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PRIMARY AND CRACK-INDUCED ANISOTROPY OF ELECTRIC RESISTIVITY BEFORE EARTHQUAKES

Abstract. Electric resistivity of a medium with an oriented system of open cracks that undergo changes when under stress is simulated numerically. The concentration of cracks - their quantity and volume - varies, along with stress rise and energy release. The same may be true for the proper resitivity of a material inside cracks. The crack system is treated as 3-dimensional, anisotropic, although homogeneous from the observer's point of view. Also, a second source of electric anisotropy of the medium, its primary anisotropy is taken into account; it is independent of cracks and unchanging. Geometrical modelling reveals the possible role of rock anisotropy in monitoring and for prospecting. Attempts to interpret experimental results are also given.

INTRODUCTION

The study of anisotropic premonitory effects in shear wave splitting was brought up in several papers by Crampin. Oriented cracks and inclusions appear to be common in many types of rocks, alignment of these cracks being under the control or at least the influence of the recent stress field. For a review of the recent state of the art see Crampin and Lovell (1991).

Electric anisotropy has also been found, both in laboratory and field experiments. Let us consider an orthogonal system of coordinates in space. The current density j in the direction of one of the axes of this system, say i, depends not only on conductivity σ and electric field E in that direction, but also on electric fields in directions j and k and appropriate constants of proportionality, σ_{ij} and σ_{ik}:

$$j_x=\sigma_{xx} E_x+\sigma_{xy} E_y+\sigma_{xz} E_z$$
$$j_y=\sigma_{yx} E_x+\sigma_{yy} E_y+\sigma_{yz} E_z \quad (1)$$
$$j_z=\sigma_{j_{zx}} E_x+\sigma_{zy} E_y+\sigma_{zz} E_z$$

The equations for electric field components are similar:

$$E_x=\varrho_{xx} j_x+\varrho_{xy} j_y+\varrho_{xz} j_z$$
$$E_y=\varrho_{yx} j_x+\varrho_{yy} j_y+\varrho_{yz} j_z \quad (2)$$
$$E_z=\varrho_{zx} j_x+\varrho_{zy} j_y+\varrho_{zz} j_z \ .$$

These are matrices of tensor of conductivity σ and tensor of (proper) resistivity ϱ. In these

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matrices, components σ_{ii} and ϱ_{ii} are called the diagonal components of the tensor. The non-diagonal components reflect the effect of anisotropy and are much smaller than the diagonal ones. There is one orthogonal coordinate system in a given medium in which non-diagonal components are zero.

In this system only

$$\varrho_{ii}=1\ /\ \sigma_{ii}\ . \tag{3}$$

This is the system of main axes of the resistivity tensor.

In recent years, it has become clear that for better use of electric methods for assessment of the state of rocks under load and for monitoring its changes, the following conditions are recommended:

first- recording of variations at many sites, with a view to finding rock and stress inhomogeneities;

second- recording along lines in several directions (at least 3) in order to account for the tensor character of ϱ - the proper resistivity;

third- searching for appropriate models of the medium to properly interpret the obtained data.

In modeling electric resitivity, the matrix of the modelled medium is usually treated as a perfect insulator. The conducting phase forms a net of inclusions which may be interconnected or separated - this leads to the problem of percolation threshold. Other approaches are also possible.

The purpose of this work was, first - to construct a model in which the influence on electric resitivity of cracks or inclusions is under the control of the geometry of these cracks and their spatial orientation; second - to check how, in this model, such factors as resistivity of material(s) inside the cracks, crack concentration and geometry of cracks influence the anisotropy and resistivity values; third - to find a method to compute the influence of anisotropy of the rock matrix itself on the resistivity of the entire complex medium, or in practice, a method to calculate the interference of two or more anisotropy sources in a medium.

GEOMETRICAL MODEL OF THE MEDIUM

The proper resitivity of a rock matrix is expressed here by a constant ϱ_0; if there is a primary anisotropy, one of the (primary) resistivity tensor components - placed in its main axes - is taken as ϱ_0, which simplifies the computation. Now let us assume that an open crack has, on the average, a certain geometrical orientation; the number of cracks and/or their size change. How do they influence the proper resitivity of the medium?

The task is to construct a model of the medium in which the proper resistivity tensor is divided into two parts- one caused by serial connections in the medium, and the other by parallel connections. This division should be connected with the geometry of the cracks or inclusions.

If all the cracks contain the same material, the proper resistivity of this material has here symbol ϱ_+. However, in simulations presented in this paper, there are two kinds of cracks, and the proper resitivity of dry ones - filled with gas - is ϱ_G, while that of wet cracks is ϱ_w. Coefficients of geometry of crack are given the symbol G; $\Delta\varrho$, $\Delta\varrho_s$ and $\Delta\varrho_p$ are the total change in proper resistivity caused by cracks, its part due to series connections and its part due to parallel connections. The open crack concentration is here α; if dry and wet cracks are considered, their concentrations are α_G and α_W, respectively. These symbols are the same as in the earlier paper (Teisseyre, 1991), in which this model was first proposed, but the geometrical coefficients were computed incorrectly. For the change due to connections in series, we have

$$\Delta\varrho_s=(\varrho_+-\varrho_0)\ \alpha\ G\ , \tag{4}$$

whence

$$\frac{\Delta\varrho_s}{\varrho_0} = \left(\frac{\varrho_+}{\varrho_0} - 1\right) \alpha\, G\,. \tag{5}$$

For parallel connections the equation is similar, but it is necessary to start from conductivity σ, not from change in resistivity:

$$\sigma_p = \sigma_0 + (\sigma_+ - \sigma_0)\, \alpha\, G\,. \tag{6}$$

From eqns. (6) and (3) we get:

$$\frac{\Delta\varrho_p}{\varrho_0} = \frac{1}{1 + \left(\frac{\varrho_0}{\varrho_+} - 1\right) \alpha\, G} - 1 = \frac{-\left(\frac{\varrho_0}{\varrho_+} - 1\right) \alpha\, G}{1 + \left(\frac{\varrho_0}{\varrho_+} - 1\right) \alpha\, G}\,. \tag{7}$$

A general formula for change in resistivity tensor component in any of the three main axes $\Delta\varrho_i$, is as follows:

$$\frac{\Delta\varrho_i}{\varrho_0} = \left(\frac{\varrho_+}{\varrho_0} - 1\right) \alpha\, G_{si} + \frac{-\left(\frac{\varrho_0}{\varrho_+} - 1\right) \alpha\, G_{pi}}{1 + \left(\frac{\varrho_0}{\varrho_+} - 1\right) \alpha\, G_{pi}}\,, \tag{8}$$

where G_{si} is the geometrical coefficient for connections in series in the i-th direction, G_{pi} is the geometrical coefficient for parallel electrical connections in the same direction. These coefficients will be discussed later.

