A MAGNETIC METHOD FOR DETERMINING THE GEOMETRY OF HYDRAULIC FRACTURES

by

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ABSTRACT

We propose a method that may be used to determine the spatial orientation of the fracture plane developed during hydraulic fracture. In the method, magnetic particles are injected into the crack with the fracturing fluid. Since the magnetization of a body with extreme dimension ratios, such as a crack, exceeds that of an equidimensional body and since this magnetization is sensitive both to orientation and geometry, this could be used to obtain information about the crack. By measuring the vertical and horizontal components of the magnetic field and field gradients at the earth's surface surrounding the injection well with superconducting magnetometers having 10^{-4} gamma sensitivity and also by measuring field direction within the well itself, it should be possible to calculate the orientation and perhaps infer the approximate geometry of the fracture surface. Experiments on electric field potential operated in conjunction with this experiment could further constrain estimates of shape and orientation.

INTRODUCTION

Since 1948 hydraulic fracture has been used extensively to increase oil well production (Hasselbrook and Waters, 1964). The process consists of applying fluid pressure to the reservoir rock exposed over a short section of the well until fracture occurs. If the pressure is maintained after rock failure, the fluid extends the fracture outward from the injection well.

The orientation of the induced fracture at the well may be determined in various ways, for example, photography of the walls of the well with a down-hole camera, deformable impression packings, acoustic logs, or radioactive tracers (Anderson and Stahl, 1967). Daneshey (1971) pointed out, however, that none of the principal stresses may be parallel to the axis of the borehole; in this case the fracture at the well may be vertical, but once the fracture extends beyond the stress field distorted by the borehole, it will become perpendicular to the least principal stress. Thus even though we may be able to determine the orientation of the fracture surface at the borehole, we cannot, at present, unambiguously determine the fracture orientation at any significant distance from the injection well.

It is often assumed that during hydrofracture of oil wells the vertical extent of the fracture is controlled by barriers above and below the fracture zone. It has been postulated that shale may act as a barrier because the horizontal stress within the shale may be higher than it is in the sandstone-producing zone (Martin, 1967). If this assumption is correct, then the length of the fracture may be very much greater than its height, but in most cases there is no way to determine the validity of this.

It is common practice to calculate the width of the fracture by assuming that the fluid pressure forces open the crack and that the rock behaves as a perfectly elastic material. The volume of the fracture is calculated by subtracting the estimated loss of fluid through the fracture walls from the volume of fluid that had been injected. From a knowledge of the volume and width of the fracture, the area of the newly formed surface can be calculated (Nordgren, 1972). Unfortunately, there is usually no way of knowing whether the theoretical predictions are correct or not.

Thus with present oil field technology there is no direct way to determine the orientation, length-to-height ratio, or the area of the fracture surfaces, but if we knew these parameters, we might be able to stimulate flow from oil or gas reservoirs more efficiently. In addition, if we could determine the geometry of hydrofractures, we might be able to devise an efficient means for creating an artificial fluid circulation system to extract thermal energy from initially dry geothermal reservoirs.

In this paper we describe a magnetic method that could be used to determine the orientation of the fracture plane and perhaps constrain details of the geometry of the fracture.

METHOD

The method that we propose is simply to inject magnetic particles with the fracturing fluid. Then by determining the amplitude and spatial gradient of the magnetic anomaly at the earth's surface around the injection well and also by measuring field direction at the fracture within the well, it should be possible to determine the approximate three-dimensional distribution of the fracture surface.

Interpretation of magnetic anomalies found in geophysical prospecting is normally difficult because the geophysicist usually does not know the magnetic susceptibility of the rock or ore body producing the anomaly, he does not know the depth of the ore body, and he has no prior knowledge of its approximate shape or mass.

