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ΠΡΟΕΔΡΙΑ ΙΩΑΝΝΟΥ Ν. ΚΑΡΜΙΡΗ

ΦΥΣΙΚΗ.— **Seismic electric currents,** *by P. Varotsos - K. Alexopoulos - K. Nomikos* *. Ἀνεκοινώθη ὑπὸ τοῦ Ἀκαδημαϊκοῦ κ. Καίσαρος Ἀλεξοπούλου.

I. INTRODUCTION

Effects have been made in the last years toward detecting anomalous earth current changes preceding earthquakes in Kamchatka mainly by Sobolev and coworkers [**1**]. They found that the electric field changed by about 100 mV/km some days (between 4 and 22) before each earthquake studied. The results have been extensively reviewed by Rikitake [**2**] who finds that these precursor anomalies do not correspond to other observed changes of physical quantities.

It is well known that pressure variations can produce under certain circumstances electric currents in solids. Best known is the piezo-electric effect that occurs in certain pyroelectric solids and that has long been studied. Another effect that has been detected only recently is the production of piezo-stimulated currents in solids containing electric dipoles. As any of these two effects could, in principle, produce currents during pressure changes in the interior of the earth, a serie of experiments was carried out during the period

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of recent seismic activity near Athens. The activity was initiated on February 24th 1981 with a 6.6 earthquake (EQ) which had its epicenter close to Halcyon Islands.

The activity still continues up to the present moment with a high density so that the search for the existence of electric currents was specially propitious. In effect, electric signals in the form of pulses were detected a few minutes before each earthquake. The present paper is a preliminary report of the results.

Part II gives the theoretical connection between pressure and piezocurrents. In Part III the experimental procedure and the main results are described. In Part IV the possibility of the observed electric pulses being of piezo-stimulaled nature is discussed.

II. THEORY

Theoretical background. Electric dipoles can change their orientation by jumping through a saddle point configuration with relaxation times τ given by [**3**]:

$$\tau = (\lambda \nu)^{-1} \exp\left(\frac{g^{m}}{kT}\right) \tag{1}$$

where g^{m} is the Gibbs energy for the reorientation (and hence migration) process. The numerical factor λ depends on the geometry of the lattice (i. e. is the number of jump paths accessible to the jumping species) and ν is a frequency factor of the order of the Debye frequency.

For a given temperature, ν and g^{m} (and hence the relaxation time τ) depend via Eq (I) on pressure. The pressure variation of the frequency ν is quickly estimated from the relation:

$$\gamma = -\frac{d\ln \nu}{d\ln V} \tag{2}$$

where γ in the appropriate Grüneisen constant and V the volume of the crystal. For small pressure variations (i. e. $\frac{\Delta P}{B} \leqslant 0.1$ where B is the isothermal bulk modulus) the change of ν is of the order of some percents if one considers that γ is usually around 2. In other words Eq (I) indicates that the explicit pressure variation of the time τ due to the pressure change of v is very small. On the other hand τ is strongly influenced by the pressure variation because the Gibbs energy g^m, which is pressure-dependent, lies in the exponent of Eq (I). The pressure variation of g^m is connected to the migration volume v^m (i. e. the difference of the volume of the crystal at the saddle point and at the ground state respectively) by:

$$v^m = \left.\frac{\partial g^m}{\partial P}\right|_T . \qquad (3)$$

The quantity v^m is usually positive (of the order of a few tenths of the mean atomic volume) which physically means that g^m — and hence τ through Eq (I) — increases on compression.

Equation (3) is of interest mainly for the study of the piezostimulated current as the piezoelectric effect is almost instantaneous.

Piezo-stimulated currents in solids containing aliovalent impurities.

Consider a crystal in the initial state (P_i, T) which contains dipoles of some nature. As an example we mention dipoles of the form: «aliovalent impurity plus cation or anion vacancy» or «aliovalent impurity plus cation or anion interstitial» created by aliovalent impurities. When an electric field ϵ is applied for a relatively long time ($t \gg \tau(T, P_i)$) the dipoles align and the solid gets a polarization given by:

$$\Pi_i = \frac{N\mu^2}{3kT}\,\epsilon \qquad (4)$$

where N is the concentration of dipoles and μ the dipole moment. If the solid is now subjected to a high hydrostatic pressure with a final value P_f the dipoles are held in their aligned positions even after the electric field is removed. This is due to an increase of g^m which according to Eq (I) results in a high relaxation time τ. A slow reduction of the pressure of the field-free material will allow the dipoles to reorientate so that a depolarization current is produced. It is interesting to note that this depolarization current maximises before the initial value P_i of the pressure is reached. This behaviour has been experimentally observed by Ai Bui et al. [4] and can be explained as follows: The decay process is governed by the relation

$$\frac{d\Pi}{dt} + \frac{\Pi}{\tau} = 0 \tag{5}$$

the integration of which gives:

$$\Pi = \Pi_i \exp \frac{\lambda}{b} \int_{P_f}^{P} \nu(P) \exp\left(-\frac{g^m}{kT}\right) dP. \tag{6}$$

