Fracture characterization with high frequency single-hole EM survey

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ABSTRACT

We present a high frequency electromagnetic (EM) inversion scheme for detecting and characterizing a fracture using single-hole data. At high frequencies, say above tens of mega-hertz, since displacement currents cannot be ignored, electrical permittivity as well as electrical conductivity is to be considered together for analyzing the EM scattering data. In this paper, we have developed a three-step inversion scheme to map the fracture and to evaluate its electrical conductivity and permittivity.

We performed EM profiling along the z-axis using three-component receivers for each source. The model was excited by a vertical magnetic dipole and the resultant magnetic fields were inverted using the non-linear least-squares method. Background resistivity and permittivity were easily obtained using vertical magnetic fields below 1 MHz and above 10 MHz, respectively. Both the vertical and dipping sheets were successfully mapped using the phase difference between 40 and 41 MHz. The electrical property of the sheet was well resolved using the information obtained in the previous two steps and secondary magnetic fields. Our study shows the potential of imaging the fracture in single-hole survey environment using the high frequency EM method.

INTRODUCTION

The art of detection and evaluation of major fractures is a crucial issue in many fields such as geothermal, petroleum and hazardous waste isolation industries. The purpose of this paper is to introduce a new fracture mapping and evaluation method. This method uses an intermediate frequency range, 100 kHz to 100 MHz, which is much higher than conventional EM methods and up to that of borehole radar.

Since both diffusion and wave propagation are considered at these frequencies, the fracture can be characterized not only by its electrical conductivity but also by permittivity. The electrical permittivity is helpful for evaluating geothermal fields because it is closely related to the water content of the fracture. In this paper, the fracture is simulated by an "inductive" thin sheet of arbitrary geometry near borehole. We have developed an inversion scheme to map the fracture and to evaluate its electrical property. The inversion scheme consists of three major steps. Both the horizontal component and vertical component of magnetic fields are used for this procedure.

Synthetic data used in the inversion were generated using the wide-band thin sheet EM modeling code WSHEET which is the whole space version of HFSHEET (Song and Lee, 1998). We describe our inversion scheme step by step.

INVERSION EXPERIMENTS

In imaging a fracture using single-hole data, the inverse problem consists of evaluating the electrical property of the background medium, and the location, geometry and electrical property of a sheet. At high frequencies, say above tens of mega-hertz, displacement currents cannot be ignored. Thus electrical permittivity as well as electrical conductivity should be considered together as inversion parameters. We have solved these parameters step by step, and our inversion scheme consists of three major steps.

Figure 1 shows two different models and survey configurations used in the inversion. Two models are exactly same except for the dip angle of the sheet. The resistivity and relative permittivity of the background medium are 500 ohm-m and 5, respectively. The size of the sheet is 4 m × 4 m with 0.1 m thickness and the center of the sheet is horizontally 2 m away from the borehole. The resistivity of the thin sheet is 5 ohm-m and the relative permittivity is 20. The x-direction is set to the perpendicular to the strike of the sheet. The other parameters are indicated on the illustration. In all calculations, the magnetic permeability is assumed to be that of the free space value and the vertical magnetic dipole source (M_z) of unit moment has been used because of the borehole orientation.

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BACKGROUND INFORMATION

In order to detect and evaluate the fracture, first of all, we have to characterize the background medium. Total H_z fields which contain relatively small secondary fields have been used to evaluate background electrical property. We have developed a simple inversion code using Marquart-Levenberg least-squares method using data at multiple frequencies and receivers. This first stage of inversion consists of two minor steps. The first step is to resolve the resistivity of the background using the data at relatively low frequencies, and the second step is to find the permittivity using the data at relatively high frequencies and the resistivity obtained in the first step. We used 0.125, 0.25 and 0.5 MHz to obtain the resistivity, and 40 and 41 MHz to calculate the permittivity.

FRACTURE MAPPING

At high frequencies where wave propagation is dominant, the phase difference between fields at two frequencies corresponds to the information of travel time in time domain. We have applied this concept to mapping a fracture.