In our problem, however, the interpretation is somewhat simplified because we can measure the mass of the magnetic material that is being injected, we know its magnetic susceptibility, we know the depth at which the fracture was initiated, and we would know that the length and height of the fracture plane containing the magnetic material producing the anomaly would be very much greater than its width. The magnetic field of a body whose thickness is small compared with its other dimensions behaves much like a sheet of magnetic material. When placed in a magnetic field at an angle to the sheet, its magnetization is enhanced and the only significant field contribution comes from the magnetization in the plane of the sheet (Johnston and Stacey, 1968). The simple measurement of horizontal field component directions in the hole after injection should indicate the orientation of the vertical fracture plane and avoid the problem of perturbed principal stress fields in the vicinity of the hole itself. This could be obtained with a crude horizontal component magnetometer operated down hole, provided, of course, that the instrument was not shielded by the steel casing. The strong moment in the plane of the sheet should dominate any horizontal moments from the casing above the instrument. The moment in this casing would be predominately vertical. If the fracture produced during fluid injection is a single plane (this is usually the case during rapid hydrofracturing) then an important consequence is that calculation of the surface expression of the magnetic field from the buried sheet of magnetic material is greatly simplified since it is necessary only to find the total induced moments in the plane of the sheet and then calculate the surface field due to these moments.

In order to determine details of the fracture geometry it is necessary to produce as large a surface anomaly as possible. The magnetic susceptibility of the magnetic particles should therefore be high, and for economic considerations the material should be cheap. A material that fulfills these requirements is magnetite. It has been found that when using angular quartz sand as the propping agent in hydraulic fractures, bridges are sometimes formed between the particles and this tends to clog the fracture and inhibit its growth. If for this reason it is not feasible to use crushed magnetite of large grain size as the propping agent, we could use rounded quartz grains to prop open the fracture and use finely crushed magnetite that would remain in suspension in the fracturing fluid. If the particles were reduced to a size comparable to the dimensions of the magnetic domains, the effective magnetic susceptibility of the material would increase by several orders of magnitude. Thus although the cost of the material increases as the grain size decreases, only a small amount of the material would be necessary to produce a measurable magnetic anomaly at the earth's surface.

An alternative material to magnetite would be iron shot. It has several advantages: (1) the particles are spherical so that the tendency to form bridges is reduced; (2) it does not crush like quartz sand does when it is used to prop open rocks with a high embedment pressure (Howard and Fast, 1970); and (3) it has a very high magnetic susceptibility so that a smaller quantity of the material would be required to produce the same magnetic anomaly at the earth's surface.

The detection of small static field anomalies against the normally much larger variations in the geomagnetic field caused directly by disturbance in the earth's magnetosphere and indirectly by telluric currents, is a common problem in searching for tectonomagnetic effects, i.e. local magnetic field changes due to stress changes in the earth's crust (Rikitake, 1968; Nagata, 1970; Johnston, 1974). Since these disturbances are global in scale and hundreds of kilometers distant, the simple technique of operating several adjacent magnetometers greatly reduces these variations. Discrimination to 0.01 gammas for a 10 km baseline has been demonstrated during magnetically quiet times (Brill, 1975) although this level is probably site dependent. For the shorter baselines, in the proposed experiment, however, where correlation between magnetometers becomes more complete, it should be possible to maintain discrimination to less than 0.01 gammas for up to 1 km baselines during magnetically quiet times. Thus if we are measuring the change in the magnetic field caused by the introduction of a fracture surface containing magnetic particles and although its amplitude may be below the ambient magnetic field noise, its gradient will be far above the ambient gradient noise. By using two magnetometers precisely located a short distance apart and taking the difference between the field at both instruments, the noise can be separated from the field produced by the fracture.

If a 0.01 gamma threshold is maintained, it is clear that it would be too small to be resolved with magnetometers currently used in geophysical exploration. Recent developments in understanding the phenomenon of superconduction have led to the design of magnetometers with resolutions of 10^{-4} gammas (Clark, 1974). These instruments are even more ideally suited to measuring field gradients and have achieved resolutions of greater than 10^{-6} gammas per cm. Although the background geomagnetic noise will be the principal limitation of this experiment, magnetic measurements of this accuracy would be more than adequate to resolve magnetic anomalies produced by hydrofractures in which magnetic particles were lodged and that had dimensions of any practical interest.

