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Generation of electric field in an earthquake preparation zone

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Abstract
Different attempts have been made to explain the generation of the electric currents before an earthquake that take place in an earthquake preparation zone; in some of them the coseismic effects are also included. In this paper we discuss the possibility to construct a model of displacement current generation in an earthquake source zone which combines polarization processes and motion of charged dislocations. Such a process is associated with the transition from isotropic to stress-induced anisotropic properties in an earthquake source zone. Concurrently, we consider the conduction currents related to a high velocity motion of charged dislocations. Another approach related to an electrokinetic model of current generation is also briefly discussed.

Key words *earthquake precursors – electric current*

1. Introduction

Polarization or depolarization currents (*e.g.*, Varotsos and Alexopoulos, 1984) are related to dipole reorientation processes under influence of stresses (or temperature). Utada (1993) presented the model estimating a source current intensity due to a time variation of electric polarization. Whitworth (1975) in his review on charged dislocations writes that in dynamical processes, when dislocations move, the electric neutrality is no longer maintained and the potentials produced can be in suitable cases quantitatively measured; the corresponding models appropriate for the earthquake formation problems are applied in papers by Gokhberg *et al.* (1985), Shevtsova (1984), Slifkin (1993). We try to combine these two approaches in a one model.

In the ionic structures, a dislocation causes an excess or a deficit of a row of ions along its line; a dislocation core becomes charged. However, the electrical neutrality of the system: dislocation core and surrounding cloud (formed by point defects) is not maintained in the dynamical processes. When dislocations move a corresponding current proportional to density of charged dislocations and their mean velocity is formed.

The counterparts of the point and the linear defects gives also rise to the displacement currents. Thus, looking for a mechanism of interaction between stresses and electric field we suggest a combined model including dipole polarization and motion of the charge dislocations under an influence of the evolving field of stresses. Dipoles are formed due to migration of defects surrunding a dislocation and this process is caused by an electric field of the charge bearing dislocations and partly by a kind of forced mechanical rotation along a slip or microfracturing planes. Depolarization may take place when dislocations coalesce (annihilation process). These polarization and depolarization current are rather of transient character. We shall also note that a dipole moment

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changes due to accelerated motion of dislocation when a distance between dislocation core and its cloud increases.

Finaly in the advanced stage of deformation, when defects coalsce and form a connected system of cracks, we may expect a possible electrokinetic effects related to migration of fluid.

The expression for a total current generated in a body under deformation just can be written as follows:

$$\boldsymbol{j} = \boldsymbol{j}^{ds} + \boldsymbol{j}^{cd} + \boldsymbol{j}^{ce} \tag{1.1}$$

where $\boldsymbol{j}^{ds}, \boldsymbol{j}^{cd}, \boldsymbol{j}^{ce}$ are the displacement and conduction currents: related to dislocation motion and electrokinetic effect.

2. Stress-rate stimulated dilatancy current: polarization due to motion of charged dislocation under influence of stresses

First, we would like to consider the polarization and depolarization currents. The stress-rate polarization transient current appears when a threshold between the isotropic properties and the oriented properties (stress induced anisotropy) is overpassed in an earthquake preparation zone. Due to interaction between dislocations, a transition from the isotropic state to the state of the oriented electrical and mechanical properties is expected during a dilatancy phase and we believe that such transient currents occur in a rather short time interval. Another effect is expected when dislocations accelerate: the dipole moment between the dislocation core and its cloud changes in time contributing to a displacement current; this process is strictly dynamic and appears only when stresses change in time.

In this model we assume that a point defects density N which undergo migration (causing dipole rotation) is proportional to a charged dislocation density α. Same applies to the corresponding time rates:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{D}{l}\frac{\mathrm{d}\alpha}{\mathrm{d}t} \tag{2.1}$$

where D is a proportionality factor, $D \gg 1$; l (in m) is a characteristic length (of a sample or of a focal region).

Transient electric current density $\boldsymbol{j}^{ds}$ (in A/m^2) is in this model expressed by a time derivative of polarization $\boldsymbol{P}$ (polarization $\boldsymbol{P}$ relates to product of density of dipoles N and mean dipole moment p: $\boldsymbol{P} = N\boldsymbol{p}$):

$$\boldsymbol{j}^{ds} = \frac{\mathrm{d}\boldsymbol{P}}{\mathrm{d}t} = \boldsymbol{p}_0\frac{\mathrm{d}N}{\mathrm{d}t} + N\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} \tag{2.2}$$

where $\boldsymbol{p}_0 = q\boldsymbol{d}_0$ is a mean dipole moment related to point defects (a part representing term statisticaly independent of time); q is a density (per unit of length of dislocation) of electric charge.

