Modelling of anisotropic resistivity changes caused by stresses

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Abstract
This paper examines the existence of oriented crack systems in the rock medium under stress load and its influence on the resistivity of the medium. Electric resistivity in the presented model depends on the rock frame's resistivity and on the influences of all the systems of cracks. In the assumed model, in the medium two or more crack classes can coexist, for example filled with gas and with aqueous solution. Examples of numerical simulations are compared to results from measurements in the laboratory and in the field – during monitoring of earthquakes and mining shocks. The relevance of this model to rock state surveying is discussed.

Key words *electric anisotropy – resistivity – rupture preparation*

1. Introduction

The occurrence of oriented crack system(s) in the rock medium under stress is assumed and its influence on the resistivity of the medium is considered. A significant content of oriented cracks, although not only of tectonic origin, is a common phenomenon in many different rocks, according to Crampin and Lovell (1991).

Here, each crack system is defined as consisting of cracks with the same orientation and shape, so three perpendicular axes of system geometry can be found. The whole medium is treated as anisotropic but homogenous. Resistivity in this model depends on the rock frame's resistivity and on the influences of all the systems of cracks. Generally, resistivity change caused by inclusions (cracks) is intermediate between two extreme cases: inclusions connected to the frame in series, and inclusions jointed with it parallelly. Inequality of resistivity changes in three directions is attributed to certain factors – geometrical coefficients – whose values result from the crack geometry. Construction of these coefficients is simple in the case of simply-shaped cracks.

In order to obtain values of resistivity tensor, resistivity change along each axis is divided into two contributions: parallel and in-series one, each of them containing an appropriate geometric coefficient.

In each crack system, two or more crack classes can coexist, for example filled with gas and with aqueous solution. In normal circumstances the effect imposed by these two types is opposite.

Examples of numerical simulations are given, with comparisons to laboratory results and observation data from monitoring earthquakes precursors. As experiments with artificial samples revealed, electric anisotropy may be caused by the geometry of oriented inclusions, in accordance with the main concepts of this model.

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2. Principal features of the modelled medium

Electrical resistivity of the medium is assumed to be the result of changes in concentration, spatial and electrical features of the medium's components, which are: rock frame and materials which fill the inclusions, or cracks. For example, cracks in rock may be dry or wet, there is also the possible occurrence of petroleum-filled cracks in the same medium, etc. Each constituent's electrical conductivity influences the conductivity of the whole medium, irrespective of differences between material conductivities. This is in contrast with the percolation models of conductivity, like that developed by Chelidze (1981), where a high contrast between the conductivity of inclusions and the conductivity of the rock frame is assumed.

To resolve the problem of resistance of compound medium in an exact way, the shape and position of each crack should be described, and then a huge set of Maxwell's equations resolved, giving distribution of electric field and current in the considered space.

The author decided to try a simpler path. First, I devised (Teisseyre K.P., 1989) the simple model in which only flat cracks were accounted. Dry cracks, having resistivity greater than the surrounding rock frame, exerted influence only on electric current perpendicular to them, adding *in series* to the resistivity. Cracks filled with aqueous solution, of greater *conductivity* than rock frame, influenced resistivity of medium as good conductors, connected with it *in parallel*. No intermediate cases, cracks with more compact shape, nor other spatial relations, were accounted. However, a new model is needed which would be more general, and at the same time allowing the three-dimensional anisotropy of the medium to be (re)constructed. In the present model resistivity tensor components are built according to the influence of the crack system. This leads to attribution *of the character of a tensor of second order* to the geometry of the crack system.

The assumption follows that the modelled medium is anisotropic and homogenous. Physically it corresponds to media with cracks roughly uniformly dispersed in space. To each crack the same proportions of dimensions and the same orientation is attributed. The influence of each crack on the tensor depends on the volume of this crack. Such construction may be useful to model media containing cracks and being under the influence of tectonic stresses, for example in areas of focal zone preparation.

In more complicated cases, several – created in this way – crack systems may coexist in the medium; a simplifying assumption should be made – that each of them is independent from the others. To study the influence of the anisotropic crack system on the resistivity, it should be viewed in the coordinate system aligned with it (otherwise the study of the cracks' influence on resistivity becomes complicated, and a diagonalization procedure is needed, which gives the resulting tensor).

An inverse problem for the simulation domain is the search for the resistivity tensor in its main axes – for component values and orientation of axes. From this, in turn, assessment of the state of the crack system would be possible and in this way the changes precursory to impending shock revealed. It must be stated that the inverse problem is far from being resolved. However, models may be useful comparing the results of simulations with records of the monitoring in the field or in the laboratory may help to calculate hidden causes of observed phenomena.