Using the phase difference between two frequencies the propagation distance of EM wave can be estimated as

$$r = \frac{\theta}{\sqrt{\mu\varepsilon/2}\left\{\omega_2\sqrt{1+\sqrt{1+(\sigma/\omega_2\varepsilon)^2}} - \omega_1\sqrt{1+\sqrt{1+(\sigma/\omega_1\varepsilon)^2}}\right\}} \quad (1)$$

If we measure the phase difference of secondary H fields in a single-hole survey, we can obtain the distance of reflection path from source to target plus from target to receiver (two-way distance).

We performed a vertical profiling along the borehole for the vertical sheet model and then we applied simple NMO (Normal MoveOut) correction common in seismic data processing to obtain the real position of the sheet (one-way distance). The phase difference was calculated using 40 and 41 MHz data. The NMO corrected one-way distances for three different Tx-Rx separations are shown in Figure 2(a). All three data give almost the same one-way distances. It means that this mapping method can be adapted to data with varying Tx-Rx separations. The distance from the borehole to the sheet can be exactly determined for the vertical sheet model. Since the boundary between reflection and diffraction is not clear from the one-way distance curve, however, the exact evaluation of the depth extent of the sheet remains ambiguous. In case of an inclined sheet, we need to use a little more complicated method than NMO correction. We can calculate the one-way distance using data sets from two receivers that have different separations from the source for a dipping reflector (Telford, 1990). One-way distances in each Tx-Rx separation after correction for the dipping sheet model are shown in Figure 2(b). The source and receiver configurations are the same as the previous vertical sheet model. The model is superimposed on the plot of one-way distances for comparison. The reflection maps the sheet quite well except a slightly different dip angle. However, it is difficult to determine the dimension of the sheet exactly. In particular, the far side edge is hardly distinguished because diffraction smears it out.

In order to solve the diffraction problem, we have applied a classical migration concept to two-way distances. After collapsing diffraction we can clearly identify the edges of the sheet. Figure 3 shows the migrated sections for the two models. Through the combined interpretation with one-way distances plot and migrated section, we can achieve the exact geometrical information for the next step inversion.

EVALUATION OF ELECTRICAL PROPERTY OF THE FRACTURE

The final step of inversion is to resolve electrical property of the sheet. Since the background electrical property and the position and geometry of the sheet have been obtained in the previous steps, we can use these parameters as known in the final stage of inversion. The remaining parameters are the resistivity and permittivity of the sheet.

Once secondary EM fields for an initial model have been calculated, the following RMS error, objective function, is constructed and used for the inversion;

$$E(\mathbf{m}) = \sqrt{\frac{1}{N}\sum_{i=1}^{4}\sum_{j=1}^{nr\times nf}\left[f_{i,j}^{o} - f_{i,j}^{c}(\mathbf{m})\right]^2}, \quad (2)$$

where f^o is the observed magnetic fields, f^c the magnetic fields calculated for the model $\mathbf{m}$, subscript i the real and the imaginary parts of two components (H_x and H_z), nr the number of receiver positions, nf the number of frequencies, and $N = 4 \times nr \times nf$ the number of data. Damped least-squares method is used, and we solved the resulting systems of equations directly using Householder transformation without forming the normal equation.

EM inversion is an ill-posed problem because its solution is neither unique nor stable. An effective way to relax this ill-posedness is to use *a priori* information. We use inequality constraint on parameters as *a priori* information (Kim et al., 1998). This inequality constraint is useful to obtain stable and realistic inversion results in most cases.

