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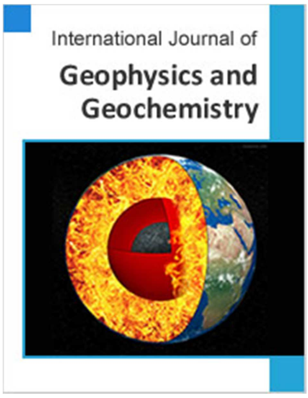

Instruments for Measuring Noise Inside the Earth

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Abstract

The knowledge of internal processes in the earth's crust is a complex but interesting scientific task. The solution of this problem attracts the attention of many scientists. But its solution largely depends on the development of means for detecting and recording internal acoustic noises in the upper part of the earth's crust, up to the boundary of the Moho. Acoustic noise can have different sources: earthquakes, tectonic processes, storm microseisms, gravitational tidal waves, anthropogenic (technogenic) impacts of various kinds, as well as cosmic ones, from impacts of meteorites to elementary particles. Underground noise has a different frequency and amplitude composition and different waveforms. The amplitudes of the oscillations sharply decrease with increasing frequency. To mitigate the disturbing effect of anthropogenic noise, measurements have to be made in wells. You can use the deep bottom of lakes, seas and oceans. In this case, the most interesting results can be obtained at the extreme point of the Pacific Ocean - at the bottom of the Mariana Trench. This point, whose depth reaches 11022 m, with an average thickness of the earth's crust under the oceans of only 5000-10000 m, is the closest to the Moho boundary. Technically, it is easily achievable for installing instruments and monitoring geoacoustic noise directly on a deep bottom. Especially for studies in the earth's crust, an original wide-band (with a frequency of 1 to 5000 Hz and amplitude of more than 240 dB), a magnetoelastic inertial geophone with a vector characteristic - a velaccmeter, has been developed. Its characteristic compensates for the decrease in the amplitudes of underground noise by increasing the sensitivity by 1000 times with an increase in the oscillation frequency by a factor of 10.

1. Introduction

When performing acoustic measurements in the earth's crust, it is necessary to take into account the specificity of the acoustic noise of the Earth and its variability in time, both on short intervals (hours, minutes, seconds, and less), and on long intervals (day, months, years and more). Short intervals of registration provide an investigation of fast wave processes occurring in the earth's crust [1]. Long intervals are more suitable for studying geoacoustic noise associated with gravitational tides and tectonic processes that provide necessary information about background deformation processes occurring in the earth's interior and their connection with external and internal actions [2]. Precisely for such continuous and continuous observations of geoacoustic noise, based on the previously developed methods [3, 4], the field instrumentation complex was comprehensively tested and fully tested, which was regularly updated and successfully used in monitoring mode when studying the internal noise of the Earth in its various regions.

The first studies, in general, were short. Their goal was to search for acoustic precursors of earthquakes, but later appeared other goals and tasks. It is appropriate to note here that natural fast wave processes in the earth's crust can be reliably detected and registered only in the long-term (high-frequency) monitoring mode for high resolution in amplitude and frequency. This is confirmed by a three-year monitoring in a well in the southern spurs of the Himalayas, [10] when strange acoustic processes with high amplitudes were discovered and recorded at the end of a three-year observation period that began with the sunset and ended with its sunrise. It was strange. The second example is the two-year monitoring in the experimental well SAFOD [1], the code only a posteriori analysis revealed short acoustic events, which are supposed to be acoustic traces of cosmic particles.

2. Structure of the Hardware-Software Complex

The hardware and software complex in its modern form consists of three parts: a geophone, an analog part and a digital part provided with a registration program. Geophones can be installed in wells, in mines, galleries, in deep cellars, and also on the surface with a depth of up to 10 m. It is possible to install geophones on the bottom of reservoirs. The depth of installation is not limited. In a special case, the geophone can be effectively used in an aquatic environment, with only about 30% of its high sensitivity being lost. To amplify the weak electric signal of the magnetoelastic geophone, a linear analog amplifier can be used, and if necessary band-pass amplifiers with center frequencies, for example: 20, 160, 500 and 1000 Hz, equipped with demodulators. Digitization of amplified or separated signals is performed by 24-bit ADCs with 4 or 16 channels and a program for recording to the hard disk of the computer. The optimal sampling rate for vector signal registration should be 100 kHz per channel, and after analogous allocation of frequency bands and demodulation it is sufficient to have a sampling rate of not more than 500 Hz per band. This significantly reduces the amount of information stored and allows you to analyze the data in real time on the monitor screen.