Since this method depends on the detection of a small static field anomalies, an obvious and necessary precaution would be to separate the anomalies produced by site equipment--for example, well casing--and any nearby basement rocks containing magnetic minerals. This would be achieved by measuring the magnetic field surrounding and in the well before and after the formation of the fracture. The difference between the two would give the magnetic anomaly caused by the magnetic particles that had been injected into the fracture.

A second problem, if the surface field is to be mapped with only one pair of magnetometers, is the precise relocation or positioning of the sensor. Stable sensor holders a meter or so above the ground avoid ground gradients but still could experience field gradients of more than 10 γ/m. Detection of 0.01 gamma static fields implies, therefore, a repositioning capability of less than 1 mm. An experiment designed to search for tectonomagnetic effects near active faults in western U.S.A. currently involves more than 122 magnetometer sensor holders along 1180 km of the faults (Johnston, 1974). The repositioning accuracy is approximately 2 mm. Difficulties are not anticipated in improving this by more than a factor or two.

Data Inversion

In any practical application of the method that we have proposed, it would be necessary to calculate the magnetic field produced by bodies of different geometries but having the same mass and magnetic susceptibility as the injected material and compare these anomalies with the observed changes in the magnetic field. This is a standard technique used by exploration geophysicists but in the method that we have proposed here the interpretation is somewhat simplified because as pointed out above we would know the mass and susceptibility of the body and in addition we would know its approximate depth and we would know that the length and breadth of the body would be very much greater than its width. The methods used to interpret magnetic nomalies can be found in any standard textbook on exploration geophysics and a detailed discussion of linear inverse theory is given by Jackson (1974).

In the following section the extreme cases of two large-scale hydrofractures being produced at Los Alamos and Rio Blanco are examined to illustrate the effects of two possible geometries and to show the order of magnitude of the surface field in the best case (i.e., oriented north-south) and the worst cases (i.e., oriented east-west).

Applications

There are presently underway two large-scale hydraulic fracture projects, the Los Alamos and the Rio Blanco, that are of considerable practical importance. If the projects are successful in their aims, the United States may become less dependent on external energy sources. Other massive hydraulic fracture projects are underway in the United States, but our analysis is restricted to the Los Alamos and the Rio Blanco projects.

The Los Alamos project was undertaken to investigate the possibilities, problems, and economics of man-made fluid-circulating systems designed to extract thermal energy from dry geothermal reservoirs (Smith, 1974). The initial plan was to drill a hole on the Jamez Plateau of north-central New Mexico where the geothermal gradient is high. The well was to be drilled to a depth of about 2 km and then water injected to form a disc-shaped fracture approximately 1 km in diameter (Figure 1). In the plan a second hole was to be drilled to intersect the fracture surface. Cold water would then be injected at the bottom of the first well and as the water circulates through the fracture it will absorb heat from the surrounding rock and the hot water or steam will be extracted through the second hole to do useful work at the earth's surface.

The magnetic moment of a linear element of thickness t, length l, and width dw of a disc-shaped sheet of magnetic material at an angle θ to a field H has a magnitude

$$m = \chi_o \, t \cdot l \cdot dw \cdot H \cos \theta$$

where χ_o is the apparent susceptibility. χ_o is related to the intrinsic susceptibility χ_i and the demagnetizing factor N by

$$\chi_o = \frac{\chi_i}{1+N\chi_i} .$$

Normal to the element $N \rightarrow 4$ but parallel to the element $N \rightarrow 0$. Values of N for ellipsoids with a wide range of dimension ratios are tabulated by Stoner (1945). Susceptibility parallel to the element χ_{OP} therefore dominates and $\chi_O \approx \chi_{OP}$. Whereas $\chi_{ON} \rightarrow 0$ where χ_{ON} is susceptibility normal to the element.

