Hydrofracture mapping and monitoring with borehole electromagnetic (EM) methods

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Summary

Much of the recent petroleum exploration and development activities in the US and around the world have focused on unconventional resources, which predominantly consist of low-permeability siltstones and shale reservoirs. Although several geophysical methods have been applied to map the fractures from the deformation or the induced microseismic events that they cause, these methods do not image the sections of the fractures held open by injected proppant. This is where electromagnetics (EM) can help.

We investigate EM methods of imaging and monitoring induced fractures from the distribution of a proppant. Here, we apply some novel field technologies, effective medium theory, and a modified proppant mix to image the propped section of an induced fracture. The 3D simulation shows that a "typical" induced fracture is visible using surface-to-well EM techniques and that the measurement depends on the height and areal extent of the fractured volume.

Introduction

Much of the recent petroleum exploration and development activities in the US and around the world have focused on unconventional resources, which predominantly consist of low-permeability siltstones and shale reservoirs. In these fields, formations are hydraulically fractured using multiple stages to achieve sufficient reservoir contact to economically produce oil and gas. Of significant interest is the extent of the induced fracturing, the characteristics of the fractured volume, and the performance prediction of a completed well. These are critical to the process but are widely variable and poorly known.

Geophysical methods for mapping and monitoring induced fractures have been recently applied with varying degrees of effectiveness. Currently used technologies involve detecting ground deformation and recording passive seismic events. With ground deformation, the displacement is measured at the surface or in shallow boreholes using precision tiltmeters. Data are interpreted to map the fracture orientation and displacement from its "bulge." The method has been effective in shallow reservoirs, but it suffers from poor sensitivity to deeper fractures and in the non-uniqueness of reconstructions (Warpinski, 2011). Passive seismic uses surface or borehole geophones to detect microseicmic events generated during the fracturing process. Data are then used to infer the location and orientation of the induced fractures. The method has been effective in fields where brittle reservoirs mark the fracture path with acoustic events (Maxwell *et al.*, 2012). In less brittle reservoirs, or in fields where natural fractures play a role, the recorded events are less diagnostic.

The emplacement of the sand or ceramic proppant is important to the performance of an induced fracture. The proppant is used to keep the fractures open and create pathways for the resource to flow. However, its presence generates little signal and little physical property contrast to which currently applied geophysical techniques are sensitive. Here is where EM methods can have a role.

We examine the potential role of electrical and EM methods in mapping the fracture proppant deep into the formation. We use 3D numerical modeling and effective medium theory (EMT) to test these methods for this application. The key assumption here is that the proppant can be made electrically distinctive from the host reservoir by introducing an additive or by coating the proppant with a conductive substance.

Applying EM and electrical methods for fracture mapping

Modern EM field systems deploy instruments on the surface, on the seabed, and in boreholes to provide measurements of formation conductivity for petroleum, mineral, and geothermal targets. Three-dimensional (prismatic) imaging of such targets is frequently done (Mackie *et al.*, 2007). Imaging of induced fractures is more challenging because of the non-uniqueness of the solutions as well as the small scale of the fractures relative to the spacing between sensors.

While it is difficult to image even a conductive fracture distribution with EM methods, such a distribution can be scaled up for easier imaging. A process for doing this is effective medium theory (EMT) (Berryman and Hoversten, 2011; Heagy and Oldenburg, 2013).

With EMT, we assign an effective property that captures the macroscopic response of a material with properties that vary on the microscopic scale. For example, a collection of isotropic spherical inclusions in a medium may be combined into an equivalent medium using the relations below (Bruggerman, 1935):

$$\sum_{j=1}^{N} \phi_j(\sigma^* - \sigma_j)\mathrm{R}^{(j,*)} = 0$$

$$\mathrm{R}^{(j,*)} = \left[1 + \frac{1}{3}\frac{\sigma_j - \sigma^*}{\sigma^*}\right]^{-1}$$

Where j indexes over the number of inclusions, ϕ_j is the volume fraction of the j^{th} inclusion, σ_j is conductivity of the j^{th} inclusion, σ^* is the effective conductivity, and R is a variable that depends on the shape and the conductivity of the inclusion.

This relation may be used, for example, in computing the equivalent conductivity of a proppant mixture. In a similar manner, aligned ellipsoids may be used to calculate the effective conductivity of a fractured medium. In this case, the conductivity will be anisotropic.

