Bulgarian Academy of Sciences. Space Research Institute
Aerospace Research in Bulgaria. 17. 2003. Sofia

ON THE SEISMIC SOURCE MECHANISM OF ELECTRIC SIGNALS

*Petko Nenovski, Boytcho Boytchev**

Geophysical Institute-Bulgarian Academy of Sciences
**Space Research Institute-Bulgarian Academy of Sciences*

Abstract

We propose a seismic electric signals (SES) model related to the charge and current production associated with a discharge process occurring in the microcrack void. The electric field is intensified until a discharge process is initiated. A current j is spread in the microcrack surroundings which follows the electric field build-up process and its cancellation. The spatial and temporal distribution of the electric field related to the current j in the microcrack void. The field is controlled by the aggregation mechanism, the discharge, and the geophysical properties of the void.

1. Introduction

The bursts of ULF and concomitant electromagnetic emissions registered before and after great earthquakes are a form of electromagnetic events connected with seismic processes. [1, 2, 3, 4] have tried to explain these electromagnetic emissions by oscillating electric dipoles. The seismic electric signals (SES) [5] are another form of electromagnetic events associated with lithospheric processes. The SES are aperiodic and their duration is from several minutes to several hours [6]. The registered SES [7,8] usually have characteristic bay-like, or bell-shaped curves of variable width and duration. Experimental data on repetitive SES signals of pulse form with nearly 24 h periodicity occurring a couple of days before the earthquake has been reported, as well as [9, 10, 2, 8] have proposed the micro-crack model of charge production and associated current connected with the micro-crack growth. They succeeded to derive the long-term evolution of the magnitude of the ULF emission prior to the earthquake. This model provides a qualitative estimate of the experimental evidence for consecutive increases and decreases of the intensity of ULF emission before the Loma-Prieta eathquake [1]. The currents connected with an ensemble of micro-cracks and the relation between the growth of their size and the current density seem to be promising mechanism of ULF emission. Molchanov and Hayakawa's model does not treat seismic electric signals (SES), although they appear to be also ULF emission. The SES duration lasts from several minutes to several hours [6]. The SES mechanism is believed to be connected with electrokinetic effects [11, 12]. The latter are highly damped while the SES signals are recorded at large distances. There are several mechanisms of charge production. The piezoelectric mechanism of charge production proposed by [13] yields polarization electric field E_c of 2×10^8 V/m for stress changes δS of 200 Bar under crystal conditions [3]. Here, the electric field E_c emerges in the void space of the micro-cracks. The process of an increase of the electric filed will however be limited because of the enormous electric fields produced within the void space formed between separated charges. In the presence of enormous electric fields, a process like the anomalous glow discharges is possible. The magnitude of the initial electric field for the discharge process depends on the crust material conditions. The discharge process could be initiated by a gas release in the void regions provoking an ionization that produces free charges. In such discharges, the produced cathode currents reach $10 \div 10^2$ A/m^2. The discharge will stop when the dipole-like electric field within the separated charges is cancelled and the ionization process becomes impossible. A widely assumed model is that the source of these SES are charges that emerge during microcrack generation. Czechovski [14] used a kinetic point of view and obtained a kinetic equation of the microphysics of cracks. By exploiting kinetic and qualitative models of crack interaction and propagation, Tzanis et al. [15] pointed out theoretically that the seismic electric signals (SES) may have a limited class of permissible waveforms of arbitrary width, or duration. On the other hand, laboratory experiments of electrification processes caused by microcracks have revealed not only charge production, but also current spikes. With crack opening times of the order of 10^{-6} s every individual microcrack yields current spikes of the order of 10-3 A/m^2. Transient and electromagnetic emissions associated with the microcracks have also been observed [16, 13]. Since the current spikes are presumably due to microcracks, various important physical characteristics of the microcrack processes are to be sought, the major ones being crack population production rate and their growth with time. We assume that the random aggregation process with an injection is a source of charges and/or currents and could be applied for both the accumulation of pressure and strain at some place and time. The currents connected with an ensemble of microcracks and the relation between the growth of their size and the current density seem to be a promising mechanism of ULF emission. In our paper, we assume current production (associated with a random aggregation mechanism of the microcracks) as a primary source of the observed SES signal and probably of some ULF electromagnetic emissions. These signals would be controlled by the electrodynamical conditions of the crust material away from the current source.

