CHARACTERISATION OF ACTIVE FRACTURES BY LOW FREQUENCY SINGLE HOLE AND CROSS HOLE ELECTROMAGNETIC MEASUREMENTS

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1. ABSTRACT

Water circulation in fractures is the dominant process for thermal exchanges and transfers in rocks, the detection and the characterisation of active fractures is thus an important element in geothermal studies. Low frequency Electromagnetic methods can be used to characterize fractures when injected fluids are significantly more conductive or magnetic than the medium. They provide information over metric, plurimetric and hectometric ranges of distance from the wall so completing information supplied by wall imagery techniques. We propose here the principle of an apparatus which realizes both single and cross hole measurements. In the first application three orthogonal transmitters and three orthogonal receivers 1.2 apart are used. The same sensors are used for the signal transmitted in other(s) hole(s) by vertical wire(s). Although in complex situations, where several discordant families are present, the orientation is difficult to be restitute, the sensitivity of measurements, in both modes, to single fracture orientation is good. In cross hole, the responses are approximately proportional to the fracture area and conductance.

2. KEY WORDS

E.M. geophysical techniques, fracture characterization in hot dry rocks, single hole, cross hole, resistivity contrasts.

3. INTRODUCTION

Water circulation within rocks is the chief process which allows us to extract energy from the earth's crust To evaluate this process techniques for fracture location are required to determinine orientations and separate those where the fluid circulates from the non active ones. As the fluid may be more conductive (brine, for example) or magnitically loaded (Sakashita and Shima, 1993), different low electromagnetic techniques can be of value for achieving these three objectives.

In downhole measurements, mapping of the wall fractures by hole imaging is now common practise (using acoustic impedance or electrical contact resistance), but their penetration is limited to approximately one centimetre. The investigated volume is thus

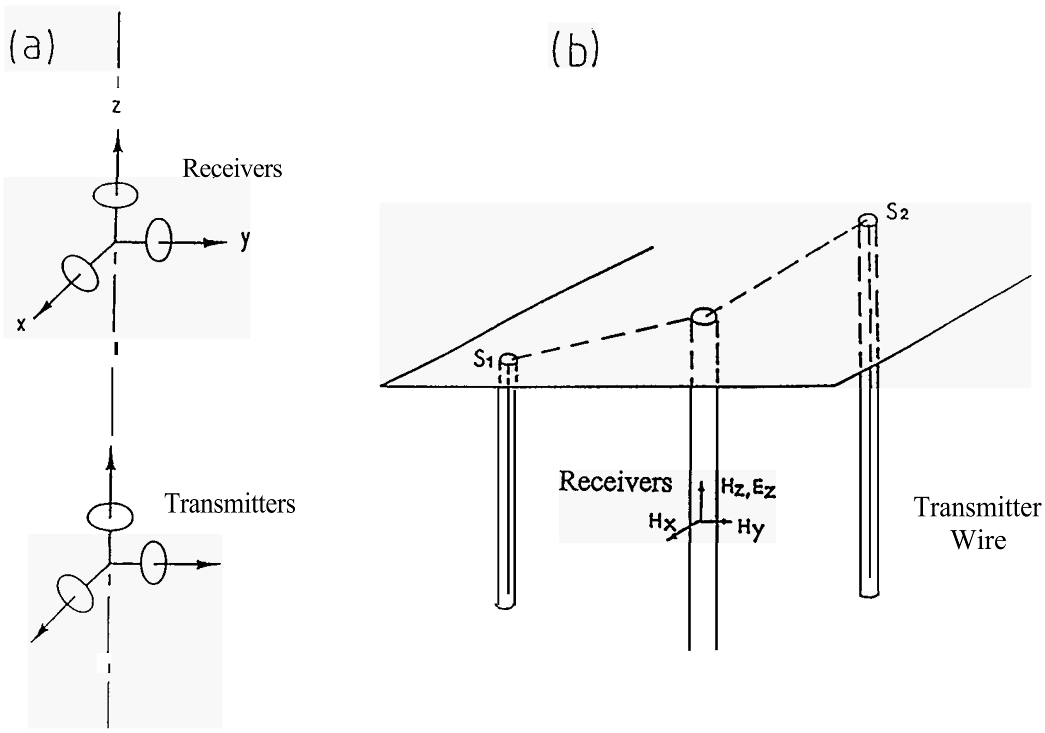

Figure 1 a) Disposition of the three orthogonal coil receiver and transmitter systems.
b) The system of emitting cables in the cross hole mode.