The first term refers to the number of point defect dipoles which undergo migration to a prescribed direction of dislocation electric field, while the second term describes time changes of the dipole moment: dislocation core-dislocation cloud; its change is due to an accelerated motion of dislocations:

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = \mathrm{q}\frac{\mathrm{d}\boldsymbol{d}}{\mathrm{d}t} = \mathrm{q}\,\tau\frac{\mathrm{d}\boldsymbol{V}}{\mathrm{d}t} \tag{2.3}$$

as distance d is proportional to dislocation velocity and may be expressed by a delay of cloud motion $\boldsymbol{d} = \tau\boldsymbol{V}$.

Combining (2.1) and (2.3) we obtain from (2.2):

$$\boldsymbol{j}^{ds} = q\boldsymbol{d}_0\frac{D}{l}\frac{\mathrm{d}\alpha}{\mathrm{d}t} + q\,\tau\frac{D}{l}\,\alpha\frac{\mathrm{d}\boldsymbol{V}}{\mathrm{d}t}. \tag{2.4}$$

Thus according to relation (2.2) variations of dislocation density in time and acceleration of dislocation motion contribute to the transient currents.

An electric field generation in dry condition was discussed in several papers already mentioned above; Varotsos and Alexopoulos (1984) considered the polarization and depolarization transient currents, Hadjicontis and Mavromatou (1994, 1995) found time related effects in rocks under stresses varying in time. We present here only new mechanisms governing these effects being aware that estimation of the respective current densities is here extremely difficult – as many parameters, like *e.g.*, difference in accelerations (caused by stress rate) between dislocations and point defects, is unknown.

In the Earthquake Premonitory and Rebound Theory (Teisseyre *et al.*, 1995; Czechowski *et al.*, 1994) the dislocation density is related to internal stresses; for an antiplane shear stress $\boldsymbol{S}$ we have in the simple case of motion and dependance only of the x-direction the following relation:

$$\alpha(x) = \frac{1}{\mu}\frac{\partial S}{\partial x},$$

while in 2D: $$\alpha(x, y) = \frac{1}{\mu}\left(\frac{\partial S}{\partial x} - \frac{\partial S}{\partial y}\right). \qquad (2.5)$$

Using the approximative expression for dislocation velocity as propotional to difference between stress and stress resistance R:

$$V = \frac{c}{R}(\boldsymbol{S} - \boldsymbol{R}) \qquad (2.6)$$

we obtain from (2.4) and (2.5) the relation

$$j^{ds} = \frac{q d_0}{\mu}\frac{D}{l}\frac{\partial^2 S}{\partial x \partial t} + \frac{q \tau}{\mu}\frac{D}{l}\frac{c}{R}\frac{\partial S}{\partial x}\frac{\partial (S-R)}{\partial t} \qquad (2.7)$$

where c is shear wave velocity.

The part of transient current density related to the first term is proportional to the second mixed derivative of stresses, while the second brings proportionality to the product of first space and time derivatives.