The surface fields due to a buried vertical sheet of magnetic material with various geometrics and azimuths can therefore be calculated by determining the surface field due to elemental moments summed over the entire sheet.

Using this technique we have calculated the vertical and horizontal field anomalies produced by a fracture of this shape propped open for a width of 1 cm and with 10 percent of the fracture volume containing iron particles with a susceptibility of 40 e.m.u. In our calculations we assumed that the total field intensity at the well was 0.5 oersteds and the magnetic declination was 60 degrees. The contours of the magnetic anomalies produced if the plane of the disc was oriented either north-south or east-west are shown in Figure 2.

In the Rio Blanco project the plan called for a massive hydraulic fracture to be created in sandstone of the Fort Union Formation contained in the Piceance basin of northwest Colorado. The purpose of the project was to stimulate gas flow from the dense gas-bearing sandstone that is estimated to contain 74 billion standard cubic feet of gas in the project area (C.E.R. Geonuclear, 1974). In the original plan a well was to be drilled to a depth of about 2 km, and fluid was to be injected into the sandstone beds to form a fracture about 1 km long. The sandstone beds range in width from several feet to several hundred feet. It was anticipated that the overlying and underlying shale would act as barriers so that the newly formed fracture surfaces would be contained within the sandstone. A schematic diagram of the geometry of one of the fractures intended to be produced is shown in Figure 1.

We have also calculated the vertical and horizontal field anomalies produced by a fracture of this shape propped open for a width of 1 cm with 10 percent of the fracture volume being occupied by iron particles. We again assumed that the total field intensity at the injection well is 0.5 oersteds and that the magnetic declination at the well is 60 degrees. The contours of the magnetic anomalies produced at the earth's surface of the plane of the fracture is either north-south or east-west as shown in Figure 3.

The models that we have examined can be readily distinguished by comparing the amplitude and asymmetry of the magnetic anomalies at the earth's surface surrounding the injection wells. The magnitudes of the anomalies are sufficiently high that they could be readily resolved by using superconducting magnetometers that measure vertical and horizontal components.

DISCUSSION

In applying the method to the solution of a field problem, it should be possible, knowing the mass, the magnetic susceptibility, and the depth at which the magnetic material was injected, to determine the approximate three-dimensional distribution of the fracture plane.

An experiment using similar principles could also be devised in which fluids with high electrical conductivity could be used to hydrofracture the rock. Measurement of electrical field potential for particular positions of the dipole receiver electrode could further constrain estimates of the shape and orientation of the hydraulic fracture. However, inhomogeneties in nearby crustal materials could severely perturb the surface electric field.

In the development of an artificial fluid-circulation system designed to extract thermal energy from a dry geothermal reservoir, it is sometimes necessary to drill a second hole to intersect the fracture plane. By using the method that we have described, it should be possible to select the drill site for the second well that will allow the most efficient fluid circulation. In addition, it should be possible by using a down-hole magnetometer in this hold also to determine the direction in which the hole should be deflected to intersect the fracture plane.

The method that we have described may also be of value in the planning of a fracture program to stimulate gas or oil production from rich but normally nonproductive fields.