Generally, the influence of a given crack system is studied in three directions, each perpendicular to the others, which are the directions of three axes of the geometry of cracks. In the simplest case, where cracks are cuboids, these directions are parallel to cuboid edges.

3. Analogies of electrical connection laws for continuous media

In any of three directions, parallel to the axes of the crack system, the influence of the crack system on the appropriate resistivity tensor component will be considered as a function of: resistivity of the rock frame ρ_0, which is taken as constant and uninfluenced by the cracks, resistivity of material *inside* the cracks ρ_+, their volumetric concentration α_+ (in other words, the ratio of total volume of these cracks to total considered volume of rock), and geometry – shape of the cracks.

If primary anisotropy – anisotropy of the rock frame – is allowed by the model, ρ is replaced by the three values: ρ_{ii}, ρ_{jj} and ρ_{kk}, relating to the rock frame's resitivities in consecutive directions i, j, k.

Further, the crack system influence is considered in two aspects, as caused by connections in series – this will be called serial – and by parallel connections – a parallel one, simply. The proportion of division into appropriate parts depends on the geometry of the cracks. Let's start from the serial aspect:

$$\rho_i^{\perp} = f(\rho_{ii}, (\rho_+ - \rho_{ii}), \alpha_+, G). \qquad (3.1)$$

Here G symbolizes crack shape.

In this formula «$-\rho_{ii}$» looks suspicious, but it corresponds to resistance of the rock frame of the volume taken by cracks (the same stands in (3.2)).

For the parallel part, the corresponding formula is the sum of conductivities:

$$\sigma_i^{\parallel} = f(\sigma_{ii}, (\sigma_+ - \sigma_{ii}), \alpha_+, G). \qquad (3.2)$$

Two geometrical coefficients are introduced for each of the three directions along the main axes of the crack system, for the serial and parallel aspect of the resistivity change (thus in all six are needed). We assume, at first, that each of these coefficients is greater than 0 and not greater than 1 and their sum for a given direction equals unity:

$$G_i^{\perp} + G_i^{\parallel} = 1 \qquad (3.3)$$

see section 5.

If current comes perpendicularly across flat inclusions, the geometrical coefficient for parallel aspect is near to 0 and serial is near to 1. That means a great prevalence of serial aspects. A contrary situation is when inclusions are long in the direction aligned with the field, while their dimensions in perpendicular directions are very small. Construction of geometrical coefficients will be explained later.

Formulae are developed which relate geometry and other parameters to resulting resistivity change. Its serial and parallel aspects are multiplied by the geometrical coefficient; total change is the sum:

$$\rho'_{ii} = \rho_{ii} + \rho_{ii}\frac{\Delta\rho_i}{\rho_{ii}} = \rho_{ii} + \rho_{ii}\left(\frac{\Delta\rho_i^{\perp}}{\rho_{ii}} + \frac{\Delta\rho_i^{\parallel}}{\rho_{ii}}\right) \qquad (3.4)$$

where under the symbol ρ'_{ii} is hidden the value of the resistivity tensor component after addition of the crack influence.

Starting from the equation for serial aspect, we have:

$$\Delta\rho_i^{\perp} = (\rho_+ - \rho_{ii})\,\alpha_+ G_i^{\perp} \qquad (3.5)$$

and for a parallel one:

$$\Delta\sigma_i^{\parallel} = (\sigma_+ - \sigma_{ii})\,\alpha_+ G_i^{\parallel}. \qquad (3.6a)$$

Transformation of eq. (3.6a) leads to:

$$\frac{\Delta\rho_i^{\parallel}}{\rho_{ii}} = -\frac{\left(\dfrac{\rho_{ii}}{\rho_+} - 1\right)\alpha_+ G_i^{\parallel}}{1 + \left(\dfrac{\rho_{ii}}{\rho_+} - 1\right)\alpha_+ G_i^{\parallel}}. \qquad (3.6b)$$

If $\rho_+ > \rho_{ii}$ both eqs. (3.5) and (3.6b) have positive values, while for $\rho_+ < \rho_{ii}$ have negative values. From eqs. (3.4) (3.5) (3.6a,b) a general formula is deduced, which is shown here:

$$\frac{\Delta\rho_i}{\rho_{ii}} = \left(\frac{\rho_+}{\rho_{ii}} - 1\right)\alpha_+ G_i^{\perp} - \frac{\left(\dfrac{\rho_{ii}}{\rho_+} - 1\right)\alpha_+ G_i^{\parallel}}{1 + \left(\dfrac{\rho_{ii}}{\rho_+} - 1\right)\alpha_+ G_i^{\parallel}}. \qquad (3.7)$$