If there are two crack phases, the formula is more complicated:

$$\frac{\Delta\varrho_i}{\varrho_0} = \left(\left(\frac{\varrho_G}{\varrho_0} - 1\right) \alpha_G + \left(\frac{\varrho_W}{\varrho_0} - 1\right) \alpha_W\right) G_{si} + \frac{-\left(\frac{\varrho_0}{\varrho_G} - 1\right) \alpha_G\, G_{pi}}{1 + \left(\frac{\varrho_0}{\varrho_G} - 1\right) \alpha_G\, G_{pi}} + \frac{-\left(\frac{\varrho_0}{\varrho_W} - 1\right) \alpha_W\, G_{pi}}{1 + \left(\frac{\varrho_0}{\varrho_W} - 1\right) \alpha_W\, G_{pi}}\,. \tag{9}$$

If it is more convenient to realize absolute changes in resistivity, formulae 5 and 7 - 9 may be changed in the following way:

$$\Delta\varrho_i = ((\varrho_G - \varrho_o)\, \alpha_G + (\varrho_w - \varrho_o)\, \alpha_w)\, G_{si} + \frac{-\varrho_o \left(\frac{\varrho_o}{\varrho_G} - 1\right) \alpha_G\, G_{pi}}{1 + \left(\frac{\varrho_o}{\varrho_G} - 1\right) \alpha_G\, G_{pi}} + \frac{-\varrho_o \left(\frac{\varrho_o}{\varrho_w} - 1\right) \alpha_w\, G_{pi}}{1 + \left(\frac{\varrho_o}{\varrho_w} - 1\right) \alpha_w\, G_{pi}}\,. \tag{10}$$

I prefer to compute relative changes of resitivity, taking ϱ_0 as 1. In this case, eqns. (9) and (10) transform to the same equation:

$$\Delta\varrho_i=((\varrho_G-1)\ \alpha_G+(\varrho_w-1)\ \alpha_w)\ G_{si}+ \qquad (11)$$

$$\frac{-\left(\dfrac{1}{\varrho_G}-1\right)\alpha_G\,G_{pi}}{1+\left(\dfrac{1}{\varrho_G}-1\right)\alpha_G\,G_{pi}}+\frac{-\left(\dfrac{1}{\varrho_w}-1\right)\alpha_w\,G_{pi}}{1+\left(\dfrac{1}{\varrho_w}-1\right)\alpha_w\,G_{pi}}\ .$$

The values of the geometrical coefficients may vary between almost 0 and almost 1. In any of three directions of crack system main axes,

$$G_{si}+G_{pi}=1\ . \qquad (12)$$

Let us consider geometrical coefficients G_s and G_p in direction i (Fig. 1). If an average crack is assumed to be a parallelepiped, the ratios of its dimensions, or in other words, tangent and cotangent functions of angles between diagonals and edges, give clues to finding the geometrical coefficients. It is necessary to introduce now temporary, say initial geometrical coefficients I_{si}, I_{pi} . For electric resitivity in direction i, remembering that the sum of the geometrical coefficients in any direction i is 1, we have

$$I_{si}=sqr\ (k*j)\ /\ i \quad ; \quad I_{pi}=1/\ I_{si}\ ;$$

$$G_{si}=I_{si}\ /\ (I_{si}+I_{pi}), \qquad (13)$$

$$G_{pi}=I_{pi}\ /\ (I_{si}+I_{pi})\ .$$

In this case, *ctg* $\delta(xz)$ is near to 1, but because *ctg* $\delta(yz)$ is near to 0, G_{sz} is near to 0; thus G_{pz} is near to 1. If the dimensions of cracks in directions x and y are the same, $G_{sx}=G_{sy}$; $G_{px}=G_{py}$. If all the dimensions of the cracks are on the average the same, all geometrical coefficients are equal to 0.5, and the cracks influence on resistivity is isotropic.

MODELLED PROGRESS OF CHANGES IN THE CRACK SYSTEM

In the modelled medium, open cracks (tensile cracks and inclusions) are abundant, and they are, at least to some extent, aligned. Their orientation is under the control of the stress field; for simplicity, it is treated here as constant (I expect that in real rocks the orientation of open cracks may undergo considerable changes during preparation for rupture, especially when shear cracks, which have a different orientation from that of tensile cracks, branch into open cracks). Also crack concentration (their total volume) depends on stresses.

The resistivity rises at the beginning of a cycle of changes, on account of the dilatancy, because most of newly opened cracks are dry; the resistivity of dry cracks is higher than that of the rock matrix.

Cracks in a rock change, move and are not isolated from pores and other cracks, so dry cracks may soon become wet or even filled with aqueous solution of low resistivity. Not only the filling of cracks with water, but also their coalescence plays its part. This slows down the process of resistivity increase; then after a turning point, or in reality after a kind of plateau, the resistivity starts to fall. Changes become quick as cracks merge and many of them become interconnected, which makes the percolation of fluid through the medium possible. The appearance of a network of cracks able to conduct fluids marks the onset of the phase of percolation. This facilitates rupture, which is expected sometime between the beginning of the fall in crack-induced surplus resitivity and the bottom of the bay-like decline of resistivity. After the shock, the system of cracks in the rock, and the rock's resistivity, may slowly recuperate and attain a state similar to the initial one, due to crack closing, and a new stress and dilatancy buildup may begin.