restricted and, as a spurious fracturation can be induced by drilling, the images may *not* be representative of the bulk rock. Techniques are therefore required for studying fractures over metric to hectometric ranges of distance from the hole.

4. MEASIJREMENT CONCEPTS

As active fractures can constitute conductive targets and E.M. methods are more sensitive to orientation than electrical methods, E.M. induction is normally preferred to gaivanic injection (Landt, 1978; Zhou et al., 1987; Tsang et al., 1993). Here two different concepts were combined. For metric to plurimetric ranges of investigation we defined a single hole instrument (Tabbagh and Giannakopoulou, 1994) where three orthogonal magnetic transmitters and three orthogonal magnetic receivers 1.2 m apart are used (Figure 1 a). Identifying each transmitter by a frequency one car: perform nine complex measurements which are presented in a matrix form:

$$\begin{pmatrix} R_{xx} & R_{xy} & R_{xz} \\ R_{yx} & R_{yy} & R_{yz} \\ R_{zx} & R_{zy} & R_{zz} \end{pmatrix}$$

where R_{ij} is a complex value corresponding to the magnetic field component measured in the j directed receiver for the signal transmitted by the i directed transmitter. For a hectometric range of investigation the three receivers are again used together with a vertical (i.e. parallel to the hole axis) electric field sensor. The signal is transmitted in another hole with a vertical wire (Figure 1 b), the phase of the transmitted current is driven by the receiver unit so that the four complex responses are determined.

5. RESULTS OF THEORETICAL MODELLING

The fracture is modelled in 3D by the moment method for both an electrical and a magnetic contrast between the filling in and the surrounding medium.

5.1 Single Hole Mode

For a homogenous medium or a horizontal fracture all tire non - diagonal terms in tlie matrix are nil. The conductivity responses are ai maximum when the fracture lies between receivers and transmitters (Figure 2) while the susceptibility responses exhibit two peaks when each group of coils is located In front ofthe fracture (Figure 3).

