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VARIATIONS OF GEOACOUSTIC EMISSION IN THE DEEP BOREHOLE: RELEVANCE TO SEISMICITY AND PHYSICAL ORIGIN

Introduction

The concepts on cracking within heterogeneous medium are actually the fundamental of modern models of earthquake preparation and its source site formation. Being the indicator of micro-fracturing processes like cracking, shifts along blocks boundary, pore coalescence, changes in interstitial fluid pressure etc., the data on spatio - temporal characteristics of acoustic emission (AE) are to contribute to such models validation and/or improvement. This equally involves the results of experiments on rocks specimens to simulate tectonic straining processes at the laboratory and that of geoacoustic emission (GAE) surveys (seismoacoustics, by other term [1]) aimed to study natural acoustic emission of embedded rocks.

The results on GAE variations recorded in a tunnel at 100 m depth (Matsushiro seismological observatory, prefecture Nagano, Japan) were represented in [2]. The measurements have been carried out with the help of three-component MAG-3S geophone designed in Earth Physics Institute of the Russian Academy of Sciences on the basis of magneto-elastic sensor [3]. The output signal of such sensor is proportional to the third derivative of the ground displacement, and the gain slope of MAG-3S geophone is equal to 60 Db for a decade of frequency change. Such characteristics allow measurement of GAE natural background with minimal amplitude of signals (evaluated as equivalent ground displacement) less than $1\cdot10^{-10}$ m. According to the results of [2] some increase in GAE level has been recorded in 5 cases of earthquakes with M=3.7÷5.2 occurred at epicentral distances up to 110 km. The observed variations have lasted during nearly 12 hours before the events. The example of mentioned results can demonstrate that geoacoustic measurements with use of high-sensitivity geophones [4] are able to provide new significant information and put some light on the earthquake preparation process. But up to now the most of surveys have been conducted in seismically inactive regions.

Interesting results related to GAE measurements with a geophone have been revealed recently in works [5-7], where another approach has been developed with similar purpose: to distinguish signals originated by stressed-strained crust from the background of extraneous noise. The authors of [5-7] argued that ultrasonic acoustic emission measurements on Earth surface can also be a diagnostic tool for changes in crust stress in seismic areas. This is possible under conditions that the sensors are installed on bedrock outcroppings, and acoustic emission signals are recorded in ultrasonic frequency range (10- 200 kHz) higher than usual frequencies of GAE measurements. According to [7] bedrocks from top to bottom can play a role of giant probe, and AE signals recorded on the outcrop are sensitive to variations of tectonic stress and, so are relevant to seismic processes. Although ultrasonic signals are not able to extend on large distances, anomalies of AE flow before strong earthquakes have been revealed during AE measurements in Apennines, Italy [5-7].

Actually the existence of distinct diurnal variations of GAE level in frequency range 10 - 200 kHz and their interrelations with changes in natural electric field strength follow from data given by [7]. Diurnal variations of GAE level were recorded also (but in frequency range 30 -1200 Hz) when the geoacoustic surveys were carried out with the help of MAGS 3S geophones installed in boreholes [4]. Sensor allocation inside deep enough borehole (700 m depth or more) where the level of geoacoustic emission is controlled by natural crust (lithospheric) processes is a proper way to provide necessary sensitivity of GAE measurements. Unfortunately the results represented in [4] have been obtained mainly by measurements in seismically inactive regions. This has not allow revealing cause-and-effect relations of characteristics of geoacoustic emissions with stressed-strained state of a terrestrial crust.

This paper is devoted to the results of the continuous geoacoustic measurements performed in 2000-2003 in the seismically active region of Kamchatka, Russia, with the use of MAG-3S geophone, installed inside deep G-1 borehole at the depth of 1035 m. Some preliminary results of these measurements were described in [8,9]. Hereinafter we analyze the results of geoacoustic measurements together with the data of seismicity of Southern and Central parts of Kamchatka.

The equipment and a technique of observations

The station for GAE measurements was built on the base of G1 borehole (Lat. 53.05 N, Long. 158.63 E) located in Petropavlovsk-Kamchatsky, a zone of deep northwest oriented fault. The depth of the borehole is 2540 m. The borehole is totally water-filled and cased along the whole length. The structure of the measuring system is presented on Fig 1. The geophone which is the main measuring unit of the system has been installed at a 1035 m depth. The body of the sensor is crowded against the casing by a spring.

The sensitivity of the vertical channel of the geophone (evaluated on preliminary amplifier output) is 0.15 $V \cdot s^3/m$, and the resonant frequency of the sensor is 1250 Hz. The sensitivity of the horizontal channels is 0.60 $V \cdot s^3/m$; the resonant frequency being 300 Hz. The output signals of geophone pre-amplifiers are transferred through armored cable to the main processing unit, located at the mouth of the well. The main analog unit provides additional amplification, subsequent filtering of the initial signals of each geophone channel by a third octave band pass filter, distinguishing the bands with the four central frequencies chosen: 30, 160, 560 and 1200 Hz, and, finally, the measurement of averaged values of output filtered and rectified signals (from each of 12 filters). The further processing of signals is realized with the help of the microprocessor controller. The functions of the microcontroller involve analog-digital converting of the input analog signals (the sampling rate is 32 Hz on the channel), calculation of average values of recorded signals in one minute moving window, and, finally, data saving on the disk memory. The data are transferred via telephone channel to the Data Management Center of the Institute of Volcanology and Seismology, Far East Department of Russian Academy of Sciences, Petropavlovsk-Kamchatsky, by a request of operator.

