Assessment of uncertainty in parametric inversion of electromagnetic field data to determine propped hydraulic fracture geometry – a semi quantitative approach

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Summary

Application of electromagnetic techniques to determine propped fracture characteristics is currently a hot topic of interest in the unconventional reservoir industry. For widespread adoption of this method, key questions on utility for making business decisions need to be addressed. The present work provides a semi quantitative framework for analyzing inversion results and its accompanying error bars. In the absence of conventional drill bit based “ground truth” data, such an approach provides a practical method for narrowing down input options for key propped fracture parameters used for making decisions on optimized well spacing, developing production forecast models, and meeting other important business objectives for the industry.

Introduction

Proppants are tiny particles usually the size of sand grains placed in hydraulic fractures to facilitate production of hydro carbons in both unconventional and now increasingly, in tight, conventional reservoirs as well. Knowledge of the location and extent of these proppants in the far field of the well bore is important in understanding and forecasting the production potential of a well and also provide guidance in the design of spacing and location of future wells and their completion design (e.g. Palisch et al. 2016). The potential economic benefits of even modest improvements on existing methods are enormous and well documented (e.g. Hoversten et al. 2015; Hoversten and Schwarzbach, 2018). Development of electromagnetic methods to determine location and geometry of propped fractures in the far field from the well has become increasingly popular in recent years (e.g. Heagy et al. 2014, Weiss et al. 2016, Palisch et al. 2016, La Brecque et al, 2016, Zhang et al. 2016, Weiss and Wilson, 2017, Hoversten and Schwarzbach, 2018).

The current work analyzes the inversion results from data acquired in two different field sites in the STACK Play in Oklahoma, USA, and provides a semi quantitative analysis of the potential uncertainty in the determined propped fracture dimensions. Similar methods deployed in offshore play based exploration, have significantly impacted the business decision making process involving several hundreds of millions of dollars, while recognizing the significant subsurface uncertainty associated with geophysical methods in poorly constrained data. Albeit of a different nature, the magnitude of subsurface uncertainty and lack of sufficient constraints are comparable to the present case. As such, it is hoped that customized adoption of such methods would impact key business decisions in this realm in a similar manner.

Method of Field Data Acquisition and Inversion

The technology for determining propped fracture geometry is based on the acquisition of two sets of geophysical electromagnetic data: a baseline survey conducted before the onset of hydraulic fracturing operations, popularly called the “pre frac” data and a second set of acquisition (“post frac”) after the insertion of specially coated proppant particles having high electrical conductivity. Stringent efforts are undertaken to ensure that the principal source of difference between the two data sets is caused by the placement of proppant in the hydraulic fracture.

Strong background constraints are imposed by well logs, seismic horizons, detailed well path geometry, etc. before performing a set of parametric and limited voxel based inversions to update the pre frac back ground model in the regions of poorest constraints and highest sensitivity, noticeably the well casings and the shallow subsurface lying above the highest well log and below the topography (Figure 1). Parametric inversions (Aghasi et al. 2011) of a set of ellipsoids with fixed electrical conductivity around perforation clusters are performed on the post frac data, which are used as a proxy for determination of propped fracture geometry (Figure 2).

Designing the Field Survey

The location and orientation of the transmitters and receivers are determined by a series of detailed forward model simulations in a roughly 8 Km by 8 Km area surrounding the target well(s) where the proppant will be placed. The earth model incorporates resistivity logs from 100 wells and captures the effect of casing from over 50 wells using a combination of upscaling and homogenization described in Schwarzbach and Haber (2018). The finalized survey geometry involves having a current source electrode located downhole near the heel of the target well, while the sink electrode is ground on the surface (or connected to a well bore) in different locations (Figure 3, top panel). The source current waveform is an alternating square pulse of fixed duration (8 s). The receivers (Figure 3, bottom panel) are approximately orthogonal electric dipoles located on the surface in an array designed to capture the optimal signal distribution from the differenced field (pre – post frac).

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Additional sources of strong local distortions of the transmitted electromagnetic field such as buried pipelines (Figure 3, bottom panel) are also taken into account in the model.