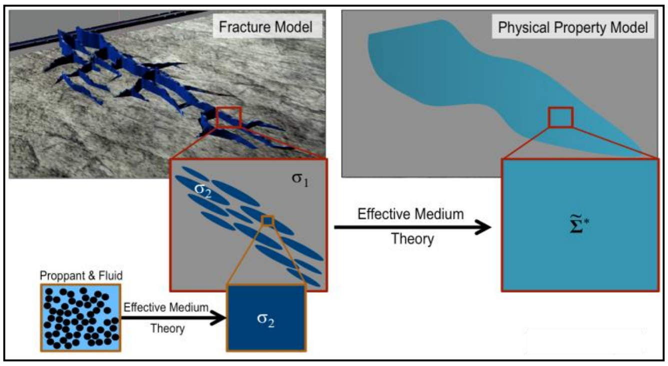

Figure 1 *An example of the workflow for the application of EMT to create an effective-conductivity model of a fractured reservoir.*

Customized Proppant Mixes

The process of inducing a fracture consists of a pressurized injection of water followed by the injection of a sand/water mix, followed by more water. The sand consists of well-sorted 60–65-sieve quartz and/or ceramic particles. A normal proppant mix consisting of sand and fresh water would be electrically invisible. Even if very salty water were used, the electrical conductivity of the limited fractured volume would provide a weak electrical signature; the sand is a different matter, however.

Whereas a hypersaline brine water has a conductivity of roughly 50.0 S/m (compared with potable water of roughly 0.02 S/m), a metallic material can have a conductivity of greater than 10^6 S/m. Metallic sands are poor proppant material, but metals and graphite are readily mixed with sand or used as coatings, thereby allowing them to retain their strength and their conductivity.

We can use EMT to estimate the conductivity of such materials. In Figure 2, we show the effective conductivity of a mixture of saline fluids and conductive sand particles. We see that a 33%-volume fraction of conductive particles will provide a step change in the conductivity of the mixture. For example, a graphite-coated sand (red circle) making a volume fraction of 50% will have an effective conductivity of 2,500 S/m. This may be sufficient for illuminating the fracture.

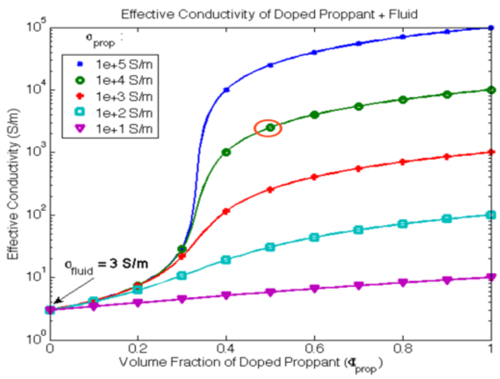

Figure 2 *Effective conductivity of proppant mixes.*

Example Problem

A typical induced fracture program might consist of up to 20 separate stages where fluids and solids are injected into a hydraulically isolated section of a horizontal well. Each stage consists of several fracture clusters where the well is perforated over a 10-m section and where 100,000–400,000 liters of fluid are injected. Such a fracture stage would consist of approximately 380 m^3 of fluid and 145 m^3 of proppant dispersed within 2.5-mm fractures in the 10-m cluster. The extent of the propped volume is 75 m, and its height is 75 m. We assume that the proppant material has an effective conductivity of 2,500 S/m and that the proppant concentration within the propped fracture is 50% of the total volume.

Using EMT, we upscale the fractures into an equivalent prismatic volume that encompasses the fracture (Figure 3), where the conductivity of the prism depends on the direction and its volume. In our model, the equivalent volume defines a region 15 m × 70 m × 70 m, where the conductivity is 3 S/m along the fracture (y and z direction) and equal to the background across it (x direction).

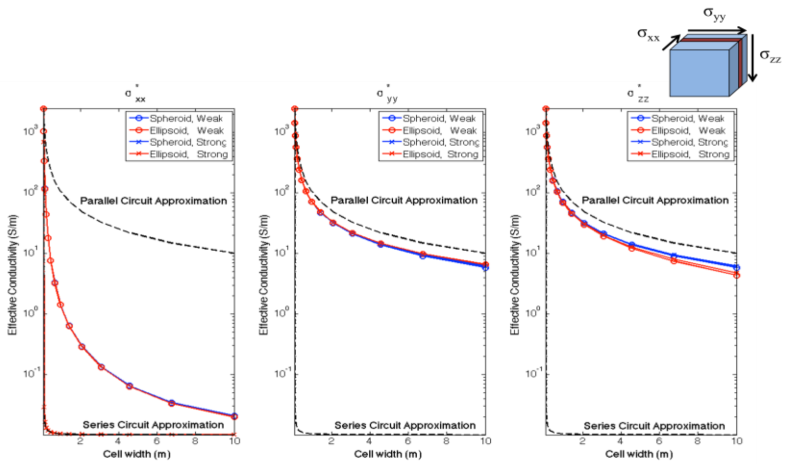

Figure 3 *Upscaling fracture conductivity using EMT.*

We now consider that the fracture cluster is emplaced approximately 1.1-km deep in the 100 ohm.m basal layer of a two-layer half space (Figure 4). We use the 3D EM code of Mackie *et al.* (2007) to conduct a simulated surface-to-borehole (STB) experiment before and after the fracture emplacement.