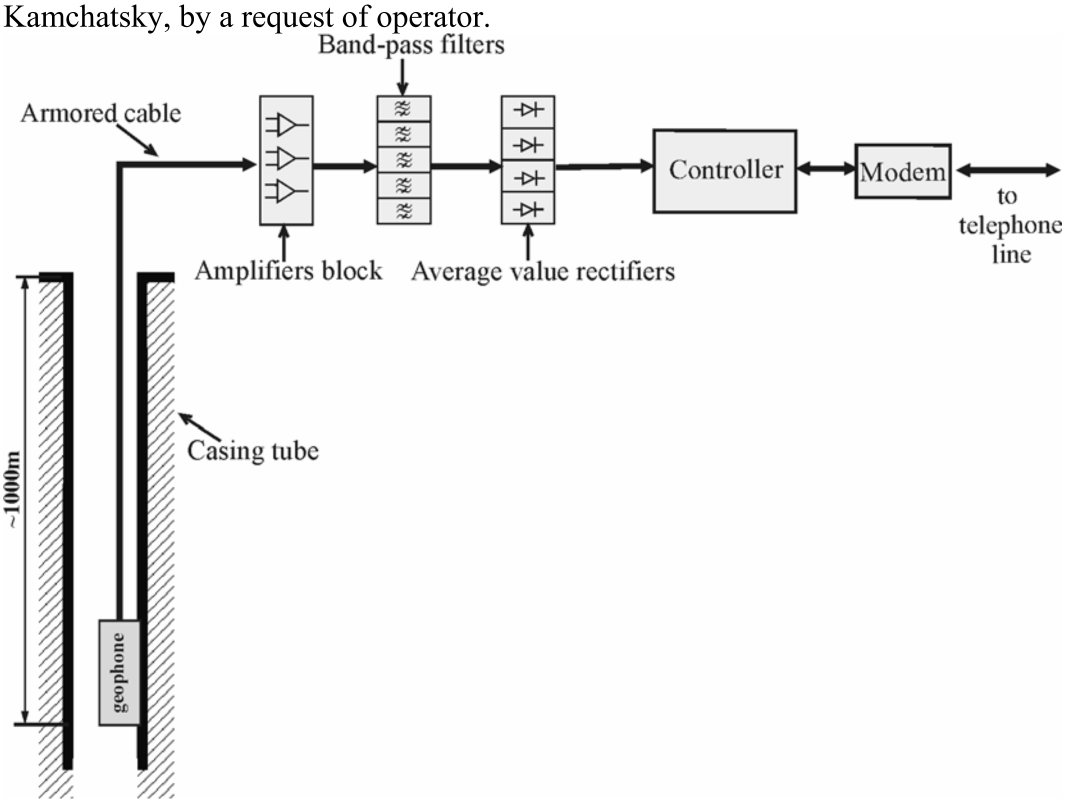

Fig. 1. The structure of measuring complex

Before geophone installation on permanent depth 1035 m, measurements of GAE level were performed on various minor depths (Fig.2)**.** At 200 m depth the level of noise in frequency bands 30 and 160 Hz dropped approximately by 17—20 dB (7-10 times) compared to that on original ground. Subsequent deepening of geophone up to 600 m depth was followed by smooth damping of the noise in the noted bands: it decreased by 10-13 dB compared to that at 200 m depth (in the band nearly 30 Hz). Sharp decrease of GAE level in low frequency bands at shallow depths was predetermined by contribution of man-made noise produced at the daylight surface. The bands with central frequencies 30 and 160 Hz were close to urban frequencies. But the man-made noise at frequencies 560 and 1200 Hz was less, and it was not able to contribute to GAE level even at shallow depths 100-200 m. Correspondingly, only slight decrease of GAE level was observed at higher frequency bands (560 and 1200 Hz).

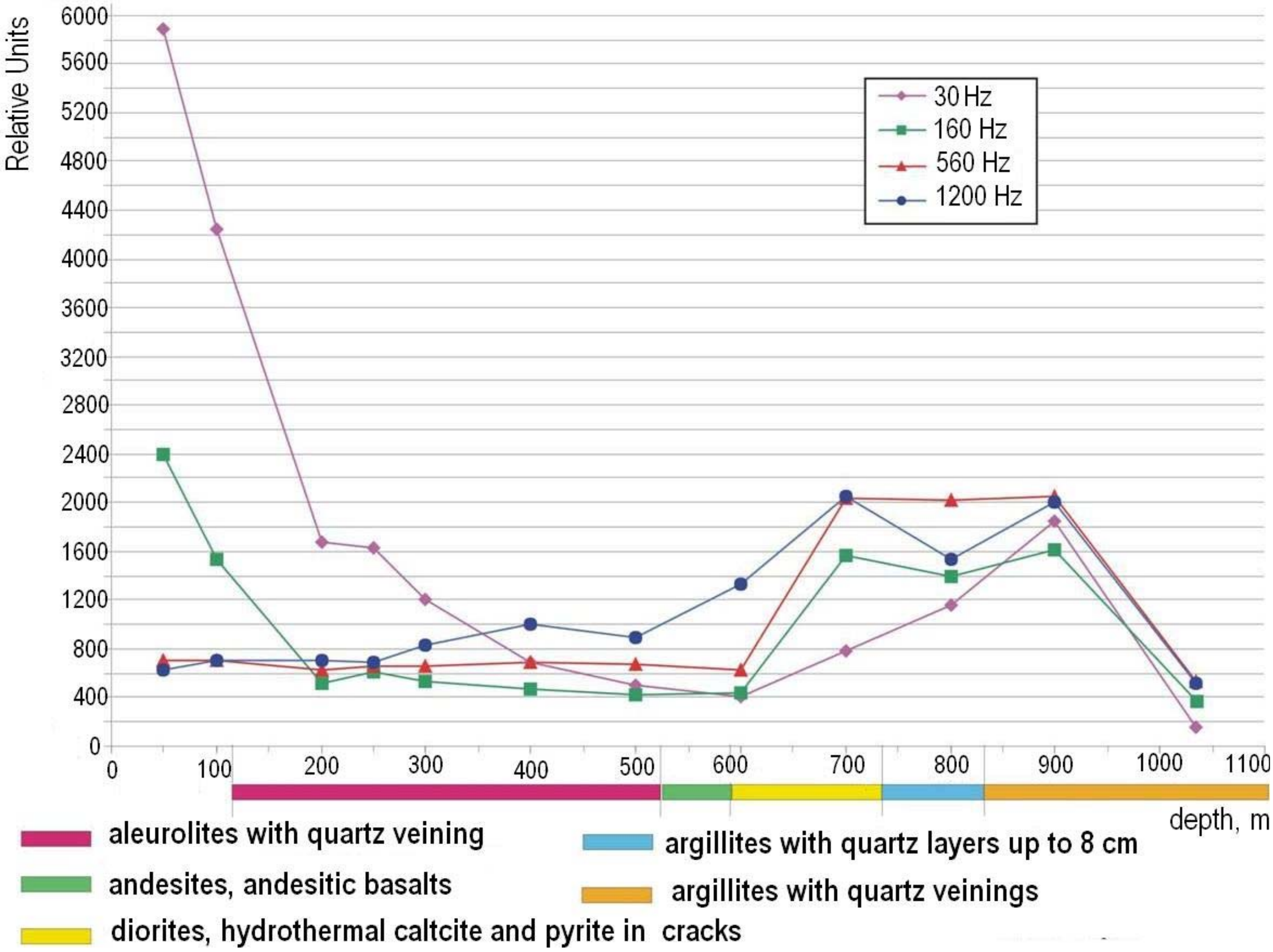

Fig. 2. The dependence of mean GAE level at several frequency bands on depth of geophone location. GAE signals horizontal component has been plotted.

However significant growth of GA.E level in all frequency bands took place in the interval of depth from 600 to 900 m. The greatest increment of noise (12-13 dB) was denoted in the bands 30 and 160 Hz. Subsequent geophone imbedding to 1035 m depth resulted in that the noise level in all the bands dropped again. The non-trivial fact of GAE amplitudes growth in all the frequency bands in the layer of 700-900 m depth and subsequent sharp GAE decrease from 900 m to 1035 m may be related to peculiar features of geologic profile at the borehole place.

G-1 borehole is located in a small valley with rocky edges. According to the geological cross-section the valley bed is filled up to 80 m depth by sandy-argillaceous deposits with inclusions of pyroclastic strata. The layer from 80 to 110 m depth is formed by siltstones and sandstones stratigraphically alternated by clay interlayers. Denser slates of uniform makeup occur at depth more than 110 m. According to the cross-section the rocks lying at depths from 520 to 840 m are characterized by horizontal schistosity. There are four explicit layers on this interval of depth (fig.2). Each layer is of 50-100 m thickness. Hydrothermal veins with pyrite and calcite are represented widely on depths from 650 to 740 m. This is dissimilar to only one layer occurring at depth from 100 to 520 m. The rocks lying at 820 - 1035 m depth represent the single strata as well. Presumably, the rocks of enhanced stratification, with softened inclusions at bedding interface cause enhanced dynamic and geoacoustic activity at that depth. In our opinion, this may explain (to a certain extent) the non-monotone GAE amplitude dependence on depths.

Certainly, the data on vertical dependence of GAE note that the layer of depth from 700 to 900 m is the most preferred for permanent measurements with the geophone (rather than its actual location at 1035 m horizon). But these data (summarized by the fig.2) was obtained after geophone installation at 1035 m depth. Thereafter, because of technical reason we had no opportunity to change the position of the geophone. The main methodical result of GAE amplitude vertical scanning (fig.2) is a direct proof that geophone installation inside the borehole at near 1000 m depth reduces greatly low frequency exogenous noise (30 and 160 Hz bands). The level of noise reduced on 40 dB (two orders of value) at 30 Hz frequency, it also reduced on 17 dB (nearly order) at 160 Hz frequency, both cases in comparison with level of noise on original ground.

