

Time-lapse 3D GPR for Fluid Flow Quantification in Fractured Carbonates: Cretaceous Orfento Formation, Madonna della Mazza, Italy

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Project Objectives

- Quantify water content changes and track flooding/drainage boundaries as the response to a controlled infiltration experiment in fractured carbonates.
- Calculate flow propagation rates within porous matrix and quantify influence of faults and deformation bands on flow.
- Mass-balance checks of moving fluid to verify water content changes computations.

Rationale

Currently, the characterization of fluid flow mostly relies on laboratory sample measurements, upscaling, and modeling. In this study we use for the first time 4D Ground Penetrating Radar (GPR) to monitor in-situ fluid flow in response to a controlled water infiltration experiment at an outcropping fractured carbonate reservoir analog. 3D GPR images in great detail show the fractures, faults, and deformation bands in the Cretaceous Orfento Formation in the Madonna dell Mazza quarry in Italy (Fig. 1). Because GPR is sensitive to changes in subsurface water content, it can be used to monitor propagation fronts represented by wetting and drying events. Variations detected in the GPR signature between time-lapse data can be linked to zones where water content changes occurred (Truss et al., 2007). Quantification of fluid flow within a network of faults and deformation bands helps the flow prediction models and residual fluid recovery.

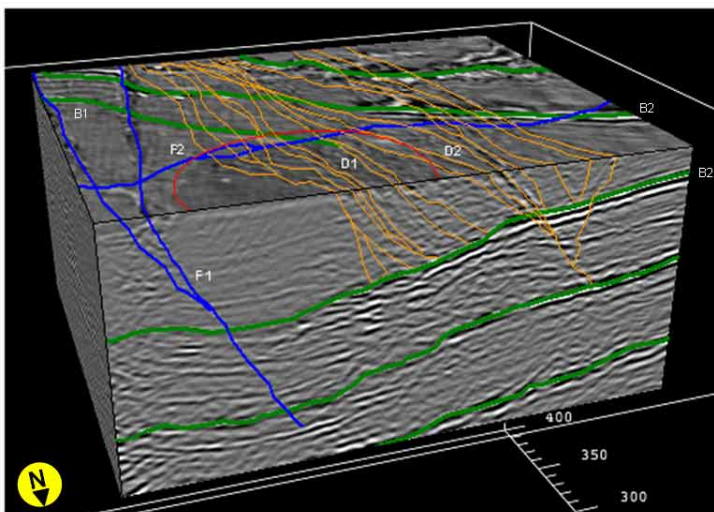


Figure 1. Three dimensional schematic interpretation of the main geological features within the GPR volume: dipping beds B1 and B2, fractures F1 and F2, clusters of deformation bands D1 and D2. The red circle indicates the area where the temporary pond was installed.

Background and Methodology for 2009 Fieldwork

In summer 2009 we performed a series of 3D GPR surveys before and after a controlled water infiltration to determine and quantify the influence of faults and deformation bands on fluid flow in a porous matrix. A temporary polyethylene pond of 4 m diameter was installed on the quarry floor and 3000 liters of water were infiltrated over 30 hours. The first post-infiltration GPR survey was acquired as soon as there was no more standing water and after the pond walls were removed. Overall, sixteen 3D GPR time-lapse surveys were conducted monitoring a 20x20x10 m volume: 2 surveys before (dry) and 14 surveys after the water infiltration (wet) tracking fluid flow over a period of 5 days.

Preliminary Results

When comparing pairs of 3D GPR data cubes, arrival time shifts for GPR reflections are caused by water content changes. A volume-warping algorithm extracts the intrinsic time shifts between pairs of GPR data cubes visualizing snapshots of flow direction and intensity (Fig. 2). In addition, gradients of time shifts provide information about how faults and deformation bands influence fluid flow with respect to the surrounding porous matrix.

Scope of the 2010 Project

Preliminary results are encouraging but yet the 16 volumes still have a wealth of information that has to be exploited: A total of 105 combinations of pairs of repeated surveys can be used to calculate intrinsic time shifts and track flow with time increments between 2 hours and several days. However, time-lapse 3D GPR processing is computationally demanding and the average time for full-density warp calculation for just one survey pair is 8 days. In order to reduce the compute times by a factor of 10 or more, we are in the process of implementing the warp code on a GPU processing unit. Once this computation bottleneck is removed, the analysis of the comprehensive 4D GPR dataset recorded at the Madonna della Mazza quarry should become more feasible.

The goal of this GPR study is to achieve a full characterization of the subsurface fluid flow in terms of:

- 1) Water content changes and tracking of flooding/drainage boundaries. Application of the Topp petrophysical transfer function to time shift volumes (Topp et al., 1980) quantifies the in-situ water content changes over time and space. Estimation of the extent of the wetting bulb will be achieved by comparing the dry initial state with the fourteen GPR surveys recorded over the following 5 days. Moreover, to characterize the dynamics of wetting, saturation, draining, and surface evaporation, we can compare pairs of repeat 3D GPR surveys recorded within a 2-3 hr interval to receive snapshots of the fluid flow over such short timeframes (Fig. 3). This dataset is unique as it consists of a continuous series of

GPR surveys where the total amount of infiltrated water moving through the porous rock volume is known.