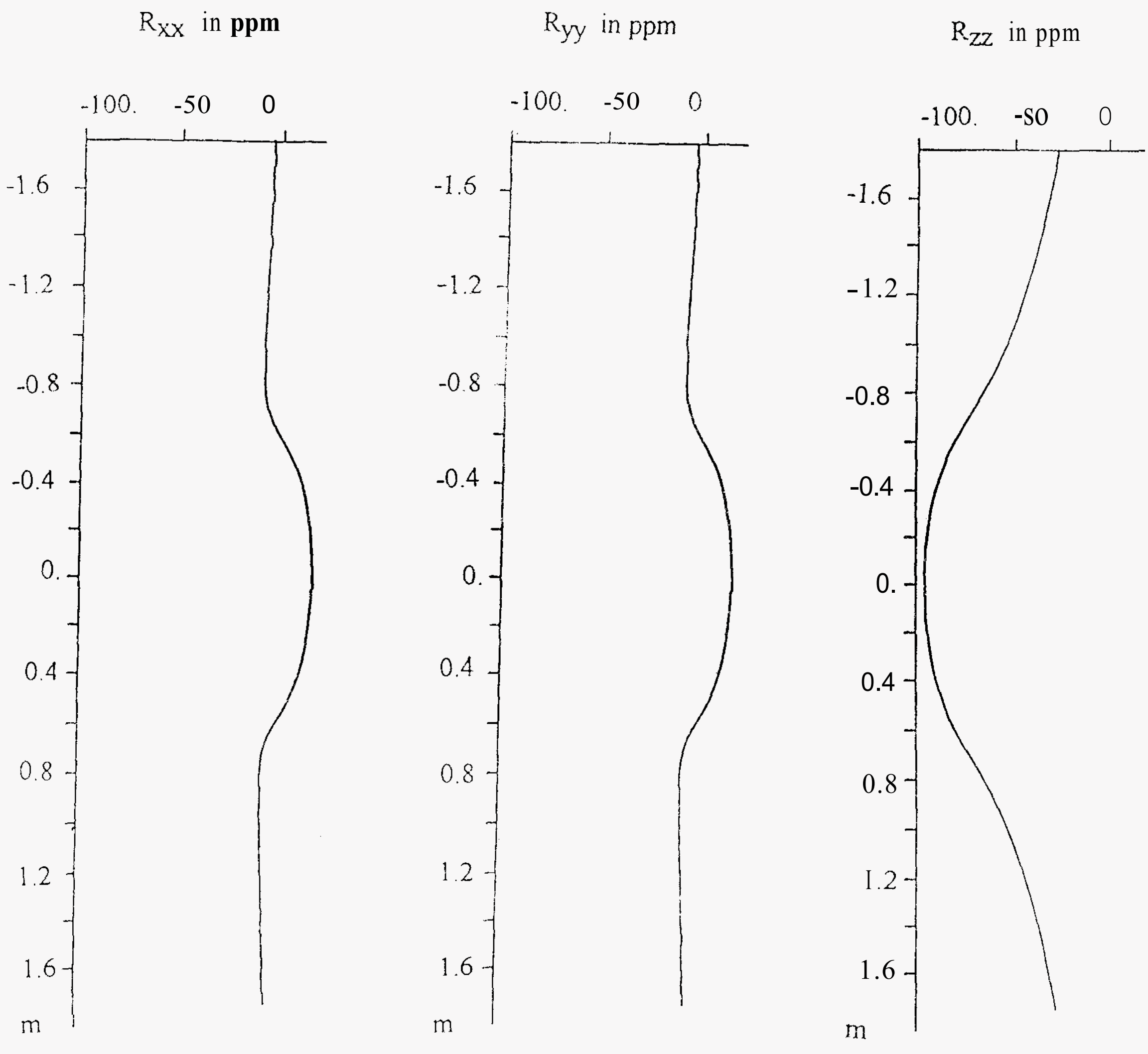

Figure 2 Single hole mode : quadrature values of the three non zero diagonal terms of a horizontal fracture, centred at 0 m, with thickness of 0.002 m, susceptibility of 0.0033 S.I. and conductivity of 10 S/m, inside a surrounding medium of 1000 Ω m resistivity and 0 0003 S ! susceptibility (The responses are expressed by the ratio ofthe secondary magnetic field to the primary one at receiver location, in ppm) The frequencies are 8000 Hz (in the x direction), 8020 *Hz* (in y) and 8040 (in z).

When the fracture is not horizontal (Figure 4 a and 4 b), the non diagonal terms are of equivalent magnitude as the diagonal ones

However the susceptibility responses are more complicated than the conductivity responses which are of greater interest for restituting the orientation. The combination of E.M. susceptibility and magnetic field measurements would be preferable to characterize high susceptibility fractures (Broun et al., 1991; Desvignes et al., in prep.). When several discordant fractures are present, ail the responses become complex and it becomes difficult to restitute the orientation ofeach.

5.2 Cross Hole Mode

For one fracture the responses are proportional to the area, to the thickness and to the conductivity or to the susceptibility contrast. The angular dependencies are simple and they correspond to sine or cosine variations (Figure 5).

But the susceptibility responses are far weaker than the conductivity ones and only this last parameter can be used for hectometric or plurimetric cross hole measurements. A fractured zone, consisting of small, random orientated fractures, whose global shape is equivalent to one fracture supplies equivalent responses and angular dependencies but again, the presence of several discordant orientations for major fractures will disturb the orientation determination.