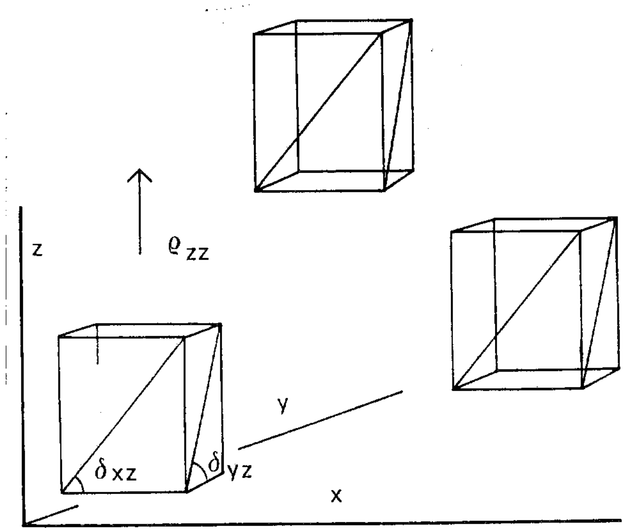


Fig. 1 — Construction of geometrical coefficients G_s and G_p for electric current in the z direction.

PRINCIPLES OF SIMULATION

The simulations presented here bear the following general characteristics:

- A medium is considered as consisting of three phases. The first of them I will call the 'rock matrix'. Inclusions and open cracks form a second phase, called 'cracks'. Closed cracks, unoriented pores and voids are not considered here. The system of open cracks is treated as homogeneous, which is justified in the case of small crack dimensions in comparison to the measuring line, and their relatively uniform distribution. Open crack systems split into two categories of cracks: wet and dry, the latter having a very high proper resistivity. The rock matrix is also treated as homogeneous, although it may be anisotropic if there exists primary anisotropy, independent of cracks and constant.

- All phases are conducting, but their conductance may differ. For simplicity, the proper resistivity of the material of dry cracks - that is to say gas - ϱ_G is treated as constant, the same applies for the resitivity ϱ_w of the aqueous solution filling wet cracks.

- The resitivity of the medium depends upon the proper resitivity of material(s) in the cracks, geometry and orientation of the crack system, concentration of cracks and properties of the rock matrix itself.

- The spatial orientation of the crack system is treated as constant.

- Also the geometry of cracks is constant in these simulations.

- To analyze the influence of cracks on resistivity, a system of Cartesian coordinates is used; its axes are parallel to the mean length of a crack (its longest dimension), mean width and mean value of its thickness.

- The influence of cracks on resistivity, along each axis, is divided into a part caused by serial electrical connections and a part due to parallel connections.

- Besides the crack-induced components of resistivity, another source of anisotropy, i.e. constant primary anisotropy, may exist in a rock too.

- Axes of the crack system may not coincide with the axes of primary anisotropy, so these two categories of anisotropic components interfere geometrically. Thus, the diagonalization procedure may be needed in computing the ϱ tensor components and location of its main axes.

Because of changes in the crack system, this localization varies in time, except for two cases

- when angles between primary anisotropy and crack system are 0 and/or 90 degrees, and when there is no primary anisotropy, so it is allowed to put zero for these angles again.

It is only the concentration of cracks (in other words, their total volume in a given volume of medium) that varies. The wet and dry crack contributions to the resitivity of the medium form subdivisions of the aforementioned serial and parallel connection parts.

SIMULATION PROCEDURE

At the beginning of the simulation cycle, initial values of resitivity tensor components are selected (if they differ - there is primary anisotropy), and the orientation of the crack system in reference to the initial orientation of main axes of resistivity tensor is determined. The mean geometry of the cracks is specified, and geometrical coefficients are computed. The proper resistivity of material inside dry and wet cracks in relation to the proper resistivity of the rock matrix ϱ_o is also specified.

The evolution of concentration of dry and wet cracks is also determined at the initial stage. For technical reasons, the simulation starts from zero concentrations of both types of cracks.

The cycle of changes is divided into a sequence of 100 stages, due to the requirement of small, differential changes. In each stage, the coordinate transformation is applied to the resitivity tensor, referring the tensor to the reference system (x y z) aligned with the orientation of cracks. This transformation is obtained in 3 steps - 3 rotations by angles ϕ_1 , ϕ_2 , and ϕ_3 . Now the crack-induced change is simulated - values of the crack system influence (which may be positive or negative) are computed with eqn. (11) and added to the resistivity tensor diagonal components:

$$\left| \varrho^{p}_{ii} \right| \rightarrow \left| \hat{\varrho}^{p}_{ij} \right| + \left| \delta\, \varrho^{c}_{ii} \right| \rightarrow \left| \pi_{ij}^{pc} \right| \tag{14}$$

(These added values are small in comparison to the resitivity tensor diagonal components because of the division of the crack-induced change into many stages). After this addition, the resitivity tensor is transformed to the former coordinate system. Now the non-diagonal components of the proper resistivity tensor appear to be even smaller in comparison to the diagonal ones. This disproportion forms the basis for the differential diagonalizing procedure:

$$\left| \hat{\varrho}_{ij}^{pc} \right| \rightarrow \left| \varrho_{ij}^{pc} \right| \xrightarrow{\textit{diagonalization}} \left| \varrho^{n}_{ii} \right| . \tag{15}$$

New values of the resistivity tensor components are computed (Appendix 2) by the diagonalization procedure, and the orientation of its main axes is also determined. The procedure is then repeated in the new stage. At the beginning of this next stage, we put: $\varrho^{p}_{ii} = \varrho^{n}_{ii}$.

Stages are repeated consecutively to form the whole sequence of changes simulating the behaviour of a medium under load.

Angles ϕ change gradually, except when they equal 0 and/ or 90°; in these cases, the diagonalization procedure is omitted by the program. For any stage, angles between the given measuring line and ϱ tensor components in the main axes, as well as the apparent resistivity value, may also be computed for a given measuring array orientation.

APPARENT RESISTIVITY

For the apparent resistivity calculation, angles of rotations that transform the coordinate system aligned with the measuring line (axis x_1 is along the electrode line) to the coordinates of the crack system have to be specified.