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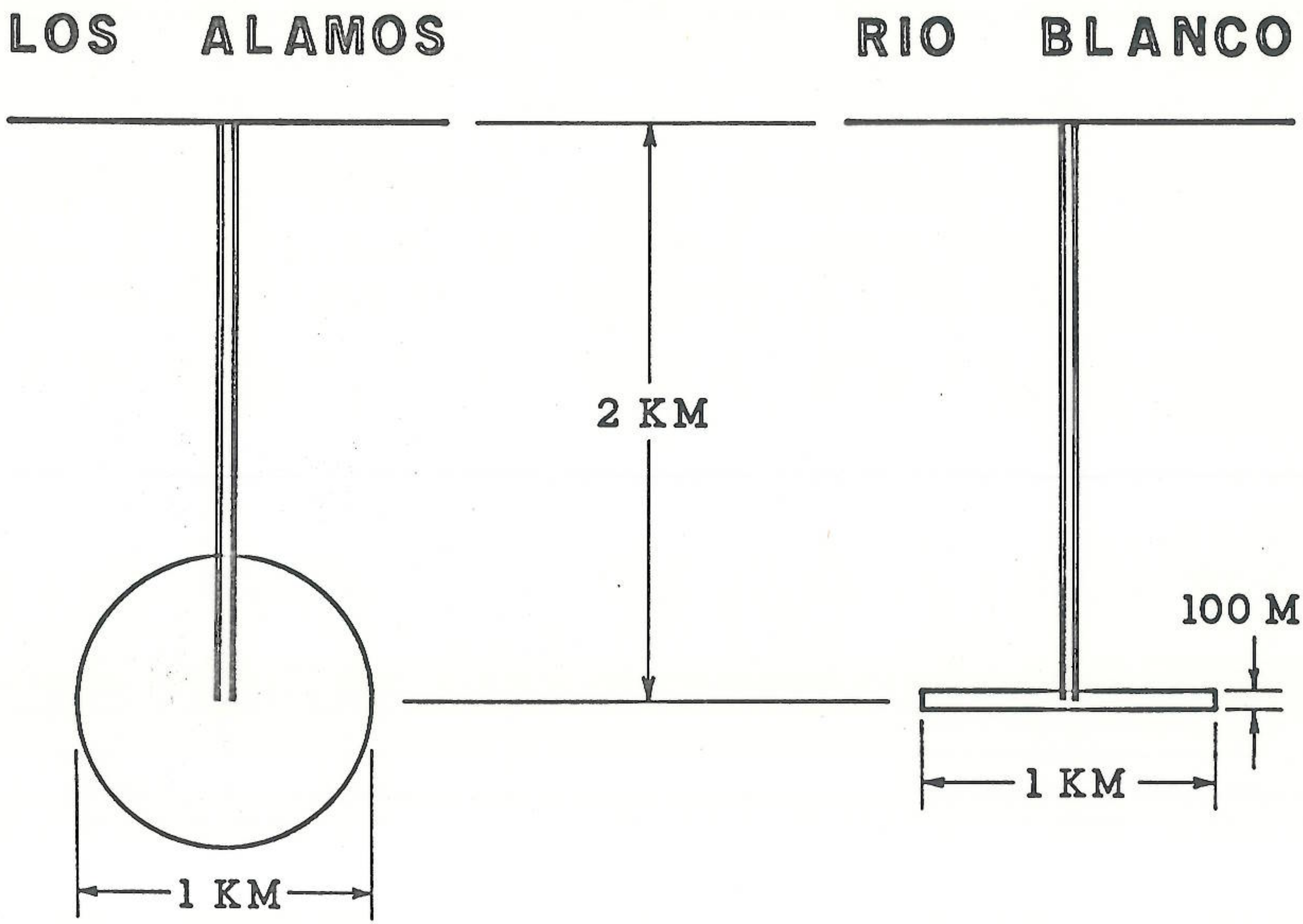
FIGURE CAPTIONS

Fig. 1. Schematic diagram of the hydraulic fractures intended to be produced in the Los Alamos and Rio Blanco projects.

Fig. 2. Contours of the vertical and horizontal components of the magnetic field anomalies for the disc-shaped fracture propped open for a width of 1 cm with 10 percent of the fracture volume occupied by iron particles. The orientation and position of the disc are shown by the straight solid line at the center of each figure. The contour intervals are in gammas.

