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Borehole to Surface Electromagnetic Monitoring of Hydraulic Fractures

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Introduction

Hydraulic fracturing (HF) has become a significant tool for enhancing production from tight formations. A variety of geophysical and reservoir engineering technologies have been developed to characterize the volume of a reservoir that has been stimulated by HF operations. The stimulated reservoir volume (SRV) is a highly sought after number. Accurate determination of the SRV can optimize production and minimize drilling costs. The most often used technology is micro-earthquake (MEQ) event location and moment tensor analysis coupled with flow simulation where fracture flow volumes are inferred from the MEQ event locations and moment tensors. The accuracy of inferred fracture volumes derived from MEQ's are limited by two major factors; 1) the velocity model required for event location is often inaccurate and 2) MEQ events, even if accurately located, do not necessarily correlate with the connected portions of fracture system which can flow back to the well.

Work continues in a number of areas with the goal of improving on current SRV prediction accuracy. One of these areas is the use of electrical (DC) and electromagnetic (EM) techniques for imaging conductively enhanced fractures. One of the first documented uses of EM for HF monitoring is described by Hibbs (2014). The work by Hibbs inspired numerical simulation of the role that conductive steel casings play in enhancing the response from deep conductively enhanced HF using transient EM responses by Hoversten et al. (2015) and Commer et al. (2015). Weiss et al. (2016) present solutions for DC responses from a HF emanating from an approximated horizontal steel cased borehole. The use of DC or EM responses for HF monitoring rely on the high conductivity of the steel cased wells to enhance the HF response allowing it to be measured at the surface. All the work to date has modelled a single steel cased borehole as either vertical or in the case of horizontal wells as an "L" shaped approximation with vertical and horizontal segments.

In this study we present forward modelling for a realistic pad of six horizontal cased wells where the true well trajectory with multiple casing strings are considered. This more accurate representation of multiple complex geometry wells is accomplished using OcTree finite difference modelling in the time domain (Haber & Heldmann, 2007). In addition, we study the resolution of the parameters of a thin conductive box used to approximate a conductive HF.

Theory

There are three computational components used to study the capabilities of a surface-based TDEM system for hydraulic fracture characterization. For the forward modelling of the transient electric fields for electric dipole sources in the presence of steel casing we use the TDEM codes of Haber and Heldmann (2007). Hydraulic fracture volumes and dimensions are derived from instrumented hydraulic fractures in operating oil fields. We used the equivalent media theory of Berryman & Hoversten (2013) to calculate the resistivity of an injectate with conductively enhanced proppant. For imaging the dimensions of the conductive fluid filled portion of the fracture zone we use a new development using parametric level set methods, (Aghasi et al., 2011).

Examples

We begin by illustrating the sensitivity of HF responses to individual casing strings with a forward simulation of a set of six horizontal wells from a single drilling pad, an arrangement common in hydraulic fracturing operations. We model the DC and transient EM response after turn-off of 10A of current into transmitters with one electrode on the surface, 1 km from the borehole, and a second electrode downhole. We assume two components of the noise; 1) a random 1% amplitude error at all times and 2) an E field noise floor of $1x10^{-10}$ V/m and a dB/dt noise floor of $1x10^{-14}$ V/m^2. Figure 1a shows the well geometry in a layered background resistivity drawn from the Permian Basin in the USA. The wells begin vertical from a single pad at the origin x=0, y=0, they deviate so that the heal and tow of the laterals are at a depth of 3km and extend to x =2500m, with a separation of 200m for each well in the y direction. The casing electrical conductivity is assumed to be $5.0x10^{-6}$ S/m. Two downhole electrode positon are simulated one at the heal of well #4 and one at x = 1800m in well #4. The simulated HF is located at x = 1900m in well #3. The HF assumes 1500m^3 slurry injected with a 15% conductive proppant by weight. After leak-off the proppant concentration in the HF is 40% leaving 600m^3 volume with dimensions 300x100x0.2 m in x, y, and z respectively centered on well #3. The HF electrical conductivity is 576 S/m (Hoversten et al., 2015).