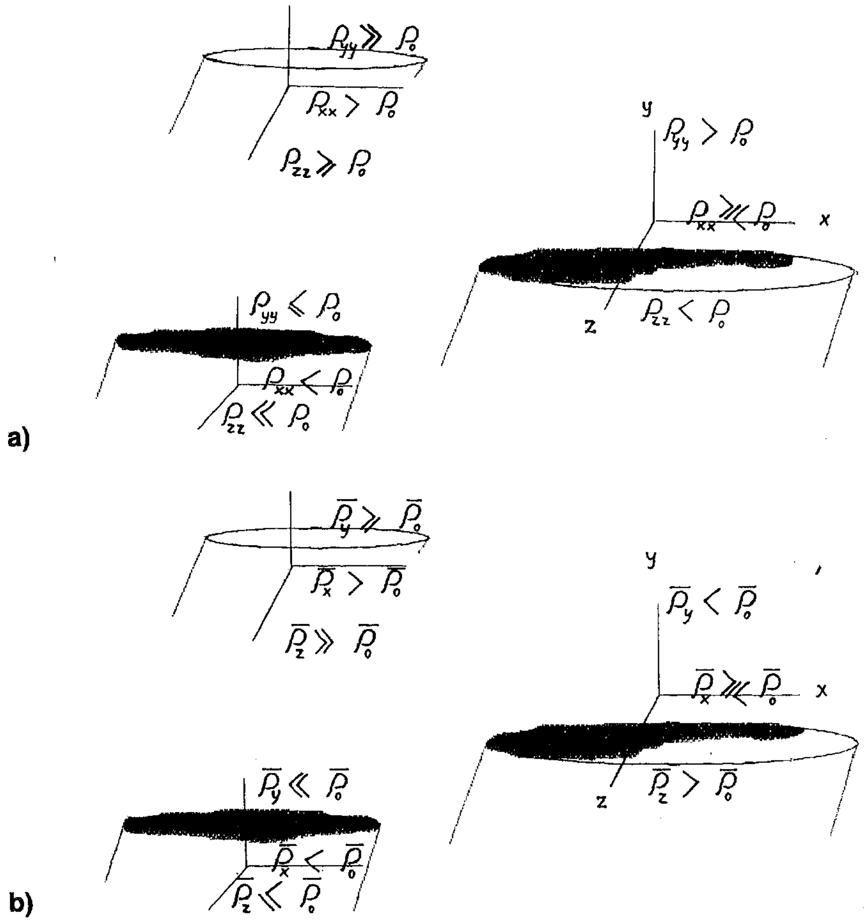


Fig. 2 — Scheme of medium with regularly distributed open cracks; three cases considered: dry cracks, cracks filled with aqueous solution and dry and wet cracks occurring together in the medium. a) influence of crack system on resistivity tensor components (related to the system of cracks); b) influence on apparent resistivity in three directions when there is no primary anisotropy.

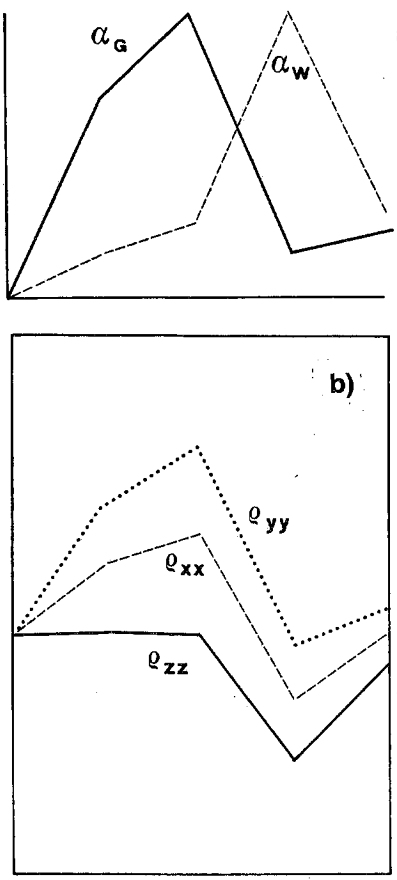
Measurements with the Wenner symmetrical, four electrode method are simulated for the assumed direction of the measurement line. The apparent resistivity is found from the formula

$$\bar{\varrho}_d = \frac{\sqrt{\varrho_{11}\,\varrho_{22}\,\varrho_{33}}}{\sqrt{\varrho_{11}\cos^2(11,\,d)+\varrho_{22}\cos^2(22,\,d)+\varrho_{33}\cos^2(33,\,d)}}\,, \tag{16}$$

(see e.g. Parasnis, 1986), where subscript d represents the direction of the measuring line, ϱ_{ii} are resistivity tensor components, and angles (ii,d) represent those between the main tensor axes and the electrode line. In particular, when the measuring electrodes form an array aligned with one of the tensor axes, the apparent resistivity is equal to the square root of the product of two components related to the remaining two perpendicular axes,

$$\bar{\varrho}_i = \sqrt{\varrho_{jj}\quad \varrho_{kk}}\,. \tag{17}$$

This is called the apparent resistivity paradox: if i, j, k are directions of the main axes of the resitivity tensor, the apparent resitivity measured in one of these directions depends not upon the resistivity tensor component in this direction but upon two other components.



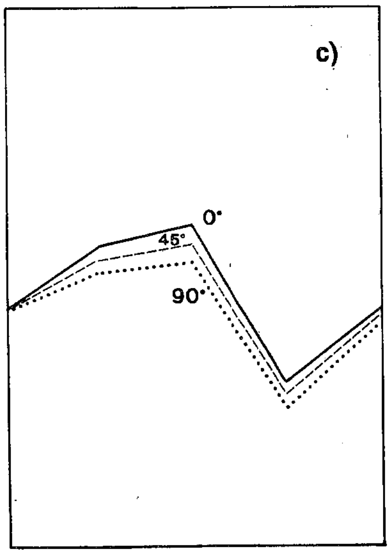


Fig. 3 — Evolution of crack system and resitivity of the medium: a) curves of concentration of dry _ α_G and wet _ α_w cracks; b) resistivity tensor components; c) apparent resitivity.