An increase in the distance between the two holes corresponds to a decrease in the response which has to be compensated by an increase of the surface or the conductivity of the fluid. However this dependence has the advantage of separating the large major fractures from the minor ones.

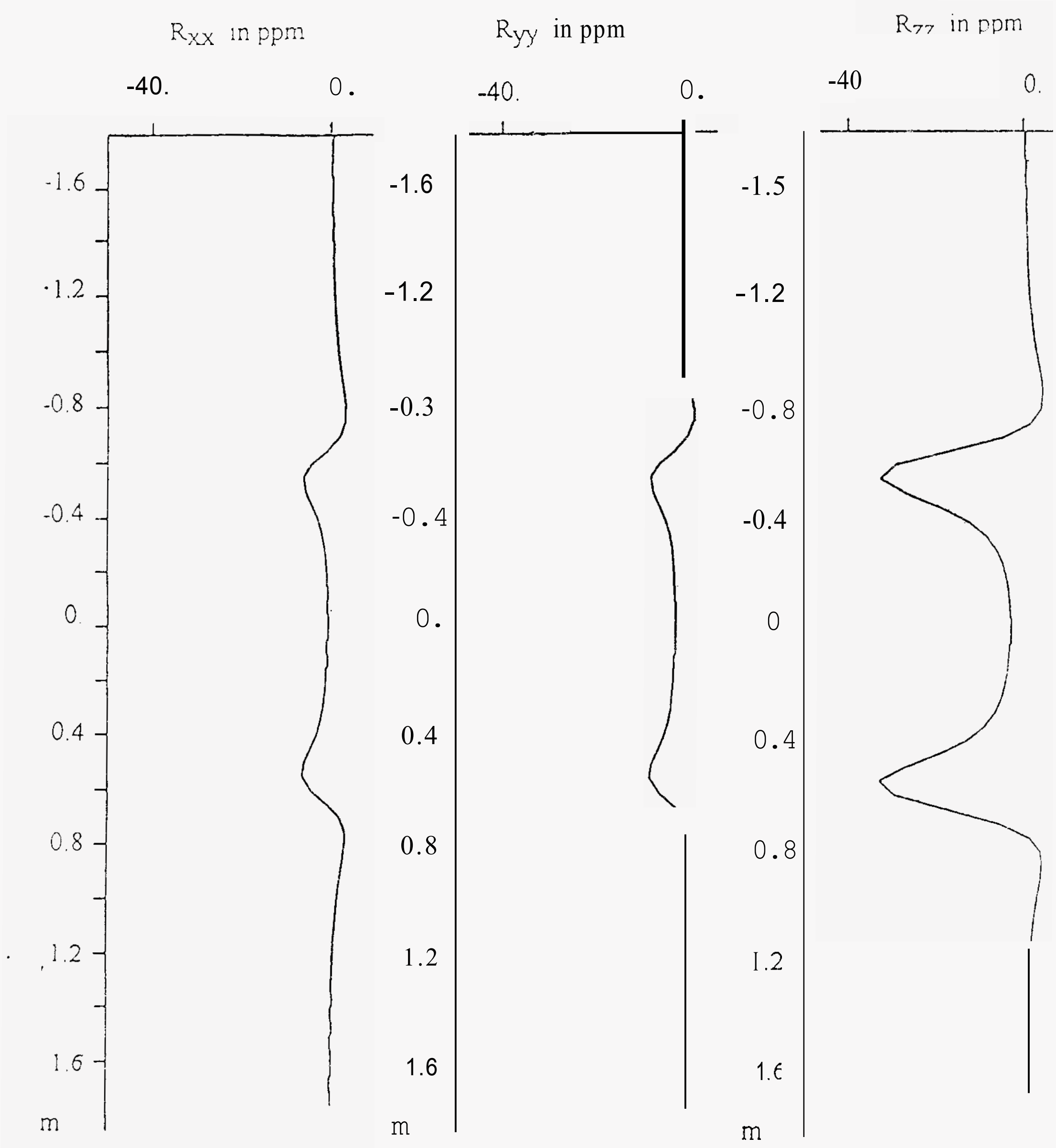

Figure 3 Single hole mode : in - phase values of the three non zero diagonal terms of a horizontal fracture, centred at 0 in, with thickness of 0.002 m, susceptibility of 0.0033 S.I. and conductivity of 10 S/m, inside a surrounding medium of 1000 Ω m resistivity and 0.0003 S.I susceptibility (The responses are expressed by the ratio of the secondary magnetic field to the primary one at receiver location, in ppm) The frequencies are 8000 Hz (in the x direction), ***8020*** Hz (in y) and 8040 (in z).

6. CONCLUSION

As can be expected from the general characteristics of inductive E.M. prospecting. the theoretical modelling confirms that the single hote and cross hole concepts are relevant to fracture detection. The magnetic susceptibility that corresponds to a greater decrease with the distance from the target, is less usable than the electrical conductivity. For single fracture or fractured zone the orientation restitution will be reliable; when several discordant orientations are present, their restitution, in practice, is not possible. But as the influence of these orientations on the direction of water circulation tends to be limited, this drawback is of little consequence.

7. ACKNOWLEDGEMENTS

The present study was funded by the French Agency A.D.E.M.E., who supplied both the grant for V.G.'s thesis and supported the calculation costs through the 2.07.0006 convention with Paris 6 university