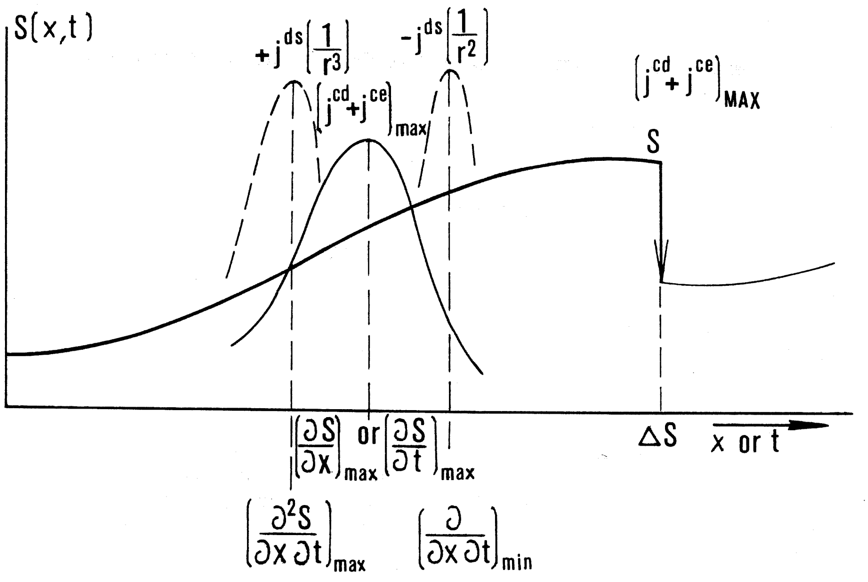

Fig. 1. Schematic diagram showing appearance of the electric currents related to the second mixed derivative of stresses and product of the first derivatives – transient displacement currents; the conduction currents and electrokinetic currents relate to first space derivative.

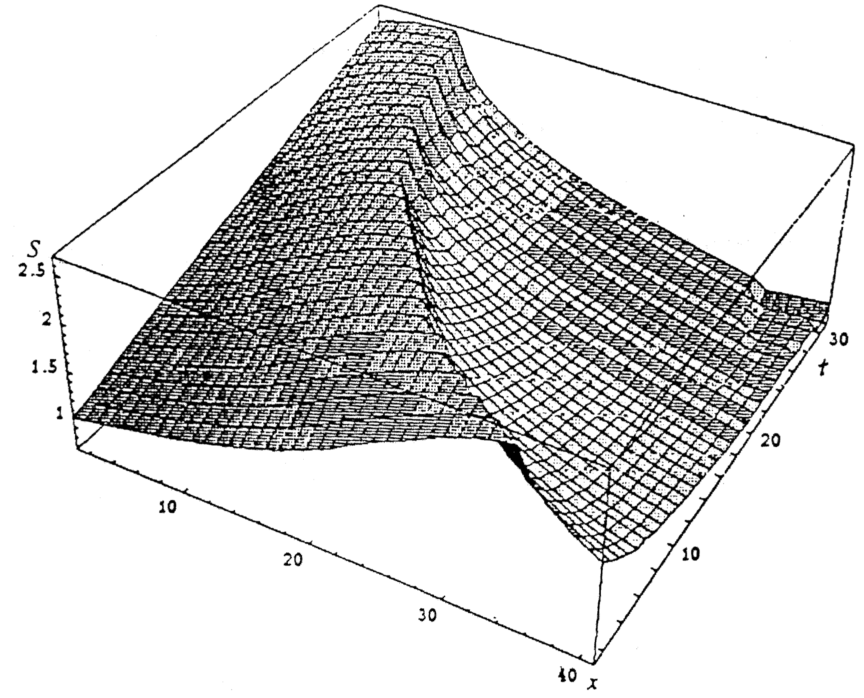

Fig. 2. Example of the 3D plot of stress evolution (after Teisseyre *et al.*, 1995).

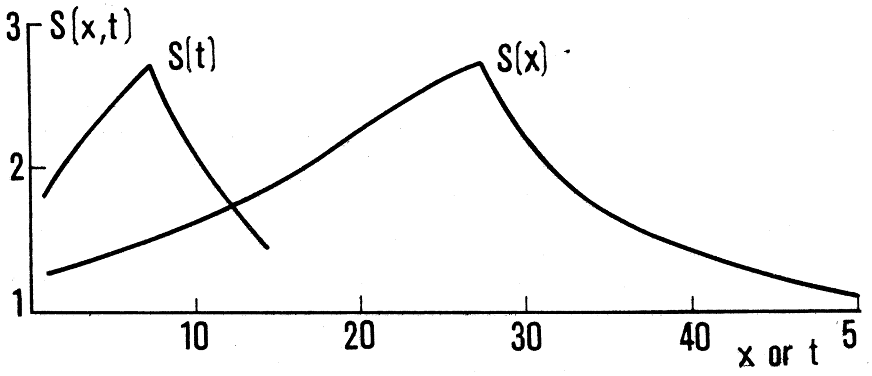

Fig. 3. Cuts of the 3D stress plot for constant x (left curve) and for constant t (right curve).

Hadjicontis and Mavromatou (1994, 1995), when discussing their laboratory experiments, found that the transient electric signals are proportional to the time rate of stress load – taking into account that in measuring device Δx is practically constant we obtain an experimental verification of relation (2.7). These transient signals are related to dislocation processes (Hadjicontis and Mavromatou, 1995) and differ essentially from the piezo-electric phenomenon in which electric field is proportional to stress itself (anisotropic effect of lattice deformation).