We tested our inversion scheme for the vertical and dipping sheet models shown in Figure 1. In both cases, a source is 0.5 m above the center of the sheet and H_x and H_z fields are measured at three receivers which are located at 0.5, 1.0 and 1.5 m below the source, respectively. The operating frequencies are 40 and 41 MHz. Figures 4 and 5 show the convergence of electrical property of the vertical and dipping sheet models after starting two different sets of initial guesses: One is 20 ohm-m resistivity and 40 relative permittivity, and the other is 2 ohm-m and 5. The resistivity is dramatically updated first although the initial resistivity is far from the exact value. However, the permittivity starts to move to the exact solution after the resistivity approaches to an almost exact value in all cases. After 6 or 7 iterations, we obtain the exact solution regardless of initial guesses.

CONCLUSIONS

We have developed a three-step high frequency EM inversion scheme for mapping and evaluating a fracture near the borehole in a single-hole survey. To obtain both the conductivity and the permittivity, we used data at both sides of the transition frequency ($\omega = \sigma/\varepsilon$) covering from diffusion to wave propagation phenomena. Our inversion scheme has been tested on vertical and dipping sheet models.

Our proposed technique is based on theoretical study, but this study can be used to set guidelines in developing practical high-frequency measurement tools for more accurate fracture detection and evaluation.

REFERENCES

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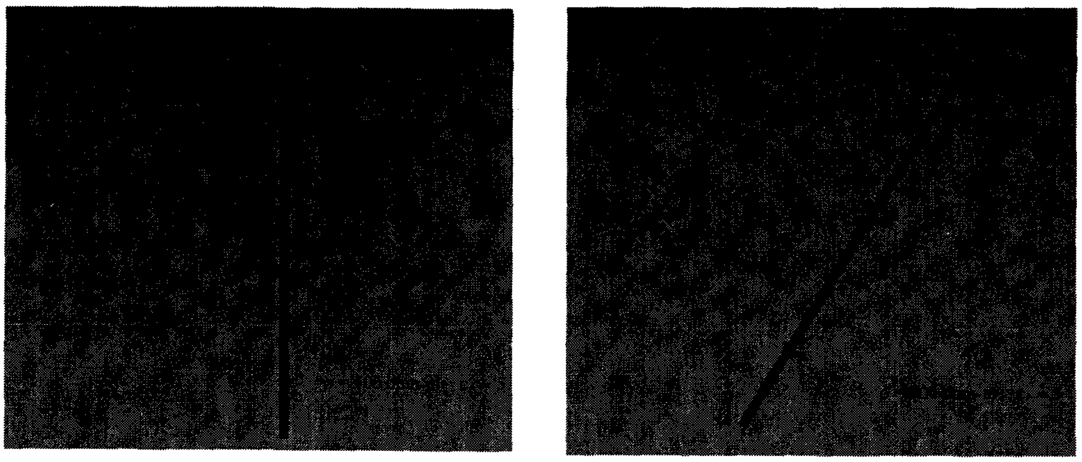
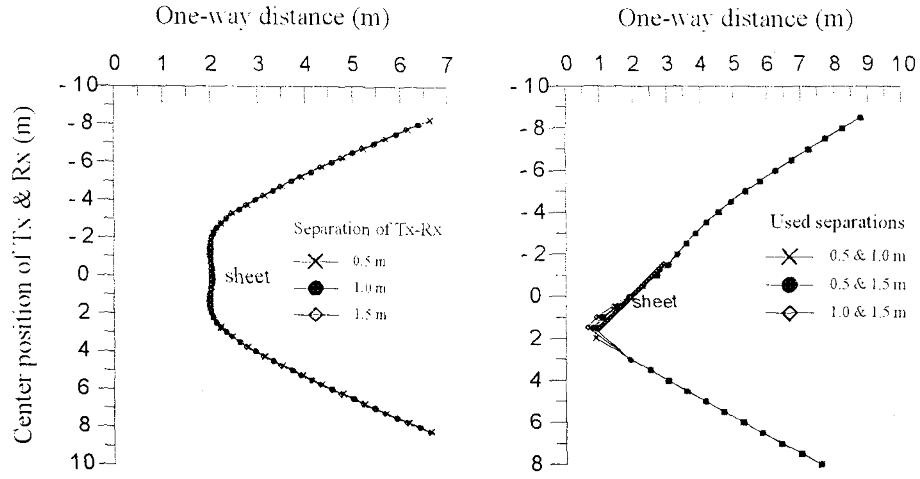
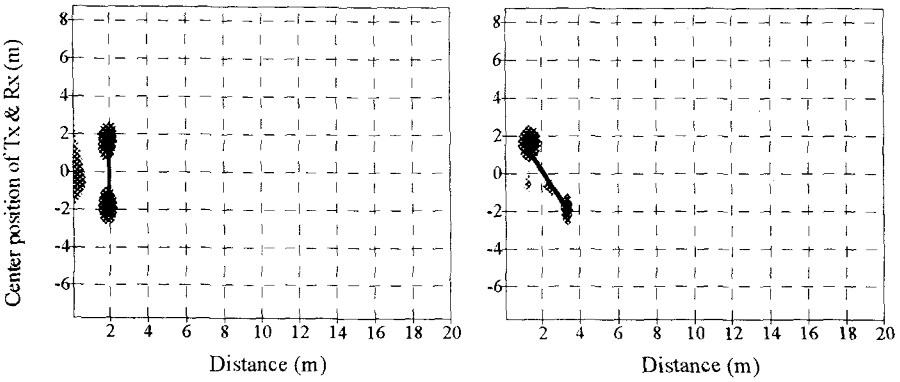