This equation gives the values of the polarization at various pressures and hence describes the time-variation of Π because the rate $b\left(\equiv -\frac{dP}{dt}\right)$ of the pressure reduction is usually known. Due to the fact that the current density J is given by

$$J = -\frac{d\Pi}{dt} = \frac{\Pi}{\tau}$$

the insertion of Eq (6) leads to

$$J = \Pi_i \lambda \nu \exp\left\{-\frac{g^m}{kT} + \frac{\lambda}{b} \int_{P_f}^{P} \nu(P)\, e^{-\frac{g^m}{kT}} dP\right\}. \tag{7}$$

An inspection of Eq (7) indicates that J maximises at a pressure $P_{J_{max}}$ for which the relaxation time $\tau(P_{I_{max}}, T)$ is given by:

$$\tau(P_{J_{max}}, T) = \frac{kT}{b v^m}. \tag{8}$$

For example in the case of 6-polyamide ($v^m = 47.9\,Å^3$) [4, 5] which was been compressed under an electric field up to $P_f = 4$ kbars ($T = 35^0$ C) and then decompressed at a rate $b = 4$ bar/sec after the field was interrupted, the depolarization current showed its maximum value at $P_{J_{max}} = 533.28$ bars; in other words the piezo-stimulated current maximised under the circumstances around $t = 133$ sec before the ambient pressure was reached.

In the case of materials showing negative migration volumes the piezo-stimulated current can be observed via the inverse procedure i. e. by increasing pressure.

P i e z o - s t i m u l a t e d c u r r e n t i n p u r e s o l i d s. In the former discussion the depolarization current arose from the reorientation of dipoles which were created by aliovalent impurities. However depolarization currents could, in principle, be observed in pure materials provided that they consist of polar molecules (e. g. H_2O). To the best of our knowledge such an experiment has not hitherto been performed. The theory of the latter case is similar to that given above but the relaxation times are many orders of magnitude shorter than those of the previous case because the pressure variation of the relaxation time τ of polar moleculus comes mainly from the pressure variation to their dipole moment.

Polarization can be induced in all solids even those that do not bear permanent electric dipole moments but the relaxation times are still shorter. In the latter solids piezo-stimulated polarization or depolarization currents are produced in the following way: during the variation of the pressure the dielectric constant ε (and hence the polarization in the precence of an external field) changes mainly due to the volume variation of the «ionic polarizability» and to a lesser extent to that of the «electronic polarizability». Therefore when a crystal is continously held under short circuited conditions the time variation of the pressure leads finally to a current the direction of which depends on whether ε decreases or increases on compression.

III. EXPERIMENTAL PROCEDURE AND RESULTS

Two brass electrodes were inserted in the ground at a distance of 50 - 100 m the direction showing towards the Halcyon inslands. They were connected with blinded wires to a Keithley 610 or to a Cary 401 electrometer. Without using any external source a continuous voltage of the order of a few hundreds millivolts was observed. The results were displayed on a chart recorded. A signal in the form of a pulse was detected before each EQ regardless of its magnitude. The detectability of the electric pulse is strongly improved if the continuous voltage is compensated. The time lag Δt between the pulse and the initiation of the EQ was easily measured with an electronic chronometer because a seismograph was always present at the place of measurements.

The measurements were often disturbed by pulses that came from the electrical power system. This was specially disagreable during the evening hours but practically disappeared at night. Pulses from television circuits made such strong pulses that they could easily be recognised