2. Random aaggregation model of charge production

First, let us mention that there are experimental evidences for micro-cracks behavior under stress conditions. A lot of laboratory experiments show that micro-cracks pass through several stages: i) at some pressure level, an initial stage of micro-cracks emerges, under which the micro-cracks are randomly distributed; ii) at the second stage, which appears at some intermediate values of the pressure, the micro-cracks tend to concentrate at a certain point, thus increasing their density, or population; iii) at some critical pressure value, the micro-cracks evolve in a fracture of example [17]. Second, under natural conditions the physics of micro-cracks is unknown, but we tentatively assume that the micro-crack dynamic behavior illustrates the spatial and temporal changes in the tectonic pressure, strain and stress prior to earthquake. Third, the primary sources of charge/current production in both cases are the stress and/or pressure changes. For a simulation of constantly increasing 'tectonic' driving forces, a two-dimensional array of particles, representing segments of the sliding surface has been considered [18]. In our study, the tectonic driving forces as a common source of charge/current production are suggested to be identical to the random aggregation model [19]. Below, we summarize briefly the major steps of this model.

According to the model we assume an ensemble of 'particles' with integer 'mass'. The particles could correspond to micro-cracks with certain length. In order to obtain the micro-cracks distribution we assume all the micro-cracks of identical geometry. The crust is considered to be a one-dimensional 'lattice'. We have discrete time steps for the 'mass' $S(n)$ at a certain nod of this lattice, where n is the number of the step, S could corresponds to the micro-crack density. Assuming a certain random process, the following stochastic equation for $S(n)$ holds [20]:

(1) $$S_i(n+1) = \Sigma W_{ij}(n)S_j(n) + 1,$$

where $S_i(n)$ is the density of the micro-crack on the i-th site at time n; $W_{ij}(n)$ is a random variable given by $W_{ij}(n) = 1$ with probability $q(i-j)$, or 0 with probability $1-q(i-j)$. As follows $\Sigma W_{ij}(n) = 1$ and $\Sigma q(i) = 1$. We consider the case with $q(i-j)$ of 1/2 for $i-j = 0$, or 1 and $q(i-j) = 0$ otherwise. The initial condition accordingly reads: $S_i(0) = 1$. We need to define the probability $p(s,n)$ and the cumulative distribution $P(\geq s)$ given by:

(2) $$p(s,n)ds = N^{-1}\Sigma\int_s^{s+ds} ds'\delta(S_i(n)-s'),$$

where N is the total number of sites and:

(3) $$P(\geq s) \equiv \int_s^{\infty} p(s')ds'.$$

We define a characteristic function

(4) $$Z(\rho,n) \equiv \langle e^{-\rho s}\rangle = \sum e^{-\rho s}p(s,n).$$

Here <...> denotes the average taken over the stochastic variables $W_{ij}(m)$, $m = 0,1,\ldots, n-1$. Functions for the density Z at $i_1,i_2,\ldots i_r$ and for r-adjacent sites are determined as follows:

(5) $$Z_r(\rho,n;\, i_1,i_2,\ldots i_r) \leq \langle e^{-\rho(S_{i1}+S_{i2}+\ldots+S_{ir})}\rangle,$$

and

(6) $$Z_r(\rho,n) = \langle e^{-\rho(S_{i1}+S_{i+1}+\ldots+S_{i+r-1})}\rangle,$$

This process is named Sheidegger rivers [21]. Qualitatively, it represent a process of production of macroscopic water mark formed along some tilted plane on which initial droplets of rainfall are consecutively accumulated at certain points into greater drops, which suddenly burst into smallerr streamlets breaking trails for the water downwards. The effective interaction forces are gravity and surface tension. We assume that the process of fractures during an earthquake is the final stage of similar processes. The micro-cracks gathered at certain points will break into a macro-crack. The interaction forces under the earthquake process are the pressures and the strength, or solidity of the lithosphere material. From (5) and (6) it follows that the distribution functions of energy release stimulated by the above-mentioned aggregation process have power law form. It is worth noting that, modelling segments of a sliding surface as two-dimensional arrays of particles [18] has yielded a similar power law distribution.