Figure 1. Vertical (left) and dipping (right) thin sheet models and survey configurations used in inversion.



(a) (b)

Figure 2. One-way distance plots for the vertical sheet model (a) and the dipping sheet model (b) after correction. The vertical and dipping sheets are superimposed, respectively.



(a) (b)

Figure 3. Migrated sections for the vertical sheet model (a) and the dipping sheet model (b). The vertical and dipping sheets are superimposed, respectively.

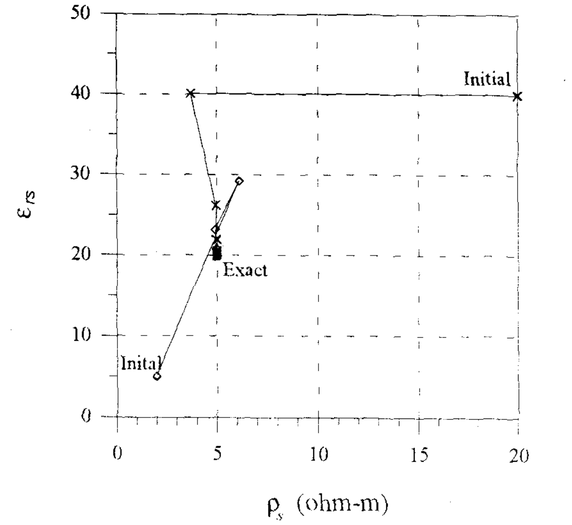


Figure 4. Convergence of electrical property of the vertical sheet as the number of iteration increases for two different initial guesses.

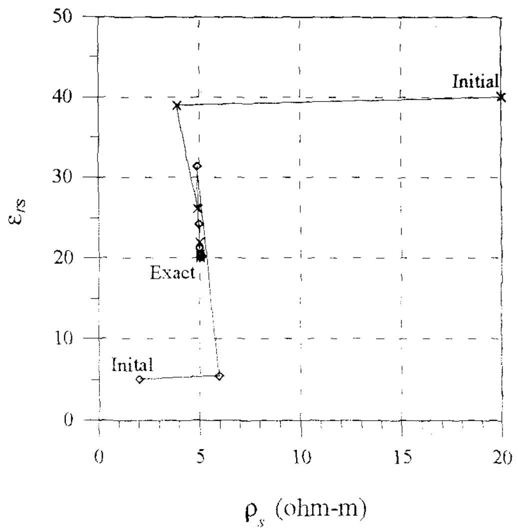


Figure 5. Convergence of electrical property of the dipping sheet as the number of iteration increases for two different initial guesses.