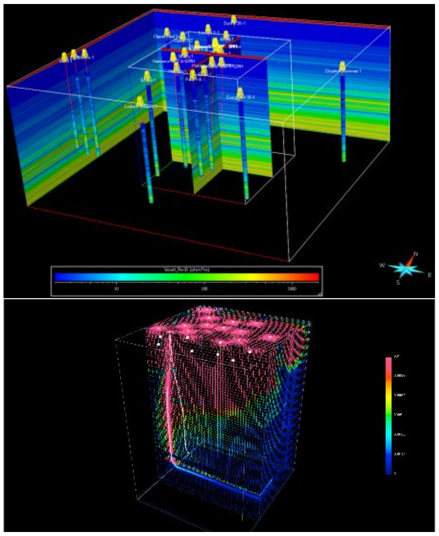

Figure 1: Resistivity earth model built from logs, seismic horizons, well casings, and topography (Top panel). Bottom panel shows how the model is updated via inversion of geophysical data acquired before treatment of targeted fracture stage.

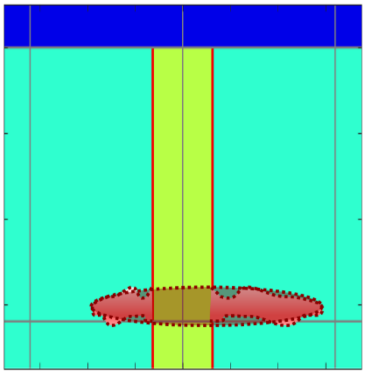

Figure 2: Approximation of complex and arbitrary shaped propped fracture by a regular geometric shape for parametric inversion. In the inversion, propped fracture height, length and width may vary. The propped fracture is not necessarily centered on the wellbore.

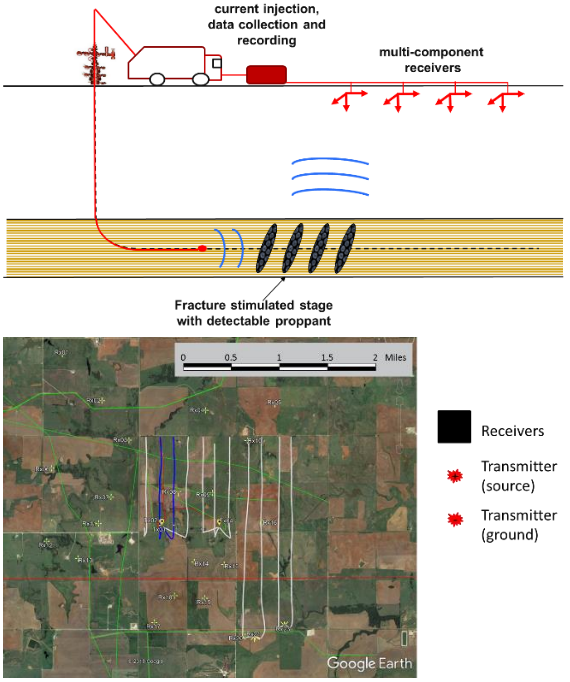

Figure 3: Top panel. Generic deployment of the data acquisition system. Bottom panel. Receiver array deployed in accordance with forward model recommendations which takes into account the distorting influences of pipelines (green lines on right panel) in addition to everything else shown in Figure 1.

Processing Acquired Data

Geophysical electromagnetic data acquired in a US oilfield setting is strongly influenced by cultural elements. These bodies like pipelines, pump jacks, powerlines, etc., oftentimes dominate the electromagnetic response at a level disproportionate to their size in the overall modeling domain (e.g. Weiss, 2017). Careful processing and modeling of data is necessary to mitigate their influence. Inversion objectives for this project were deemed to be best achieved by working in the frequency domain. Through a sequence of processing steps, it can be shown that a jack knife statistical approach is capable of clearly separating the post – frac signal from pre – frac even when the mean difference between the two can be very small (~0.18%). Additional processing steps including static shift corrections were applied to the data prior to inversion.