Results of continuous GAE surveys on 1035 m depth

Continuous GAE measurements started in August 2000. In this section we consider peculiar features of temporal dependences of geoacoustic emission obtained from continuous surveys in the period 05.08.2000- 31.07.2003. During primary data analysis we have focused on such point as a manifestation of characteristic diurnal variations of averaged GAE level. Characteristic variations constitute diurnal geoacoustic emission distributions (DGAED) of 24 hours periodicity which usually emerge in aseismic periods [8].

Specially developed program for PC has been used to establish the presence or absence of DGAED in GAE time series from 05.08.2000 to 31.07.2003. Sometimes a simple visualization of these time series (plotted output) can reveal diurnal variations occurrence. The program of the GAE time series processing is based on “recognition” of the GAE variations similar to logistic function of sunrise/sunset g (t), so-called meander (trial rectangular increment). The function g (t) is equal to 1 (unity) when the Sun is above the horizon, and it is -1 after a sunset. The algorithm of recognition involves the selection of such coefficients of regression *a* and *b*, to minimize the regression function (below) in the given time window

$$R = \sum_i (f(t_i) - ag(t_i) - b)^2, \tag{1}$$

where $f(t_i)$ - current value of GAE level, t – time.

Coefficients *a* and *b* can be determined from system of the equations:

$$\frac{\partial R}{\partial a} = 2a\overline{g^2} - 2\overline{fg} + 2b\overline{g} = 0;$$
$$\frac{\partial R}{\partial b} = 2b - 2\overline{f} + 2a\overline{g} = 0; \tag{2}$$

where the lines above variables or expressions note their averaging over time window.

As result of the solving system of the equations (2) one can receive:

$$a = \frac{\overline{fg} - \overline{f}\cdot\overline{g}}{1 - \overline{g}^2}; \qquad b = \frac{\overline{f} - \overline{fg}\cdot\overline{g}}{1 - \overline{g}^2}; \tag{3}$$

The received expressions mean that the coefficient *a* is the averaged amplitude of DGAED, *b* - daily average level of GAE. Coefficients *a* and *b* concern to data on entire window (all n counts of function $f(t_i)$).

We have selected a two-day window (n = 2880) for computations with the help of above algorithm. Transition intervals of 30 min length close to the estimated times of Sun rising and a sunset have been excluded while computations. The exceeding of the threshold value a_c =500 relative units (RU) by the average amplitude of DGAED has been considered as a criterion of presence of GAE diurnal distribution provided that the maximal value of DGAED amplitude was equal to a_{max}=2804 RU.

The result of computations is that the characteristic diurnal variations have been distinguished in GAE time series during approximately 60 % of observation time. An example of such variations in temporal intervals from August, 13-16th, 2001 and September, 3-7th, 2001 is presented on Fig.3,a,b (Greenwich time is hereafter used). Transition times from the minimum values of emission level to the maximal one and vice versa are about 5-10 minutes. The moments of transitions are correspondent with the times of terminator line crossing (times of sunset and sunrise) for the observation point. The most explicit diurnal variations (day time minima and nocturnal maxima) have been revealed on GAE series recorded by channels for vertical components, with the central frequencies of 30 Hz and 160 Hz.

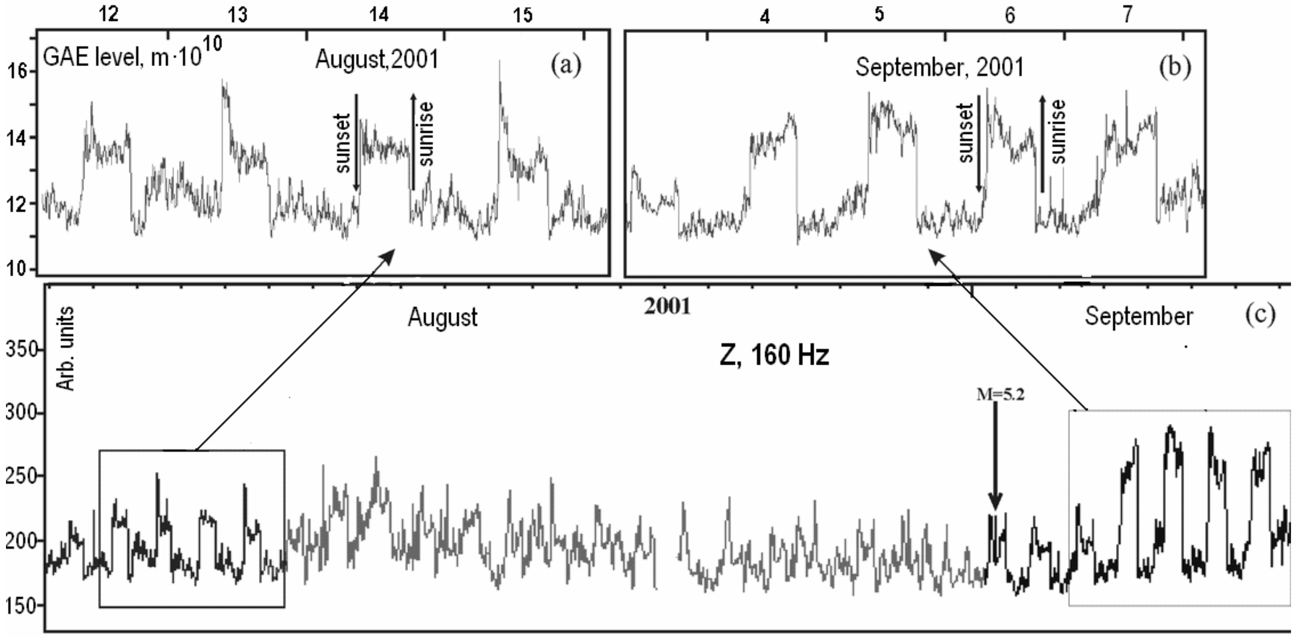

Fig. 3. A plot of characteristic diurnal variations of mean geoacoustic emission level (for Z component of GAE signals in a band with central frequency of 160 Hz). The Greenwich time is noted on time axis

The changes in GAE characteristics related to the preparation of earthquakes

As a rule, considerable perturbations of the diurnal GAE distributions (DGAED) have been observed before earthquakes $M_{LH} \geq 5.0$ occurred in the area of the Kamchatkan subduction zone. Typical examples of such perturbations prior to the earthquakes are presented on Fig.3 c and Fig.4. Fig.3 c shows the disturbance of DGAED before an M_{LH}=5.2 earthquake occurred on September 1st, 2001, at 120 km distance towards northeast out of the observation point. In this case the diurnal GAE distributions which is apparent enough in the interval August 12-16st, 2001 is of distortion (up to entire disappearance) occurring from August 17-31st, 2001. Restoration of the usual DGAED takes place just after the earthquake.

Before the seismic swarm in October 2002, occurred at 170 km to the south of Petropavlovsk-Kamchatsky the DGAED disappeared seven days prior to the first shock (Fig.4). Until this moment, a steady diurnal distribution was observed during about three months. Being typical for aseismic periods, GAE day - night variations restored a day after the strongest (M_{LH} =5.7) earthquake of the swarm.

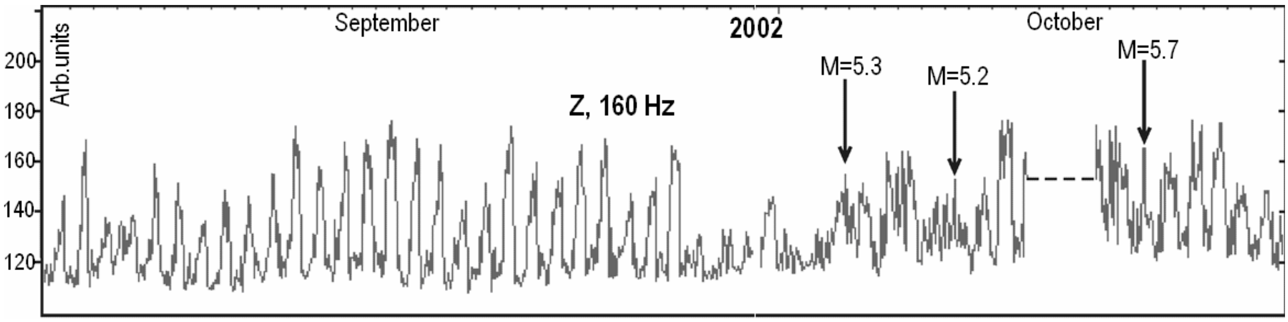

Fig. 4. Examples of loss of diurnal GAE distributions (DGAED) prior to the occurrence of earthquakes. Dashed line – data gaps.