Without quoting all the steps of the aggregate model we shall mention only that the number n corresponds to time t and r (site) - to a one-dimensional spatial coordinate, e.g. x. It is noteworthy to mention that the density of micro-cracks is given by the number of connected lattice sites which constitute a river-like cluster in (1+1) dimensional space-time. In the limit $n \to \infty$, the characteristic function $Z_r(\rho,n)$ tends to $Z_r(\rho,n)$ with the following relationship:

(7) $$Z_{r+1}(\rho)+(2-4e^{r\rho})\, Z_r(\rho)+ Z_{r-1}(\rho,n) =0$$

It corresponds to steady-state condition. In the most important case of time-dependent condition, the following relationship holds:

(8) $$Z_r\,(\rho,\, n+1)=e^{-\rho r}\,[Z_{r+1}(\rho,n)+ 2Z_r(\rho,n)+ Z_{r-1}(\rho,n)]/4$$

In a system with continuous time and spatial coordinates the above equation has its counterpart:

(9) $$\partial Z/\partial t = (D/2)\partial^2 Z/\partial x^2 - \rho x Z,$$

where diffusion rate D and background 'particle' (microcrack) production ρ are determined from the physical characteristics of the crust material and the driving forces. The first term in the right-hand side results from the effect of aggregation due to the short-range interaction, while the second term results from the uniform input of new microcracks. The distribution $Z(x,t)$ is expected to be a source of charges and/or currents.

Several authors have involved discharge mechanisms of free charges to examine processes of electrification of gases trapped in rock pores [22,16]. The magnitudes of the discharge electric fields and currents can be compared with the charge production and the currents magnitudes observed under microcracks conditions. The charge density measured in microcracks amounts to $q = 10^{-3}$ C/m2 [23, 22]. Since any fluctuations of free charges generated in rock specimen should disappear after a time $\tau \approx 10^{-5} \div 10^{-7}$ s, the magnitude of the current spikes j ($j = q/\tau$) is $10^2 \div 10^4$ A/m^2. Such currents of $10^2 \div 10^4$ A/m^2 detected from rock specimen even exceed the currents flowing in glow discharges and are comparable with those of arcs. The orders of current magnitudes are suggestive for some forms of discharges involved in the microcrack physics. Hence, it is quite reasonable to suggest that the electric field build-up will stop at time t_0. Such a characteristic time exists even assuming another mechanism for charge production, e.g. mechanical one connected with the microcrack growth [10]. A process of gas release is expected in the microcrack void. In the presence of electric fields of sufficient magnitude the gas is ionizable. During such a discharge process, the charges accumulated at individual microcrack boundaries are effectively exhausted. Thus, electric field of 10^4 V/m or more is easily reduced to nearly zero magnitudes by, for example, an anomalous low-pressure discharge process [24]. The currents $j_0(x,t)$ that emerge will flow in the surroundings with certain velocity v determined by the state of the crust material around the source. Electric fields depending on the crust conductivity are induced as well. The source for the electric field is then $dj_0(t,x)/dt$. The current production due to the aggregation mechanism of microcracks could however continue irrespectively of any process of electric charge discharge. In general, growth time t_0 depends on the possible rates of gas release and the properties of the aggregation mechanism. We assume that microcrack distribution Z(x,t) is a measure of the current rate source. Therefore, assuming that current density rate is proportional to distribution Z(x,t) we have

(10) $$\partial\rho_0/\partial t \cong a\, Z(x,t),$$

where a is a constant. The electric current density rate $\partial j_0(x,t)/\partial t$ is connected to the particle density distribution rate by the relation $\partial j_0(x,t)/\partial t = v\partial\rho_0/\partial t$, where v is the charge velocity. The latter is considered to be nearly constant for the crust material under the stress action. Therefore, the time evolution of the SES is determined from the competitive action of the charge/current aggregation rate given by (9) and the dissipative effect of the crust material between the source and the measurement point. The electric field generated by the currents produced at some area ($-x_0 < x < x_0$) and time t is determined by

(11) $$(\Delta - \partial^2/\partial t^2 - \mu_0\sigma_{crust}\partial/\partial t)E = \mu_0\, \partial j_0\,(t, x)/\partial t,$$

where Δ is Laplace's operator, z is the propagation direction of the electromagnetic disturbances generated by transient current $j_0(x,t)$ localized in x direction, where

(12) $$\partial j_0(x,t)/\partial t \;\cong v\partial\rho_0(x,t)/\partial t \propto Z(x,t\,) = \sqrt{(1/t)}\exp(-x\,^2/2Dt) + O(\rho),$$
$t \leq t_0$