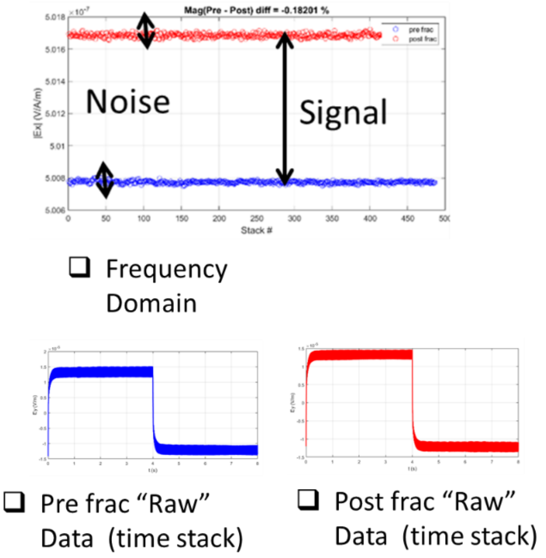

Figure 4: Processed data example. Jack knife statistical approach of spectral amplitude estimation (top panel) separate pre frac and post frac signals quite clearly even for small amplitude differences.

Parametric Inversion of Processed Data

The likely range of stress on proppant governs the potential value of in situ proppant electrical conductivity. For a given value of electrical conductivity, parametric inversion yields propped fracture dimensions of length, width, and height of ellipsoidal geometry at a given frac center location (Figure 5 left panel). Note that it is not necessary for the fracture to be centered on the well bore.

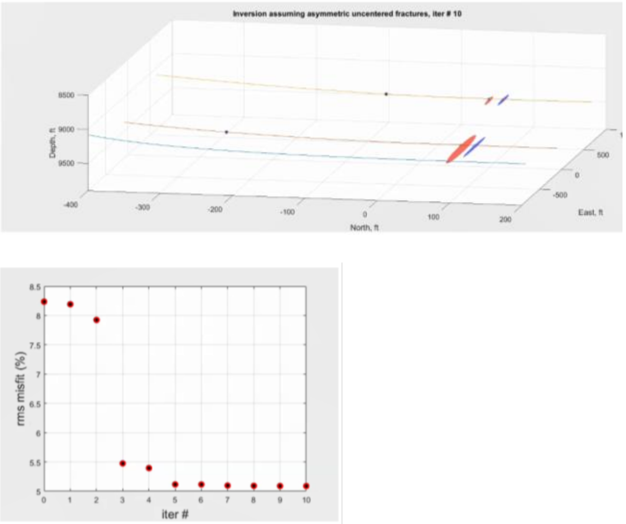

Figure 5: Parametric inversion of propped fractures to determine, length, height, width, and position. Top panel shows the shows final dimensions and location of the ellipsoids. Bottom panel shows the root mean square misfit.

Assessing Uncertainty in Inverted Fracture Geometry

Different values of proppant electrical conductivity provide varying dimensions and locations of the fracture with varying levels of data misfit. With adequate computational resources, and time, it may be possible to provide a fully quantified estimate of uncertainty in inverted location and dimensions of propped fracture geometry. In fact, such attempts have already been made for simple 1D and 2D problems involving separate geophysical applications (eg. Mackie et al. 2018).

The paucity of "ground truth", and limited sensitivity of the geophysical data introduces significant subjectivity regarding utility of such a quantitatively rigorous approach in the present case. As such, an explicit acknowledgment is made upfront in presenting a semi quantitative approach, which embraces the subjective nature of the evaluation, while honoring known quantitative bounds on the data, both of geophysical and non geophysical origin.

Overall, in keeping with concepts of classical probability theory, confidence in propped fracture geometry (C_{FG}) is given as:

$$C_{FG} = C_{apriori} + C_{INV} \times C_{\sigma_{eff}} \quad (1)$$

Where

$C_{apriori}$= Confidence in apriori information; e.g. fracture simulation models, knowledge of production data and a combination thereof and other things, such as the presence of an existing parent production well, existence of a competent geological layer, etc.

C_{INV}= Confidence in geophysical inversion.

$C_{\sigma_{eff}}$= Confidence in determination of expected in situ effective electrical conductivity of proppant.

