Investigating the potential of using conductive or permeable proppant particles for hydraulic fracture characterization

Lindsey J. Heagy, Douglas W. Oldenburg, UBC Geophysical Inversion Facility, University of British Columbia*

SUMMARY

Delineation of the stimulated region of a reservoir due to a hydraulic fracture completion is a key component for analyzing the success of the fracture treatment. The proppant used to keep the fracture pathways open provides a medium through which the physical properties of the fractured volume can be artificially altered. If this alteration is significant, the opportunity for a geophysical analysis of this problem is introduced. We investigate the potential of adding magnetic and electrically conductive particles to the proppant to provide an electromagnetic geophysical target. We use numerical simulations of the response of a simple model to investigate which physical properties of the fractured volume might lead to detectable signal. Magnetic particles have high potential since they respond at low frequencies. This signal can be enhanced by the inductive response due to conductive particles.

INTRODUCTION

An essential aspect to understanding hydraulic fractures is determining the volume of reservoir which has been stimulated by the fracture treatment. A key factor in this is the distribution of the proppant, the particles used to keep the fractures open. This leads to the goal of being able to monitor the distribution of the proppant after a fracture treatment. If the physical properties of the proppant are sufficiently different from the host then a geophysical experiment could possibly be used to delineate the propped region. The potential for a successful experiment depends upon many factors, including the physical properties of the proppant and host, the distribution and volume of proppant, the type and strength of transmitter, the choice of receiver and its noise characteristics, the coupling between the transmitter, propped volume and receiver, as well as infrastructure such as well casing and background noise. The goal of this research is to make a first order investigation into the feasibility of including magnetic and/or conductive particles in the proppant to act as a geophysical target.

To characterize the fractured region we use a cross-well electromagnetic survey. This survey benefits from having both the transmitter and receivers in close proximity to the target, as opposed to a surface survey which suffers from signal distortion in inhomogeneous overburden and signal attenuation through conductive formations overlying the target. These factors are especially significant for environments like shale gas plays where proppant volumes on the order of 10 m^3 - 100 m^3 are sought in layers that are kilometers beneath the surface.

In a cross-well EM survey, eg. (Wilt et al., 1995; Spies and Habashy, 1995) a receiver tool is positioned in one well, and a transmitter tool in a second well. The transmitter acts as a vertical magnetic dipole, consisting of a vertical-axis magnetically permeable core wrapped with several hundred turns of wire. It is capable of transmitting frequencies from 1 Hz - 1000 Hz. For low frequencies, the transmitter has a magnetic moment of 5,000 Am^2, but as the frequency is raised above 100 Hz, the transmitter moment is reduced due to eddy current losses. By 500 Hz, the moment is reduced to several hundred Am^2 (Wilt, 2004). The receivers are induction coils which also consist of a magnetically permeable core and are wrapped with thousands of turns of wire. They are capable of detecting magnetic fields on the order of $10^{-8}\mathrm{A/m}$ after taking repeated measurements and averaging the results (Wilt, 2004). Both single and three component receivers can be deployed (Wilt, 2004). Together, the transmitter strength and receiver sensitivity limit the maximum separation between the two survey wells to approximately 1km (Wilt, 2004).

To conduct the survey, the receiver tool is positioned in the well, and the transmitter tool is logged over the depth interval of interest. The receiver tool is then repositioned, and the process repeats until the depth interval of interest has been adequately sampled (Wilt et al., 1995; Wilt, 2004). Ideally, to get sufficient coverage, a depth interval that is 1.5-2 times longer than the separation between the survey wells should be logged (Wilt et al., 1995; Zhou, 1989). This process has been used to monitor several enhanced oil recovery projects including a CO_2 injection (Wilt, 2004), a steam flood (Wilt, 2004), and water injections (Alumbaugh and Newman, 2007; Wilt et al., 1995). Such a survey could provide a novel way of characterizing hydraulically fractured reservoirs, and has the potential to add valuable information to our understanding of hydraulic fracture geometry. Our goal is to investigate this potential through the use of synthetic modelling. Realistic fracture networks are undoubtedly complicated and will require 3D EM modelling. However, at this investigative stage, much can be learned by working with simple geometries. We begin by looking at the model of a permeable, conductive sphere in a whole-space.