For cases where two classes of cracks coexist and have a common geometry and orientation, we find:

$$\frac{\Delta\rho_i}{\rho_{ii}} = \left(\left(\frac{\rho_G}{\rho_{ii}} - 1\right)\alpha_G + \left(\frac{\rho_W}{\rho_{ii}} - 1\right)\alpha_W\right)G_i^{\perp} +$$

$$-\frac{\left(\frac{\rho_{ii}}{\rho_G} - 1\right)\alpha_G G_i^{\parallel}}{1 + \left(\frac{\rho_{ii}}{\rho_G} - 1\right)\alpha_G G_i^{\parallel}} - \frac{\left(\frac{\rho_{ii}}{\rho_W} - 1\right)\alpha_W G_i^{\parallel}}{1 + \left(\frac{\rho_{ii}}{\rho_W} - 1\right)\alpha_W G_i^{\parallel}}. \quad (3.8)$$

Here ρ_{ii} is a component of the resistivity tensor for the rock frame, parallel to a given direction i, ρ_G is the resistivity of gas that fills empty cracks, ρ_W is the resistivity of water in the second class of cracks, and α_G, α_W are concentrations of gas and water-filled cracks, respectively.

If we assume that the medium has its own anisotropy, independent of cracks, in the formula above we should put not ρ_0, but ρ_{ii}, which has the character of a second order tensor. This anisotropy is called here the *primary anisotropy*. Its eventual presence extorts diagonalization after adding the crack influence. In this way, more crack systems, with different geometry or/and orientation, could also be taken into account.

4. Contrast distribution functions

The model, whose essence lies in the formula (3.8), may be unmodestly called elegant, but it is improbable that the real medium behaves accordingly. A short consideration leads to the conclusion that inserting a very high value of ρ_+ results in an enormously large value of $\Delta\rho_i$ and that putting for ρ_+ a very low value gives the resulting ρ_i very close to 0. Thus, factors lowering the crack system influence should be put, to make the model realistic. We may achieve this by applying the Contrast Distribution Function. Many such functions can be found, one was in fact already used in a former paper (Teisseyre K.P., 1995). Here a different function is attributed to lower the contrast in the case of highly resistive inclusions, than in the case when inclusions have greater conductivity than the rock frame.

4.1. *Great resistivity cracks: electric current deviation*

If crack/inclusion has a higher resistivity than the surrounding rock frame, I assumed that when the electric field comes across such inclusion, part of the current finds a way around it. Therefore, the effective resistivity of material inside the inclusion cannot be unrestrictedly high, for given ρ_0, resistivity of rock frame, it may attain only a certain finite value. To model this hypothesis, an arc-tangens function is used. For small α_+ (volumetric concentration of the cracks), a good way in modelling would be to replace in the formula (3.8) ratio ρ_+/ρ_{ii} by the following normalized equivalent: $\frac{4}{\pi}$ arc tg $\left(\frac{\rho_+}{\rho_{ii}}\right)^{1/3}$. For high concentrations, this equivalent should be close to ρ_+/ρ_{ii}. Therefore, I took the following formula as universal. For $\rho_+ > \rho_{ii}$, I assume the ρ_+/ρ_{ii} equivalent as follows:

$$\left(\frac{\rho_+}{\rho_{ii}}\right)_{\mathrm{Eq}} = \left(\frac{4}{\pi}\,\mathrm{arc\,tg}\left(\frac{\rho_+}{\rho_{ii}}\right)^{1/3}\right)^{(1-\alpha_+)}\left(\frac{\rho_+}{\rho_{ii}}\right)^{\alpha_+}. \quad (4.1)$$

In the exponent 1/3 is taken to reduce the crack influence.

4.2. *Low resistivity cracks: size influence*

The situation with $\rho_+ < \rho_{ii}$ is different. Therefore, I intend to connect the effective ρ_+/ρ_{ii} ratio with the dimension of inclusion in a given direction i. Descriptively, it is easy for the current to enter an inclusion filled with material of greater conductivity. But such image works well for long enough cracks. Shorter cracks should give an inhibiting effect. Also the cracks' volumetric concentration α_+ should be taken into account – if it is high, inhibition is milder because cracks are surrounded by a smaller volume of rock frame.

Mathematically, the following expression corresponds to these ideas.

