4D GPR for Fluid Flow Quantification in Fractured Carbonates: Cretaceous Orfento Formation, Madonna della Mazza, Italy

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Project Objectives

- Calculate volumetric water content changes and visualize wetting/draining zones of a controlled infiltration experiment in fractured carbonates.
- Compute flow rates within porous matrix and quantify the influence of faults and deformation bands on fluid flow.
- Compare the results with the Miami Oolite infiltration experiment and dynamic fluid flow simulation.

Rationale

Characterization of the parameters controlling fluid flow mostly relies on 0.01-0.1 meter scale lab measurements, up scaling, and modeling. To visualize and quantify fluid flow at a more realistic scale of 1-10 meters, we conducted a field experiment injecting and monitoring a moving water mass into a fractured grainstone reservoir analog. 4D GPR is used in this study to quantify local water content changes, delineate wetting and drainage zones, and determine the influence of faults and deformation bands on fluid flow. Characterizing the dynamics of fluid flow in a porous matrix is possible because of variations detected in the GPR response between time-lapse data (Truss et al., 2007). Quantification of fluid flow within a network of faults and deformation bands helps in perfecting flow models and residual fluid recovery.

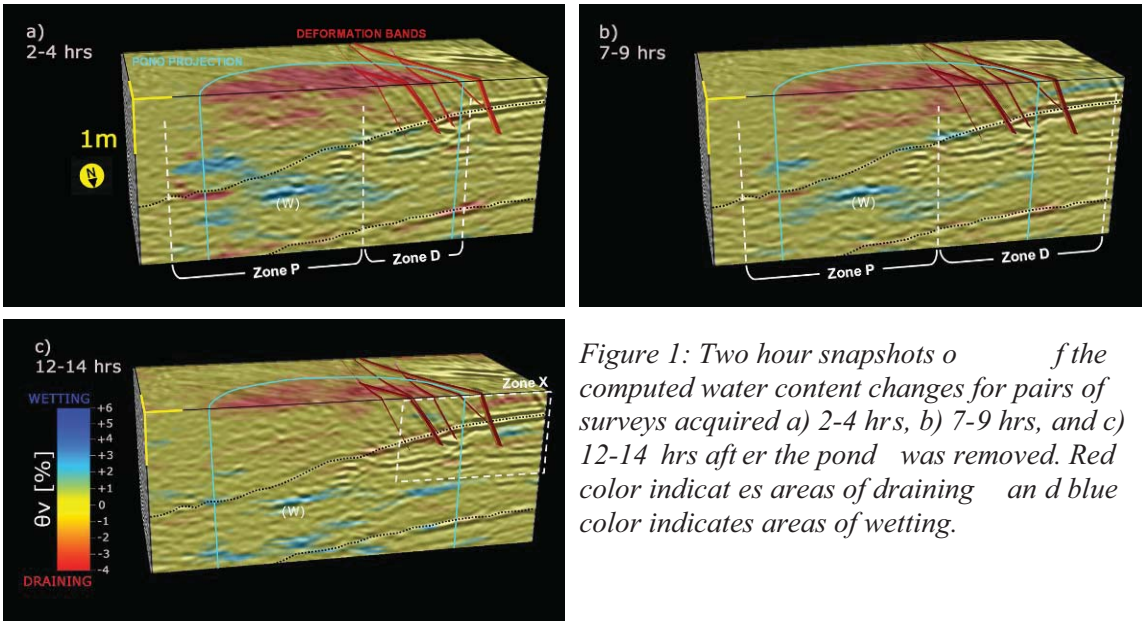

Figure 1: Two hour snapshots of the computed water content changes for pairs of surveys acquired a) 2-4 hrs, b) 7-9 hrs, and c) 12-14 hrs after the pond was removed. Red color indicates areas of draining and blue color indicates areas of wetting.

Project Background and Fieldwork

Data were acquired in summer 2009 at the Madonna della Mazza quarry. This quarry is cut into a sequence of Upper Cretaceous rudist grainstones (Orfento Formation) located in the Majella anticline in southern Italy. We chose the infiltration area where previously acquired 3D GPR surveys revealed the coexistence of dipping layers, faults, and deformation bands in a high porosity matrix. Average porosity and permeability is 30% and 300 millidarcy (mD), respectively. 3000 liters of water were infiltrated over 30 hours from a polyethylene pond with a 4-meter diameter installed on the quarry floor. The time-lapse dataset consists of sixteen repeated 3D GPR surveys (2 before and 14 after the infiltration) monitoring a 20x20x10 meter rock volume over 5 days. A 3D rotary laser positioning and guidance system coupled with a 200 MHz GPR system achieved high-resolution 3D data quality and centimeter precise repeatability between surveys.

