Using well casing as an electrical source to monitor hydraulic fracture fluid injection

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Summary

The depth to surface resistivity (DSR) method transmits current from a source located in a cased or open-hole well to a distant surface return electrode while electric field measurements are made at the surface over the target of interest.

This paper presents both numerical modelling results and measured data from a hydraulic fracturing field test where conductive water was injected into a resistive shale reservoir during a hydraulic fracturing operation. Modelling experiments show that anomalies due to hydraulic fracturing are small but measureable with highly sensitive sensor technology. The field measurements confirm the model results, showing that measured differences in the surface fields due to hydraulic fracturing have been detected above the noise floor.

Our results show that the DSR method is sensitive to the injection of frac fluids; they are detectable above the noise floor in a commercially active hydraulic fracturing operation, and therfore this method can be used for monitoring fracture fluid movement.

Introduction

Monitoring fracture propagation using steel well casing to distribute an electrical current into the subsurface has become an increasingly popular topic in the geophysical literature (e.g., Weiss et al., 2015). By transmitting current through the well casing, the subsurface in the vicinity of the well is energized, and measurements of the resulting electric fields at the surface are sensitive to the electrical resistivity of the energized subsurface. If the injected fluid and proppant are sufficiently electrically conductive, the bulk resistivity of the energized region near the well casing may be lowered enough to cause a measureable anomaly at the surface.

The depth to surface resistivity (DSR) method measures the electric field at the surface using capacitively coupled receivers, while transmitting a current from a downhole source to a distant surface electrode (Hibbs et al, 2014). The well casing acts to distribute the electric current along the well, and this current distribution is affected by both the casing resistivity and the resistivity of the subsurface surrounding the casing (Schenkel and Morrison, 1991). Measurements at the surface are sensitive to the electrical resistivity of the energized subsurface, and an inversion of the measured surface fields will provide an image of the electrical resistivity of the subsurface. In a typical survey the surface fields are measured both along and perpendicular to the fracture directions throughout the hydraulic fracturing operation. The resulting time lapse measurements indicate how the injection of conductive fluids has changed the surface fields, which in turn can be used to understand where the hydraulic fracture fluids have travelled (e.g., fracture orientation and fracture extent).

Further technical details discussing the use of a cased well to measure the response due to hydraulic fracturing operations may be found in studies by Hoversten et al. (2014) and Weiss et al. (2015).

Method

To demonstrate the DSR method for imaging hydraulic fractures, we present a modelling example where an electrical source is connected at depth to a horizontal well that assumes an earth model that is simplified from a Marcellus shale play in West Virginia. Since the DSR method is most sensitive to the electrical resistivity of the subsurface, these results may be applicable to regions with similar electrical resistivity profiles. The well is lined with steel casing, the depth is 2260 m, and the distance from the heel to the toe is 2270 m. The source is connected to the casing at 1800 m along the horizontal from the heel, and current is driven from the down casing source to a surface return electrode located 700 m to the east of the down casing source location.