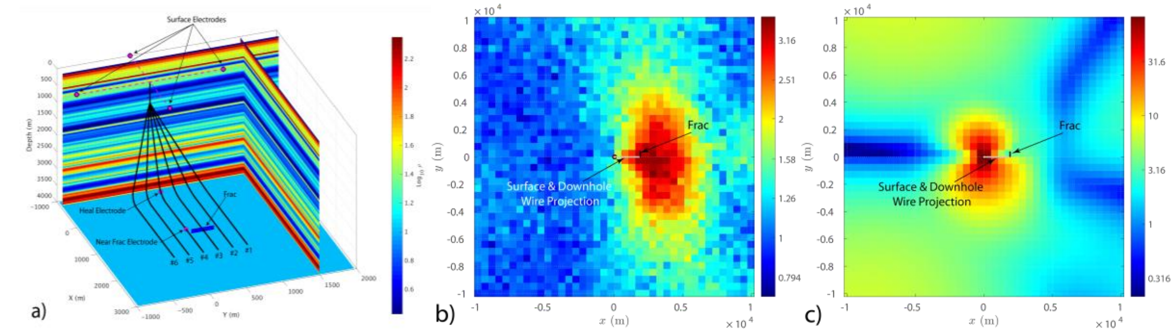

Figure 1 *Realistic six well configuration for horizontal wells from a single drilling pad. Figure 1a) shows well trajectories, electrode locations for four surface-to-borehole transmitters, heal and near frac downhole electrode locations, the background layered resistivity structure, and the frac location. Figure 1b) shows the RMS given by equation 1 for the background and frac response for transient times 0.1 to 1 sec for the* E_y *field. Figure 1c) shows the RMS given by equation 1 between the frac responses when well #6 is not included in the calculations for transient times 0.1 to 1 sec for the* E_y *field.*

We use equation 1 to represent the data difference displays, where *i* is the index of the time channel, N is the total number of times, d_i^A and d_i^B are two different responses, and d_i^{std} is the noise standard deviation.

$$RMS = 1/\sqrt{N}\left[\sum_{i=1}^{N}\frac{\left(d_i^A - d_i^B\right)}{d_i^{std}}\right]^{1/2} \quad (1)$$

In figure 1b d_i^A is the response with the HF present and d_i^B is the background response, 45 logarithmically spaced time channels from 0.1 to 1.0 sec are used.

Figure 1b shows that the HF electric field in the y direction (E_y) response has a maximum value of 5 noise standard deviations and has significant spatial extend where the response is > 1. This is a good response and as we show this allows critical HF parameters to be determined. Figure 1c shows equation (1) where d_i^A is the HF response with all six wells and d_i^B is the HF response when well #6 is not included. The effects of not modelling the one well that is farthest from the HF well is almost 10x larger than the effects of the HF itself. Similar results hold for all surface components of E and dB/dt. These simulations demonstrate that it is essential to be able to model all of the steel infrastructure in the vicinity of a HF monitoring survey if HF properties are to be accurately extracted from inversion of the field data.

All inversion studies shown approximate the horizontal wells with an “L” structure with 3km vertical section and a 2km lateral in the x direction. Two wells separated by 200m in the y direction, one for the downhole electrodes and one for the HF are considered. The example shown in Figure 2 uses transmitter surface electrode #3, the surface electrode to the east, closest to the HF.

While the inversion for the HF parameters is the objective, it is necessary to first characterize the background model and the casing properties. In practice multiple logs as well as other geophysical and geologic information will be available to help with background characterization. In these examples we will assume that the pre-HF data and background layer boundaries (20 in this example) from logs are used to invert for the background layer conductivities. A three stage inversion sequence is used for the pre-HF data. First the conductivities of the two casings and the 20 layer are randomly drawn from defined bounds. The casing bounds are +- 5% of 5.0x10^{-6} S/m and the layer conductivity bounds are +- 50% of the log values with a 20% randomness added to the bounds. With the casing conductivity fixed the layer conductivities are solved for, next the inverted layer conductivities are fixed and the casing conductivities are solved for. Finally, both the casing and layer conductivities are solved for. A number of three-stage inversions are done with random start models and the mean parameters are calculated. Figure 2a shows the mean layered resistivity's for this example from 3 inversions.

Once the background has been estimated from the pre-HF data we use a double difference (DD) scheme for the frac parameter inversions. Equation 2 shows the expression for the DD data (d_{HF}^{DD}), where. d_{HF}^{obs} is the observed post-HF data, d_{back}^{obs} is the observed pre-HF data, and $d_{back\ Inv}^{cal}$ is the calculated data from the pre-HF data inversion mean model.

$$d_{HF}^{DD} = \left(d_{HF}^{obs} - d_{back}^{obs}\right) + \ d_{back\ Inv}^{cal} \qquad (2)$$

We have found using the double difference approach produces far better HF inversion results, particularly if the pre-HF inversion is not able to fit d_{back}^{obs} well.