$C_{\sigma_{eff}}$, in turn, is a function of uncertainty of laboratory measurements for a given pressure ($U_{\sigma_{ex}}$) as well as the uncertainty in conductivity due to the uncertainty in estimate of actual stress on proppant ($C_{\sigma\_stress\_in\_situ}$) at the time of measurement.

$$C_{\sigma_{eff}} = C_{\sigma\_stress\_in\_situ} \times U_{\sigma_{ex}} \quad (2)$$

Amongst them, $U_{\sigma_{ex}}$is fairly quantitative as measurements are performed in controlled laboratory settings with clear standard deviation estimates for a given stress value. On the other hand, $C_{\sigma\_stress\_in\_situ}$ has considerable uncertainty in the absence of potentially expensive downhole pressure gauges. Surface pressure gauges, coupled with geomechanical considerations, provide a "semi quantitative" estimate of confidence.

Similarly, C_{INV} is "cautiously" estimated utilizing a combination of quantitative and semi quantitative factors. An oft stated business goal for geophysical inversions is to

10.1190/segam2019-3215139.1

provide an "80 – 20" solution. In the absence of drilling/ground truth results, a "high confidence" inversion may thus correspond to 20% uncertainty in "ground truth". The "Maastricht template" developed by Shell (2004) in play based exploration PoS (Probability of Success) estimates (Figure 5) can be customized to assess inversion confidence in a qualitative/semi quantitative manner. In the current adoption of this template, 50% confidence implies a "coin toss" regarding confidence in a particular inversion outcome being realistically reflective of true subsurface conditions. A 100% confidence would imply that the realized subsurface outcome has no more than a +/- 10% error bar (80 – 20 solution). Applying this approach to the estimation of confidence in propped fracture geometry, we are able to construct combined cumulative distribution functions (CDF) of exceedance by estimating the confidence of individual inversion runs and the parameters used therein as shown in Figure 7. By combining the CDFs for different attributes of length, height, and width, it is possible to construct a single CDF for the fracture as shown in Figure 8. The hot (red) colors indicate a relatively high likelihood that the fracture geometry is likely bigger, while the cool (blue) colors would indicate a relatively high likelihood of a smaller fracture geometry. By overlaying a generic inversion outcome on this distribution profile, it is possible to estimate first order potential error bars in the inversion. We can also provide meaningful guidance of what parameters are relatively better resolved than others, thereby providing a possible explanation of where the "missing" volume of proppant may have gone to.

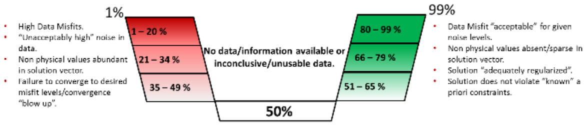

Figure 6: Risking template used for assessing confidence in geophysical inversion results. Adopted and modified from play based exploration risking template developed by Shell (2004).

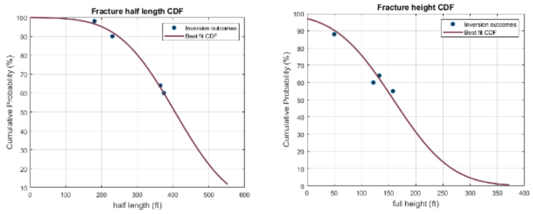

Figure 7: A best fit CDF for fracture half length (left panel) and height (right panel) using the outcome of individual inversion runs. Normal Gaussian distribution is assumed.

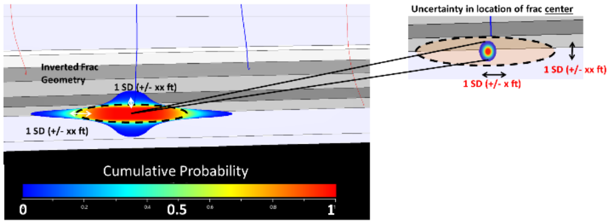

Figure 8: Combining the cumulative probabilities for length and height into a single cumulative distribution function of exceedance. Individual data points provide the likelihood that the propped fracture geometry is greater than that value.

Conclusions

A semi quantitative method for assessing uncertainty in resolved fracture geometry using geophysical inversion of electromagnetic data has been developed. The confidence estimate embraces all conventionally used quantitative methods (data misfit norms, model resolution/sensitivity matrix, the data resolution matrix, etc.) to assess the "validity" of a specific geophysical inversion. The method aims to address the gap between the estimate of a subsurface physical property (electrical conductivity of propped fracture) and the subsurface entity it represents (e.g. propped fracture height, length, and width). It also has the potential to provide meaningful guidance on how to utilize geophysical inversions more meaningfully in the business decision making process.

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