3. The Geophone

A geophone is a device from a well-known series: a microphone, a hydrophone and a geophone, which designates an acoustic signal transducer in a solid earth crust into an electrical signal. The most common electrodynamics geophone (velosimetr), in which an inertial mass is an electric winding suspended in a magnetic field on springs. The output signal of such a geophone is proportional to the speed of the electric winding relative to the magnetic field. The winding has a mechanical resonance, whose frequency f_0 depends on the mass of the winding and the rigidity of the suspension springs. The sensitivity of such a system decreases as the frequency of oscillations decreases less than f_0 in proportion to the cube of the signal frequency (f^3) and grows in the operating range proportional to f^1 at frequencies above f_0. Geophones of this type are used, mainly, for seismic prospecting. Their operating frequency range is limited to a frequency of 110 Hz. Another type of geophone is a piezoelectric (accelerometer), who's output voltage in the operating range increases in proportion to f^2. Velosimetr and accelerometer are not effective for geoacoustic studies because their amplitude-frequency characteristics and dynamic range do not allow recording fast processes with small amplitudes against the background of slow processes with large amplitudes.

A new type of geophone is a magnetoelastic (velaccmeter), its output voltage increases in proportion to f^3 [5] to mechanical resonance, and then is proportional to f^1. The frequencies of the mechanical resonance of the vector components of the new geophone from hundreds to thousands of Hertz, depending on the purpose and design. At present, the fifth generation of the MIG-3V magnetoelastic geophone sensor (Magnetoelastic Inertial Geophone Three-component Vector) is available with improved properties. In Figure 1 the right-hand geophone of the fourth generation of MAG-3C (PSAK-3SM) is shown on the right, and its sensor with a cruciform sensor [6] is shown to the left. Sensitivity of the sensor: $0.12\times10^{-3}\mathrm{V}\times\mathrm{m}^{-1}\times\mathrm{s}^3$ for vertical direction and $0.6\times10^{-3}\mathrm{V}\times\mathrm{m}^{-1}\times\mathrm{s}^3$ for horizontal directions. The frequencies of mechanical resonance: 1200 Hz for vertical direction and 350 Hz for horizontal directions. The dynamic range is not less than 240 dB. This difference in resonant frequencies and sensitivity of the vertical direction and horizontal directions is associated with the design features of the downhole tool, which involves minimizing the cross section of the device with a large vertical dimension. The lack of a downhole geophone is the susceptibility of the measuring channel of the vertical direction to the electromagnetic fields. However, when using a geophone in a well, this deficiency is partially compensated by the steel casing.

Figure 1. *The magnetoelastic geophone of the fourth generation.*

4. The Fifth Generation of the Sensor

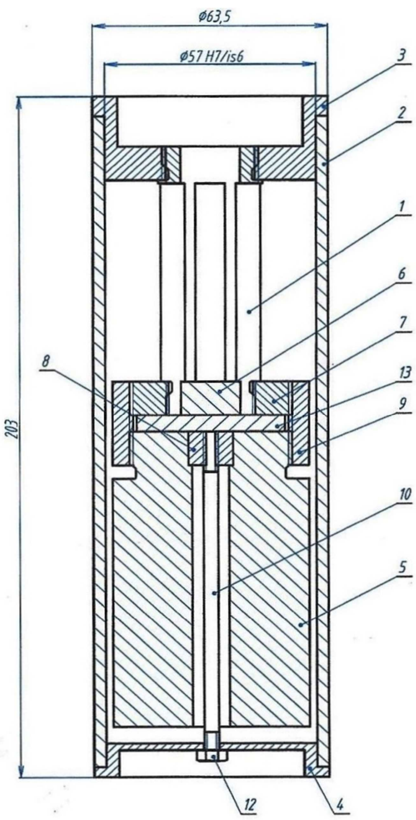

Figure 2. *The scheme of the sensor fifth generation.*

Advantages of the design of the fifth generation geophone sensor [7], the design of which is shown in Figure 2 is that the rigidity of the magnetoelastic transducer is increased and compared with the fourth-generation sensor and more uniform in all directions. In turn, this significantly increases the frequency of mechanical resonance of the horizontal components of the converter, expands its frequency and dynamic ranges and increases the sensitivity. This improves the characteristics of the three-component geophone, and increases the accuracy of determining the azimuthally characteristics of the perceived oscillations. For this purpose, the sensor element of the magnetoelastic transducer is made, instead of a rectangular symmetrical cross, in the form of a tube with symmetrical grooves for measuring windings, which further simplifies its manufacture and increases strength and reliability under extreme conditions.