Here, v is the velocity magnitude of the charges that spread through the surrounding in the form of current; O (ρ) is a small term proportional to $\rho(\rho << 1)$. Fig. 1 illustrates the time envelope of microcrack production associated with the random aggregation mechanism of stress, or strain forces. The current density shape with time depends strongly on the magnitude of the diffusion coefficient D. Let us study the propagation characteristics of the electromagnetic disturbances generated by transient current $j_0(t,x)$ localized in time and x direction. For convenience we will study the potential behavior along the z axis. Hence, we examine only solutions around x = 0, where $x<<z$.

(13) $$(\partial^2/\partial z^2 - \mu_0\varepsilon_0\partial^2/\partial t^2 - \mu_0\sigma_{crust}\partial/\partial t)E = \mu_0\,(va)Z(x,t),$$

Thus, the equation resembles the telegraph equation of transmission line of conductivity σ_{crust}, where inductance L and capacity C stand for permeability μ_0 and the permitivity ε_0 [25]. This equation will account for the SES generation from a microcrack source Z(x,t) and propagation effects in one direction, z. The induced electric field magnitude is determined from the current production magnitude of $j_0(t,x)$, i.e. a. Equation (13) is solved in a straightforward way. The solution reads:

(14) $E(x,t;k) = \mu_0(va)/2[\exp(\gamma t)\int Z(x,t)\exp(-\gamma t)dt + \exp(-\gamma t)\int Z(x,t)\exp(\gamma t)dt]$,

where the characteristic time γ is given by

(15) $\gamma = -\sigma_{crust}/2\varepsilon_0 (1 - \surd(1 - 4k^2\varepsilon_0/\mu_0\sigma_{crust}^2))$,

and k is the wavenumber of the ULF disturbance spectrum assumed to propagate along z. In the case of sufficiently small wavenumbers, i.e.:

(16) $k << \mu_0\sigma_{crust}/2$,

we obtain:

(17) $\gamma \cong -k^2/\mu_0\sigma_{crust}$

The characteristic time γ has real values for $\mu_0\sigma_{crust} > 2k$ and it is a complex quantity for $\mu_0\sigma_{crust} < 2k$. In the latter case, we have ULF events with frequency ω:

(18) $\omega = \surd(k^2c^2 - \mu_0^2\sigma_{crust}^2/4)$

and damping rate:

(19) $\gamma_p = -\mu_0\sigma_{crust}/2$.

Fig. 2 illustrates the behavior of both quantities, γ and the frequency ω. It follows that there are two different regions of ULF disturbances: i) first, a region of only aperiodic ULF disturbances where $2k/\mu_0\sigma_{crust} < 1$; ii) second, a region of damped electromagnetic waves of frequency ω and damping rate γ_p where $2k/\mu_0\sigma_{crust} > 1$. It follows that periodic solutions exist at shorter spatial scales and/or smaller conductivities σ_{crust}. The crucial parameter is the wavenumber k. The main constraints for the spatial scales ($\sim 2\pi/k$) come from the microcrack source size and its depth. The former is to be related to the spatial spectrum of the current source $\mathbf{j}_0(x,t)$. The source depth determines the characteristic size of the electromagnetic field localization. For example, if the source depth is 10 km, the upper frequency of the ULF/ELF/VLF signal is about 10 kHz. The spatial spectrum is limited by the size of the fracture event that follows microcrack growth.

Let us examine the case of aperiodic ULF disturbances. For convenience, we shall neglect the displacement current, it corresponds to the assumption that the velocity of light c goes to infinity. Then, the basic equation yields only aperiodic solutions. Eq. (13) possesses a general solution in the form (provided that $c \to \infty$):

(20) $E(x,t;k) = \mu_0(va)(1/\surd t)\exp(-z^2\mu_0\sigma_{crust}/4t)\int \exp(z^2\mu_0\sigma_{crust}/4t - x^2/2Dt)dt$