Fig. 3. Contours for the vertical and horizontal components of the magnetic field anomalies for the slab-shaped fracture propped open for a width of 1 cm with 10 percent of the fracture volume occupied by iron particles. The orientation and position of the slab are shown by the straight solid line at the center of each figure. The contour intervals are in gammas.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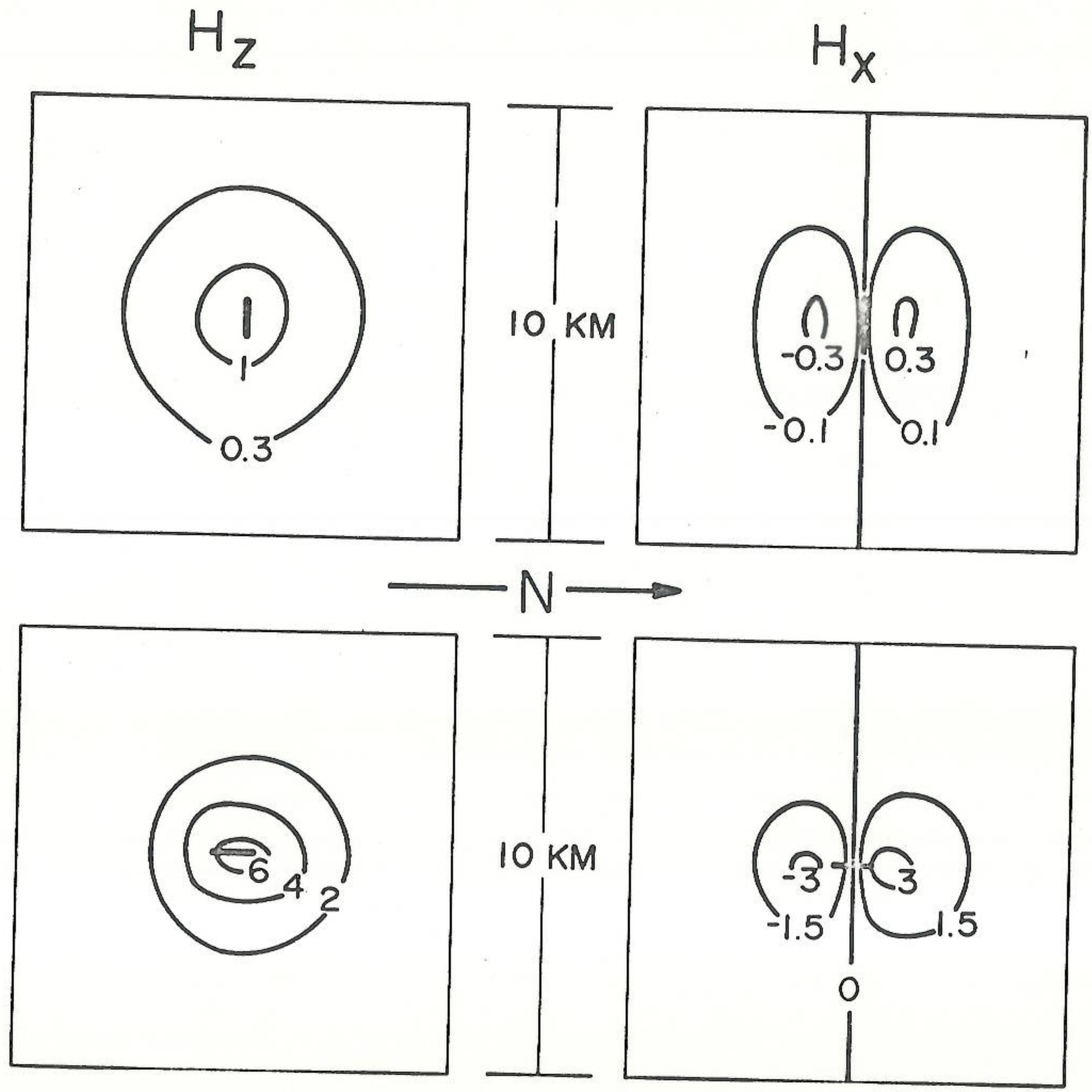
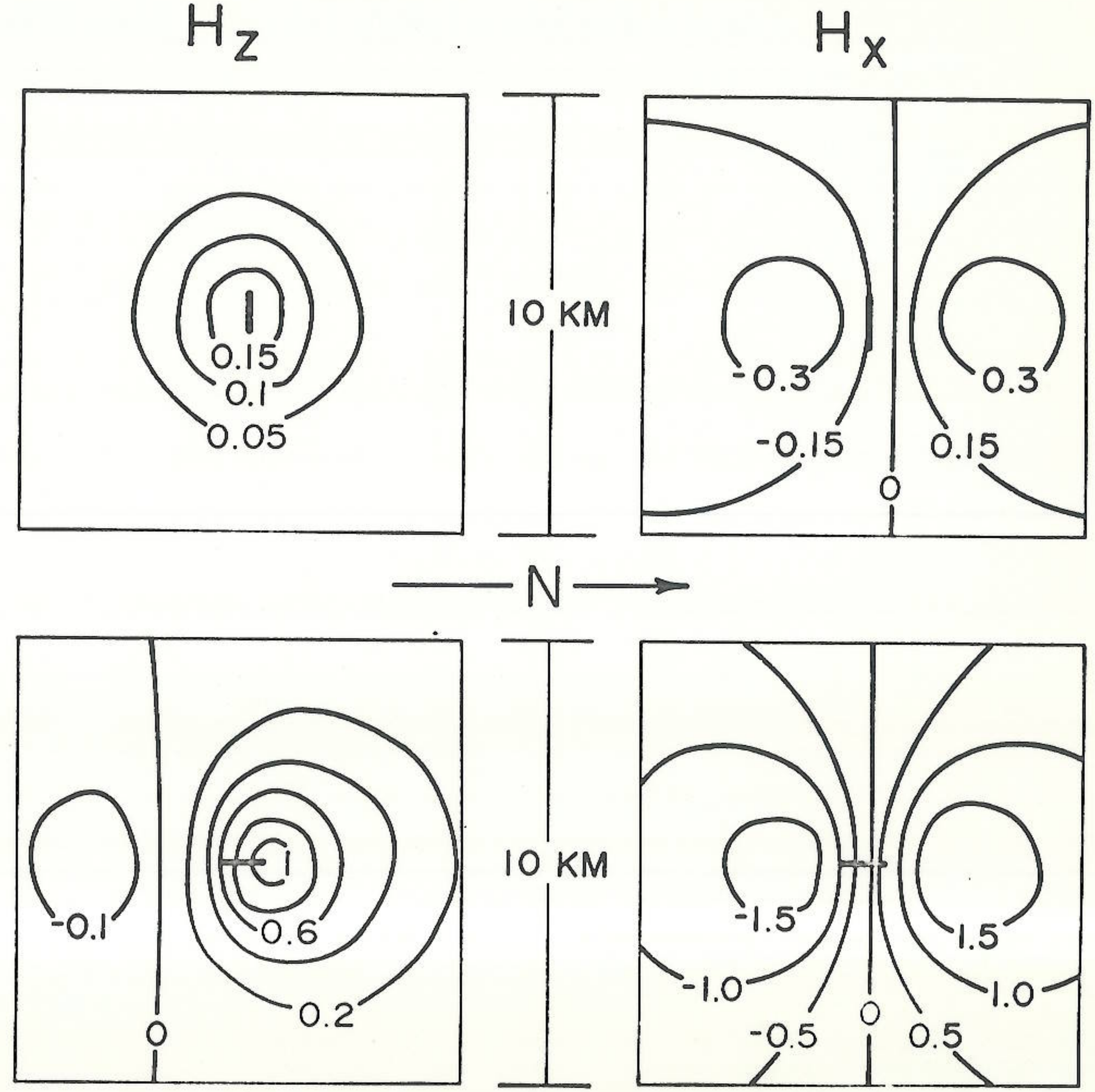


Fig 3

RIO BLANCO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