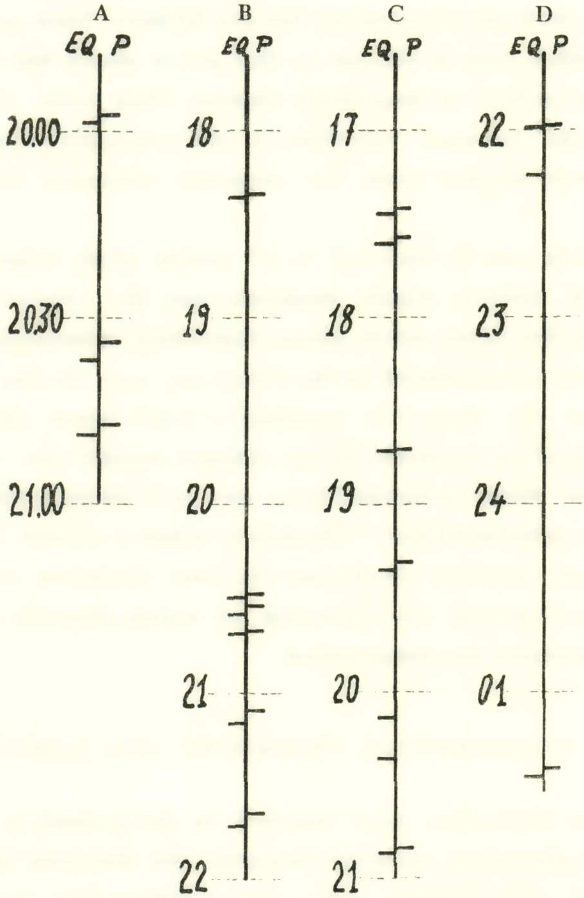

Fig. 1. Low seismicity - Earthquakes and pulses at Glyfada. (A) April 7th, (B) April 9th, (C, D) April 15th.

and disregarded. The 50 cycles/sec influences were always present as could be seen on the screen of an osciloscope but they disturbed in no way as the chart recorder was not influenced by them.

The phenomenon of the occurence of an precursor electric pulse for each EQ has been studied at five different sites (Perachora, Domvrena, Villia, Glyphada and Vari) lying at a distance of about 20 - 80 Km from the main epicentral zone. Measurements taken from March 9th until May 9th regard some hundreds earthquakes with magnitudes up to 4.8 and various epicentral distances.

During the first days of the present investigation the seismic activity was very high. This fact complicated the analysis because it was

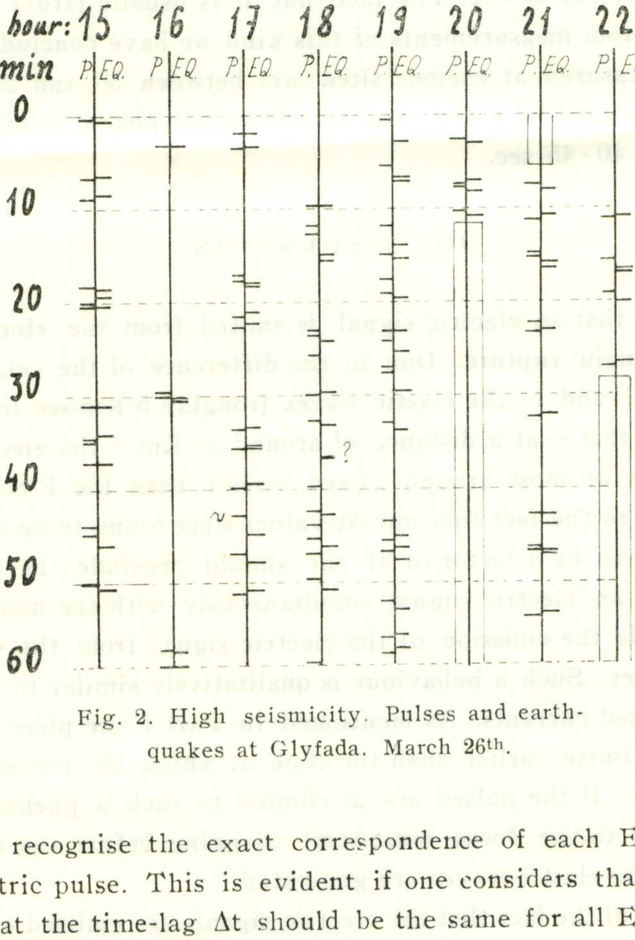

Fig. 2. High seismicity. Pulses and earthquakes at Glyfada. March 26th.

difficult to recognise the exact correspondence of each EQ to its precursor electric pulse. This is evident if one considers that there is no demand that the time-lag Δt should be the same for all EQ; therefore when two EQ (and therefore their precursor electric signals) differed only by a few minutes an unique «one to one» correspondence was not always possible.

The phenomenon of the interconnection of a pulse to an EQ could be verified only during periods for which the seismic activity happened to be low. The results during such periods of relative quietness are shown in Fig. 1. One easily recognises the correspondence of an electric signal of each EQ.

Representative sets of measurements during periods of high seismic activity are given in Fig. 2. A one to one correspondence can still be observed. As the electric signals always preceded the earthquakes the correspondence was made more visible by shifting the time scale of the EQ in all cases by 60 sec. The fact that Δt is usually larger than 60 sec is evident. From measurements of this kind we have concluded that the Δt-values measured at various sites vary between 30 and 240 sec. The Δt-values recorded at a site close to Athens (Glyphada, Vari) systematically exceed 40 - 45 sec.