The numerical solutions of stress evolution equations (Teisseyre *et al.*, 1995) give the examples of stress increase; we can use these examples to determine the stress derivatives (fig. 1). Electric currents can be observed at the extrema of the corresponding derivatives; these transient currents evidently precede a seismic event; a time lag probably depends on the material properties and on the stress concentration rate in an earthquake preparation zone.

An example of stress evolution as functions of the independent variables x and t is presented in fig. 2, while fig. 3 gives the respective cuts along x = const and t = const.

Looking on these cross-sections in time and space we find that a stress evolution course in time and space is to some extent similar (fig. 3); for graphic representation simplicity, we have thus put in fig. 1 interchangeably for the horizontal axis the x and t coordinates.

In fig. 1 the moments of the current maxima are indicated – the two current maxima related to second mixed derivative correspond to currents of the opposite signs; the respective space derivatives of dislocation density differ in sign. The first peak of displacement current appears due to the polarization of point defects in a range of influence of the dislocation electric fields, while the second peak relates to depolarization current due to the action of these fields ceasing when dislocations coalesce. Another maximum related to accelerated motion of dislocation appears at the extremum of the product of the first (space and time) stress derivatives.

3. Conduction currents

Park (1994), in his discussion of constraints on mechanism of current generation, turned my attention to the problem of coseismic current, while several papers presented at the Conference in Positano focussed on the electrokinetic effect.

Conduction current may be related to the motion of charged dislocation at high velocities when dislocations become separated from their clouds (compare *e.g.* (1.1)); such current would be proportional to dislocation density and its velocity. For a simple antiplane case we obtain using (2.5):

$$j^{cd} = q\,\alpha\,V = \frac{q\,c}{\mu}\,\frac{(\boldsymbol{S}-\boldsymbol{R})}{[R^2+(S-R)^2]^{1/2}}\,\frac{\partial S}{\partial x}. \tag{3.1}$$

This current is related to only a high velocity of dislocations, as for lower velocities a dislocation cloud is near its core and we can expect only displacement currents. Here, for high dislocation velocity instead of (2.6) we have had to use the more refined expression after Mataga *et al.*, 1987:

$$\boldsymbol{V} = c\,\frac{(\boldsymbol{S}-\boldsymbol{R})}{[R^2+(S-R)^2]^{1/2}}.$$

Two corresponding maxima of the first derivative are related to the preparatory stage and to massive defect motion during coseismic process. Eventualy observable current related to preparatory processes for $\left|\frac{\partial S}{\partial x}\right|$ = max would depend on the distance between the observational point and the site where this maximum actually takes place. However, this site moves in time during preparatory processes and thus these variable distances may give rise to a bay type current effect at the observational spot (Sobolev, 1975). At rupture process, the rapid movements in a zone of seismic event bring a strong electric effect.

Finally the electrokinetic current depends on the process of formation of connected crack systems; surely these processes play in some cases a very essential role in earthquake preparation and in the related percolation process; electrokinetic current (streaming current induced by fluid flow) depends on pressure gradient:

$$j^{ce} = \frac{(\xi\epsilon)\,\varepsilon\zeta}{\eta}\nabla p \qquad (3.2)$$

where: ϵ and ξ are rock porosity and ratio of pore fluid saturation; ζ and ε are electrokinetic potential and dielectric constant; η is viscosity.

In our model, rock porosity (and hence, in many circumstances also, a degree of fluid saturation) depends of defect coalescence processes (processes leading to a state of connected crack system); Teisseyre (1995) has shown that the coalescence process can be expressed by dislocation density changes $\int \mathrm{d}\,\alpha$ where $\mathrm{d}\,\alpha$ is related to a corresponding small stress drop. Dislocation density is related to stress derivative by (2.5) hence we obtain:

$$\int_0^t \mathrm{d}\,\alpha = \frac{1}{\mu}\int_0^t \mathrm{d}\left(\frac{\partial S}{\partial x}\right) = \frac{1}{\mu}\frac{\partial S}{\partial x} \qquad (3.3)$$

assuming that at $t = 0$ a stress derivative is small.