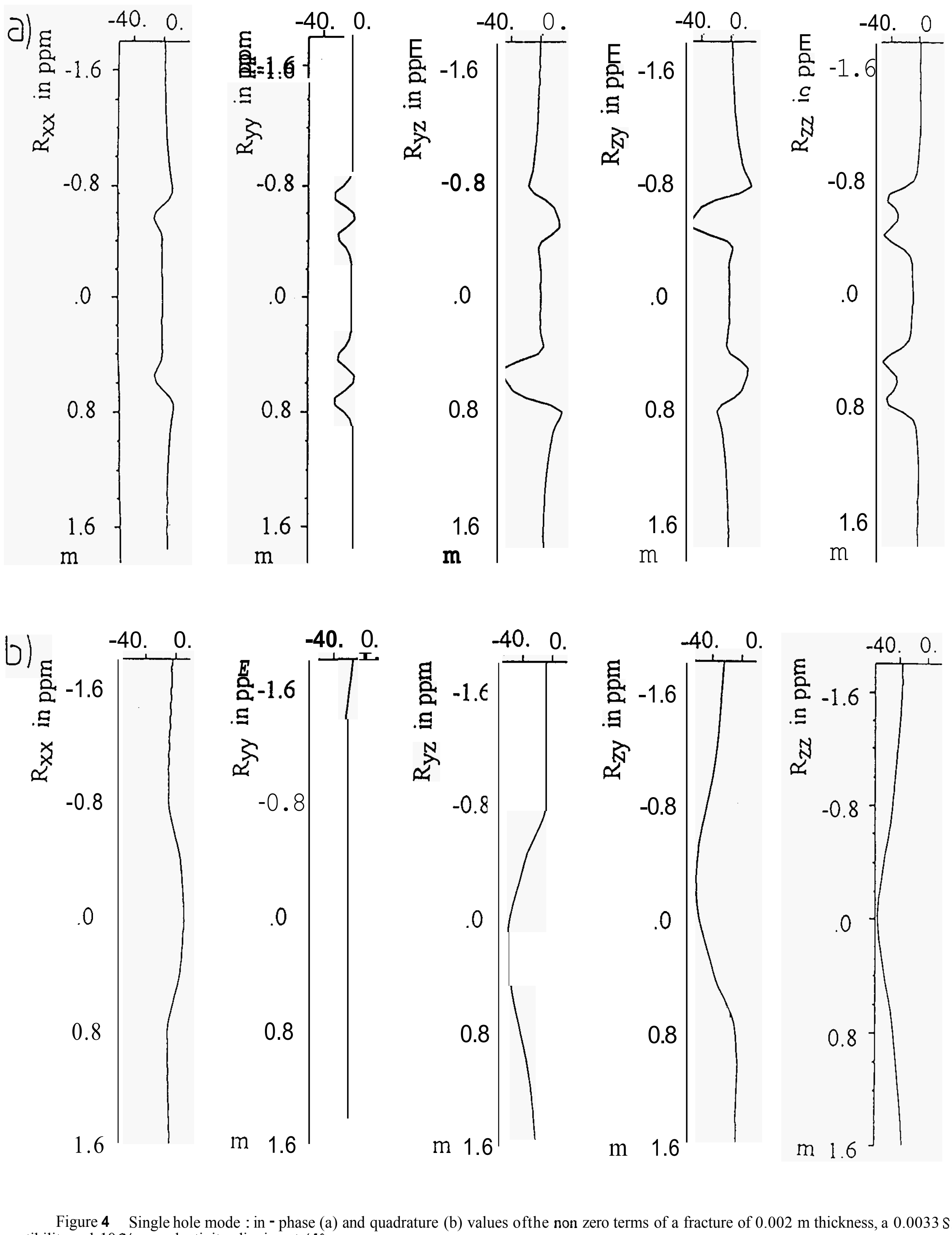

Figure 4 Single hole mode : in - phase (a) and quadrature (b) values ofthe non zero terms of a fracture of 0.002 m thickness, a 0.0033 S.I. susceptibility and 10 S/m conductivity, dipping at 45°.