A simple calculation (without taking into account the holes and grooves for the windings) shows that the cross section in the form of a rectangular cross and with dimensions h = 2.8 cm and d = 0.4 cm has a cross-sectional area of 2.08 cm^2, and the moment of inertia of its section 0.74 cm^4. At the section of the annular shape with dimensions d = 2.8 cm and d_0 = 2.0 cm, the cross-sectional area is 3.01 cm^2, and the moment of inertia 2.23 cm^4. The ratio of the moment of inertia of the section of the annular shape to the moment of inertia of the cross section with the shape of the rectangular cross is three, that is, the rigidity of the transducer with the ring shape of the cross section of the sensing element is three times larger than in the cross-sectional shape in the form of a rectangular cross. This means that the frequency of the mechanical resonance of horizontal components with equal length and inertial mass for a converter with an annular cross-section of the sensor is three times greater than for a similar transducer with cross section of a sensitive element in the form of a cross. The increase in the cross-sectional area of the converter proportionately increases its stiffness in the axial direction. Thus, the use of the new generation MIG-3V sensor in the downhole geophone expands the range of operating frequencies of vector geoacoustic measurements. At the same time, the sensitivity and dynamic range increase.

The fifth-generation MIG-3V sensor is designed for installation in a downhole tool with an electromechanical clamp produced by OYO Corporation, but this does not exclude the possibility of using downhole tools from other manufacturers having an instrument box diameter greater than 2.5 in. and a depth of more than 8 in. The diagram shows the main parts: sensor 1, body 2, upper and lower supports 3 and 4, inert mass 5 and magnet 13. Measuring windings are not shown. When the body moves in an inert mass, a force proportional to the acceleration of the displacement appears and changes the mechanical stresses in the individual parts of the sensor element, which is magnetized by a high-energy magnet. Depending on the direction of the body displacement in different parts of the sensing element, the mechanical stresses are proportional to the orthogonal projections of the vector of the initial displacement on the axis of the sensing element and cause corresponding changes in the magnetization of these parts. This, in turn, generates an EMF in the windings corresponding to the orthogonal components of the original displacement vector, which are proportional to the rate of acceleration of the displacement, i.e. the third time derivative of the body displacement. It is this peculiarity of the magnetoelastic geophone sensor - the velaccmeter - that causes its sensitivity to increase by 60 dB when the frequency is increased by a factor of 10 and allows, in contrast to conventional velocimeters and accelerometers, to measure the displacement in millionths of a nanometer at a high frequency with simultaneous large displacements at low frequencies.

5. Directivity Diagram of the Horizontal Components of a Vector Geophone

The directional characteristics of the sensitivity of the horizontal components H1 and H2 of the fourth-generation vector geophone were investigated on a vibration seismic platform with a frequency of 16 Hz (the optimum frequency for the platform-geophone system). The geophone PSAC-3C (MAG-3S) was installed vertically in the center of the platform and rigidly fixed in the pivot device. The platform was given horizontal sinusoidal oscillations. The direction of the axis of symmetry of component H1 (the axis of maximum sensitivity of component H1) relative to the direction of motion of the platform was successively set in steps of 15° in the range from -90° to + 90° by rotating the geophone around its vertical axis. In Figure 3 that the experimental data fit well on the theoretical curves of the directivity diagram of the horizontal components of the vector geophone. A good coincidence of the phases of the three components is ensured by the use of a single inert mass and the precision of the mechanical processing of the sensor's rigid sensor element. Experimental study of the vertical radiation pattern due to the technical complexity of the procedure was not carried out; however, there is no doubt that it also has the form of a three-dimensional cosine eight. There is also no doubt that the fifth-generation MIG-3B sensor (Figure 2) has an even more accurate radiation pattern and phase identity of the components, which are mainly determined by the accuracy of the mechanical processing of the sensor element.