RESULTS OF SIMULATION EXAMPLES

In the examples presented here, length of cracks = z = 10; width = x= 3; thickness = y = 1 , in conventional units. From this, the computed geometrical coefficients are

$$G_{sz} = 0.0291 \ , \ G_{pz} = 0.9709 \ ,$$

$$G_{sx} = 0.5263 \ , \ G_{px} = 0.4737 \ ,$$

$$G_{sy} = 0.9677 \ , \ G_{py} = 0.0323 \ .$$

The maximum dry crack concentration is 0.1, and maximum wet crack concentration is 0.15. The evolution of these crack concentrations is shown in upper parts of Figs. 3-5. Ratio ϱ_G/ϱ_O is 8, ratio ϱ_w/ϱ_o is 0.25.

I present two series of computer plots: the curves of resistivity tensor component values and those of apparent resistivity. For given ϱ component curves, curves for apparent resistivity at three different measuring arrays are plotted. For all these plots, two features are common: the horizontal axis corresponds to time, and to the left of the frame there are numbers giving the resistivity range for this frame in conventional units. The orientation of the measuring arrays is chosen here in relation to the coordinate system aligned with crack-system. In all three plots of apparent resistivity curves, results for three arrays are shown: for the array aligned with the x component of the crack-influence vector, these curves are marked with 0°; for the array aligned with the y component, with 90°; and for the array lying on surface xy, in the middle

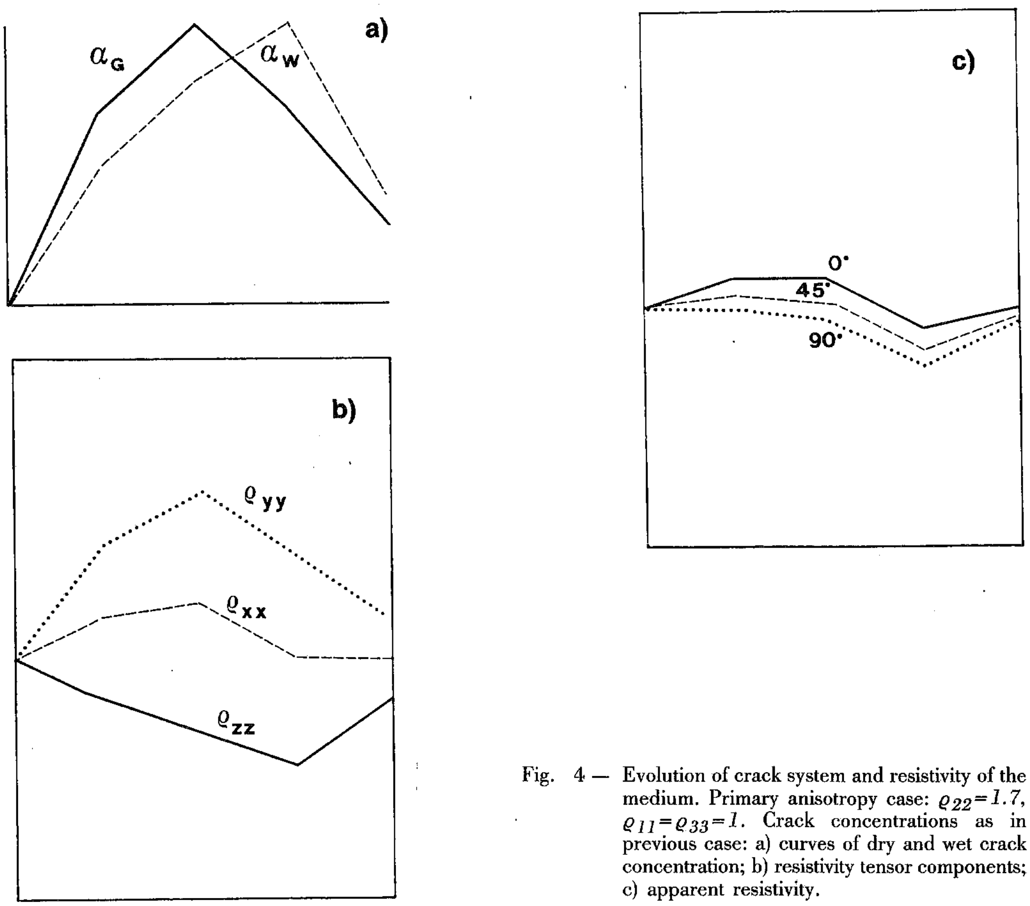


Fig. 4 — Evolution of crack system and resistivity of the medium. Primary anisotropy case: $\varrho_{22}=1.7$, $\varrho_{11}=\varrho_{33}=1$. Crack concentrations as in previous case: a) curves of dry and wet crack concentration; b) resistivity tensor components; c) apparent resistivity.

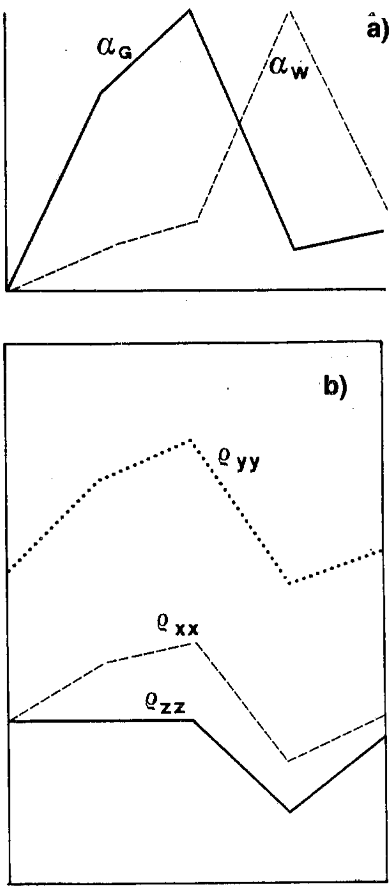
between the two other arrays, these curves are marked with the symbol 45°.

I have selected three situations for modelling. In all three cases, the crack concentration rises and then falls.