We used for statistical analysis the catalogue of earthquakes of the Geophysical Service of the Russian Academy of Science. According to this catalog, 56 earthquakes $M_{LH}\geq 5.0$ including aftershocks of strong earthquakes occurred within 550 km in Petropavlovsk-Kamchatsky from 1.08.2000 – 31.07.2003. A subsample of 36 seismic events has been selected and used for analysis, taking into account 15 earthquakes of magnitude $M_{LH}\geq 5.0$, occurred in near-field zone (inside a circle of R≤300 km radius) and 21 earthquakes of major magnitude ($M_{LH}\geq 5.5$), with epicenters located in circular zone R≤550 km. Parameters of these earthquakes are given in Table 1 (in Appendix), and the epicenters mapping is shown on Fig 5. The strongest M_W =7.3 earthquake in the last five years, occurred on November 17th, 2002, at H = 459 km depth is also presented in Table 1. The epicenter of the earthquake was located in the Okhotsk Sea at 1000 km from the point of observation.

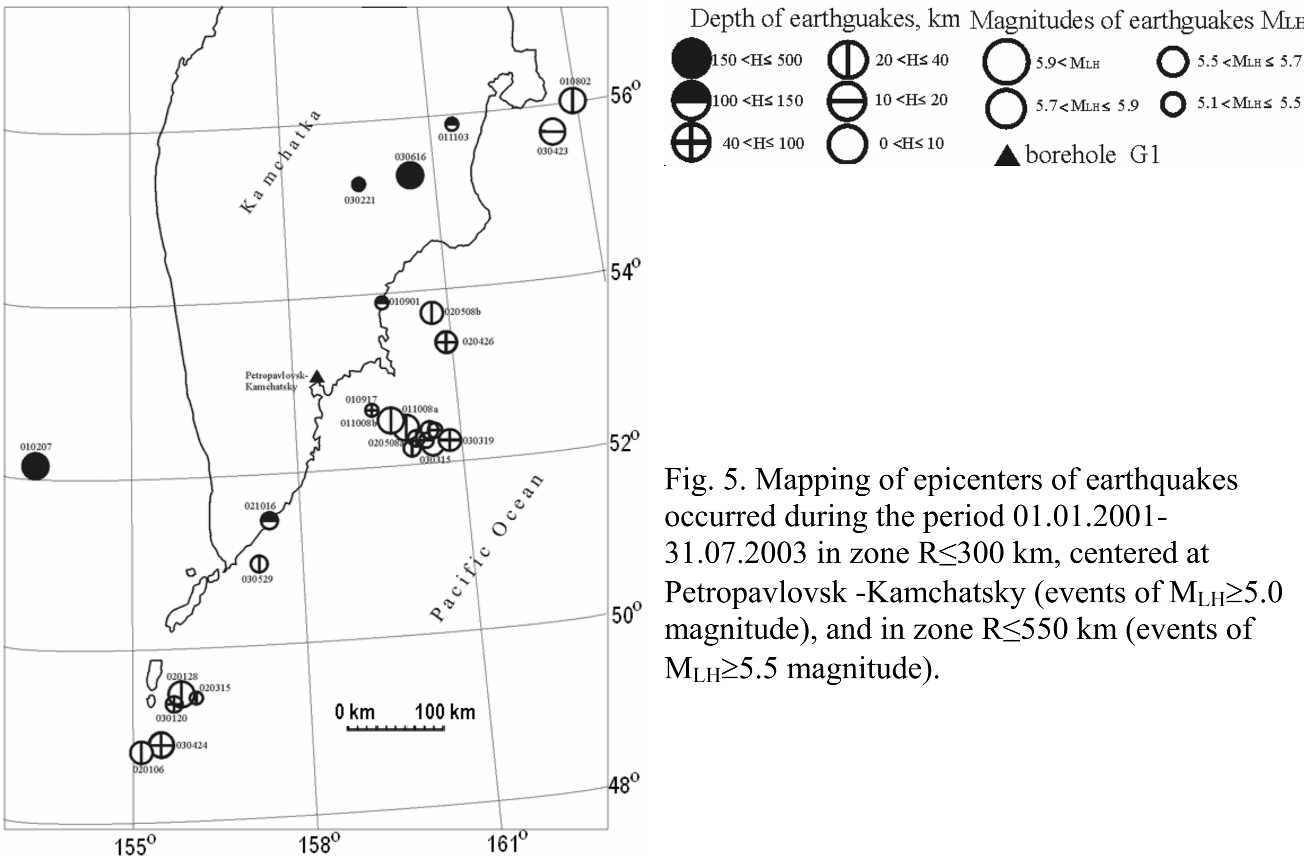

Fig. 5. Mapping of epicenters of earthquakes occurred during the period 01.01.2001-31.07.2003 in zone R≤300 km, centered at Petropavlovsk -Kamchatsky (events of $M_{LH}\geq 5.0$ magnitude), and in zone R≤550 km (events of $M_{LH}\geq 5.5$ magnitude).

The fig.6 represents schematically the results of the comparison of periods of DGAED presence or absence and instant times of occurred earthquakes. It is shown that earthquakes mostly occur during period without characteristic diurnal variations. So, the disappearance of such variations may be considered as a possible candidate to play role of short-term precursor. Below we consider the relationship between DGAED disorder/ restoration and strong earthquake occurrence.

Actually, not every episode of disorder of GAE diurnal distribution was followed by an earthquake (as it is shown on fig.6). Meanwhile, the disturbances of DGAED (full disappearance or degradation) occurred before all 15 earthquakes of magnitude $M_{LH}\geq 5.0$ inside circular zone around point of observation, of 300 km radius. Also, such disorders occurred before all 21 strong earthquakes, $M_{LH}\geq 5.5$ which epicenters located at distances less than 550 km from the geophone point. The same is valid for the case of the strongest $M_W = 7.3$ earthquake occurred on 17th, 2002 at 1000 km epicentral distance.