ANALYTICAL MODEL

The response of a permeable, conductive material to an applied electromagnetic field is given by Maxwell's equations. In the frequency domain, they are:

$$\nabla \times \mathbf{E} + i\omega\mu\mathbf{H} = 0 \tag{1}$$

$$\nabla \times \mathbf{H} - (\sigma + i\omega\varepsilon)\mathbf{E} = \mathbf{J_s} \tag{2}$$

where $\mathbf{E}$: electric field, $\mathbf{H}$: magnetic field, $\mathbf{J_s}$: source, μ : magnetic permeability, σ : electric conductivity, ε : electric permittivity, ω : angular frequency of the source.

For our model, we approximate the proppant distribution of as a sphere with a radius of 20m, positioned mid-way between the transmitter and receiver wells. This volume is representative of either a single stage or several small fracture stages (Fisher et al., 2004; Maxwell and Cipolla, 2011; Mayerhofer et al., 2010). For this simulation, the wells are separated by a distance of 300m, as shown in Figure 1. This distance is constrained by the size of the target, the physical property contrast, the transmitter strength, and the receiver sensitivity. The bulk magnetic permeability and electric conductivity of the sphere are given by μ_2 and σ_2, respectively. As most hydraulic fracture completions take place more than 1 km below the surface, we can make the approximation that the background is a whole-space, with uniform magnetic permeability and electric conductivity.

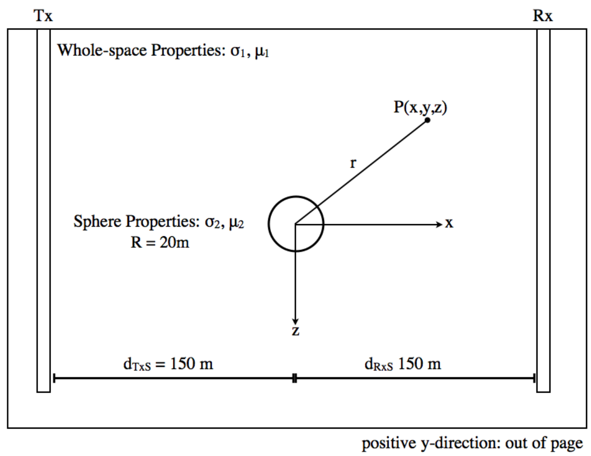


Figure 1: Sphere Model. (Not to scale)

If the radius of the sphere is small compared to its distance from the transmitter, then the inducing field from the transmitter can be modelled as a plane wave. The secondary field produced by a conducting, permeable sphere in the presence of an alternating magnetic field has an analytical solution given by Ward and Hohmann (1988):

$$\mathbf{H} = H_0 R^3 (M - iN) \frac{3xz\hat{\mathbf{x}} + 3yz\hat{\mathbf{y}} + (2z^2 - x^2 - y^2)\hat{\mathbf{z}}}{r^5} \qquad (3)$$

where H_0 : inducing field oriented in the z-direction, R : radius of the sphere, and $M - iN$ is given by:

$$M - iN = \frac{2\mu_2(\tan\alpha - \alpha) - \mu_1(\alpha - \tan\alpha + \alpha\tan\alpha)}{2\mu_2(\tan\alpha - \alpha) + 2\mu_1(\alpha - \tan\alpha + \alpha\tan\alpha)} \qquad (4)$$

with $\alpha = k_2 R$, where k_2 is the wavenumber in the sphere. The general expression for the wavenumber is given by

$$k^2 = \omega^2\mu\varepsilon - i\omega\mu\sigma \qquad (5)$$

where μ and σ are defined in the region of interest.

To approximate the value H_0, we assume the same geometric spreading and attenuation due to ohmic losses experienced by a vertically-oriented dipole in a whole-space. For simplicity, we assume that the center of the dipole is at the same depth as the center of the sphere, giving

$$\mathbf{H_0} = \frac{m}{4\pi d_{\mathrm{TxS}}^3} e^{ik_1 d_{\mathrm{TxS}}} (k_1^2 d_{\mathrm{TxS}}^2 - ik_1 d_{\mathrm{TxS}} - 1)\hat{\mathbf{z}} \qquad (6)$$

where m : magnetic moment of the transmitter, d_{TxS} : distance between the transmitter and the centre of the sphere, and k_1 : wavenumber of the whole-space.