For $\rho_+ < \rho_{ii}$, I assume effective ρ_+/ρ_{ii} equivalent to:

$$\left(\frac{\rho_+}{\rho_{ii}}\right)_{\mathrm{Eq}} = \left(\frac{\rho_+}{\rho_{ii}}\right)^{(i/l)(1-\alpha_+)/3} \tag{4.2}$$

where l is characteristic length (here I assumed that l is equal to the distance between the current electrodes A and B). In extreme cases where $\alpha_+ = 1$, we obtain $\left(\frac{\rho_+}{\rho_{ii}}\right)_{\mathrm{Eq}} = \left(\frac{\rho_+}{\rho_{ii}}\right)$, and a sufficient condition for the same result is when $i = l$. In a process of simulation, relative dimensions i, j and k are chosen by the user, and later the dimensional factor is introduced. When for transformed ratios of resistivities we put symbols of their equivalents, the final equation for resistivity change in a given direction i (one of the directions of the crack system geometry) will be:

$$\frac{\Delta\rho_i}{\rho_{ii}} = \left(\left(\left(\frac{\rho_G}{\rho_{ii}}\right)_{\mathrm{Eq}} - 1\right)\alpha_G + \left(\left(\frac{\rho_W}{\rho_{ii}}\right)_{Eq} - 1\right)\alpha_W\right)G_i^{\perp} + \\ - \frac{\left(\left(\frac{\rho_G}{\rho_{ii}}\right)_{\mathrm{Eq}}^{-1} - 1\right)\alpha_G G_i^{||}}{1 + \left(\left(\frac{\rho_G}{\rho_{ii}}\right)_{\mathrm{Eq}}^{-1} - 1\right)\alpha_G G_i^{||}} + \\ - \frac{\left(\left(\frac{\rho_W}{\rho_{ii}}\right)_{\mathrm{Eq}}^{-1} - 1\right)\alpha_G G_i^{||}}{1 + \left(\left(\frac{\rho_W}{\rho_{ii}}\right)_{\mathrm{Eq}}^{-1} - 1\right)\alpha_G G_i^{||}}. \tag{4.3}$$

The equivalent ratios are defined as ratios, reduced in such a degree, as to permit the geometrical approximation to be used for parallel and series connections in a continuum.

5. Geometrical coefficients

To achieve anisotropic model of influence on rock resistivity by the oriented crack system, it is necessary to connect the shape of the inclusion with the geometrical coefficients. This is a part of a calculation of the resistivity change, in all three main axes, with regard to both serial and parallel parts of the change. Let's start from the case of resistivity variations along the direction of the electric field, *i.e.*, when the current passes perpendicularly through consecutive objects (layers) with different resistivities: R_1, R_2 etc. The sum of resistances of all layers is equal to the resistance of the whole medium: $R = \Sigma R_{(n)}$. We assume that the length of an object in which the electric current flows through a system of layers is i, and object (here for object please put any one of the mentioned inclusions) is a cuboid with dimensions i, j and k. Introducing a new layer into the medium, we have some change of the total resistance; such a variation related to direction i may be expressed as follows:

$$\delta R = \int_0^j \int_0^k \int_0^i \delta\rho_{ii}\,\mathrm{d}v = jk \int_0^i \delta\rho_{ii}\,\mathrm{d}i \tag{5.1}$$

where $\delta\rho_{ii}$ is a relative change in materials resistance, $\left(\frac{\rho_+}{\rho_{ii}} - 1\right)$, and for isotropic rock frame $\left(\frac{\rho_+}{\rho_0} - 1\right)$, per unit surface perpendicular to the current direction.

For parallel connection the variations of resistivity in planes ij and ik influence the conductance of the medium: $S = \Sigma S_{(n)}$.

We obtain:

$$\delta S = \int_0^i \int_0^j \int_0^k (\delta^{(j)}\sigma_{ii} + \delta^{(k)}\sigma_{ii})\,\mathrm{d}v = \\ = ij \int_0^k \delta^{(k)}\sigma_{ii}\,\mathrm{d}k + ik \int_0^j \delta^{(j)}\sigma_{ii}\,\mathrm{d}j \tag{5.2}$$

where $\delta^{(k)}\sigma_{ii}$ and $\delta^{(j)}\sigma_{ii}$ are relative changes of conductance per unit surface parallel to the current direction. The geometrical coefficients appear to be nondimensional, thus crack influence as expressed in eq. (3.8) is independent of the crack sizes. However, Contrast Distribution may bring size dependence. From (5.1) and (5.2), it follows that geometrical coefficients are proportional to:

for series connections $G_i^{\perp} \propto jk$ (5.3a)

and for parallel connections

$$G_i^{\parallel} \propto (ij + ik). \quad (5.3b)$$

After accepting the statement that geometrical coefficients are proportional to adequate views on the inclusion (5.3a,b), the simplest further assumptions are:

$$G_i^{\perp} + G_i^{\parallel} \propto (jk + ij + ik) \quad (5.3c)$$

and, because $G_i^{\perp}$, $G_i^{\parallel}$ are not related to any absolute dimensions,

$$G_i^{\perp} + G_i^{\parallel} = 1$$

thus the expression (3.3) achieves its explanation. This follows also from the fact that we divide current only into two parts.