Porosity changes depend on the dislocation density changes and hence can be approximated by the following relation:

$$\epsilon = \epsilon_0 + \epsilon_1 \frac{\partial S}{\partial x}.$$

A pressure gradient is independent of the antiplane stresses (for the in-plane stresses – edge dislocations – we have a contribution related to a trace of dislocational stress tensor: $\nabla p = \nabla p_0 - \frac{1}{3}\nabla\,(\mathrm{tr}\,\boldsymbol{S})$. Finally we obtain for an electrokinetic current density:

$$j^{ce} = \frac{\xi\varepsilon\zeta}{\mu\eta}\nabla p_0\left(\epsilon_0 + \epsilon_1\frac{\partial S}{\partial x}\right). \qquad (3.4)$$

In any case, the electrokinetic current reaches a maximum for $\frac{\partial S}{\partial x}$ at its extremum, assuming that a threshold of percolation is overpassed (a quantative pattern of electrokinetic current corresponds thus to first space derivate of stresses; compare fig. 1).

4. Correlation between magnetotelluric fields and seismic activity

Rozluski and Yukutake (1993) correlated the transformed magnetotelluric activity with the transformed seismic activity in Japan. The transformed magnetotelluric activity is given by the transmission coefficient as a function of time. We refer here to the incident and reflected electromagnetic plane waves of an outer origin and also due to sources inside the Earth (the non-inductive signals), such as those related to tectonic activity. The transmission coefficient is defined by $T = 1 - R$, where R means the reflexion coefficient (ratio of the energy flux of the reflected plane wave to that of the incident wave). In the absence of non-inductive signals, we have $0 \le \boldsymbol{T} \le 1$. Hence the case $\boldsymbol{T} < 0$ may indicate an electromagnetic source inside the Earth. To define the transformed seismic activity we shall refer to fig. 4;

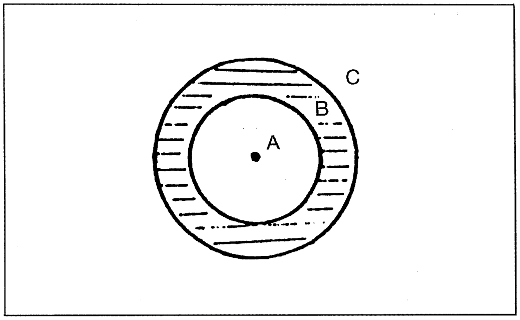

Fig. 4. Schematic diagram showing three zones having different characteristics of the electric signals related to different stress characters:

zone A: | signal: $\frac{1}{r^3}$ | ≫ | signal: $-\frac{1}{r^2}$ |;

zone B: | signal: $\frac{1}{r^3}$ | comparable with | signal: $-\frac{1}{r^2}$ |;

zone C: | signal: $\frac{1}{r^3}$ | ≪ | signal: $-\frac{1}{r^2}$ |.

the mentioned authors have assumed that the earthquakes from the different circular zones A and C around a site of telluric measurements contribute to the transformed seismic activity with signals proportional to magnitudes but opposite in their signs and with different space dependences: from zone A we take only $1/r^3$ function, while from the events from zone C we take only $1/r^2$ function; the seismicity from zone B is neglected. The transformed seismic activity is thus defined by the following formula:

$$H = \sum M\left(\frac{d}{r^3} - \frac{1}{r^2}\right) \exp\,[-(h-h_0)/\delta^2], \quad L = 24^h \tag{4.1}$$

where M is a particular seismic magnitude; a summation extends over a 24 h period, $\boldsymbol{h}$ is a corresponding depth of focus and $\boldsymbol{h}_0$ is a constant.

The transformed seismic activity means here a time distributition of magnitudes observed around a telluric observation site with magnitudes reduced by the factor $1/\boldsymbol{r}^3$ in the nearby circular zone (up to about 30 km) and by the factor $-1/\boldsymbol{r}^2$ in the farther zone (starting from about 50 km on); here the differences in the signs correspond to the differences in the displacement current directions predicted in the above discussed model. Teisseyre (1995), assumed that at the beginning the stress evolution process is related to small (loop) dislocations and this process has a 3D character with