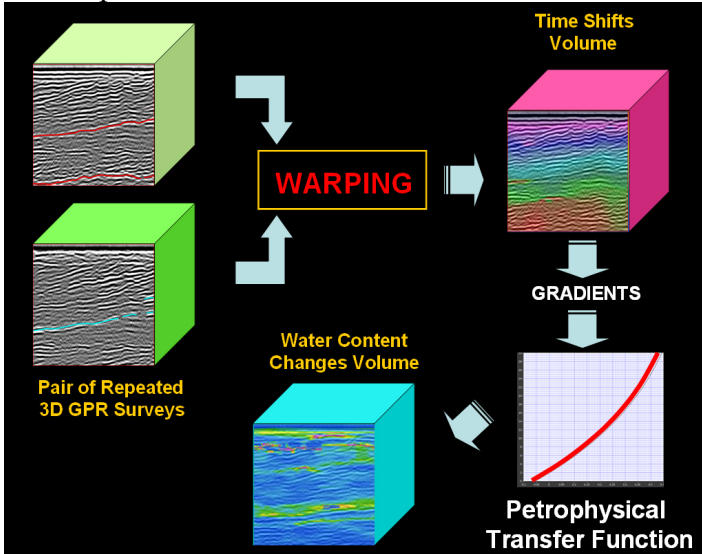


Figure 2. Warping extracts the intrinsic time shifts between pairs of time-lapse volumes. Application of the Topp petrophysical transfer function yields volumetric water content changes over time and space.

- 2) Flow propagation rates through major fluid conduits and the porous surrounding matrix. With a semi-transparent rendering of the water content change volumes over the regular 3D GPR data, the hydraulically most active faults and deformation bands can be identified together with a quantification of fluid transport within these zones.

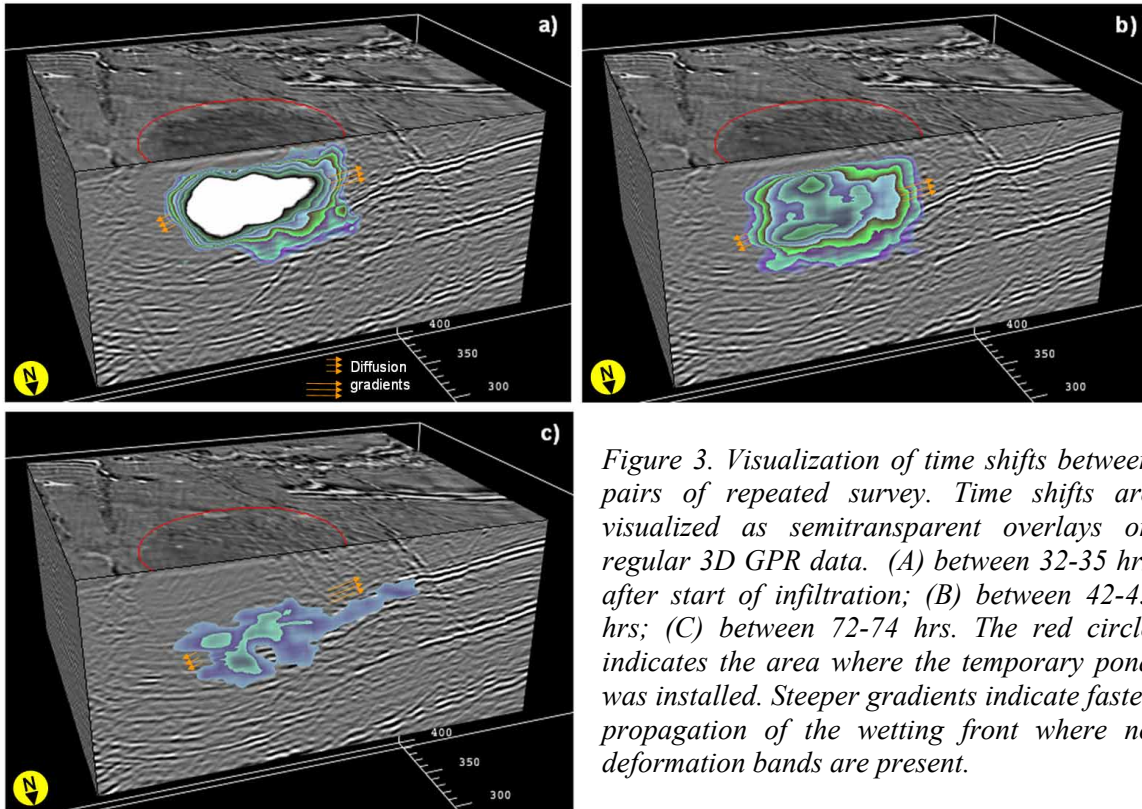


Figure 3. Visualization of time shifts between pairs of repeated survey. Time shifts are visualized as semitransparent overlays on regular 3D GPR data. (A) between 32-35 hrs after start of infiltration; (B) between 42-45 hrs; (C) between 72-74 hrs. The red circle indicates the area where the temporary pond was installed. Steeper gradients indicate faster propagation of the wetting front where no deformation bands are present.

- 3) Fluid mass balance used to verify the water content change computations. In our previous 4D GPR experiments conducted within the Miami Oolitic Limestone, mass balance calculation showed that volumetric water content change estimates from 4D GPR datasets are accurate within a few percent.
- 4) Compare time-lapse GPR results with conventional infiltration and evaporation measurements performed in the field and on samples

Key Deliverables

Integrate water content change volumes, propagation rates, quantification of fluid mass balance, conventional 3D GPR data, and rock sample measurements to fully characterize stratigraphic-structural-hydraulic relationships at the Madonna della Mazza Quarry. This pilot project also introduces a workflow applicable to other outcropping reservoir analogues where a precise understanding of flow processes is needed.

References

Topp, G.C., Davis, J.L. and Annan, A.P., 1980, Electromagnetic determination of soil water content: Measurements in coaxial lines. *Water Resour. Res.* 16: 574–582.

Truss, S., Grasmueck, M., Vega, S., and Viggiano, D.A., 2007, Imaging rainfall drainage within the Miami oolitic limestone using high-resolution time-lapse Ground Penetrating Radar, *Water Resources Research*, Vol. 43, No. 3, W03405, doi: 10.1029/2005WR004395.