Now because the sum of both coefficients for a given direction is 1, normalization is needed, therefore:

$$G_i^{\perp} = jk/(jk + ij + ik);$$

$$G_i^{\parallel} = (ij + ik)/(jk + ij + ik). \quad (5.4).$$

The geometrical coefficients may be devised differently, for example in Teisseyre K.P., (1991) a different method of calculation was presented.

6. Field observations, experiments and numerical simulations

6.1. *Results from surveys in the seismic areas*

In Kayal's and Banerjee's (1988) results from brittle rocks (quartzite metamorphics) in Shillong Plateau, there was an anisotropic apparent resistivity.

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,

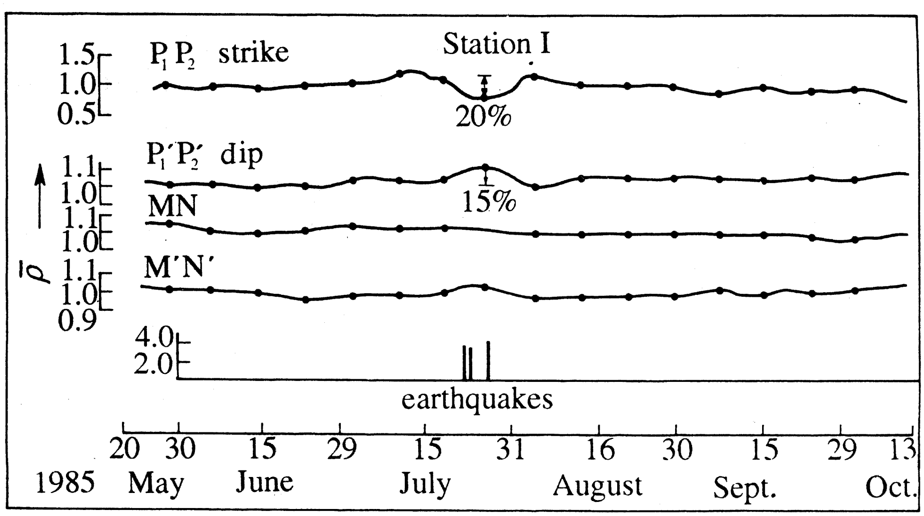

Fig. 1. Relative changes of apparent resistivity observed in Shillong Plateau (after Kayal and Banerjee, 1988).

respectively; $M\ N$ and $M'\ N'$ were located in between. During a third of the active periods, in the middle of summer 1985, there was a precursory bay-like rise in resistivity, by some 15%, recorded in the strike direction $P'_1\ P'_2$, followed by a decrease of about 30% all in 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. At two other directions practically no changes were recorded (see fig. 1). We may assume that the crack orientation was close to vertical planes; in the discussed case, these planes were perpendicular the strike of the geological formation; and coexistence of dry and wet cracks occurred. Thus it is possible to explain observed variations in terms of the model discussed above – by the concurrence of dry and wet cracks of roughly the same geometry and orientation.

In nearby station 2, located on more plastic rocks (phyllite), anomalies in resistivity were recorded in the same time span, but isotropic. This is not surprising, as a common orientation

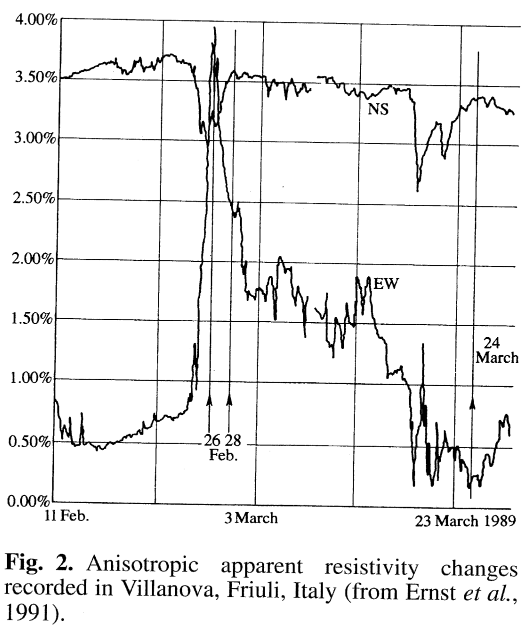

Fig. 2. Anisotropic apparent resistivity changes recorded in Villanova, Friuli, Italy (from Ernst *et al.*, 1991).

of tectonic cracks over a large area is less probable in weaker medium.