Using an expression for the integrand we arrive to the following analytical expression for E(x,z;t):

$$E(x,z;t) = \mu_0(va)(pE_1(p/\tau_0) + \tau_0 \exp(-p/\tau_0)t^{-1/2}\exp(-z^2\mu_0\sigma_{crust}/4t)), \quad t > t_0 \quad (21)$$

$$E(x,z;t) = \mu_0(va)(pE_1(p/t)/\sqrt{t} + \sqrt{t}\exp(-p/t))\exp(-z^2\mu_0\sigma_{crust}/4t)), \quad t \le t_0$$

where $p = x^2/2D - z^2\mu_0\sigma_{crust}/4$, and $E_1(p/t)$ is the elliptical integral [26]. The principal contribution comes from the first term. An examination of (14) shows that the SES forms are determined from the parameters D and $\mu_0\sigma_{crust}$ entering in p. Indeed, the distance $d = \sqrt{(x^2 + z^2)}$ at which the aperiodic signal still has a non-negligible amplitude depends on D and crust conductivity σ_{crust}. Comparing both terms in p we observe that the time envelope of the signal depends crucially on the size of the charge localization x_0 and the distance d between the charge source and the point of electric field measurement. Under low conductivity, reasonable values of charge localization size x_0 and diffusion D conditions, the sign of p is practically positive. The localization size of the aggregation of stresses usually does not exceed 1 km, while for diffusion D we could choose a value of about $1 \div 100$ m^2/s [27, 28]. The latter is taken from the electrokinetic mechanism model. Fig. 3 illustrates the SES shape for different values of parameter p.

Under isotropic conditions, e.g. when the center of aggregation of stresses is not collocated with faults, the time evolution for an isotropic aggregation stress and consequent charge and current production is illustrated in Fig. 4. Positive p values correspond to rock conditions where σ_{crust} lies in the ranges $10^{-6} \div 10^{-4}$ S/m. Inversely, under negative p conditions, no distinctive SES signals of duration of half an hour, or up to several hours are possible. One can see that, under high conductivity conditions, e.g.$\sigma_{crust} > 10^2$S/m, and a distance of about 100 km, the sign of p could even become negative. We note that under high conductivity conditions, e.g. under sediment, or soil conditions, the SES envelope will have duration greater than that under rock conditions. It is quite possible for such SES events to be comparable to the diurnal variations of the Earth potentials. In such a case, they could not be substracted from the diurnal variations. Another feature of the SES events is that the electric field is oriented mainly in one direction, probably perpendicular to the fault plane. Fig. 5 illustrates various forms of the SES envelope. Along the z direction, the SES envelope does not depend on distance d, the SES amplitude however decreases. Along the x direction, the SES changes its structure (Fig. 4). Even under isotropic conditions, the SES behaves differently in the x and z directions. The SES envelope usually has a triangle form. In other cases, the SES envelope possesses 'shark fin' profile (Fig. 4). This effect is probably related to the fact that the aggregation mechanism acts also in the x direction. Therefore, the SES form will change according to the course of the aggregation mechanism. Recalling the Ralchovsky and Komarov observations [8], the greatest SES event has a form similar to case b) in Fig. 4. Our model could be applied if there were isotropic conditions in the Earth crust. Under real conditions, the Earth surface acts as a reflection boundary for the SES sources placed at certain depth. We do not consider either the additional effects coming from possible differences in the conductance on both sides of the fault plane (x = 0). In reality, the characteristic time t_0 is not constant, as well. In general, we could expect quite complex SES forms depending on distance, orientation, depth, Earth surface and geology conditions at the measurement site, etc.

3. Comments

The microcrack production process is responsible for the charge density rate, $\partial\rho_0/\partial t$. Equation (13) for the electric field built-up (that we suggest) contains on the right hand side the source term that is proportional to the current density rate. The electric field built-up process will break down at time t_0 due to the discharge process. The mechanical stresses and strains will initiate further microcrack production and the seismic electric signal generation process will be resumed. The aperiodic electric field signal related with microcracks at great distances and in a preferable direction is examined in detail. The aperiodic SES has two parameters that have to be known: relaxation (duration) time γ and microcracks 'diffusion' D. The duration is controlled by the spatial scales of the electric field disturbance that could arrive at the Earth surface from the earthquake center located at some depth. The diffusion of microcracks depends on the mechanical properties of the geological materials, the inhomogeneities of various scales and is controlled by the level of pressures and strains related to the active tectonic processes.