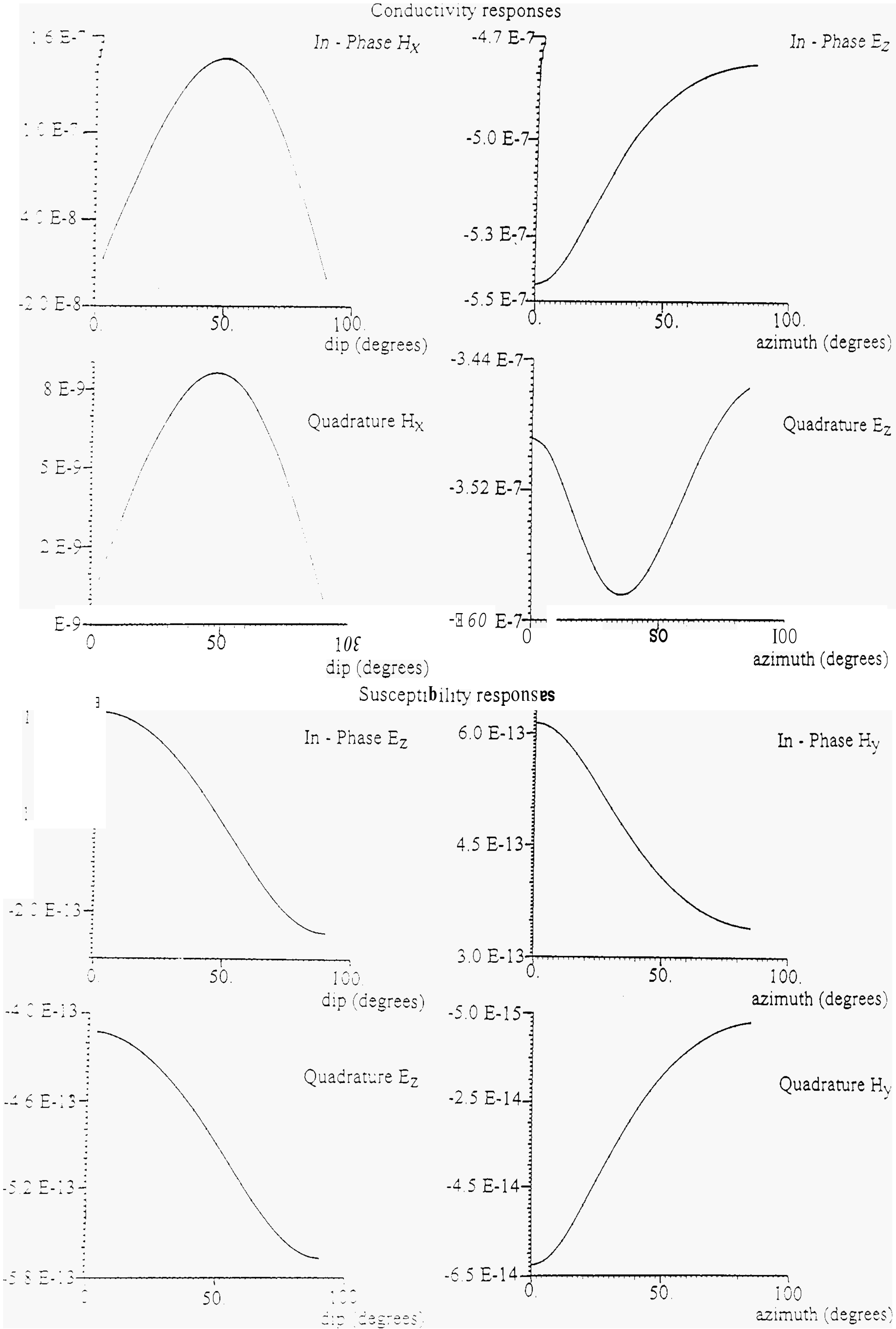

Figure 5 Cross hole mode : angular dependencies on the azimuth ϕ and the dip θ of a square plane conductive or magnetic fracture with dimensions of 300 × 300 × 0.002 m, resistivity of 0.1 Ω m and susceptibility of 0.005 S.I, lying in a medium of 1000 Ω m resistivity and 0.0005 S.I. susceptibility equidistant between two boreholes 600 m apart in the x direction. The cable emits at frequency of 500 Hz at a depth of between 1200 and 1800 m and the signals was recorded at a depth of 1700 m.

8. REFERENCES

Broun, P., Thomas, T. and Lillie, F. (1991). Analyse structurale a partir de diagraphies de gradient de champ magnetique. Exemple du gîte aurifère des Farges (Massif Central Français). ***Chronique de la recherche minière,*** 503, pp. 27-35.

Desvignes, G., Fielberg, F., Kuhnke, F. and Tabbagh ,A (in prep.). Combined interpretation of susceptibility and magnetic field logs in presence of dipping layers. ***18th General Assembly*** *E.G.S.,* ***Wierbaden 3-7 Mai.***

Landt, J.A. (1978). ***A magnetic induction technique for mapping vertical conduchon fractures, theory of interpretation.*** Informal Report L.A 7333 - **M.S.** Los **Alamos** Scientific Laboratory. 18pp.

Tabbagh, A and Giannakopoulou, V. (in press). Model calculations of the response of thin dipping layers to a three orientated low frequency electromagnetic tool under realistic boundary conditions. *Scientific* ***Drilling.***

Tsang, C.F., Hufschmied, P.and Hale, F.V. (1990). Determination of Fracture Inflow parameters with a borehole fluid Conductivity logging method. ***WaterReseources Research,*** 26(4), pp. 561-578.

Zhou, Q., Becker, A, Morrison, H.F.,Golstein, N.E. and Lee, K.H. (1987). Fracture detection using subsurface electromagnetic techniques. 28th ***US Symposium on*** *Rock Mechanics*, Tueson. pp. 5-17.

Sakashita, S. and Shima, H. (1993). Controlled source magnetic susceptibility tomography using cross hole data : A numerical evaluation. *63rd Ann.* ***Int. Meeting.*** *S.E.G.,* ***Expanded Abstracts,*** pp. 377-380.