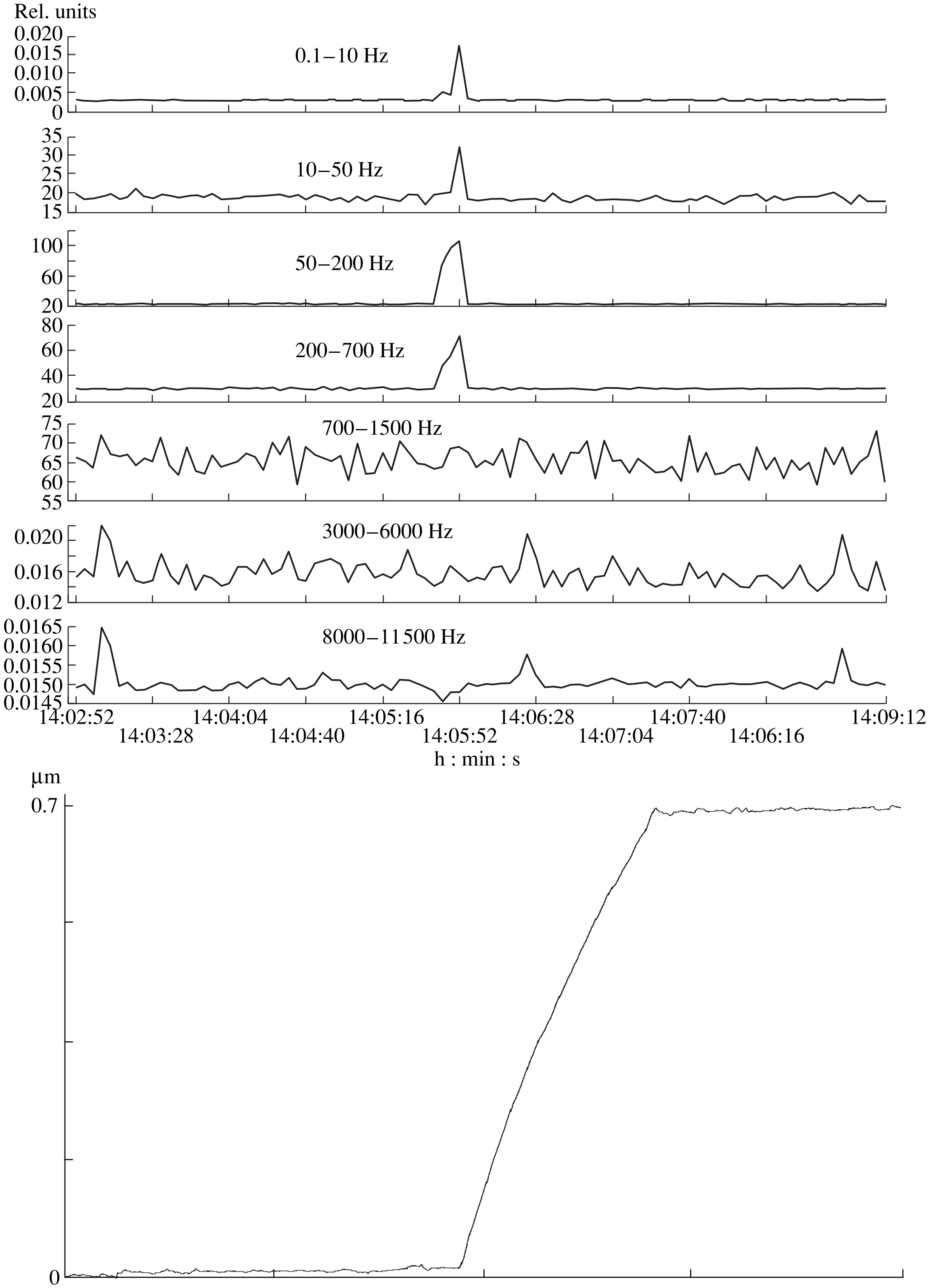

**Fig. 3.** Deformation shift on Feb. 14, 2006. Closeup of Fig. 1.

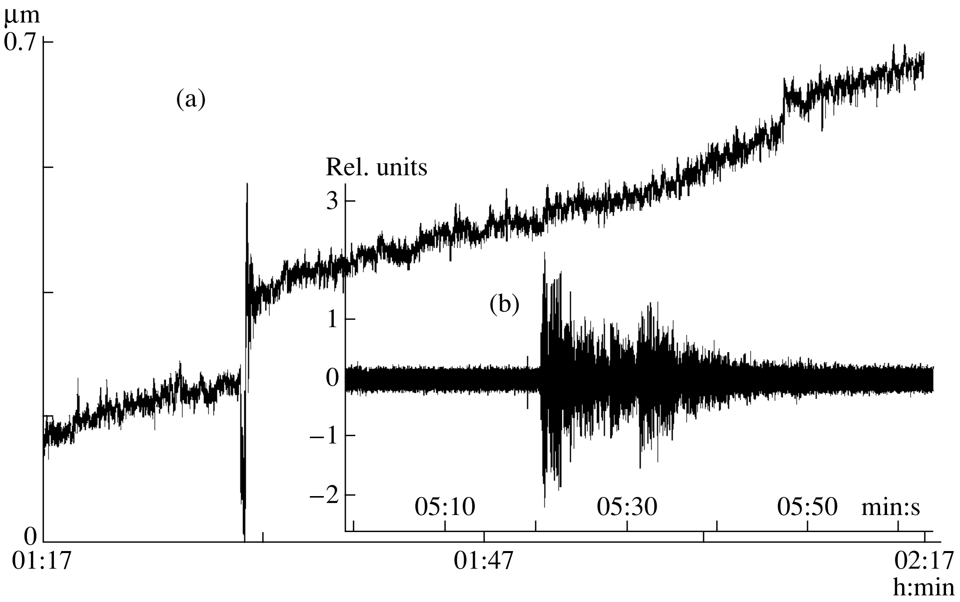

**Fig. 4.** Examples of (a) deformation shift and (b) acoustic emission during the seismic signal arrival.

A special role belongs to the high-frequency range, which has the most effective response to acceleration of the strain rate.

Thus, deformation–acoustic activity, which appears on the eve of earthquakes, can be considered a complex precursor of a seismic event.

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