In the first two (Figs. 3 and 4) the abrupt rise in wet crack concentration is delayed; this models a two-phase evolution of the crack-system: a percolation phase is preceded by a dilatancy phase, when the dry crack concentration is much higher. In the first of these cases, Fig. 3, there is no primary anisotropy; in the second case, Fig. 4, there is distinct primary anisotropy. If cracks are not taken into account, ϱ_{22} in this case is 1.7, while the two other components equal 1 in conventional units. The axes of the coordinate system aligned with the primary resistivity tensor do not coincide with the axes of the crack-system. In the presented case, transformation from the first to the second system is simple - only rotation around axis 3" (= axis 3) is needed (different angles between the primary anisotropy system and the crack system lead to a shift in apparent resistivity curves, but I decided to show only one case here). The change in shape of the apparent resistivity curves, dependent on the discrepancy between the two coordinate systems, that of primary anisotropy and that of cracks, does not appear very evident.

In Fig. 4 (lower part), to the usual plots for measuring arrays i.e., aligned with crack-system axis x; aligned with the y axis and lying exactly in between, a fourth line is added, the dashed one, copied from the plot for apparent resistivity at the measuring site on the xy surface, 25° from the x axis. Interestingly, at this simulated measuring array, the obtained values are higher than on other arrays. Also the curve for the 45° - array located between the x and y axes - is interesting: it crosses the 0° curve and reaches higher values during the dilatancy phase.

The influence of both the crack-system and the primary anisotropy is seen in such a series



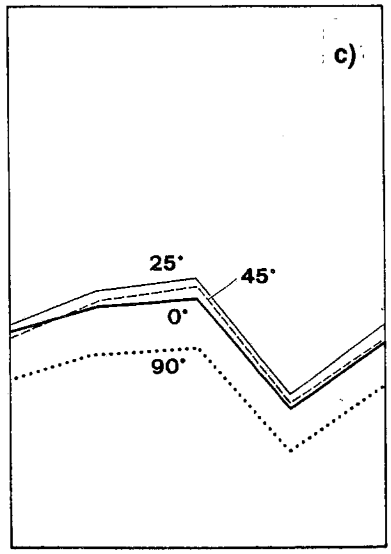


Fig. 5 — Evolution of crack system and resistivity of the medium. Case of almost concurrent progress of changes in dry and wet subsystems: a) curves of dry and wet crack concentrations; b) resistivity tensor components; c) apparent resitivity.

of computations; they may be also found from the series of measurements by differently oriented measuring arrays, during period of changes in the medium, connected with the load and strain evolution.

Primary anisotropy and crack-induced anisotropy can, in some cases, mask each other, their effects being reinforced or weakened. Changes in apparent resistivity curves are usually not as sharp as changes in curves of the tensor components.

To conclude, I don't think that results of resistivity measurements made once at many places, nor a curve of resistivity changes at one site, should be considered a valuable source of spatial information about dynamic processes in the rock.

The third situation - coexistence of both kinds of cracks (see upper part of the Fig. 5), with all other variables as in the previous cases, gave the simulation results shown in Fig. 5, middle and bottom. The apparent resistivity changes for two perpendicularly situated arrays sometimes have here opposite signs. At a certain line orientation, there may not be revealed any changes of resistivity and thus we will not observe precursory signals.

In this model, there is no other kind of interaction between the crack system and the primary anisotropy system, except for the creation of new resistivity tensor main axes and diagonal values in these axes. This needs a change in the future; I am currently preparing a model in which the anisotropy of resistivity tensor do affect the computation of the crack-induced changes.

It must be also emphasized, that in my model the influence of cracks on resistivity is not affected by the degree of connectivity in the crack system, nor by crack dimensions - only concentration - total volume of cracks in a given volume of medium, plus crack mean geometry and orientation, play their part.

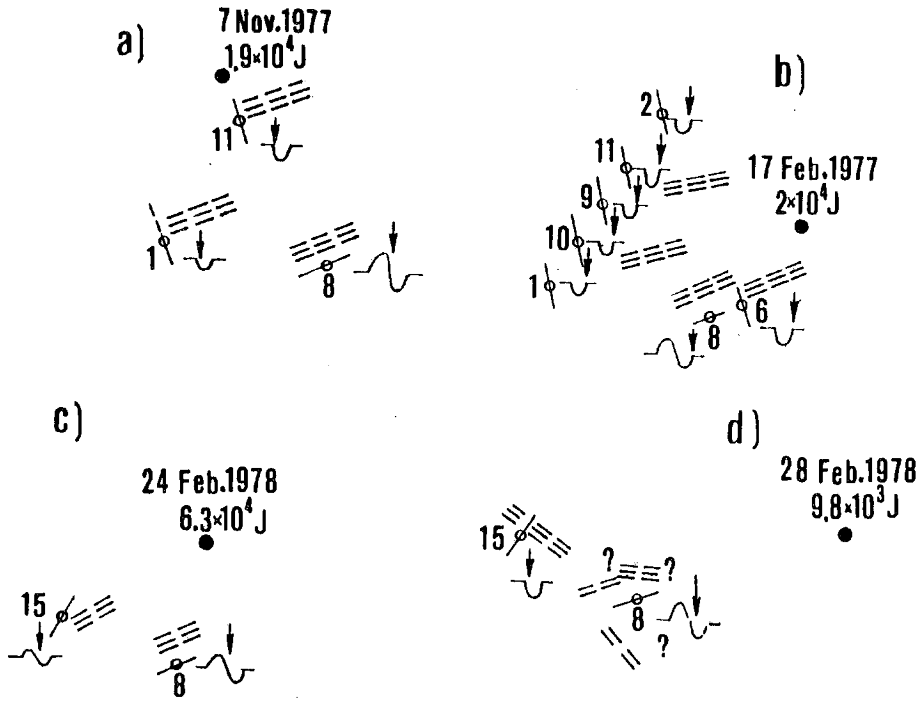


Fig. 6 — Scheme of apparent resistivity changes recorded in the copper mine Lubin, Poland. Orientation of the measuring arrays is shown as well as, schematically, curves of measured resistivity and the tremor (arrow). Epicentres of four seismic events are symbolized by black dots.