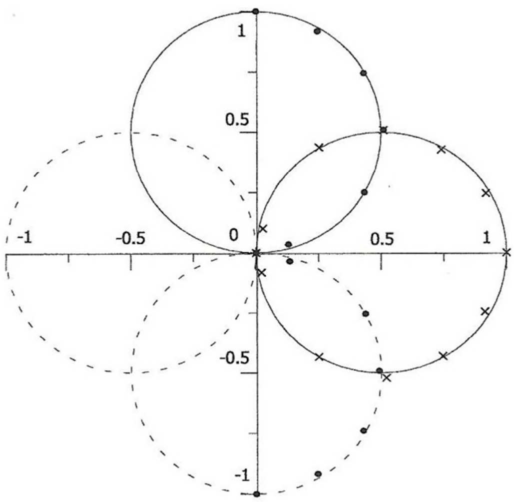

Figure 3. *- - - -,——- theoretical curves; ××××, ····· - experimental data.*

6. Discussion

The first record on March 24, 1989, shown in Figure 4, was made using a magnetoelastic four-generation MAG-3C (PSAK-3SM) geophone. She largely determined the direction of searching for acoustic precursors of earthquakes. The record was made at a depth of 1336 m in well 123 with a depth of more than 2000 m. The well was drilled at the boundary of two oil fields in the Pripyat trough in Belarus [8]. The depth of 1336 m was attracted by the abnormally high level of acoustic noise. It is noteworthy that no noise was observed above and below 50 m from this point. The assumption was that in the vicinity of the selected point, located in the middle of the "dirty" salt array 700 m thick, there is a layer with an abnormally high acoustic conductivity, in which waves from micro earthquakes propagate over large distances. According to seismologists, the micro earthquake in Figure 4 (channel No. 1 with a band of 0.5-40 Hz) occurred at a distance of 100-120 km. Similar processes in the detected layer are observed continuously at intervals of 10 to 30 minutes. Verification of the stability of processes in 1990 and 1992 this is confirmed. It was interesting that each event was preceded by an increasing flow of acoustic pulses in frequency bands with a demodulation of 500 Hz (channel No. 2) and 1000 Hz (channel No. 4), which appeared 6-10 minutes before the earthquake. The most effective band was 500 Hz. In the 30 Hz band (channel No 3), activity before the earthquake was not observed. On paper tape without demodulation, only a band of 0.5-40 Hz was recorded and all channels were without averaging. This made it possible to transfer the high sensitivity of the geophone to the final product (amplitude of the pen) without attenuation.