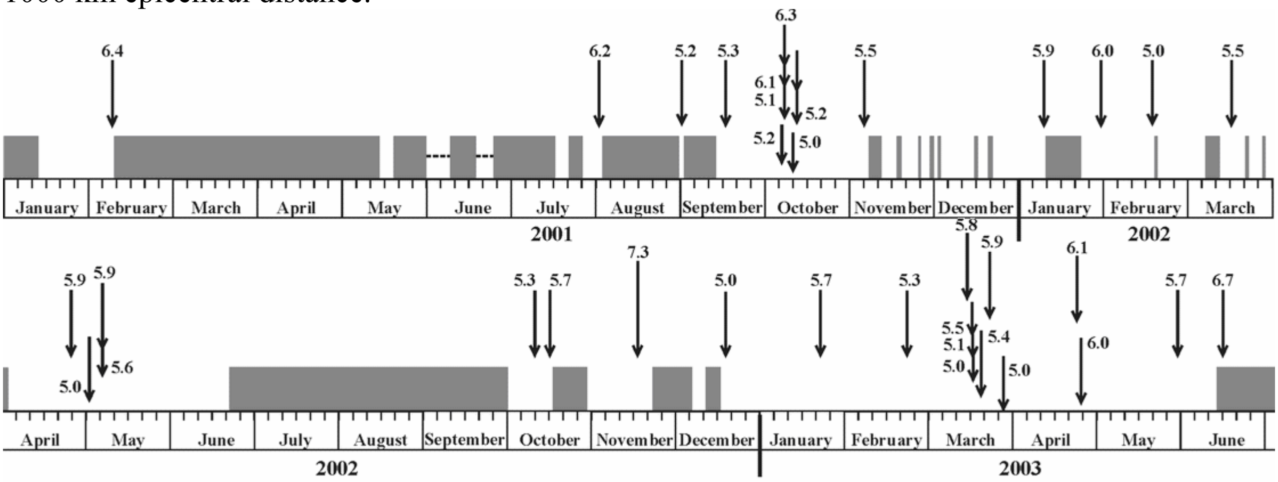

Fig. 6. The periods of presence/absence of diurnal variations of GAE versus times of major earthquakes occurrence. The earthquakes with $M_{LH}\geq 5.0$ occurred at epicentral distances of $R\leq 300$ km from the base station and the earthquakes with $M_{LH}\geq 5.5$ occurred at epicentral distances of $R\leq 550$ km. The earthquake of 17.11.2003, $M_w = 7.3$ occurred at near1000 km epicentral distance. Dark boxes - presence of characteristic DGAED, dashed line - data gaps.

So, the disorder of diurnal variation may be considered as necessary but not as sufficient condition of closing earthquake. This concerns only time of earthquake occurrence. Our measurements at the single point give no result on prediction of place of shock.

Temporal intervals from the beginning of "usual" DGAED perturbation until the moment of earthquake $M_{LH}\geq 5.0$ are in limits 1÷25 days. The relationship between noted temporal intervals and parameters of the earthquakes is still hardly debatable. This also concerns the recovery time for diurnal distribution after earthquake occurred. Restoration of DGAED after moments of earthquakes takes several days in about 30 % of all cases, but in some cases the recovery time was much greater.

It is worth to remark that we considered several of limits on magnitude M_{LH} and radius of epicentral zone R. We attempted to separate strong enough earthquakes (occurring times to be compared with presense/absence of diurnal variations) and the flow of weak and moderate seismic events. On the other hand, we need sufficient accumulation of strong events for the analysis. Enumeration of possibilities resulted in the optimal choice of above limits of magnitude M_{LH} and radius R. We selected two limiting values of M_{LH} (5.0 and 5.5) and two correspondent values of R (300 and 550 km) for the sake of strong validity of the results. Our optimal choice of M_{LH} and R limits allowed to obtain above relationship between GAE diurnal variations and seismic process in studied region. Another selection of these limits may modify the result represented on the fig.6. For example, a reducing of M_{LH} limit provided the same value of radius R entails a growth of number of earthquakes occurred on the background of GAE diurnal variations.

In one case earthquake occurred during period of diurnal distribution restoration, when the time of DGAED disappearance was over. This is not contradictory to the fact that the disappearance of DGAED preceded the occurrence of all 37 earthquakes. But we prefer to consider this debatable case as unsuccessful event.

We estimated the probability of coincidence of anomalies of GAE observations (disorder of characteristic diurnal variations) and strong earthquake occurrence with the help of probability binomial distribution technique. The binomial distribution describes the probability $P(q,n,k)$ of occurrence of k unsuccessful events in n tests on conditions that the probability of successful result of individual test is (1-q) :

$$P(q,n,k) = C^k_n (1-q)^k q^{n-k}, \qquad (4)$$

Where C^k_n is a binomial coefficient which is determined by the formula $C^k_n = n!/[\,k!(n-k)!\,]$

To use (4) we associated the number n of tests for GAE data with the number of strong earthquakes which occurred independently one of another during the time of observations. Some seismic swarms were recorded in period October, 2001 – March, 2003. Since shocks in a swarm were not independent events, we considered each swarm as a test (in the same manner as an ordinary earthquake). On account of swarms the total number of independent seismic events (tests) is n=26. Only one earthquake occurred when the characteristic diurnal variations were present (the date is 16.06.2003, see fig.6). So, k = 1 and the number of successful events is $(n - k)$ = 25. A value of probability q may be estimated as a ratio of time without GAE diurnal variations to total time of observations. In the case considered q =0,4.

The binomial distribution gives following numerical estimate of probability for noted value of parameters q,n,k: $P = 1.8 \cdot 10^{-9}$. Such value of probability is very small as compared to unity, and also in comparison with the maximum of expression (4). It is well known that the expression of binomial distribution (4) reach maximum when $q= (n-k)/n$. In our case the maximum of (4) is approximately equal to $P_{max} \approx 0.18$.

By the way, in a conditional case when all 37 earthquakes are independent, n=37, and k=1 the value of probability P for the same q is of order of 10^{-14}. So, the hypothesis is not valid, that a disorder of characteristic diurnal variations and final phase of earthquake preparation is random coincidence

Interrelation to electromagnetic measurements and laboratory results

To study correlation between DGAED and variations of averaged strength of natural electromagnetic (EM) field we carried out synchronous measurements of GAE and EM variations. The underground electric antenna has been used for measurements of vertical component of natural electric field, E_N. The perceptibility of the antenna has been reached with wire elements of more than 1 km length: free conductor of multicore cable of the geophone and borehole casing. The parameters of electromagnetic measuring channels were identical with geoacoustical ones (the only difference is in the source of signals), measurements were carried out in the same frequency bands. The measurements started in May 2003 at the same point (G-1 borehole). It is worth emphasizing that we intended to involve just electromagnetic field because of following a priori reason. It is well-known that a temporal dependence of natural electric field (vertical component E_N, in particular) has diurnal variations with nocturnal maxima and day time minima. This fact resulted from studies of characteristics of radio noise and electromagnetic waves propagation in the frequency band 30 Hz - 30 kHz [10, 11]. It is lightning discharges in remote world thunderstorms centers that are the main sources of electromagnetic waves in noted frequency band at North-Eastern part of territory of Russia [11]. The day-night variations of ultra low frequency (ULF) electromagnetic field is pre-determined by daylight sharp deterioration of radio wave propagation condition in a waveguide between ionosphere and the Earth surface primarily due to lowering of ionosphere height resulted from daylight occurrence of D-layer at near 80 km height. For Kamchatka region the ULF electromagnetic emission with explicit diurnal variations is caused mainly by lightning discharges in remote world thunderstorm center, located on azimuth 190-255 degree.

The results of simultaneous geoacoustic and electromagnetic measurements demonstrated that the variations of GAE level and electromagnetic ones were practically identical during periods when DGAED were steady. Meanwhile such periods coincided with quite aseismic times. During these periods the cross correlation coefficient ρ was of order of value ρ=0.80÷0.99. So, for instance ρ =0.91÷0.99 for interval of 9-12 April, 2004, Fig.7; ρ =0.92÷0.93 for interval of 15-17 June, 2003, Fig.8. But, before strong earthquakes (a day or more) and during relaxation periods after the events the variations of GAE and of electromagnetic field became dissimilar: ρ =0.53÷0.89 for interval of 13-19 April, 2004, Fig.7; ρ =0.001÷0.34 for interval of 28 May -09 June, 2003, Fig.8.