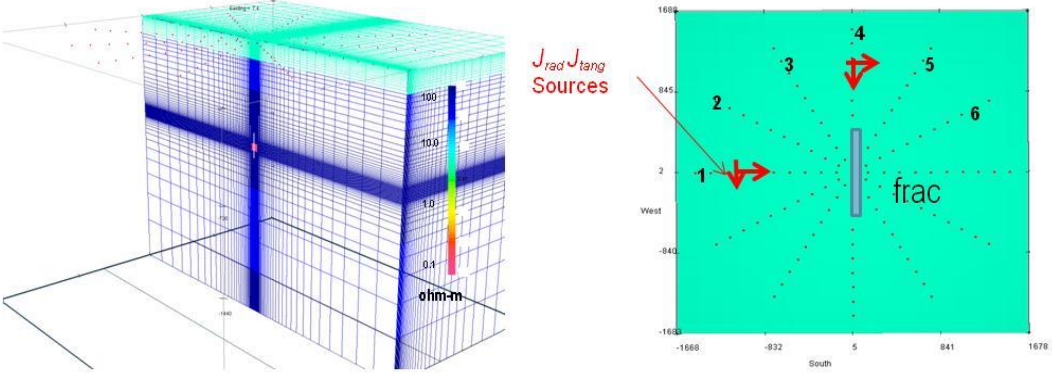

Figure 4 *Model and field configuration for surface to borehole measurements.*

In Figure 5, we plot the field response and field difference, with and without the propped fracture, using an electrical dipole source operating at 100 Hz oriented along the fracture and offset from the well from 50 to 1,000 m. We use borehole-based electrical- and magnetic-field receivers positioned in the treatment well over a 300-m depth interval that encompasses the fracture. The results indicate a substantial anomaly because of the propped fracture (Figure 5). The anomaly covers a large depth and spatial interval, and we note that similarly sized anomalies are measured from other source orientations. The vertical magnetic field, which is zero for a J_{rad} source within a homogeneous or layered medium is a substantial anomaly (Figure 5b).

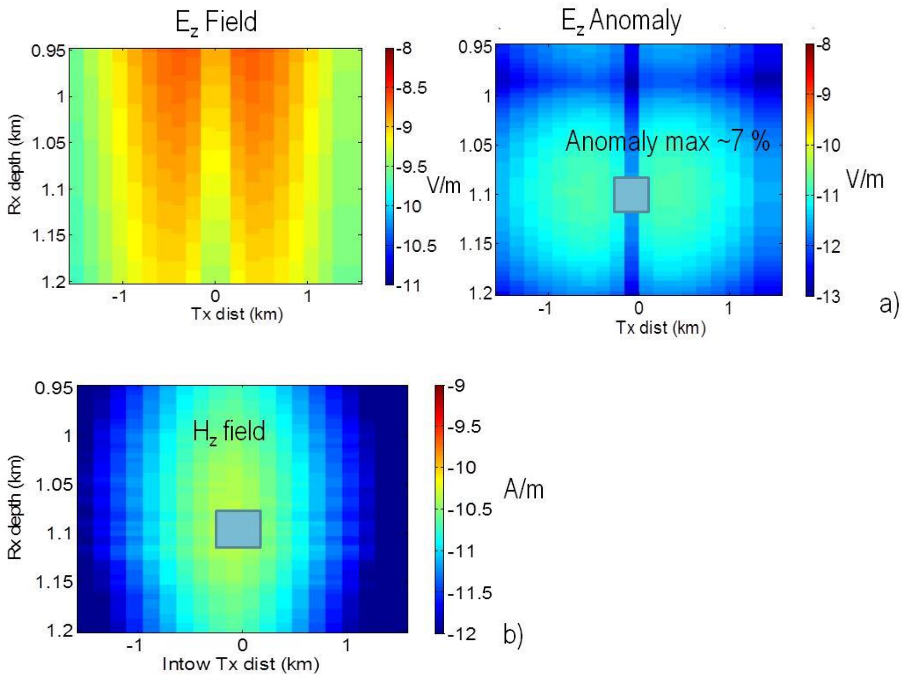

Figure 5 a) *Borehole electrical field and field anomaly from a surface based electrical source over an induced conductive fracture (box),* ***b)*** *vertical magnetic field over the fracture.*

The above simulation shows a significant response to an induced fracture with an electrically conductive proppant, but it is an idealized case. We are assuming that a conductive proppant is available, that the treatment well may be used for imaging, and that it is not cased with steel. We note, however, that solutions to these issues are in progress (Cuevas, 2013).

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