Having specified the geometry of the model, we next assign the physical properties of both the fractured volume and the host.

Target with a high magnetic permeability

Assuming particles with a high magnetic permeability, such as magnetite, are added to the proppant mixture an inducing magnetic field will cause the sphere to magnetize and generate electric currents thereby producing a secondary magnetic field. This secondary magnetic field is generated at any frequency.

To examine this scenario, we need to assign parameters for the transmitter, receivers, and the physical parameters of the fractured volume. For the transmitter, we use a moment of 5,000 Am^2, and for the receivers we use a noise threshold of 10^{-8}A/m, consistent with Wilt (2004). For the background we use a magnetic permeability equal to that of free space, $\mu_1 = \mu_0 = 4\pi \times 10^{-7}$ NA^{-2}, and a conductivity of $\sigma_1 = 1 \times 10^{-2}$ S/m. Both of these parameters lie within the permeability and conductivity ranges typical of most reservoir rocks. In this case, we will assume that there is no conductivity contrast, and the conductivity of the sphere is $\sigma_2 = 1 \times 10^{-2}$ S/m. The types of particles that could be used and the resultant bulk magnetic permeability are not yet determined, but for our modelling purposes we assume $\mu_2 = 1.5\mu_0$.

Figure 2 shows the amplitude of the secondary magnetic field at the receiver well bore resulting from a permeable sphere in a whole-space with the given parameters. The black dashed line marks the noise threshold for the receivers. For the frequency range 1 Hz - 10,000 Hz, the secondary signal generated by the target is measurable at the receiver well bore. However, there is significant variation of signal strength with frequency. The strength of the signal increases with frequency until between 1,000 Hz and 10,000 Hz, where the effects of attenuation become more significant. By 100,000 Hz, attenuation in the background essentially kills the signal. This suggests that for a given parameter set, there is an optimal frequency which maximizes signal amplitude by balancing the secondary response of the target with signal attenuation in the host.

Target with a high electrical conductivity

In this case, we assume that the permeability of the sphere is equal to that of the whole-space, $\mu_2 = \mu_0$, and that the conductivity of the sphere provides the physical property contrast. We use a conductivity value of 1 S/m for the sphere, and 10^{-2} S/m for the whole-space. This conductivity contrast could be due to the presence of conductive particles, saline hydraulic fracture fluid or some combination of the two. Figure 3 shows the magnitude of the $x-$ and $z-$components of the magnetic field at the receiver well bore.

In this scenario, the secondary field amplitudes are more sensitive to variation in frequency, having the greatest observed amplitude at 10,000 Hz. For the parameters chosen, the maximum amplitude is approximately equal to the maximum amplitude obtained using the magnetic particles. However, if the

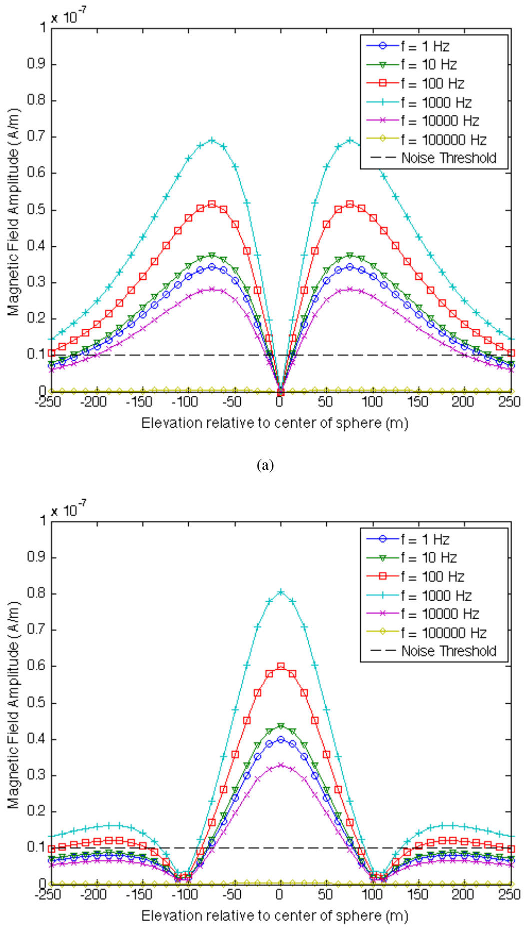


Figure 2: (a) Magnitude of the $x-$component of the secondary magnetic field due to a magnetic sphere. (b) Magnitude of the $z-$component of the secondary magnetic field due to a magnetic sphere.