EXPERIMENTAL DATA - INTERPRETATION

Simultaneous changes at different sites in a copper mine

Resistivity changes before and after tremors, as found by Stopiński in a copper mine, were large and often bay-like in shape (Stopiński, 1986, Stopiński and Teisseyre R. 1982). What was also striking was their similar trend on parallel measuring arrays of the Wenner type - see Fig. 6. This may be interpreted as evidence for similarity of the rock structure and behaviour with that of our model - spatially uniform but anisotropic, with parallel open cracks. The resistivity probably changed due to a change in crack concentration and in the resistivity of the material inside. This was already assumed in the previous paper (Teisseyre K.,1988), in which results of much simpler modelling were presented. The inferred crack orientation is perpendicular to those measuring arrays on which an apparent resistivity increase during the dilatancy phase was not observed. The same electrode arrays reveal, during the percolation phase, a profound decrease. For the electrode array parallel to the cracks longest dimension, the increase of resistivity in the dilatancy phase would be the greatest, while the decrease during percolation phase - the smallest. For some cases, this simple method of crack orientation evaluation works well - results are quite consistent.

Some discrepancies between the obtained resistivity curves and the model may be caused by the effect of primary anisotropy, which may change the shape of the resistivity rise and fall.

Anisotropic changes with opposite signs - field results

Kayal and Banerjee (1988) have found probable anisotropy of apparent resistivity in brittle rocks (quartzite metamorphics) in the Shillong Plateau during active periods in June 1984 and mid-summer 1985. Electrodes were situated at first in two horizontal linear (perpendicularly

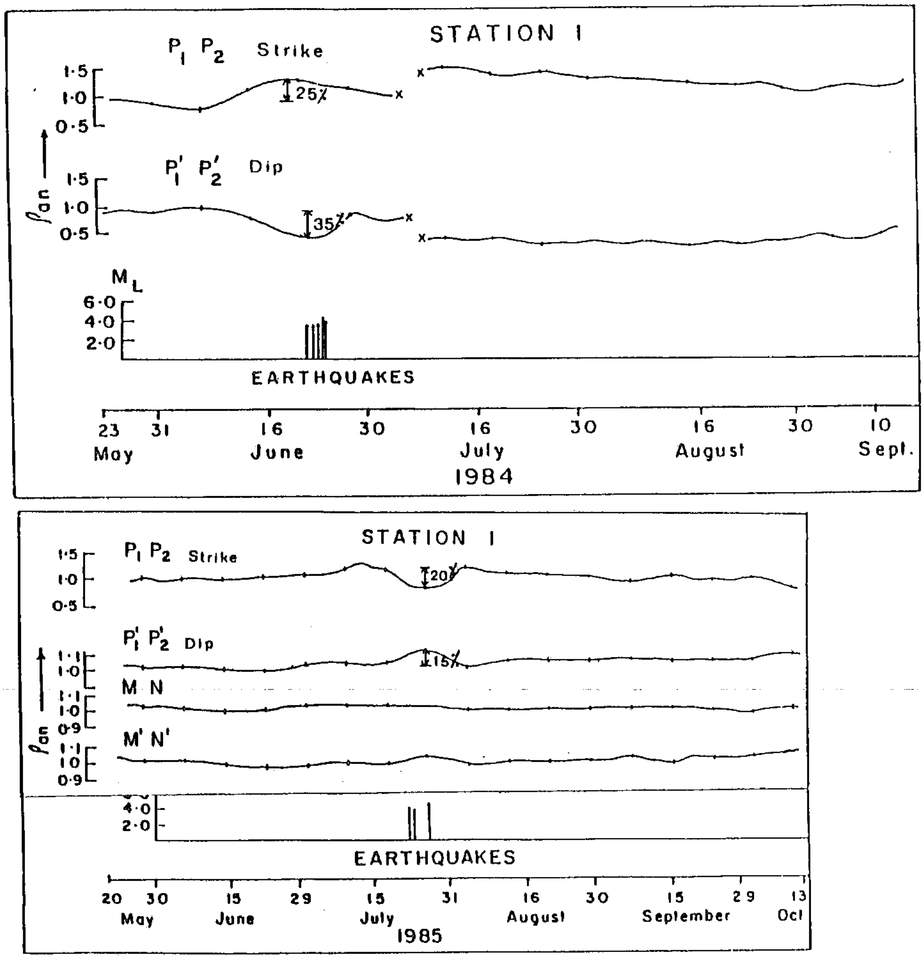


Fig. 7 — Apparent resistivity anisotropy observed in Shillong Plateau (from Kayal and Banerjee, 1988).

oriented) arrays; these were located in directions P_1 P_2 and P_1' P_2'.

Although Kayal and Banerjee used in their research a different, not Wenner's method, the relation between the tensor of resistivity components and the apparent resistivity remains similar.

After the first active period had passed, which gave intriguing results, two other arrays were added; thus, during the two active periods that followed, electrodes were situated there in four horizontal linear arrays, their directions separated by 45°. Directions P_1 P_2 and P_1' P_2' were located along the strike and dip of the formation, respectively; M N and M' N' were located between.

During the first active seismic period in the course of investigation, bay-like anomalies in the resistivity curves were recorded - an increase in direction P_1 P_2 and decrease in direction P_1' P_2' - see Fig. 3 in those authors' paper, Fig. 7 in ours. During the third active period, in the middle of summer 1985, anisotropic resistivity anomalies appeared again. But this time, in the strike direction P_1 P_2 , there was a precursory rise in resistivity - some 15%, followed by a decrease of about 30%, all during the 12 days preceding the first earthquake in a series of three. During this active period, the only clear anomaly of resistivity in direction P_1' P_2' was the bay-like increase, to some 15% above the initial, almost steady level. In the two other added directions, almost no changes were recorded.