An examination of the SES shapes determined from parameters D and γ shows that high conductivity conditions, e.g. $\sigma_{crust} > 10^{-2}$ S/m result in SES signals of duration comparable with the diurnal variations of the Earth potentials. Therefore, clear SES signals with duration of half of hour or up to several hours are to be formed under rock conditions where σ_{crust} lies in the range $10^{-6} \div 10^{-4}$ S/m. Inversely, under higher conductivity conditions, ULF signals are plausible for characteristic spatial scales of hundreds of meters or kilometers. In our model of the SES signal there are other parameters – the distance d to the epicentre of the incoming earthquake and the angle θ between the fault axis and the direction to the measurement point. The relationship between distance d and angle θ and x is given by $x = d \sin(\theta)$.

As follows from the above analysis, a fundamental characteristics of the proposed aggregate model of SES is the anisotropy of the generated signal. The main component of the SES signal could be observed mostly in the direction perpendicular to the fault axis, i.e. the pair of electrodes should be oriented in the direction perpendicular, or normal to the fault axis. This suggestion corresponds to experimental evidences that all the SES signals are one-dimensional. Indeed, the bay-, or bell-shaped signals are clearly visible in one of the two orthogonal tracks of the electric field measuring systems. They have usually been registered either in the E-W direction [7] or in the N-S direction [8]. The other track remained at noise level, i.e. undisturbed.

4. Conclusion

Our model of the SES signal describes electric field production due to the current density generation during microcrack aggregation process. The current associated with this electric field build-up dissipates in the surrounding medium and governs the spatial and temporal distribution of the electric field. The electric field built-up process will break down due to the discharge process. We demonstrate that, in additional to ULF/ELF/VLF wave events, the generated seismic electric signal (SES) possesses pulse-like (aperiodic) behavior. The initial anisotropy of the stresses and associated currents are the cause for an electric field that is oriented perpendicular to the forthcoming fracture events. Thus, electric field responses at great distance from the current sources are possible and our model reveals another mechanism of electric field generation that is not connected to electric field due to charge dipoles.

Acknowledgements. The authors are obliged to Prof I. Kutiev, Prof. L. Christoskov, Dr. B. Rangelov and V. M. Chmyrev for reading the manuscript and their valuable comments. P. Nenovski also thanks Prof. M. Hayakawa for the receipt of the Final 2001 Report of the NASDA's Earthquake Remote Sensing Frontier Project.

References

1. Fraser-Smith, A. C., A. Bernardi, P. R. McGill, M. E. Ladd, R. A. Helliwell, and O. G. Villard, Low frequency magnetic field measurements near the epicenter of the Ms 7.1 Loma Prieta earthquake, Geophys. Res. Lett., 17, 1990, 11465-11468.

2. Molchanov, O.A., M. Hayakawa, Generation of ULF electromagnetic emissions by microfracturing, Geophys. Res. Lett., 22, 1995, 3091-3094.

3. Warwick, J.W., C. Stoker, T. R. Meyer, Radio emission associated with rock fracture: possible application to the great Chilean earthquake of May 22, 1960, J. Geophys. Res. 87, 1982, 2851-2859.

4. Gershenson, N.I., M. B. Gokhberg, A. V. Karakin, N. V. Petviashvili, A. L. Rykunov, Modeling the connection between earthquake preparation process and crustal electromagnetic emission, Phys. Earth Planet. Inter., 57, 1989, 128-138.

5. Uyeda, S., Introduction to the VAN method of earthquake prediction, in The Critical Review of VAN: Earthquake Prediction from Seismic Electric Signals, ed. Sir J. Lighthill, World Scientific Publishing Co., Singapure, 1996, 3-28.

6. Hayakawa, M., O. Molchanov, A. Tronin, Y. Hobara, Y. T. Kodama, Seismo-electromagnetic phenomena in the Lithosphere, Atmosphere and Ionosphere, Earthquake Remote Sensing Frotier Research, Final Report, March 2001, Unioversity of Electro-Communications, Chofu, Tokyo. 2001.

7. Varotsos, P., K. Alexopoulos, Physical properties of the variations of the electric field of the Earth preceding earthquakes, Tectonophysics, 110, 1984, 73-98; 99-125.

8. Ralchovsky, Tz. M., L. N. Komarov, Periodicity of the earth electric precursor before strong earthquakes, Tectonophysics 145, 1988, 325-327.

9. Meyer, K., R. Pirjola, Anomalous electroteluric residuals prior to a large imminent earthquake, Tectonophysics, 125, 1986, 371-376.