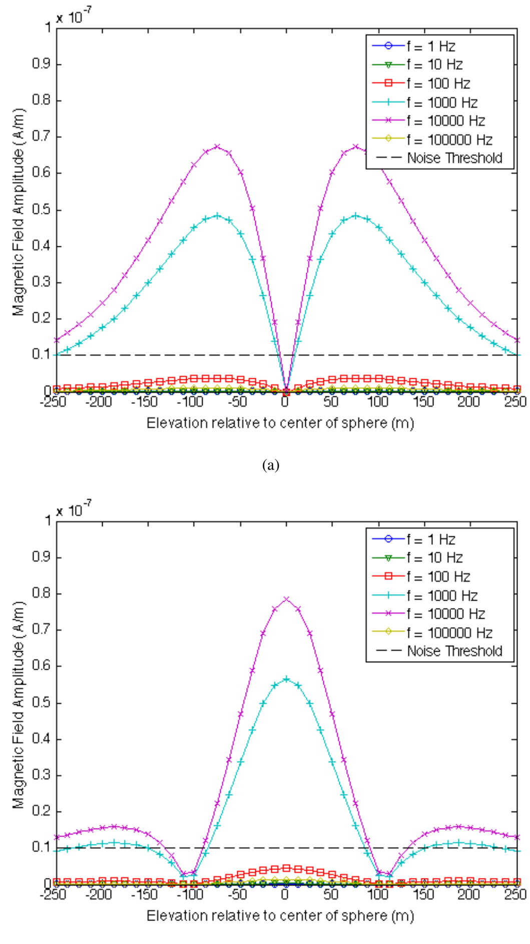
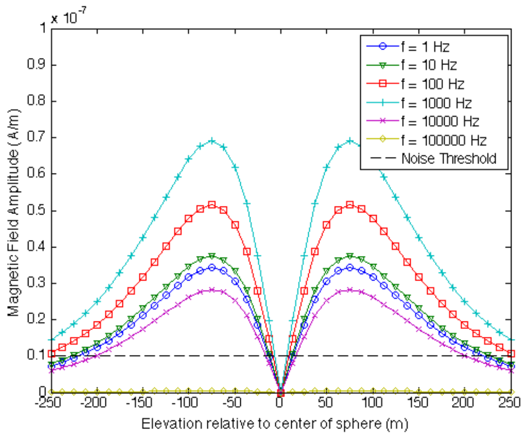


Figure 3: (a) Magnitude of the $x-$component of the secondary magnetic field due to an electrically conductive sphere. (b) Magnitude of the $z-$component of the secondary magnetic field due to an electrically conductive sphere.

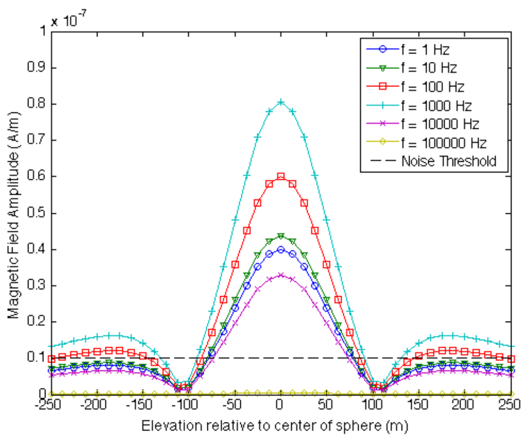
survey is done in a setting where the transmitter well is cased with steel, high frequencies are disproportionately attenuated as electrical currents are established in the casing. This reduces the effective transmitter moment (Wilt, 2004), which in turn reduces the amount of signal capable of exciting the target. Thus, depending on the survey environment, using frequencies in the range 1,000 Hz - 10,000 Hz may not be a feasible option.

