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Hydro-frac Monitoring Using Ground Time-domain EM

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SUMMARY

This paper explores the sensitivity of surface based time domain electromagnetic systems for monitoring hydraulic fractures. The steel well casing of the frac well acts primarily as a DC current path that charges the conductive fracture zone during the transmitter on-time. This increases the current density in the fracture zone several orders of magnitude above that without the steel well connection.

The background resistivity for production environments range from Bakken shale (30 Ohmm) to West Texas carbonates (500 Ohmm). The transient decay response from fracture zones with steel casing produces anomalies between 5% (30 Ohmm background) and 150% (500 Ohmm background) for Ex-Ex coupled surface systems for a 1500 bbl injection (a small frac stage) at 3km below the surface when a conductively enhanced proppant is used.

An adequate characterization of hydraulic fractures will no doubt require the integration of multiple disciplines, including production/injection data and other geophysical techniques. EM methods can play an important role because they can sense where fluid and conductively enhanced proppant actually go.

Introduction

Hydraulic fracturing of reservoirs has been used in the hydrocarbon industry for over fifty years, however with the onset of high production from unconventional reservoirs its use has significantly increased. Efficient production of hydraulically fractured reservoirs requires accurate prediction of the extent and active surface area of fractures or fracture networks that are created and/or activated. In recent years micro-earthquake (MEQ) surveys to locate where the formation ‘pops’ when fractured has become critical input to discrete fracture models (DFM) used in simulation. Coupled geomechanical modelling and flow simulation in MEQ derived DFM models are used to predict stimulated reservoir volume (SRV). MEQ event locations are critically dependent on the velocity model used. SRV estimates can change dramatically when velocity models are updated. Even when MEQ event locations are accurate, by themselves MEQ events cannot tell if injected proppant has reached the MEQ event locations or if fractures associated with MEQ events are connected to the well bore. Additionally, existing fractures which may open and accept proppant may not produce a measureable MEQ event. Thus the SRV estimates which are critical for optimal well placement as well as reserve estimates can be extremely uncertain.

EM methods can play an important role in improving fracture models used in simulation because they can sense where fluid and conductively enhanced proppant actually go. Single borehole EM logging and crosswell EM imaging are available but have limited spatial coverage dictated by well locations; a surface technique can provide increased spatial coverage of resistivity variations and hence proppant distribution as well as reduced cost when compared to borehole techniques.

This paper explores the sensitivity of surface based time domain electromagnetic systems for monitoring hydraulic fractures. Typical proppant slurries can have electrical resistivities close to brine which in some circumstances can provide enough of a resistivity contrast to image with electromagnetic techniques. However, conductively enhanced proppant mixtures can significantly increase the resistivity contrast between the slurry filled fracture and the formation and thus enhance the ability of an EM technique to detect and map the fractures. Recently Pardo and Torres-Verdin (2013) have shown that EM logging tools can have sensitivity to fractures filled with electrically enhance proppant, although with a sensitivity limitation of 100 to 150m on the fracture extent.

Method and/or Theory

We calculate the transient responses for various practical field electric dipole sources using the time domain electromagnetic (TDEM) codes of Commer & Newman (2006) and Haber and Heldmann (2007). Hydrofracture volumes and dimensions are derived from instrumented hydrofracture 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. Figure 1a shows the injectate resistivity as a function of the fraction of proppant contained in the slurry. For graphite coated sand at 40% concentration the injectate conductivity is 2500 S/m.

The volume of injectate per frac stage can range from 1000’s to 100,000’s of barrels (bbl). The frac model used for Figure 1b is equivalent to 1500 bbl. into a plane 410m by 90m (horizontal by vertical). This represents a small frac stage, derived from field operations, and is thus a worst case scenario. A single 5mm thick 440m x 90m frac provide the equivalent volume and is material averaged into TDEM finite-difference cells on the order of meters to simulate the fracture zone. Numerical tests comparing very fine mesh solutions verify the accuracy of our equivalent media models.

The 1500 bbl fracture cannot be seen at the surface above the expected EM noise levels even at a relatively shallow 1km depth when the steel well casing is not included in the model. However, the steel well casing of the frac well acts primarily as a DC current path that charges the conductive fracture zone during the transmitter on-time. This increases the current density in the fracture zone several orders of magnitude above that without the steel well connection. The background resistivity for production environments range from Bakken shale (30 Ω m) to West Texas carbonates (500 Ω m).

The transient decay response from fracture zones with steel casing produces anomalies between 5% (30 Ωm background) and 150% (500 Ωm background) for Ex-Ex coupled surface systems for a 1500 bbl injection at 3km below the surface. Figure 1b shows the before and after percent difference when the 1500 bbl fracture is emplaced at 3km below the surface in a 500 Ωm background. The fracture extends from -170 to +240m. Not only is there a significant signal but there is spatial variation in the response, indicating the potential to track proppant placement.

While the numerical simulations show a high sensitivity to conductive fractures, 3D unconstrained anisotropic pixilated inversion shows low spatial resolution. If spatial constraints from prior information is available then 3D pixilated inversion of the highly constrained zone can provide reasonable conductivity estimates. Given that the objective is to have the surface EM data define the spatial distribution of thin conductive features it seems new developments in 3D parameterized inversion are needed to accommodate the general variability of the background as well as the geometrically constrained nature of fractures. Ideas for this will be proposed to stimulate discussion.

Figure 1a Injectate slurry conductivity as function of proppant concentration and proppant conductivity. 40% graphite coated sand in 3 S/m brine produces 2500 S/m injectate.

Figure 1b) Constant offset time section for Ex % anomaly from 1500 bbl frac at 3km in 500 Ωm background. Frac extends from -170 to +240m in X, frac edges are vertical white lines. Horizontal x oriented 50m dipole sources are used.

Conclusions

Three dimensional time domain modelling has shown that realistic sized hydraulic fracture zones can produce surface electric field responses that are measurable above field acquisition noise levels (3.0 E-10 V/m). The presence of the steel well casing is essential to channel current into the conductive fracture in order to produce measurable decay signals at the surface from fractures at commercially important depths (up to 3km).

References

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