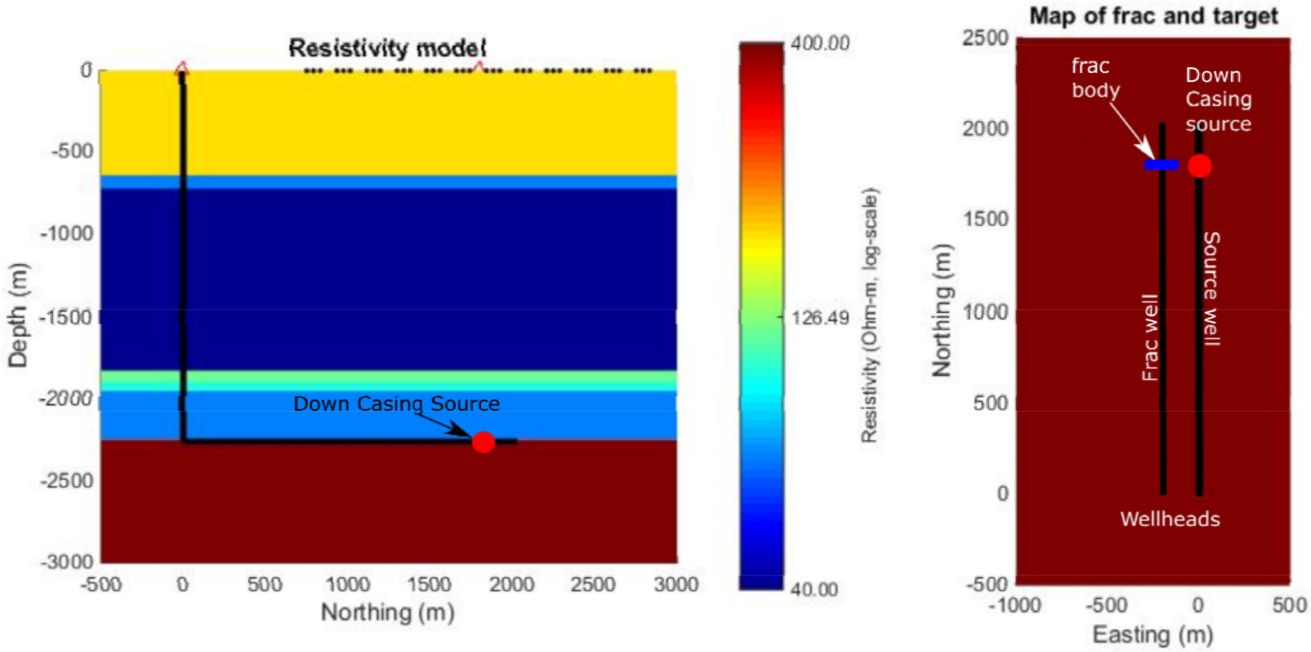

Figure 1: Left - Vertical slice showing the 1D resistivity model used with reference to the horizontal well. Right – map view showing the frac target body in reference to the source well.

The frac well has the same geometry as the source well (Figure 1).The resistivity model contains 6 layers ranging from 40 Ωm to 400 Ωm, with the highest resistivity associated with the shale reservoir.

The difference between the surface fields measured before frac and after frac operations will be referred to as the anomalous field. In the model presented here the anomalous field has the greatest magnitude in the east-west direction, and therefore the following analysis is focused only on the east-west electric fields.

In order to determine an applicable frac target size we follow Heagy et al. (2014) by assuming that the total frac body is made up of a discrete set of fractures. Each discrete fracture has a width of 2.5 mm, a length of 120 m, and a height of 80 m. We assume that within a 40 m frac stage there are 30 discrete fractures induced by the injection of 4500 bbl of fluid and proppant. We model those fractures as a set of conductors in a parallel circuit (note that the electric field near the frac body is nearly perpendicular to the source well; therefore we need only be interested in the conductivity in the same direction). Using a moderately conductive fluid and proppant mixture of 130 S/m (Hoversten et al., 2014), we arrive at a total resistivity for the entire 40 x 80 x120 m body of 4 Ωm set within the 400 Ωm shale reservoir.

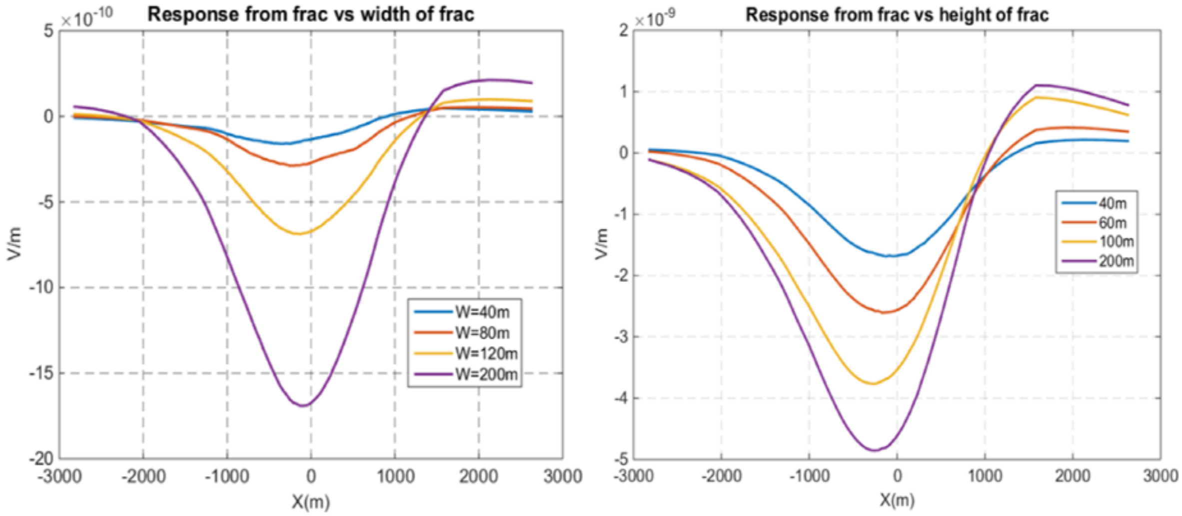

Figure 2: Plots showing the surface anomaly along an east-west profile directly over the frac body

Figure 2 shows the modelled anomalies along an east-west line over the frac body for a number of different frac bodies. The left plot shows different anomalies when the height is held at 80 m, the length (along the well) is held at 40 m, and the width (perpendicular to the well) is varied. The right plot shows anomalies when the width is held at 120 m, the length is held at 40 m, and the height is varied.

The values plotted in Figure 2 are using 1A of transmitted current, and measured over a 1 m receiver separation. In the case where 10 A is transmitted and measurements are made over 100 m receiver separation the expected noise floor in the same scale as Figure 2 is $1x10^{-11}$V/m. This indicates that the smallest frac targets modelled for Figure 2 result in a measureable anomaly at the surface.