Another example is taken from the resistivity measurements in the Friuli seismic region (Ernst *et al.*, 1991). Before 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. 2, left part of fig. 24 in the original paper). 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 gave no distinct precursory signals.

6.2. *Anisotropy revealed in monitoring in the mine*

It must be noted that it is impossible to measure the components of the resistivity tensor directly. However, if there are many measuring arrays, differently oriented, it is possible to find which ones are oriented near tensor's main axes. Stopinski found, during research in the Lubin copper mine, resistivity changes before and after tremors. These changes were large and often bay-like in shape (Stopinski, 1986; Stopinski and Teisseyre R., 1982). On parallel measuring arrays they exhibited a similar trend, thus inferring crack orientation in a relevant area was in some cases possible (Teisseyre K.P., 1989 – on basis of the simpler model, mentioned above). The crack orientation, deduced in this way, was perpendicular to those measuring arrays on which no apparent resistivity increases were observed during the dilatancy phase.

The same measuring sites later gave a profound decrease, interpreted as a symptom of perculation phase in the rock mass. Increased resistance in the dilatancy phase should be greatest for the electrode array parallel to the cracks' longest dimension, and a decrease during the percolation phase should be in this direction smallest.

Some more examples of anisotropic resistivity changes of tectonic origin were published by Teisseyre K.P. (1989, 1991, 1995).

6.3. *Laboratory experiments*

Measurements were conducted on cubic artificial samples, made of gypsum; part of the samples contained oriented inclusions, made from highly conducting silver glue, in the form of parallel bands, not in contact with the walls of the sample. A two-electrode method was employed and measurements were made through the sample. Arrangement for measurement was as follows: a pair of square, gold-plated electrodes was squeezed with the sample, insulated from outside and connected to an impedance analyzer.

After recording of resistance *vs.* frequency in one direction, two analogical series of measurements were performed – along two other directions in turn. This research revealed that in the samples resistance anisotropy exists, although not very high. Signs of differences between results for different directions were in most cases as expected, the measured conductance being highest when current direction was along inclusions, lowest, bonded with direction perpendicular to inclusion planes, while the third direction, aligned with these planes, though not with the inclusions' longest dimension but perpendicular to it, gave intermediate results. Beside this, conductance of the samples was positively correlated with the frequency of measuring current. Plots of two consecutive measuring series, on the same sample, are gathered in fig. 3. These measurements were made after the sample had been drying for *circa* 6 h when obtained conductivity was in the range 180-700 μS.

As only crack-imitations were used, no pressure was applied. Also no search for specific area in the sample, such as that conducted successfully by Kurita (1986), was tried in these experiments.

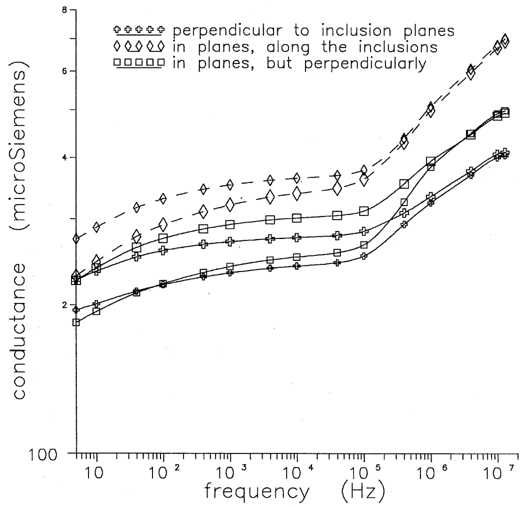

Fig. 3. Conductance of cubic gypsum sample, weighing about 110 g and containing 40 bands of conducting glue. After a first series of measurements in three directions, a second was done. Smaller symbols: first series; bigger symbols: second series.