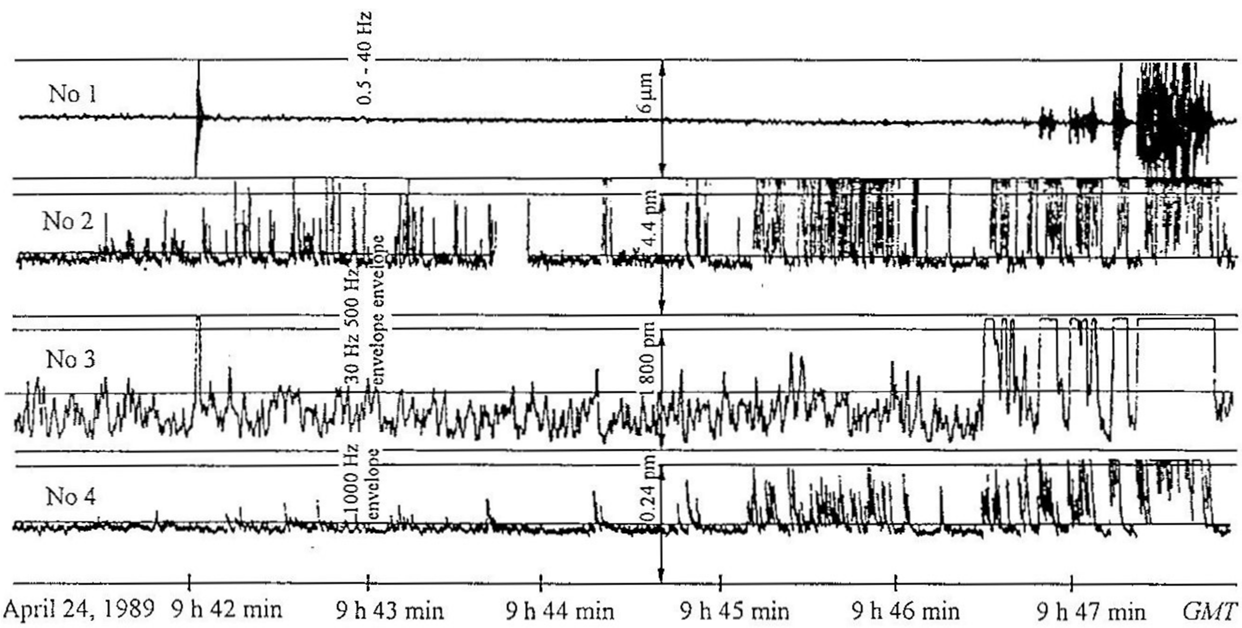

Figure 4. *The process of development of earthquake precursors.*

The investigations were continued in May-June 1990 near the San Andreas Fault in Parkfield California in conjunction with LBNL and USGS. It was assumed that in an area with a high intensity of earthquakes, the previously discovered connection will be confirmed. But the experiment was short and not effective due to force majeure circumstances: a high level of high-frequency noise from the gas outlet in the well Pearson Well through perforation at a working depth of 800 m and the forced termination of the experiment due to leakage of the cable head on the third day of the experiment [9].

The longest monitoring was carried out in the territory of the first in the south of the Euro-Asian continent point of long-term observations of seism acoustic emission in New Delhi of the Republic of India [10]. For this purpose, a well was drilled in the territory of the Mountain Seismological Observatory in the northern part of New Delhi and a point of seism acoustic observations with a new geophone was created. The geophone is installed on the bottom of a dry, cased with a steel pipe, a well 100 meters deep. Registration started in October 2007 and was conducted until March 2010. Time is UTC. In order to register acoustic signals for a long time on the hard disk of the computer in automatic mode, it was decided to register the average signals for 1 minute. In the initial period of registration until November 2009, there was a powerful industrial noise. In October 2009, for no apparent reason, the situation changed dramatically. Industrial noise ceased to be observed. What happened at this time on the nearest territory to the well is unknown. Chaotic in nature, the noise disappeared, and in the data, starting from November 2009, there were regular increases in noise. The registration fragment for the period from 17 to 23 February 2010 is shown in Figure 5. Amplitudes of noise (average for 1 minute the value of the acceleration speed in ADC units) increased sharply at sunset and also sharply decreased at sunrise. To detect this process it took three years of continuous registration. Unfortunately, the experiment in March 2010 was terminated due to the end of the Intergovernmental Agreement, and it is not known what happened during the vernal equinox, when the day and night amplitudes of the solar strain component SD become equal.