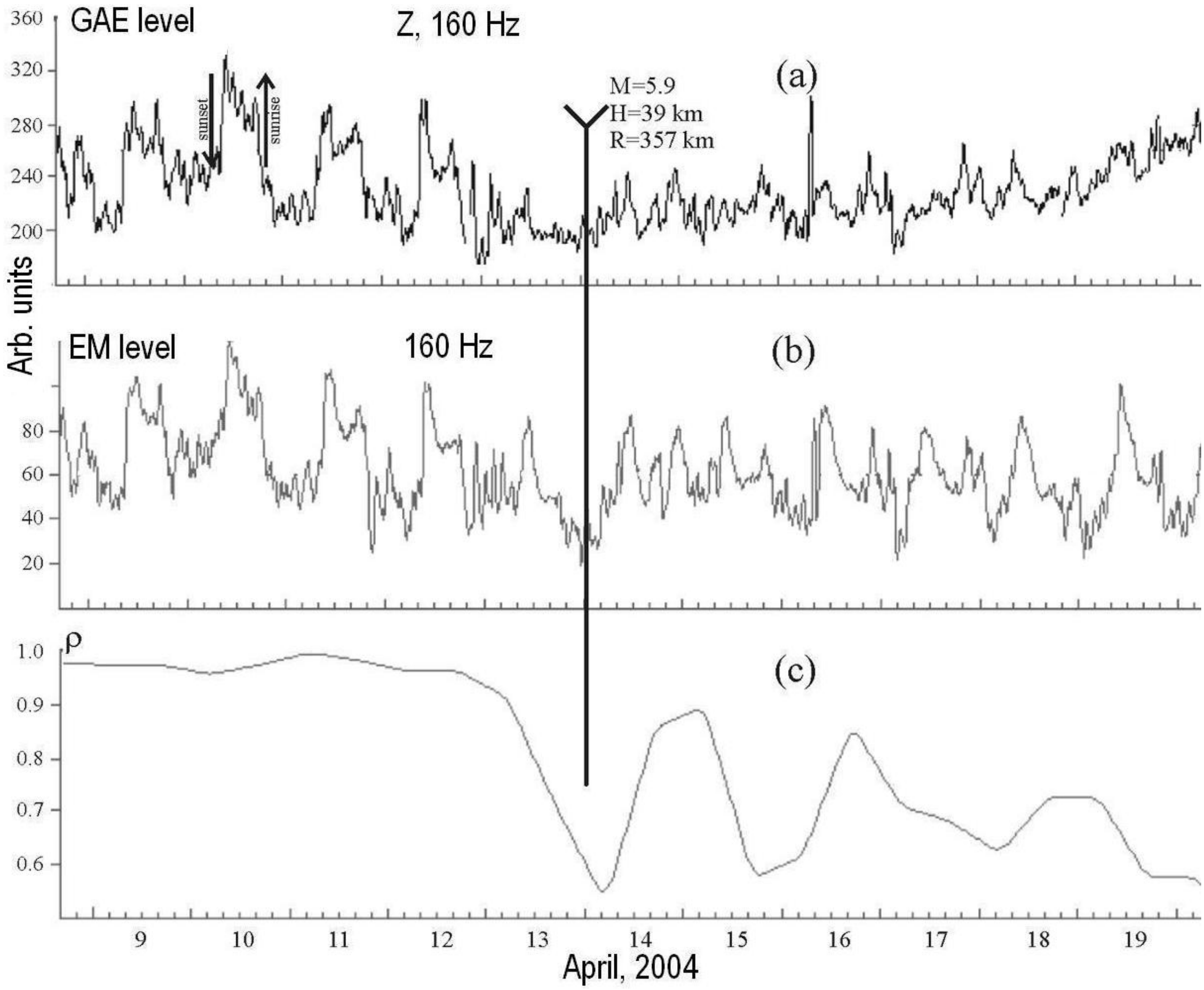

Fig. 7. Results of simultaneous measurements of geoacoustic and electromagnetic temporal variations: a- GAE level measurements at 160 Hz frequency band (Z component); b- EM field level measurements at the same frequency band; c-cross correlation coefficient ρ. The vertical line indicates earthquake moment.

High correlation of diurnal variations of GAE and electromagnetic field during aseismic period is correspondent with the result of [7] where diurnal variations of AE level on bedrocks outcroppings with maxima occurred at local nighttime (similarly to GAE, see interval of 9-12 April, 2004, Fig.7) were described.

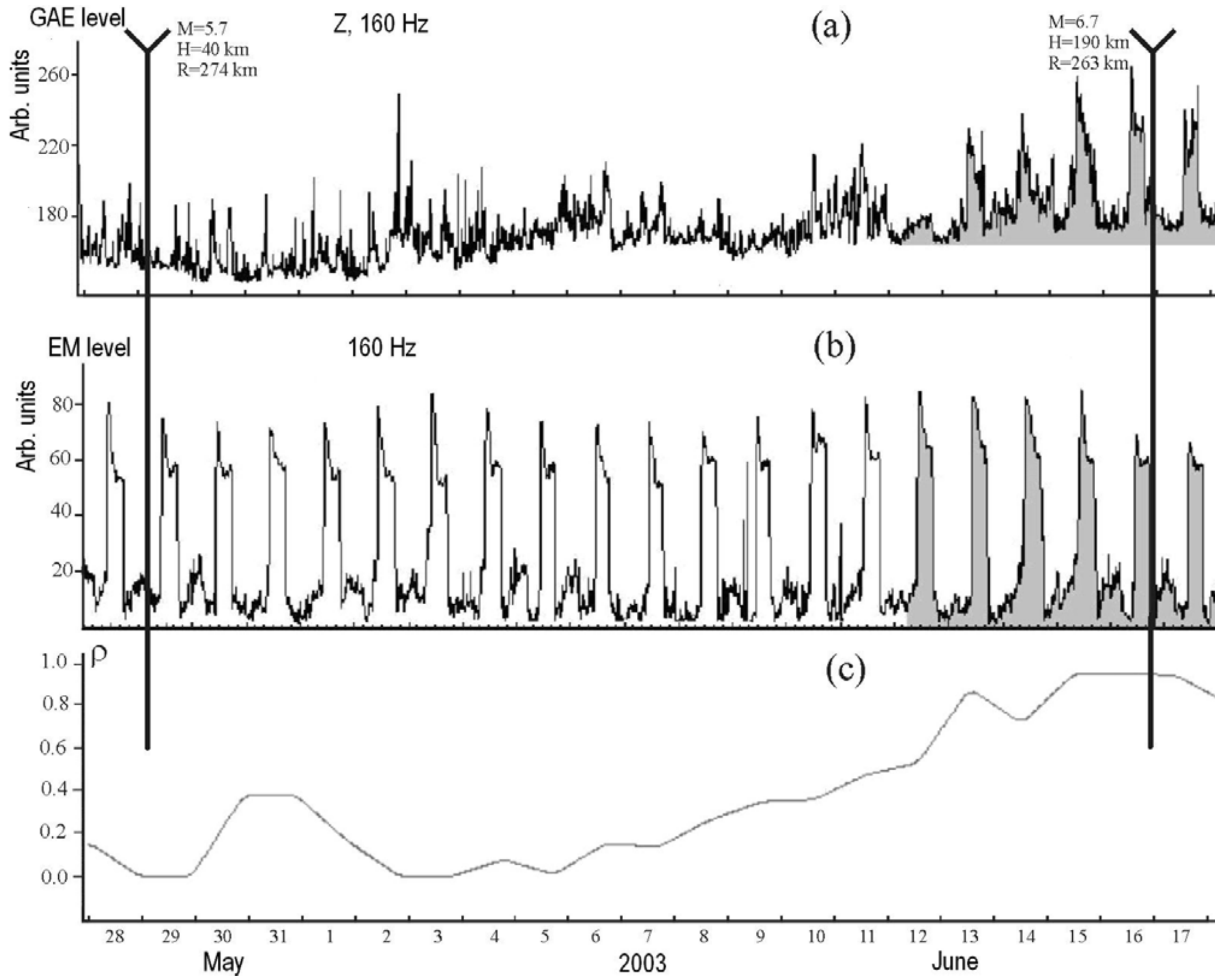

Fig. 8. An example of resumption of day- night variations of mean GAE level: a,b,c- the same as on the fig 7.

The synchronization of increase/decrease of AE and of natural telluric electromagnetic field have been remarked also. Both temporal dependences can be characterized with meander line. The similarity of daily distributions of GAE and AE which differ by frequency range and depths of sources are to speak in favour of that this phenomenon is a manifestation of behavior of the loaded geological medium. No particular factor like bias of electric induction over long cable or thermal stress near bedrocks surface due to nighttime cooling [7] is adequate for consistent explanation of those synchronized variations.

