Imaging Fluid Flow and Transport in Discrete Fractures Using Ground Penetrating Radar

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STATUS: Long-term project in progress
TIMING: Significant results to be reported – Results currently available to membership
FUNDING: Partial from DOE 07-358509

Purpose
Accurate prediction of fracture flow properties is critical to the efficient development of reservoirs. Flow in fractured formations is highly heterogeneous and difficult to predict. The objective of this work is to study fractured near-surface reservoir analogues for remote determination of fracture hydraulic properties and time-lapse monitoring of flow of fluids using GPR. Recently developed GPR methods of monitoring ground water flow will be extended to imaging multi-phase flow through fractures and monitoring the efficiency of enhanced oil recovery methods. High-resolution field imaged fracture properties will be incorporated to reservoir flow model simulations.

Project Description
Predicting flow and transport in fractured formations remains a challenge. Flow through this highly heterogeneous medium is controlled by fracture aperture, channeling along the fracture (i.e., aperture variability), and fracture connectivity. Our earlier work has developed GPR methods for imaging fractures and mapping aperture variability (Figure 1) (Tsoflias, 2008), differentiating between air filled (drained) and water filled (saturated) portion of a fracture plane during hydraulic testing (Figure 2) (Tsoflias et al., 2001), and identifying variations in fracture water salinity (Figure 3) (Tsoflias and Becker, 2008).

Our research, currently funded by the U.S. Department of Energy, is developing GPR methods to obtain an independent measure of the spatial distribution of fracture aperture and fluid tracer concentration. We are investigating the GPR response of water-saturated fractures of varying aperture containing native formation water or a saline tracer of varying concentration. For a fracture enclosed in a homogenous matrix, reflection amplitude is expected to increase from a value of zero for zero layer thickness to maximum reflection strength when layer thickness is approximately equal (depending on wavelet shape) to \( \frac{1}{4} \) of signal wavelength \( (\lambda) \) in the medium filling the fracture. EM theory also predicts that electrically conductive (lossy) media yield complex reflection and transmission coefficients that result in signal phase shift (Straton, 1941). The Fresnel equations describe the dependence of the complex reflection coefficient to layer thickness, electrical conductivity, permittivity, signal frequency, angle of incidence and wavefield polarization. Our work including field experiments, analytical solutions of the Fresnel equations and FDTD numerical simulations has shown that at a fractured geologic setting a saline tracer will cause a characteristic and predictable change to the reflected GPR signal amplitude and phase. This new understanding of GPR response to fracture properties allows us to remotely measure fracture aperture, predict fluid content and measure tracer concentration.
The ongoing investigation is developing GPR methods for remote, quantitative characterization of fracture flow and transport properties. The proposed work will further advance the GPR theoretical, modeling and reservoir analog field work to study fracture flow of multiple phase fluids analogous to hydrocarbon reservoirs. Field investigations will monitor flow through discrete fractures of water, water-air, vegetable emulsions of varying viscosity to simulate oil, and fluids of varying salinity to quantify fracture transport properties and monitor flow through formation matrix. Field GPR experiments will also monitor the efficiency of reservoir analogue simulated enhanced oil recovery methods, such as gelled polymers developed by KICC’s TORP to control flow through fractures in oil reservoirs. Furthermore, the GPR methods will be applicable to radar observations that could be made in boreholes, allowing fracture imaging of a region extending 10 to 30 m away from the borehole and down to borehole depths of actual hydrocarbon reservoirs. Such methods could prove useful to the development of new electromagnetic based downhole technologies for hydrocarbon exploration.

**Deliverables**

The proposed work will advance GPR methods for remote, quantitative characterization of flow and transport properties of fractured hydrocarbon reservoir analogues. The new GPR methods will allow the study of flow in well-understood near-surface reservoir analogs by simulating multiphase flow and fluid types found in hydrocarbon reservoirs. Quantitative observations of flow and transport through fractures and matrix will be integrated with reservoir simulation studies for prediction of hydrocarbon reservoir performance.

**References**


Figure 1. a) Perspective view of a 200 MHz 3-D GPR data displayed along with wellbores and caliper log curves (blue curves). Distinct reflections correlate spatially to horizontal fractures (f1, f2 and f3). b) GPR reflection amplitude map of f3. Well locations are shown as solid circles (after Tsoflias, 2008).

Figure 2. (left) GPR line during pumping test at well 13. Single trace inserts of the FDTD modeled waveforms for saturated, partially saturated and drained fracture models, are shown along with the corresponding recorded waveforms outlined by white boxes. (right) Amplitude map of the 28 ns peak during pumping at well 13. (from Tsoflias et al., 2001).