10. Molchanov, O. A., M. Hayakawa, On the generation mechanism of ULF seismogenic electromagnetic emissions, Phys. Earth Planet.Inter. 105, 1998, 229-238.

11. Mizutani, H., T. Ishido, T. Yokokura, S. Ohnishi, Electrokineti phenomena associated with earthquakes, Geophys. Res. Lett. 3, 1976, 365-368.

12. Jouniaux, L., J. P. Pozzi, Permeability dependence of streaming potential in rocks for various fluid conductivities, Geophys. Res. Lett., 22, 1995, 485-488.

13. Nitsan, U., Electromagnetic emission accompanying fracture of quartz-bearing rocks, Geophys. Res. Lett. 4, 1977, 333-337.

14. Czechowski, Z., A kinetic model of crack fusion, Geophys. J. Int. 104, 1991, 419-422.

15. Tzanis, A., F. Vallianatos, F., S. Gruszow, Phys. Earth Planet. Int. 105, 2000, 201-210.

16. Cress, G.O., B. T. Brady, G. A. Rowell, Sources of electromagnetic radiation from fracture of rock samples in laboratory, Geophys. Res. Lett. 14, 1987, 331-334.

17. Rikitake, T., Earthquake prediction, Developments in Solid Earth Geophysics, Ser. 9, Elsevier Sci. Publ. Company, Amsterdam. 1976.

18. Troyan, V. N., N. A. Smirnova, Yu. A. Kopitenko, Th. Peterson, M. Hayakawa, Development of complex approach for searching and investigation of electromagnetic precursors of earthquakes: Organization of experiments and analysis procedure, in Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes, ed. M. Hayakawa, Terra Scientific Publishing Co., Tokyo, 1999, 147-170.

19. T a k a y a s u, H., I. N i s h i k a w a, H. T a s a k i, Power-law mass distribution of aggregation systems with injection, Phys. Rev. A37, 1988, 3110-3117.

20. I s h i z a k a S., in Proc. Ist. Symp. For Science on Form, ed. S. Ishisaka, KTK Scientific, Tokyo, 1986, 15.

21. H u b e r G., Scheidegger's rivers, Takayasu's aggregates and continued fractions, Physica A, A 170, 1991, 463-470.

22. E n o m o t o, J., H. H a s h i m o t o, Emission of charged particles from indentation fracture of rocks, Nature 346, 1990, 641-643.

23. O g a w a T., K. O i k e, T. M i u r a, Electromagnetic radiation from rocks, Jour. Geophis Res., 90, 1985, 6245-6249.

24. G r a n o v s k i y, V. L., Electric current in gases (in Russian), eds. L.A. Sen and V.E. Golant, Nauka, Moscow, 1971.

25. L a n d a u, L.D., E. M. L i f s h i t s, Electrodynamics of continuous media (in Russian), Theoretical Physics, vol. VIII, second edition, Nauka, Moscow. 1982.

26. A b r a m o v i t z, M., I. A. S t e g u n, Handbook of Mathematical Functions, Nat. Burreau of Standarts, Appl. Math. Series, 55, 1964.

27. D o b r o v o l s k y, I. P., N. I. G e r s h e n z o n, M. B. G o k h b e r g, Theory of electrokinetic effects occuring at the final stage in the preparation of a tectonic earthquake, Phys. Earth Planet. Inter. 57, 1989, 144-156.

28. F e n o g l i o, M.A., M. S. J o h n s o n, J. D. B y e r l e e, Magnetic and electric fields associated with changes in high pore pressure in fault zone – application to the Loma Prieta ULF emissions, Proc. Workshop LXII, Menlo Park, CA, 1994, 262-278.