The following section describes the field experiment carried out, the results of which indicated that the measured anomaly is consistent with the modelled anomaly.

Examples

Figure 3 shows time lapse measurements of the east-west electric field from five different receivers during frac operations in the Niobrara formation of Colorado. In this project there were three horizontal wells being utilized, and the map in Figure 3 indicates the location of the frac wells (A and B), with respect to the down casing source (yellow star). Further details about the survey are recorded by Hibbs (2015).

The noise floor measured in this survey was about 0.1 nV, and the measured anomalies were on the order of 0.5 nV, giving an estimate of the signal-to-noise ratio at about 5:1. The magnitude of the north-south anomaly (not displayed) is much smaller than the east-west anomaly, which matches well with the expectations from the modelled results.

Time lapse measurements for five separate receivers are shown in Figure 3 (station locations are indicated by the red triangles on the map), and indicate that the magnitude of the anomaly related to fluid injection lies well within the range of magnitudes predicted by the modelling (Figure 2).

There is a consistent pattern to the time lapse measurements, where the surface fields increase (red circle) or decrease (blue circle) as fluid is injected, and relax when the injection is stopped. There is also a longer wavelength component to the anomaly which shows a gradual increase/decrease in the anomalous fields over a number of frac stages, and a settling of the fields by the time frac stage B27 is complete. Measurements made at nearby stations show a similar pattern, and are not shown to keep the figure readable.

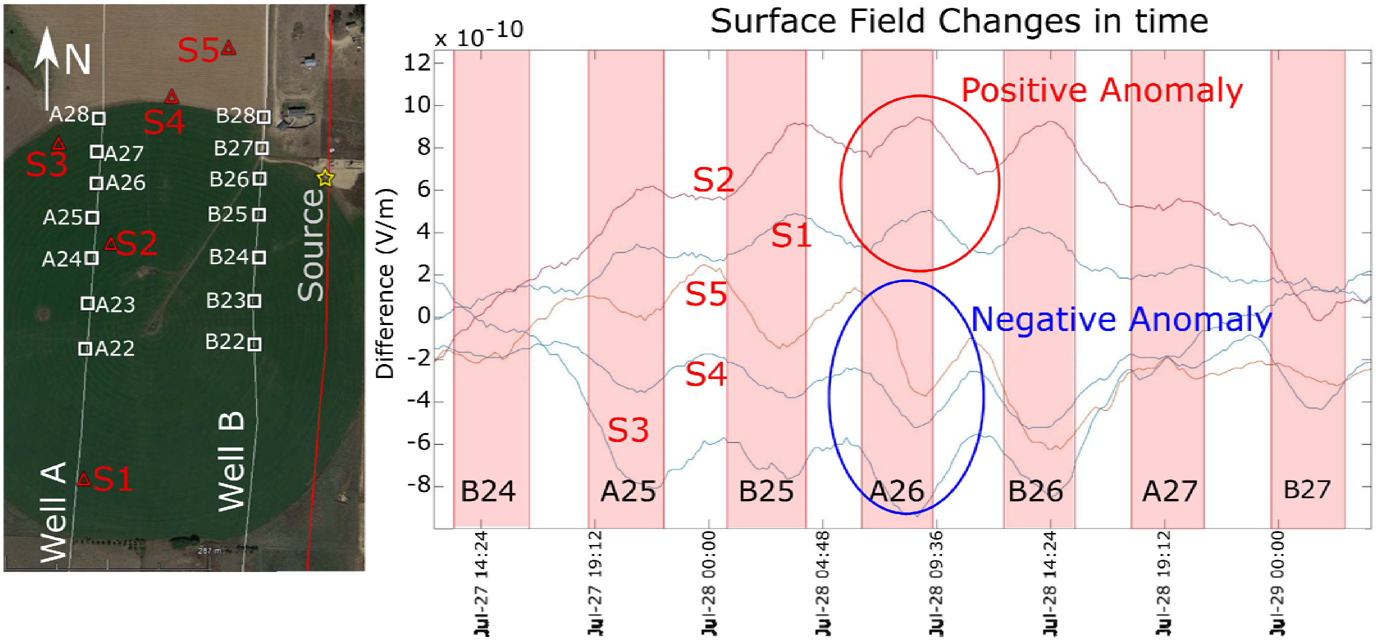

Figure 3: Time lapse differences in the surface field correlated with frac stages.

Conclusions

Through both numerical modelling and field testing we show that the DSR method is sensitive to the injection of frac fluids into a shale reservoir. As well as matching the modelled anomaly magnitude, the measured data indicate a pattern in which resistivity changes are correlated directly to the injection of fluids. These differences are all related to a change in the electrical resistivity due to pumping conductive fluids into the shale formation, and as a next step will be used in an inversion workflow designed to provide an image of how the electrical resistivity of the subsurface changes, and hence pinpointing where the frac fluids have migrated during hydraulic fracturing.

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