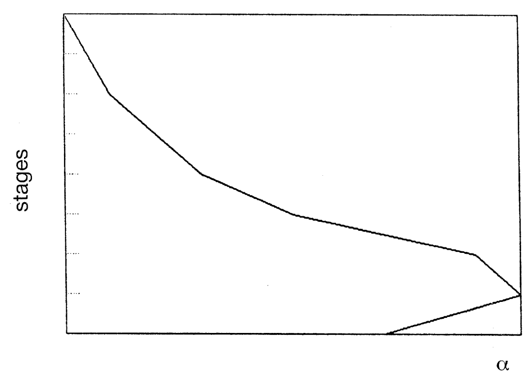

Fig. 4. Relative concentration, both of empty and water-filled cracks, in the cases of numerical simulation presented here. From top to bottom of the plot: consecutive stages.

6.4. *Numerical simulations*

In all the simulations presented here, input data regarding relative crack concentrations were taken for every other tenth stage, these values made the sequence: 0, 0.5, 1, 2, 3, 5, 9, 10, 7. For intermediate stages, intermediate values of the crack concentrations were calculated. Figure 4 is the diagram of relative crack concentrations.

These numbers were multiplied by factor 0.022 in the case of water-filled cracks, by 0.011 in the case of empty or gas-filled cracks