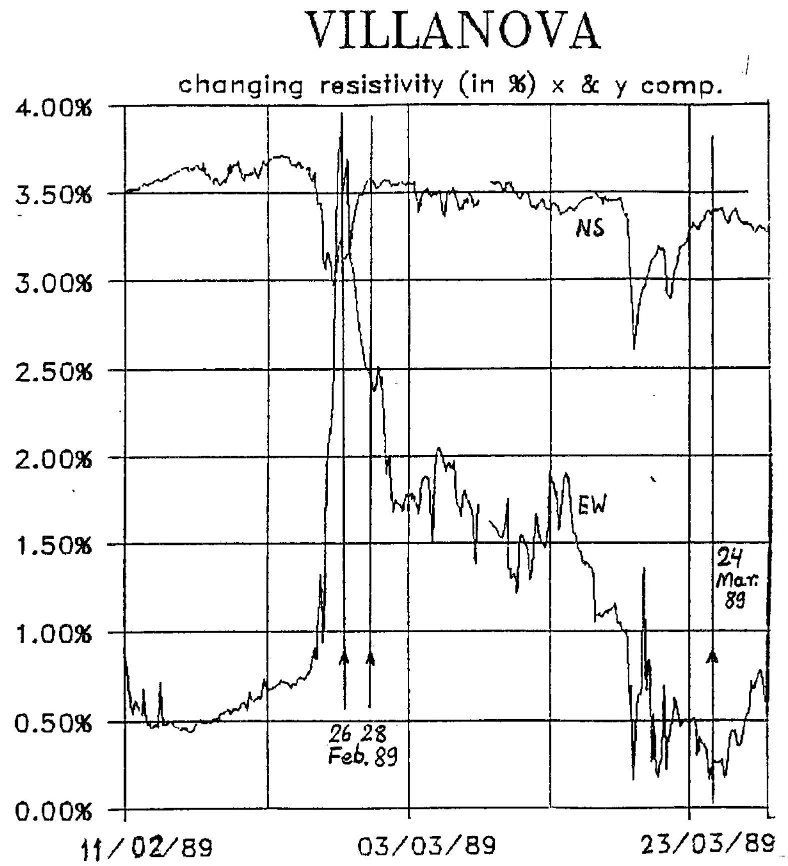


Fig. 8 — Apparent resistivity anisotropy observed at Villanova, Friuli, Italy (from Ernst et al., 1992).

It is to be noted, that in nearby Station 2, located on more plastic rocks (phyllite), though anomalies in the recorded resistivity were found in the time span around this active period, these were isotropic.

Let us try to interpret these results. We may assume that the crack orientation was close to the vertical planes. In the first case, these planes were aligned with the strike of the geological formation; in the latter (mid-summer 1985), the alignment was perpendicular to the strike. In both cases, the coexistence of dry and wet cracks occurred. Such orientations can explain the observed variations in terms of the model discussed above - the concurrence of dry and wet cracks.

Another example is taken from the resistivity measurements in the Friuli seismic region (Ernst et al.,1992). Before the nearby earthquakes of 26 and 28 February 1989 and 24 March 1989, there was an increase of apparent resistivity on one line and a decrease on the perpendicular one (Fig. 8). For these earthquakes, distances to the epicentre were about 30, 20 and 36 km and magnitudes were 3.5, 4.2 and 3.2, respectively. More distant earthquakes apparently gave no distinct precursory signals.

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Appendix 1

Program in Basic for computing the geometry of the crack system and the influence of crack system on proper resistivity

This program is part of the whole computing program.

Geometry:

```
print"Geometry"
input"mean length of the crack ";z
input" their mean width";x
input" and thickness "y : print

rem I..- Initial Geometrical Coefficients
Isz= sqr(x * y)/ z : Ipz= 1/ Isz
                     SumIZ= Ipz+ Isz
Gsz= Isz/SumIZ : Gpz= Ipz/ SumIz
print"Gsz = "Gsz; " Gpz = ";Gpz
Isx= sqr(z * y)/ x : Ipx= 1/ Isx
                     SumIX= Ipx+ Isx
Gsx= Isx/ SumIX : Gpx= Ipx/ SumIX
print"Gsx = "Gsx; " Gpx = ";Gpx
Isy= sqr(x * z)/ y : Ipy= 1/ Isy
                     SumIY= Ipy+ Isy
Gsy= Isy/ SumIY : Gpy= Ipy/ SumIY
print"Gsy = "Gsy; " Gpy = ";Gpy

Way:
print"if you want to change mean shape, press g"
where S = input S (1)
if where S = "g" or where S = "G" then goto Geometry
Cracks:
input "concentration of dry cracks _ "; ag
input "concentration of wet cracks _ "; aw
input " rogaz/ level "; gazlevel
input " rowat/ level "; watlevel
roSeries= (gazlevel- 1)* ag + (watlevel- 1)* aw
print"roSeries = "roSeries
roZs= roSeries* Gsz
paralgaz= (1/gazlevel - 1)* ag: paralwat= (1/watlevel - 1)* aw
roZp= - paralgaz* Gpz/ (1+ paralgaz* Gpz) - paralwat* Gpz/ (1+ paralwat* Gpz)
Zlevel= roZs + roZp
roXs= roSeries* Gsx
roXp= - paralgaz* Gpx/ (1+ paralgaz* Gpx) - paralwat* Gpx/ (1+ paralwat* Gpx)
Xlevel= roXs + roXp
roYs= roSeries* Gsy
roYp= - paralgaz* Gpy/ (1+ paralgaz* Gpy) - paralwat* Gpy/ (1+ paralwat* Gpy)
Ylevel= roYs + roYp
print"roZ/level = " Zlevel
print"roX/level = " Xlevel
print"roY/level = " Ylevel
print"again ? - press a"
where S = input S (1)
if where S = "a" or where S = "A" then goto Way
```

Appendix 2

The diagonalization procedure

Diagonalization procedure consists of four consecutive transformations of resistivity tensor: rotation around axis 1, axis 2', axis 3'' and axis 1'''. Theoretically, the sequence could be different, but always if it starts with the i axis, it must end with the i''' axis. Angles of these rotations, α_s , must be small.

Angle α_s of rotation is calculated before each step on the principle:

$$sin\ \alpha_s = \frac{\varrho_{ij}}{\varrho_{ii} - \varrho_{jj}} , \qquad (18)$$

where α_s is angle of rotation (in radians), and ϱ are the components of the resistivity tensor. After each rotation, these components of the tensor which comprise $sin^2\ \alpha_s$ are made equal to zero.

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