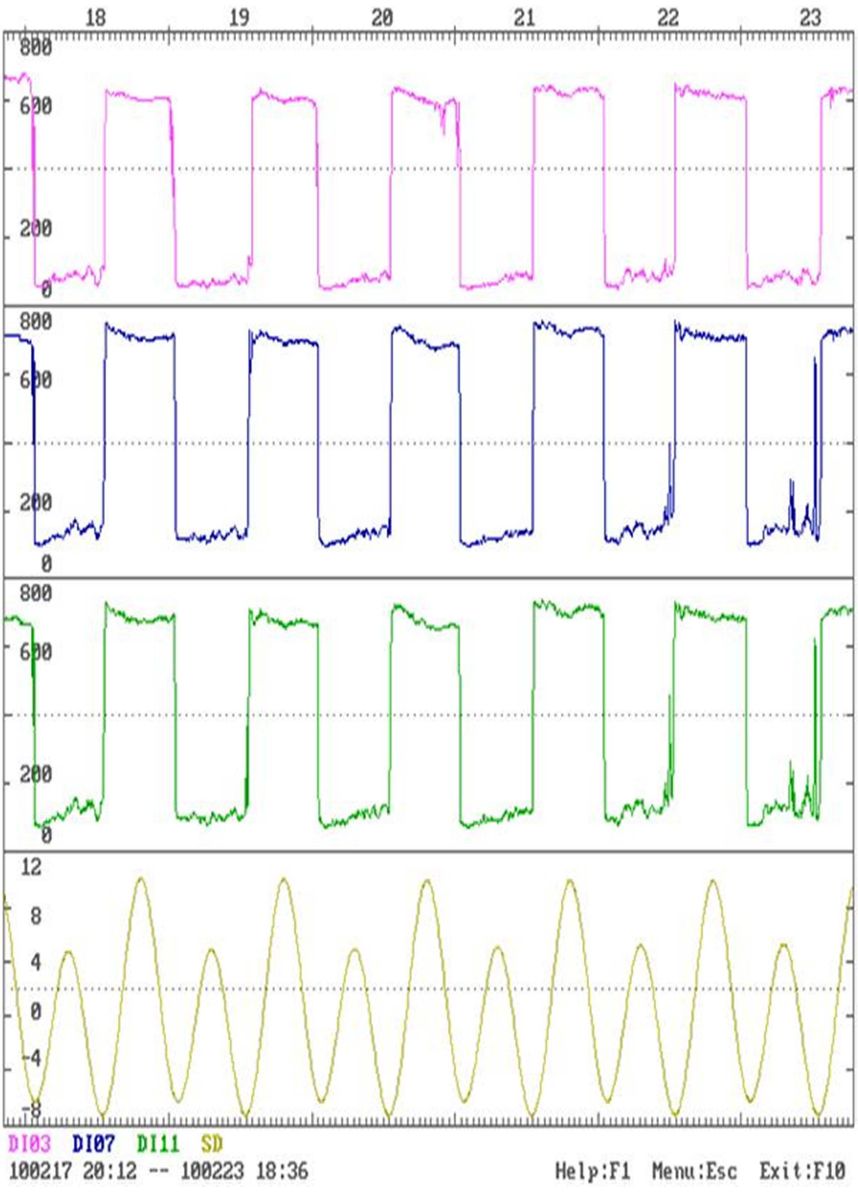

Figure 5. *From top to bottom: amplitudes of acoustic emission in 500 Hz bands (DL03, DL07 - horizontal directions, DL11 - vertical direction) and SD - solar tidal relative strain (10^{-9}).*

The used technology of registering the average values of acoustic signals performed well its functions in solving a number of fundamental and applied scientific problems related to the study of the connection of tidal deformations and acoustic emission. When searching for earthquake precursors, detecting underground nuclear explosions and in other fundamental and applied research, it greatly reduced sensitivity and masked fleeting events. Indeed, when the detected signal was digitized and averaged over 1 minute, about 2000 points were converted into a figure; the amplitudes were summed and divided by 2000. If, for example, at that moment an event occurred with a duration of 0.03 s or less, its amplitude decreased by 2000 times, and it was almost impossible to detect such an event. Modern systems allow the recording of short signals, such as an acoustic emission certificate or an acoustic event associated with a cosmic particle, at full scale without averaging, keeping the high sensitivity of the geophone and the possibility of continuous automatic recording in the final product.

7. Conclusions

The carried out works: design, research and field tests allow to draw a conclusion that the problem, how to hear the acoustic noise of the Earth, in principle is solved. There are prototypes of a fourth-generation geophone [6] and a design and technological project for a fifth-generation geophone [7]. A fifth-generation experimental geophone set of 10 pieces was manufactured, tested at the Geoacoustic Company (VNIIFTRI) and in 2005 handed over to the customer for a seismic-control system "Blue Stream". Full-scale studies have been carried out with equipment that allows recording the main signals in the earth's crust effectively and without loss of data quality, which are of practical interest for fundamental and applied research [1].

It did not mention the most massive use of geophones - in seismic exploration - just because it's a trivial task. Although the use of a new geophone in this area will give a tangible effect by increasing the resolution of seismic prospecting. There was also no mention of the possibility of using a fifth-generation vector geophone with axial symmetry [7] as a worthy alternative to a scalar hydrophone. To do this, it is necessary to equip the outer sealed housing with an angle reflector [11], adding a vertical reflector disk. In addition, the technical part of the patent application for a vector geophone (hydrophone) with a central symmetry that can be used as a vector geophone on the terrestrial (or lunar) surface (at the bottom), in the ice column or as a vector hydrophone in an area of unlimited depth is prepared. Processing of large data sets obtained during monitoring can be performed by a special program WinABD [12].

In conclusion, I want to thank all LBNL and USGS staff who somehow took part in the laboratory preparation of the downhole geophone and conducted field research in the experimental well of the SAFOD test site in Parkfield.

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