IV. DISCUSSION

Assume that an electric signal is emited from the «focus» at the time of the main rupture. Due to the difference of the velocity of the electric signal and of the elastic waves (roughly 5 Km/sec for P-waves) it is evident that — at a distance of around 70 Km — the electric signal should arrive at most around 14 sec earlier than the P-elastic wave. However due to the fact that our Δt-values were found to be appreciably greater (at least by a factor of 3) one should preclude the case of the emittance of an electric signal simultaneously with the main rupture. In other words the emission of the electric signal from the «focus» has to occur earlier. Such a behaviour is qualitatively similar to the case of piezo-stimulated currents. As mentioned in Part I the piezo-stimulated currents maximise earlier than the time at which the pressure attains its final value. If the pulses are attributed to such a phenomenon the pressure close to the focus must start changing before the main crack from which the elastic waves are generated.

In spite of the fact that the electric signals are emitted earlier than the elastic waves and therefore show the behaviour expected for the piezo-stimulated currents this explanation of their cause is in no way guaranteed. Further the model for dipolar solids implicitely assumes that the rocks were subjected for long periods of time-longer than τ (P_i) — to a constant electric field. In effect telluric currents are known in certain cases to be relatively steady thus testifying to a steady electric field at least near the surface.

The above model for the explanation of the observed signals cannot lead to a quantitative estimation of the expected values of Δt because the constitution and other properties of the earth close to the focal region is still unknown. There is another indication supporting the «piezostimulated currents» as an explanation. The Δt-values measured at Glyfada systematically group around the following values 55 to 60, 90, 140, 240 sec. This is not unexpected. Earthquakes of the same mechanism with their focus at the same depth and further with the same rock constitution should show comparable Δt-values because in the compressed region the existing dipoles and the b-values should be similar.

We have been informed that the earthquakes in the region of Halcyon islands originate at more than one focus. A multiplicity of the Δt-groups could be consistent with the above in formation. Such a correspondence is being currently investigated by the seismologists of the University of Athens.

We wish to acknowledge the readiness of Prof. J. Dracopoulos and Drs. N. Delimbasis and K. Macropoulos of the chair of seismology of the University of Athens for giving us all available seismological data and apparatus.

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Note added on the proof: A signal of the same form but of greater duration has been noticed to occur around 7 hours before an earthquake.

ΠΕΡΙΛΗΨΙΣ

Κατὰ τὴν τρέχουσαν μετασεισμικὴν περίοδον, ποὺ ἤρχισε μὲ τὴν διαταραχὴν τῆς 24ης Φεβρουαρίου, παρετηρήθησαν πρὶν ἀπὸ κάθε δόνησιν γήινοι ἠλεκτρικοὶ παλμοί. Ἡ μορφὴ τοῦ ἠλεκτρικοῦ πεδίου κατὰ τὴν διάρκειαν τοῦ παλμοῦ δὲν ἦτο δυνατὸν νὰ προσδιορισθῇ μὲ ἀκρίβειαν, πάντως ἡ διάρκεια τοῦ παλμοῦ εἶναι τῆς τάξεως τῶν 5 msec. Τὸ ὁλοκληρωμένον φαινόμενον ἦτο εὔκολον νὰ παρατηρηθῇ καὶ νὰ καταγραφῇ αὐτογραφικῶς. Ἐμελετήθησαν περισσότεροι ἀπὸ τετρακοσίους

σεισμοὺς εἰς τοὺς ὁποίους εὑρέθη, ὅτι ὁ παλμὸς προηγεῖται τοῦ σεισμοῦ κατὰ 30 sec ἕως μερικὰ πρῶτα λεπτά. Αἱ ἀκριβεῖς τιμαὶ εἶναι δυνατὸν νὰ ταξινομηθοῦν εἰς ὀλίγας ὁμάδας. Ὡς ἐξήγησις τοῦ φαινομένου προτείνεται ἡ παραγωγὴ ἠλεκτρικῶν γεωρευμάτων λόγῳ ἀποπολώσεως εἰς τὴν περιοχὴν τῆς ἑστίας κατὰ μίαν σχετικῶς βραδεῖαν ἀνακατανομὴν τοῦ πεδίου τῶν ἐλαστικῶν τάσεων. Συμφώνως πρὸς τὴν θεωρίαν τὰ ρεύματα ἀποπολώσεως ἐμφανίζονται πρὶν νὰ λάβῃ ἡ πίεσις τὴν τελικήν της τιμήν.

REFERENCES

1. G. A. Sobolev, In «Earthquake precursors» ed. M. A. Sadovsky. I. L. Nersesov and L. A. Latynina (Acad. Sci. USSR, Moscow 1973) pp. 216 and references therein.
2. T. Rikitake, In «Earthquake prediction» pp. 212, 290 Elsevier (Amsterdam 1976).
3. P. Varotsos and K. Alexopoulos, Phil. Mag. A, **42**, 13 (1980).
4. Bui Ai, P. Destruel, Hoang the Giam and R. Loussier, Phys. Rev. Lett. **34**, 84 (1975)
5. S. Radhakrishna and S. Haridoss, Phys. Stat. Sol. (a) **41**, 649 (1977).