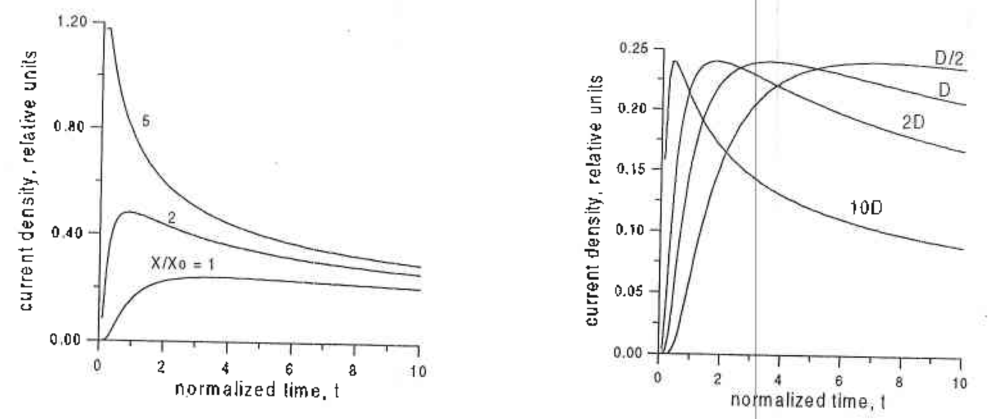

Fig. 1. Microcrack density production Z(x,t) according to random aggregation mechanism. The production depends on the position x and diffusion coefficient D.

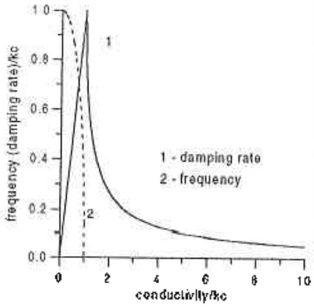

Fig. 2. The frequency and the damping rate of SES and ULF disturbances vs. normalized conductivity: $\sigma_{crust}/(2k/\mu_0 c)$.

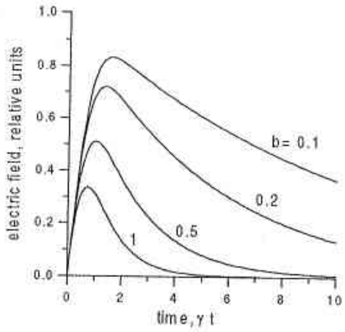

Fig. 3. The SES envelopes for given wavenumber k provided that the discharge moment $t_0 \to \propto$. Time is normalized – $T = \gamma t$. Parameter $b \equiv \sqrt{D}d\cot g(\theta)/\gamma$ (see text)

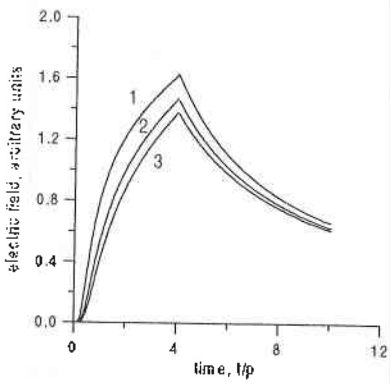

Fig. 4a

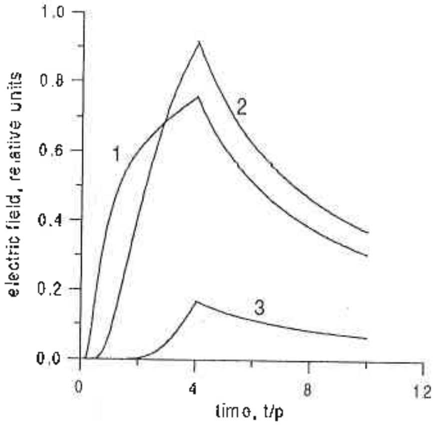

Fig. 4b

The SES envelopes in z (5a)) and x (5b)) directions. Curves 1–3 correspond to different distances: 1) 100/√π km; 2) 200/√π and 3) 400/√π km. Various forms of SES envelope in x direction are indicated. In x direction the SES envelopes feature either triangle form of different amplitudes, or 'shark fin' profile.

ВЪРХУ МЕХАНИЗМА НА ГЕНЕРАЦИЯ НА СЕИЗМИЧНИ ЕЛЕКТРИЧЕСКИ СИГНАЛИ

Петко Неновски, Бойчо Бойчев

Резюме

Предложен е модел на генерация на сеизмични електрически сигнали (СЕС), свързан с формирането на заряди и токове при процеса на разряд в пространството на микропукнатини. Електрическото поле в микропукнатината нараства до започването на разряден процес. След формиране на електрическото поле и неговото неутрализиране токът j се разпространява в околността на микропукнатината. Изследват се пространственото и времевото разпределение на електрическото поле, свързано с тока около микропукнатината. Полето зависи от скоростта на агрегация, разряда и геофизичните свойства на средата.