The comparison of results obtained by borehole GAE measurements with the results of laboratory experiments with loaded specimens exposed to electromagnetic field [12-14] has become to the idea of unified role of electric field for AE and GAE variations. According to the experiments referred above electromagnetic action over rocks specimens which are tested by press driven compressive loads accompanied by appreciable growth of AE activity. The main feature of revealed effect of AE electrostimulation is the temporary growth of averaged level of AE activity after short time impact or during a session with enhanced electric strength, provided that the main compressive load is constant and its value is in the range from 0.7 up to 0.95 of disruption. This is so- called AE response to electric power action, EPI, [14,15]. Heuristically, such acoustic emission response to EPI seems to look similar to the effect of nighttime GAE level growth correlated to nocturnal enhancement of electric field level (the more value of natural electric field strength the more level of GAE in the same frequency band). Our approach to unified consideration of laboratory and full-scale survey results is based on the similarity of stressed state of embedded rocks and laboratory tested ones. Actually, AE responses were recorded on specimens when the main compression stress was in the range 20 - 100 MPa. A tectonic stress at nearly one km depth is of the same order of value [16].

But a difficult point for the hypothesis of electric stimulation of nighttime GAE level (resulting in the modulation) arises during quantitative estimates of strength of natural electric field and that applied in laboratories. Quantitative estimates to analyze the observed modulation of GAE level by natural electromagnetic emission of the Earth are as follows. According to reference [11] the maximal value of electric component of the EM field measured on Earth surface, over the whole frequency band may be evaluated as 0.45÷1.0 mV/m. The damping of electric component at 1 km depth, calculated for 160 Hz and the soil of moderate moisture (the conductivity is about $\sigma = 0.01$ $(\text{Ohm}\cdot\text{m})^{-1}$) is near 9 db. Hence, the amplitude of electric field strength at the depth of geophone location can not exceed 0.16÷0.36 mV/m.

Meanwhile, according to the data of laboratory experiments [12, 13] electric pulses to trigger AE activation are of strength amplitude $E_N \sim 800 \div 1600$ V/m. So, the level of strength of electric field acting on rocks embedded at nearly one km depth is at least 6 orders of magnitude less than that of the field influencing the specimens during laboratory tests. To continue discussion of AE/GAE scaling and relation to electric field of high or weak strength one need more information on experimental conditions under which the AE responses to EM pulses are evident. The newest results on sensitivity of rocks specimens to electric pulses are relevant to the discussion as well.

Towards physical modeling of GAE modulation and electric action.

On previous experiments to study triggering effect of EM field pulses researchers applied to a specimen rather strong electric pulses [13-15, 17,18]. Among the referred experiments some modeling works were performed at Research Station of Russian Academy of Sciences, RS RAS, in Bishkek city (formerly IVTAN, Institute for High Temperatures) with the aim to simulate the effect of powerful electromagnetic discharges (pulses of a geophysical magneto-hydro-dynamic generator, MHD) on spatio- temporal redistribution of microseismicity in the Bishkek test area [Tarasov et al., 1999]. The application of strong pulses simulating full-scale EPI was justified by this intention. Besides, the amplitude of electric strength multiply exceeded that of stray field inevitably induced at a laboratory. But the ponderomotive force associated with such pulses was still negligible in comparison with the main compression load (the ratio was of order of 10^{-7}, as noted in [15]). This technique allowed distinguishing the solitary response of AE (specific reaction of tested material) from spontaneous spikes of AE occurring even at constant load.

Motivated in part by considerations on kinetic process of inelastic straining and microcracking (and consequently relationship between AE and EM field), we performed in 2007 new experiments on rocks specimen. This time the experimental task was to establish presence or absence of AE variation of loaded rocks during action of electric pulses of reduced amplitude (less than E_N in previous experiments). This may be relevant to physical modeling of observed GAE variations. We used the same experimental technique for rocks specimens test and the same measuring system as in previous experiments conducted as Bishkek Research Station of RAS. As before, experiments to study aforesaid interrelation of electromagnetic and acoustic emission effects involved the specimen test by fixed compressive load and additional electric supply. AE signals were recorded on wide frequency region 80 kHz -2 MHz with the help of measuring AE channels. Each channel included noise-immune sensor (SE2MEG, DECI Inc., USA), preliminary and main amplifiers and ADC. The sensitivity of the AE channel was of order of $k_{A,P} = 0.7 \cdot 10^{-5}$ V /Pa (it was approximately estimated as a product of sensitivity of used SE2MEG sensor by magnification factor of the apparatus). Experimental set up was described in details in [13,14].

The only modification was in software. For recent experimental campaign we developed a new program of AE signals filtering with the help of third octave band pass numerical filter. The idea was to make AE data processing in the same manner as that of geophone measurements (see section 2). We obtained temporal dependences (plots) of averaged AE amplitude in the band with 100 kHz central frequency. During last experimental series we tested 5 intact samples (granodiorite-1, granite-2, gabbro -1, and rock salt- 1). First of all we verified on recent experiments that the growth of averaged AE amplitude (at 100 kHz frequency band) correlated to increment of AE activity. This included the cases when activation was triggered by electric pulses. So, we can restate the results of our previous works in the following equivalent form: the growth of "AE level" due to electric influence occurs when the fixed compressive load over tested rock specimen is from 0,75 to 0,95 of maximal value (fracture of given specimen). The change in strain components during triggered activation is under 10^{-5}.

New filtering software improved signal to noise ratio in the experiments and allowed continuous AE recording (no interference affected the result, even in moments of electric source power on/off). This was used for next stage of simulation of electric influence over GAE. The approach involved multifold periodic power action. In more details, intervals of electric action of 150-180 s length were alternated with the same duration intervals without electric supply and vice versa. During each interval of electric action the G5-54 generator supplied the specimen by square waveform pulses of 5-15 V amplitude, 4 mcs duration, and 50 kHz frequency. In certain respects such regime of electric action on a specimen may be similar to repeated, everyday effect of natural electromagnetic field variations. Particularly, a pulse of G5-54 generator seemed to play role of a signal from thunderstorm on real space-time scale.

We conducted two sessions with periodic power on/off during granite specimen test by a noiseless press; the main load was being 0.9 of maximal. The total length of the sessions was 1.5 hours. The amplitude of applied electric pulses was of reduced value (3.5-10 times less) in comparison with that of previous, "uniform" sessions with G5-54 generator. Fig. 9 has demonstrated the temporal plot of AE activity during the sessions with "alternated EPI". Increments of AE activity were recorded in these experimental sessions as the responses to electric field pulses of strength amplitude 100 – 300 V/m (correspondent with noted generator voltage). Previously, during sessions with uniform electric pulse sequence, we observed AE responses of this material under the same load provided the strength of electric field was over 500 V/m. As noted in the paper the value of electric strength reaches 800 -1600 V/m, for the pulses giving rise to AE activation. So, the experimental sessions demonstrated that effective regimes of electric action are possible, and electric field pulses of reduced strength may result in AE variations.