Conductive, permeable target

The combination of conductive fracture fluid and proppant particles with a high magnetic permeability, or the addition of a proppant material which is both conductive and permeable could provide a geophysical target which has both a high conductivity and magnetic permeability. Figure 4 shows the amplitudes of the magnetic field measured at the receiver well for a sphere with magnetic permeability $\mu_2 = 1.5\mu_0$, and electric conductivity $\sigma_2 = 1$ S/m.



(a)



(b)

Figure 4: (a) Magnitude of the x-component of the secondary magnetic field due to a magnetic, electrically conductive sphere. (b) Magnitude of the $z-$component of the secondary magnetic field due to a magnetic, electrically conductive sphere.

The secondary fields generated in this scenario combines the best aspects of both the permeable and conductive target cases. At low frequencies, the magnetic response dominates. As the frequency is increased, the conductive response becomes significant and boosts the signal amplitude. This behaviour is especially significant when considering the survey environment. If both of the survey wells are open, then the inclusion of both magnetic and conductive particles could significantly increase the signal amplitude and improve data quality. However, if one or both of the wells are cased, the conductive response is negligible and magnetic particles provide the best chance of obtaining a viable signal.

CONCLUSION

The sphere model provides a basis for understanding the potential use of EM for delineating hydraulic fractures. We have shown that at low frequencies, the signal strength increases with frequency. However, if the frequency is too high, attenuation losses prevent usable signal from being obtained. Over the usable frequency band, the magnetic response dominates at low frequencies, and as the frequency increases the conductive response becomes more significant. The relative merits of using magnetic or conductive particles (or fluids) depends on many factors. In order to address these we shall use a more sophisticated fracture model which predicts the porosity, fluid, and proppant distribution. By assigning electromagnetic properties to the fluid and proppant, and using a 3D EM modelling code that allows for these more complicated geometries, we shall be able to simulate realistic surveys. This will provide insight into how the distribution of the particles and fluid affects the large scale electromagnetic properties of the fractured rock volume, as well as the role of target geometry on the signal.

Our work thus far shows the potential benefit of using magnetic particles for signal detection. Ultimately, we are interested in delineation of structure in order to better determine the distribution of proppant within a reservoir. Detection is only the first, necessary, component of this more challenging problem.

ACKNOWLEDGMENTS

The authors would like to thank Michael Wilt and Jiuping Chen for their clarifications on cross-well EM surveys, and the members of the EM group meetings for their support and insightful discussions.

REFERENCES

Alumbaugh, D., and G. Newman, 2007, Three-dimensional massively parallel electromagnetic inversion II. analysis of a crosswell electromagnetic experiment: Geophysical Journal International, **128**, 355–363.

Fisher, M., J. Heinze, C. Harris, C. Wright, and K. Dunn, 2004, Optimizing horizontal completion techniques in the barnett shale using microseismic fracture mapping: Presented at the SPE Annual Technical Conference and Exhibition.

Maxwell, S., and C. Cipolla, 2011, What does microseismicity tell us about hydraulic fracturing?: Presented at the SPE Annual Technical Conference and Exhibition.

Mayerhofer, M., E. Lolon, N. Warpinski, C. Cipolla, D. Walser, and C. Rightmire, 2010, What is stimulated reservoir volume?: SPE Production & Operations, **25**, 89–98.

Spies, B., and T. Habashy, 1995, Sensitivity analysis of crosswell electromagnetics: Geophysics, **60**, 834–845.

Ward, S., and G. Hohmann, 1988, Electromagnetic theory for geophysical applications: Electromagnetic methods in applied geophysics, **1**, 131–311.

Wilt, M., 2004, Oil reservoir characterization and CO2 injection monitoring in the permian basin with crosswell electromagnetic imaging: National Energy Technology Laboratory (US).

Wilt, M., D. Alumbaugh, H. Morrison, A. Becker, K. H. Lee, and M. Deszcz-Pan, 1995, Crosswell electromagnetic tomography: System design considerations and field results: Geophysics, **60**, 871–885.

Zhou, Q., 1989, Audio frequency numerical modeling and tomographic inversion for reservoir evaluation: PhD thesis, PhD Thesis, Department of Engineering Geosciences, University of California, Berkeley.