The HF zone is represented by a parametric level-set (Aghasi et al., 2011) where the x, y, and z center coordinates of a box, the length, height and thickness of the box, three rotation angles about the coordinate axes, and the box conductivity make up the ten possible parameters. We fix the x center at the frac location in the well and fix the three rotation angles. Fixing the pitch and role of the box is justified in most cases due to the large stress asymmetry at depth that produces mostly vertical HF that are confined within geologic units, nearly parallel to the surface in the vicinity of the HF. We assume the azimuth of the HF is determined by regional stress and other data. Forward model sensitivity studies have shown that azimuth changes within +-10 degrees are barley visible above the noise and are poorly resolved in inversions. We fix the thickness of the box at the minimum OcTree cell size of 2m. The HF conductivity of 576 S/m for 0.2m thickness is up-scaled to 57.6 S/m for a 2m thick HF.

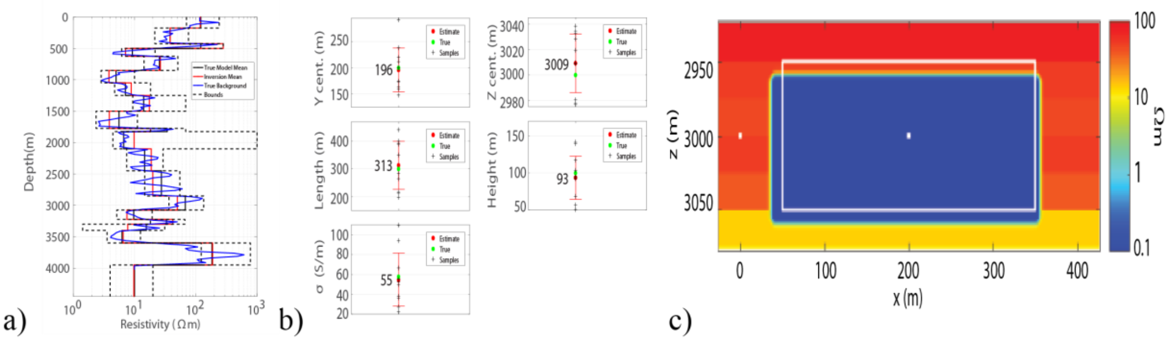

Figure 2. Panel a) shows the 20layer background inversion from three runs of the three stage background inversion described in the text. Panel b) shows the mean HF parameters, the individual samples and one standard deviation from 10 runs from random start models within the bounds. The vertical parameter axes ranges are the bounds, which are asymmetrically biased toward the high value to insure the mean is not the center point of the bounds (which would indicate no HF information in the data). Panel c) is a color-coded X-Z depth section along the HF, the white dots are the two well casings that are perpendicular to the figure, and the white rectangle is the true HF dimension.

Figure 2b and 2c show the results of a set of ten inversions for the five free box parameters, each inversion starting from a random set of parameters within the bounds. The bounds are purposely set to be asymmetric with a high side bias of at least 50%. If there were no parameter sensitivity in the inversions the mean values would be the mean of the bounds, which they are not. Based on numerous inversions with different data, noise, source geometries and background conductivity structure we find that at least 90% of the parametric box inversions converge to an RMS data misfit less than 1.1, but the non-uniqueness of the problem is significant and the averaging of 10 or more random start models is required to achieve good estimates of the box representing the HF.

From this and many other tests we conclude that the HF length and conductivity estimates are the most accurately estimated in both 10x higher and 10x lower data noise. Use of E, dB/dt or both provide the same conclusions. The least well resolved parameters are both the vertical center and the height of the box.

The location of the downhole electrode, at the heal or near the frac is a practical one since to place an electrode in the lateral of the well requires a tractor and increases cost. Of course an electrode nearer the HF increases the response significantly. In the example shown here, the HF response for a heal electrode is close to the noise level for the Electric fields and only 1 to 2 standard deviations above the noise for dB/dt. While the HF response is significantly lower for the heal electrode compared to the electrode nearer the HF, inversion of the heal data is still able to provide good length and conductivity estimates, albeit with higher error than for the electrode nearer the HF.

Conclusions

Inversion of surface EM data for parameters of an electrically conductive box used to represents a HF zone is possible under the conditions studied here. The strong effect of steel infrastructure such as the well casings require that any numerical scheme used to model HF EM data is capable of accurately modelling ALL of the casings in the vicinity of the HF. Modelling that approximates only one or two wells will have errors that exceed the response of the HF, thus rendering accurate inversions unlikely. The length and conductivity of the HF are the best determined parameters which is important for helping to guide well separation and determining the distribution of conductively enhanced proppant.

In practice, there are significant challenges to accurately characterize all the steel in an HF environment and to increasing our ability to characterize HF geometries and conductivity distributions with greater complexity than a single box. The work to date is however encouraging, showing that there is information in the data and that our numerical modelling capabilities are progressing rapidly. The OcTree codes used here will be able to model all the necessary wells in a parametric inversion shortly. In addition, developments in unstructured finite-element codes is progressing rapidly with the prospect of having a choice between OcTree and finite-element based inversion in the next year or two.

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