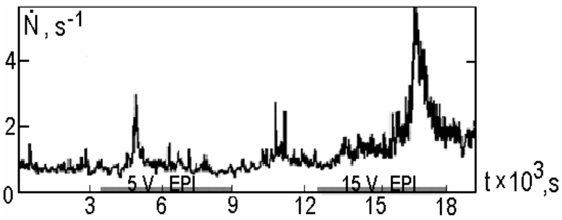

Fig. 9. Temporal plot of AE activity of fine-grained granite specimen during electric action in alternated regime. The loading coefficient is k=0,9. Electric supply is square pulses produced by G5-54 generator, E_N amplitude is nearly 100 V/m (in first EPI session), and E_N = 300 V/m (in the second). Times of electric action are noted by a bar

In a real crust GAE should be much more sensitive to electric actions because of electrokinetical phenomena (the water is present inside pore-fissure space). But the main factor influencing various modes of acoustic- electric correlation on natural and laboratory scales is the difference in sensitivity of measuring channels for GAE (borehole) and AE (specimens). Let us compare these parameters expressed in the same units. As remarked above in the section 2 the sensitivity of geophone vertical channel with respect to third derivative of displacement is equal to $k_{G,3}$ = 0.15 V· s^3/m. Considering the frequency band around central frequency f= 160 Hz , one can re-calculate the velocity sensitivity. It is equal to $k_{G,V} = k_{G,3} \times (2\,\pi\, f)^2 = 1.5\ 10^5$ V· s/m. As regards sensitivity of the AE channel used in the laboratory experiments, it is calibrated to pressure oscillations, $k_{A,P}$ =0.7 ·10^{-5} V/ Pa. A proper way to derive the sensitivity of AE channel with respect to velocity is using the well-known formula for pressure perturbation Δp in propagating acoustic waves $\Delta p = \rho\, c\, v$, where ρ is a density, **c**- velocity of body waves, v- perturbed velocity. Taking typical values of rocks specimens parameters (granite, marble etc) ρ~ 2.2 10^3 kg/m^3; c ~ 4 10^3 m/s, we obtain $k_{A,V} = k_{A,P} \times \rho\, c$ = 60 V· s/m. This is 2500 times less than the sensitivity of geophone channel. But such sensitivity is of typical order of magnitude for wide-band acoustic emission apparatus, AE based systems for nondestructive check etc. Naturally, the extension of width of frequency band in AE measurements up to 2 MHz (2000 times more in comparison with nearly 1 kHz range of GAE frequencies) involves a sensitivity drop of the same order of value.

The effect of electric activation of AE of rocks specimen has been established with the help of AE channel with such (moderate) sensitivity [12,13]. Only microcracks of appreciable length (tens microns or more) contributed to recorded responses of AE activity to electric pulses. The experience of studies of cracking and solid's fracture speaks in favour of self-similarity concept validity. Processes in major zones are similar to those in minor domains. The behavior of longer (but subcritical) and shorter cracks should be similar. The growth of small cracks of near micron range is also influenced by electric pulses. Before, its signature in AE data was never resolved (noisy experimental conditions, insufficient sensitivity of AE channels). The technique developed for deep borehole measurements with the geophone allows high sensitivity [3, 8]. Clearly, a density of smaller cracks (source-sites of GAE and AE) exceeds considerably that of larger cracks. Moreover, the volume of GAE data acquisition by sensitive geophone is several orders more than typical volume of laboratory tested specimen. So, there are favorable conditions to detect GAE variations related to sought-for electric action. The correlation has been found, between temporal variations of GAE and natural electric in ULF range (see section 3). We can conclude that the topical results of field and laboratory measurements are in agreement providing that the mechanism of electric stimulation is kinetic (this means: the more electric strength E_N, the more reaction of GAE; and also the more sources interacting with E_N, the more activation).

It should be noted that deep borehole measurements with high sensitivity geophone highlighted a new mode of electromagnetic effect which can be characterized by phase synchronization of GAE and electric strength variations rather than one-fold triggered growth of emission after electric impact [14, 20]. The existence of this mode may be in a reasonable agreement with a tendency of slip synchronization that is reported by [21]. From the physical viewpoint the cause of both manifestations of electromagnetic effect is unified, it is related primarily to microcracking activation/retardation.

Finally we remark that the disappearance of DGAED before strong earthquakes and its subsequent recovery may be related to a change in sensitivity of the geological medium for electromagnetic modulation. Changes in such parameters as crack opening displacement and medium permeability (indirectly depending on the slightest variation of stressed-strained state, and controlling the water filtration) are to become more influential for GAE level than electromagnetic action. Obviously, this can take place shortly before earthquake in a precursory area (as described by a scenario of dilatant - diffusive model), and after seismic event. But this aspect is beyond the possibility of discussed modeling experiments that involves rocks specimens test by constant value compression.

Summary

Continuous geoacoustic measurements in deep boreholes with high-sensitivity geophones are an effective method of monitoring of the stressed-strained state of the geological medium. Deepening of the geophone at 1000 m depth in borehole at Petropavlovsk-Kamchatsky has allowed to reduce the level of man-caused noise on two orders of value in the band of 30 Hz central frequency, and reduce it almost by an order of magnitude in the 160 Hz band. Moreover, such deepening has practically eliminated the bias of meteorological factors on measurements of vertical component of GAE signals. GAE measurements with the help of geophone have revealed diurnal temporal distribution of GAE level in bands with central frequencies 30 and 160 Hz. Diurnal distribution of GAE is presumably related to daily variations of the level of electromagnetic field strength in Earth crust. The loss of geoacoustic day-night variations shortly before any strong enough earthquake appears to occur simultaneously with pre-seismic changes in stressed-strained state of the geological medium (final phase of earthquake preparation).

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Appendix: Table 1.

Earthquake's parameters, date 2001.01.01-2003.07.31, location R≤300 km, M_{LH}≥5.0; location R≤550km, M_{LH}≥5.5; location R≤1000 km, M_W>7.0. **Note**: H- earthquake depth; R- distance from epicenter to borehole G1.

Earthquake No	Date	M_{LH}	Lat.N	Long.E	H, km	R, km
010207	2001:02:07	6.4	52,28	153,66	476	346
010802	2001:08:02	6.2	56,21	164,05	25	495
010901	2001:09:01	5.2	53,92	159,75	134	120
010917	2001:09:17	5.3	52,84	159,98	41	191
011007	2001:10:07	5.2	52,39	160,67	2	153
011008a	2001:10:08	6,1	52,62	160,46	31	129
011008b	2001:10:08	6.3	52,65	160,49	24	130
011008c	2001:10:08	5.1	52,5	160,59	15	142
011009	2001:10:09	5.0	52,43	160,59	18	146
011010a	2001:10:10	5.5	52,51	160,57	17	141
011010b	2001:10:10	5.2	52,46	160,72	8	152
011103	2001:11:03	5.5	55,93	161,35	104	366
020106	2002:01:06	5.9	48,67	155,09	40	543
020128	2002:01:28	6.0	49,29	155,98	21	454
020215	2002:02:15	5.0	52.12	159,89	18	130
020315	2002:03:15	5.5	49,44	155,96	21	439
020426	2002:04:26	5.9	53,36	160,99	57	160
020503	2002:05:03	5.0	52,49	160,79	20	155
020508a	2002:05:08	5.6	52,22	160,44	32	150
020508b	2002:05:08	5.9	53,73	160,93	35	170
021008	2002:10:08	5.3	52,72	160,30	33	115
021016	2002:10:16	5.7	51,66	157,68	108	165
	2002:11:17	M_W= 7.3	47.82	146.21	459	1050
021218	2002:12:18	5.0	52,91	159,82	40	79
030120	2003:01:20	5.7	49,06	155,88	54	480
030221	2003:02:21	5.3	55,45	159,79	349	279
030315	2003:03:15	5.8	52,15	160,66	4	166
030317a	2003:03:17	5.0	52,25	160,58	13	155
030317b	2003:03:17	5.1	52,09	160,72	13	174
030317c	2003:03:17	5.5	52,26	160,54	32	153
030318	2003:03:18	5.4	52,23	160,61	15	159
030319	2003:03:19	5.9	52,16	160,85	48	176
030325	2003:03:25	5.0	52,02	160,70	40	178
030423	2003:04:23	6.1	55,98	163,44	20	450
030424	2003:04:24	6.0	48,76	155,21	42	531
030529	2003:05:29	5.7	50,65	157,53	40	274
030616	2003:06:16	6.7	55,3	160,74	190	263