Method and 2010 Preliminary Results

Event timeshifts and amplitude differences between repeated surveys are related to subsurface water content changes. GPR reflection travel timeshifts are extracted from survey pairs with a 3D warp algorithm, followed by quantification of volumetric water content changes with the Topp petrophysical transfer function (Topp et al., 1980). For three different infiltration stages, volumetric water content changes have already been computed with an accuracy of 1% (Figure 1). Results show that the momentary wetting and drainage zones are located in the undisturbed strata, compared to strata disturbed with deformation bands. The decrease of permeability, relative to the surrounding rock matrix, slows down the fluid flow across deformation bands (Fossen et al., 2007). We also observe how the gravity driven transport of water, occurring in the first stages of the experiment (with greater hydraulic heads), shifts to a capillary driven transport, indicating that the hydraulic regime changed within 12 hours.

Tasks for 2011

1. Extensive computation of water content changes during the entire experiment over time intervals ranging from 2 hours to 5 days from the start of the infiltration.
    - Preliminary results of water content changes generated for three stages indicate that monitoring the behavior of the infiltrated water mass over time and space is possible with our data. The implementation of a 3D warp code on a GPU processing unit will be completed to process a total of 105 possible pair combinations within the 16 time-lapse GPR volumes. This unique dataset will be used to reach a comprehensive visualization and quantification of fluid flow dynamics with unparalleled accuracy.
2. Comparison of flow behavior in the fractured carbonates of the Madonna della Mazza quarry with the results from the infiltration in the undisturbed Miami Oolite.
    - The first GPR time-lapse experiment was in the oolitic shoal system of the Pleistocene Miami Limestone where 3200 liters of water infiltrated strata with porosities ranging from 20-50% and permeabilities up to 1 Darcy

(Grasmueck et al., 2007). The water preferentially propagated along the dipping stratigraphy, causing an asymmetric wetting bulb. There are indications of local breakthroughs across stratigraphic boundaries (Figure 2). The comparison of the two infiltration experiments allows the role of sedimentary structures, such cross bedding in the Miami Oolite, versus structural deformation, such as deformation bands in the Orfento Formation, to be assessed.

3. Comparison with Eclipse dynamic fluid flow simulation.
    - With guidance from Ray Mitchell (ConocoPhillips), a static model was built of the cube from the infiltration experiment in the Madonna della Mazza quarry. Kirsten Gustafson (ConocoPhillips) then translated the model into Eclipse for dynamic fluid flow simulation (Figure 2). We plan to run several simulations and compare the results to the flow behavior measured with the time-lapse GPR surveys.
4. Integration of 4D GPR results with petrophysical measurements on sample plugs and thin sections analysis.
    - In order to comprehensively capture the flow behavior of the rudist grainstone facies from the plug to the meter scale, plugs from various stratigraphic intervals will be analyzed for their porosity, permeability, velocity, and electrical resistivity.

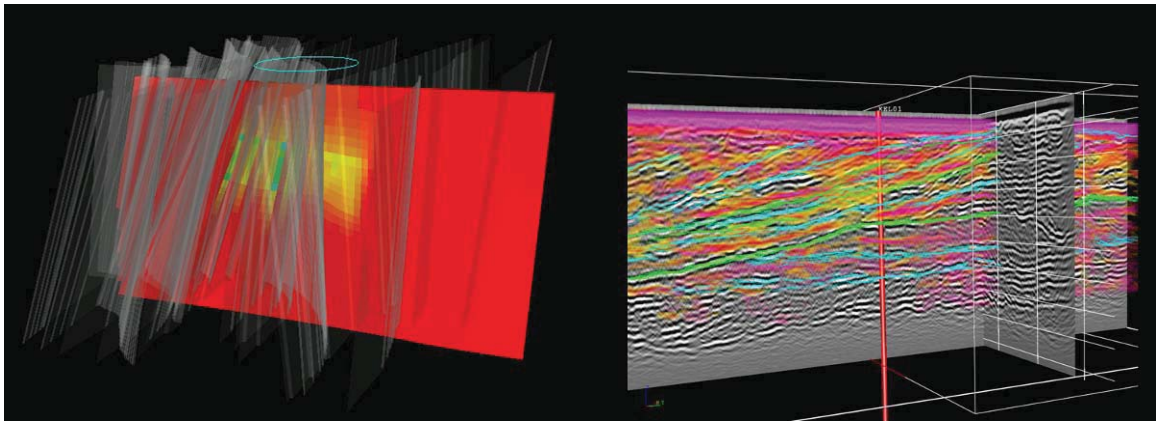

Figure 2: Snapshot of saturation changes from the Eclipse fluid flow simulation. Faults and deformation bands are rendered semitransparent (left). Overlay of regular 3D GPR data and water content changes in the Miami Oolite infiltration experiment (right).

Key Deliverables

This project will deliver fully characterized stratigraphic-structural-hydraulic relationships for the Madonna della Mazza Quarry. This characterization includes the integration of water content change volumes, propagation rates, quantification of fluid mass balance, conventional 3D GPR data, and rock sample measurements. This project also develops the tools and a workflow applicable to other outcrop reservoir analogues where a precise understanding of flow processes is needed.

References

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