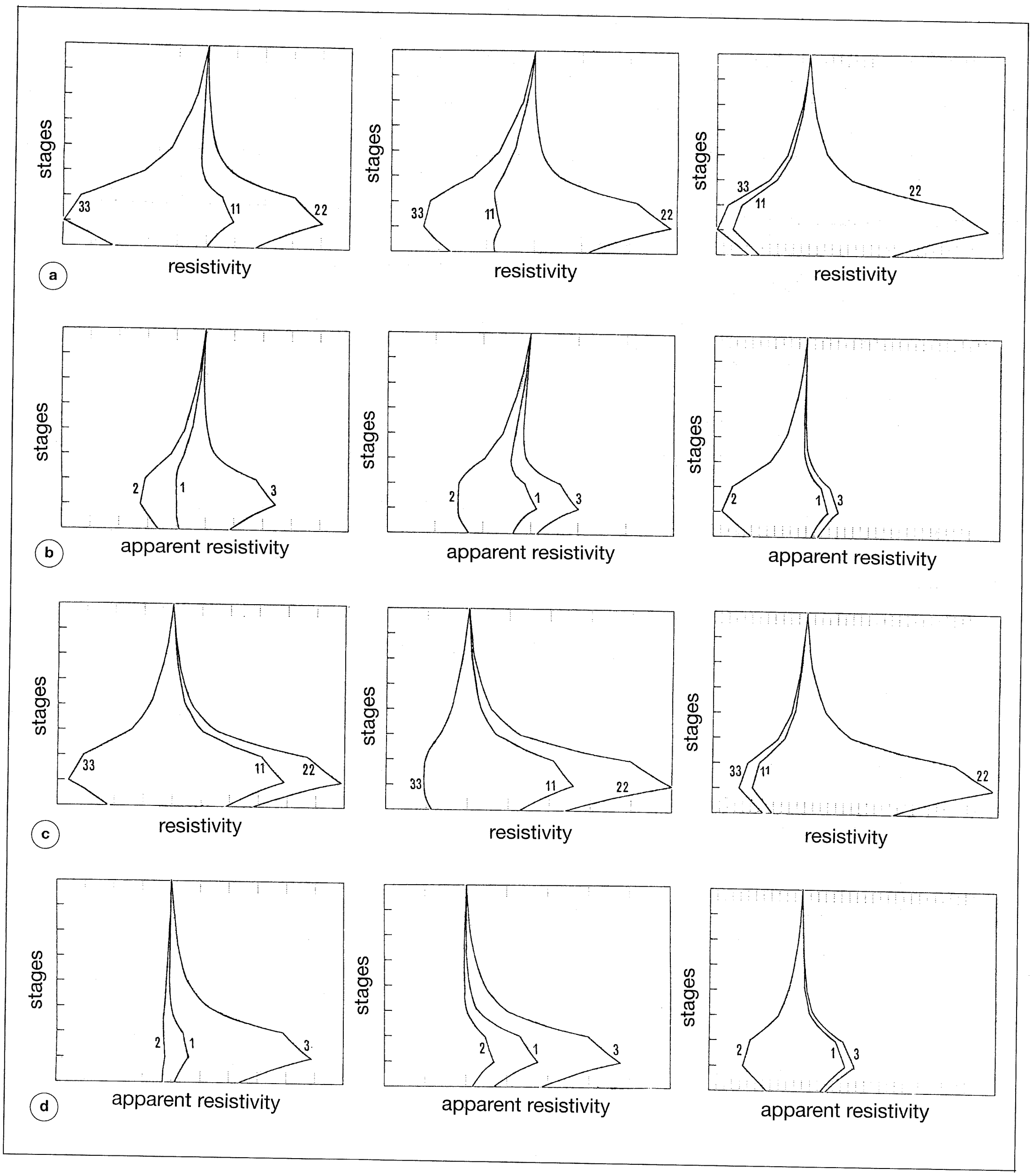

Fig. 5a-d. Results of six courses of numerical simulation. Left column: relative dimensions of cracks 1.4, 1, 20. Middle column: relative crack dimensions 15, 9, 20. Right column: relative crack dimensions 15, 1, 20. Two upper rows: dimensional coefficient = 0.02, two lower rows: dimensional coefficient = 0.01. On vertical axes – consecutive stages, from top to the bottom; horizontally – resistivity, in conventional units. Curves 11, 22, 33 – resistivity tensor components; 1, 2 and 3 – curves of apparent resistivity at electrode arrays situated respectively along axis 1, 2 and 3 of the crack system.

so that the volume of water-filled cracks was always twice as large.

Each simulation run consisted of 81 stages. No primary anisotropy was assumed; examples of primary anisotropy influence in simulations were presented in Teisseyre K.P. (1995).

Figure 5 shows the results of six simulation courses grouped in three cases. In all cases ρ_G (resistivity of gas) is 50000, ρ_W (resistivity of water) is 0.00005, while rock frame resistivity ρ_0 is 1. Three geometries of the crack were tested. In one series of simulation courses, relative dimensions of cracks are 1.4, 1 and 20, thus cracks are rod- or pen-like – this is case 1. In case 2 they are 15, 9 and 20. In the third case relative dimensions are 15, 1 and 20 – so the cracks are flat. Parts (a) and (c) are resistivity tensor diagrams; in the whole of fig. 5 the vertical axis corresponds to time; results for consecutive stages are plotted from the top to bottom of each picture. Resistivity changes along the horizontal dimension. The apparent resistivities, at simulated arrays situated along axis 1, axis 2 and 3 are plotted, for these cases, in parts (b) and (d) of fig. 5, as curves 1, 2 and 3, respectively. The scale for apparent resistivities plot is always the same as the scale in the adequate tensor components plot. The order of apparent resistivity values is opposite to the order of resistivity tensor components because if the measuring array lies along one of the (resistivity) tensor axis, a so-called paradox of apparent resistivity appears. In the author's simulation programs, at this moment, if crack size is taken into account, all cracks have the same size.

Two values of dimensional factor (which influence wet cracks' effective resistivity) were chosen for the presented examples: 0.02 and 0.01. The Contrast Distribution Function for good-conducting cracks was devised in such way, that small crack size diminishes the effect which this crack imposes on resistivity. The size effect is clearly seen in cases 1 and 2, a decrease of resistivity due to wet crack prevalence was greater in parts (a) and (b) of the diagrams which correspond to dimensional factor = 0.02, then when it is 0.01, parts (c) and (d). In case 3, representing flat cracks, the difference is very small. Only in case 3 was the horizontal scale the same in all four parts; in other cases it was the outcome of the resulting data. Also in case 3 the range of resistivity tensor components was widest: from 0.76 to 1.5 conventional units. In case 2 a) and b) the range on the horizontal axis was the most narrow – from 0.85 to 1.15 conventional units.

Input data were deliberately chosen, as to obtain concurrent changes of opposite signs, similar to those found by Kayal and Banerjee (1988).

7. Concluding remarks

The importance of many-directional resistivity measurements is stressed, as only in this way could resistivity tensor components be calculated. From this, in turn, the crack state of the medium may be deduced. Changes in cracks precede and, in fact, cause the rupture, so an effective method of monitoring them would be extremely profitable. For any sufficiently large area, where crack orientation and geometry is roughly constant, a model like that presented here may be applied to help in the interpretation of resistance survey results. Simpler models, like those of Carrara *et. al.* (1994) or Teisseyre R. (1983) connect the resistivity of the compound medium with crack-and-pore content and the degree of water infiltration into these spaces. In the model by Teisseyre R. (see also Stopinski and Teisseyre R. 1982) connections between cracks also play a very important role. While these models help in understanding of crack state and processes influence on resistivity, their drawback comes from disregarding the directional features of the cracks. Thus, these models are not anisotropic, while results from many investigations, both in the field and laboratory, reveal the existence of electrical anisotropy in stress-loaded media. 3D anisotropic models may help in prognostic research, also in electric methods domain.

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