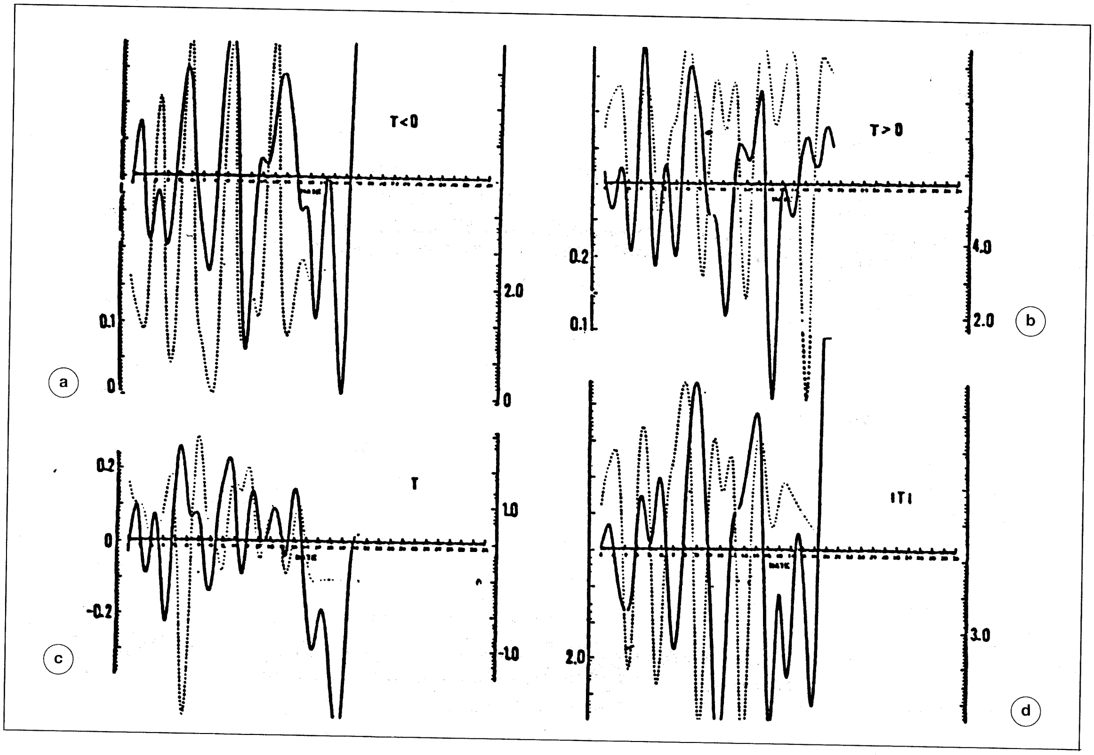

Fig. 5a-d. The smooth fits of the transformed seismic activity (broken line) and the average of the transmission coefficient (solid line), Yatsugatake, Japan, February, 1991. Relative scales: on right for the transmission coefficient and on left side for the transformed seismic activity. a) Curve of $|T'|$ visualising the part $T < 0$; b) curve of T'' visualising the part $T > 0$; c) curve of T; d) curve of $|T|$ (after Rozluski, 1995).

a stress dependance like $1/\boldsymbol{r}^3$, while in the later, advanced phase of evolution, dislocations group and coalesce into longer strips, and the process changes into 2D type with a stress dependance like $1/\boldsymbol{r}^2$. Due to these differences in the stress dependance with distance we would observe the telluric signals different in signs from the seismic events that have occurred at different distances to the telluric observation site, that is from zones A and C; these different signals are related to different moments of the preparatory processes before the corresponding events. Thus restricting ourselves to the displacement currents, we may represent a magnetotelluric activity by the averaged time functions given by transmission coefficients as defined above.

From these considerations we found that an even more simple correlation may exist when limiting the analysis only to zone A or C. For zone A we take from the transmission coefficients T' given by a negative part of T ($T' = |T|$ for $T < 0$) and we compare it with the seismic activity given by the $1/r^3$ terms in formula (4.1), while for the zone C we take only part $T > 0$ ($T'' = T$ for $T > 0$) and for seismicity the $1/r^2$ terms of (4.1).

The corresponding smooth fits of transmissions and seismic activities are presented in fig. 5a-d. We can see that the correlation for the near source zone A with transmission $T < 0$ and a transformed seismic activity from zone A, seems to be the best, giving also a visible preceding time between the increases in T', and seismic activity. For the case of T'' and seismic activity from zone C″ we obtain almost coseismic correlation. This is in accordance with a mechanism of transient current pulse generation presented in fig. 1; the second pulse is close to a seismic event. In fig. 5a-d we have also put, for completeness of presentation, the correlation between T and H as well as for $|T|$ and the sum of $1/r^2$ and $1/r^3$ terms of $\boldsymbol{H}$.

Comparing these considerations with the correlation between the transmission coefficient and the transformed seismic activity in Japan (as presented above) we find a rather good agreement with our expectations (Rozluski, 1995).

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