Time-Lapse Joint Inversion of Seismic and Resistivity Data during Production of Oil in Carbonate Rocks*

A. Revil[1], M. Karaoulis[2], and J. Zhang[2]

Search and Discovery Article #120087 (2013)
Posted February 28, 2013

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG Hedberg Conference, Fundamental Controls on Flow in Carbonates, July 8-13, 2012, Saint-Cyr Sur Mer, Provence, France, AAPG©2012

[1]Colorado School of Mines, Dept. of Geophysics, Golden, CO, USA (arevil@mines.edu)
[2]Colorado School of Mines, Dept. of Geophysics, Golden, CO, USA

Abstract

Time-lapse joint inversion of geophysical data is required for a number of important problems in geosciences including the management of oil and gas reservoirs and the sequestration of CO_2 (e.g., Kowalsky et al., 2006). In some cases, the inclusion of the physics of the monitored process directly in the inversion of the geophysical data can help to reduce the non-uniqueness of the geophysical inverse problem (e.g., Liang et al., 2011) (see Figure 1). If we consider joint inversion problem of geophysical data alone, there are essentially two types of strategies that can be used, one based on the use of petrophysical models to link geophysical methods (e.g., Hertrich and Yaramanci, 2002; Rabaute et al., 2003; Kowalsky et al., 2006; Woodruff et al., 2010) and one based on the use of structural similarities between the sought physical properties (e.g., Gallardo and Meju, 2003, Linde et al., 2006). Because different rock properties are usually sensitive to different aspects of the texture of porous materials (e.g., fracture versus matrix properties for dual porosity systems), the joint inversion based on petrophysical models may have some difficulties in a certain number of cases while the joint inversion based on the structural similarities (Gallardo and Meju, 2003) may have a better chance to work out the contributions from the different property groups, especially for time-lapse tomography.

Several strategies are also possible for the time-lapse inversion of geophysical datasets. While sequential time-lapse inversion is generally successful (e.g., Karaoulis et al., 2011a), the result is sensitive to the inversion of the first snapshot of the physical process under study. Thus, the traditional approach of inverting separately different snapshots and comparing the results may not be the favoured strategy here. The actively time-constrained (ATC) approach of Kim and Karaoulis (Kim et al., 2009; Karaoulis et al., 2011a, b) seems to be a very suitable approach to invert simultaneously a complete time-lapse geophysical dataset using time as a fourth dimension and using a time-based regularization term into a generalized cost function.

In this presentation, we combine the structural joint inversion and the active time-constrained time-lapse inversion together to invert cross-hole data and we discuss the advantages in combining these two approaches together for the monitoring of partial saturation changes during the production of oil in carbonate reservoirs. This approach will be first illustrated below on a simple problem. A joint time lapse inversion between ERT and GPR is shown by Doetch et al., 2010. In their approach time lapse inversions were used by using the difference inversion

(LaBrecque and Yang, 2001). This approach minimizes the differences with respect a background model of each time step separately. In our approach, time is introduced to the system and encompasses all space models during the entire monitoring period (global system). The minimized cost function includes a global misfit for all data during the entire monitoring period.

We first test the joint inversion scheme to a simple time-lapse model using a set of 3 snapshots for a moving target between two wells. We use a bipole-bipole array for the DC resistivity (P1 and C1 electrodes in borehole A, P2, and C2 electrode in borehole B) with a total of 1100 measurements. The synthetic data are contaminated with a 3% noise level.

Figure 2 shows the results for cross-gradient time-lapse joint inversion, which are much better than the results obtained from the independent inversion or the time-lapse inversion of the seismic and resistivity data taken independently (not shown here). The blue colors indicate an increase in the resistivity or seismic velocity while the red colors indicate a decrease. The cross-gradient time-lapse joint inversion considerably improve the results of the inversion in the sense that there are much less spatial artifacts in the tomograms for the other types of inversion.

We will show examples associated with the multiphase flow of oil and water during a simulated two-phase flow production in a carbonate rock. The numerical modeling of the transport equation will be used to estimate the evolution of the saturation in the formation, and then the change in seismic velocity and resistivity. Then we will simulate the acquisition of cross-hole data for seismic and DC resistivity. These data are contaminated with noise, and inverted using our time-lapse joint inversion algorithm. The reconstructed resistivity and seismic velocities will be used to estimate the evolution of the saturation, which will be compared with the true distribution.

References Cited

Doetsch, J., N. Linde, and A. Binley, 2010, Structural joint inversion of time-lapse crosshole ERT and GPR travel time data: Geophys. Res. Letters, v. 37, L24404, doi:10.1029/2010GL045482.

Gallardo, L.A., and M.A. Meju, 2003, Characterization of heterogeneous near-surface materials by joint 2D inversion of dc resistivity and seismic data: Geophys. Res. Lett., v. 30/13, 1658, doi:10.1029/2003GL017370.

Hertrich, M., and U. Yaramanci, 2002, Joint inversion of surface nuclear magnetic resonance and vertical electrical sounding: Journal of Applied Geophysics, v. 50/1-2, p. 179-191.

Karaoulis, M., J.H. Kim, and P.I. Tsourlos, 2011a, 4D Active Time Constrained Inversion: Journal of Applied Geophysics, v. 73/1, p. 25-34.

Karaoulis M., A. Revil, D.D. Werkema, B. Minsley, W.F. Woodruff, and A. Kemna, 2011b, Time-lapse 3D inversion of complex conductivity data using an active time constrained (ATC) approach: Geophysical Journal International, v. 187, p. 237–251, doi: 10.1111/j.1365-246X.2011.05156.x.

Kim, J.H., M.J. Yi, S.G. Park, and J.G. Kim, 2009, 4-D inversion of DC resistivity monitoring data acquired over a dynamically changing earth model: Journal of Applied Geophysics, v. 68/4, p. 522-532.

Kowalsky M.B., J. Chen, and S.S. Hubbard, 2006, Joint inversion of geophysical and hydrological data for improved subsurface characterization: The Leading Edge, v. 25/6, p. 730-734.

LaBrecque, D.J., and X. Yang, 2001, Difference inversion of ERT data: A fast inversion method for 3-D in situ monitoring: J. Environ. Eng. Geophys., v. 6/2, p. 83–89, doi:10.4133/JEEG6.2.83.

Liang, L., A. Abubakar, and T.M. Habashy, 2011, Estimating petrophysical parameters and average mud-filtrate invasion rates using joint inversion of induction logging and pressure transient data: Geophysics, v. 76/2, p. E21-E34.

Linde, N., A. Binley, A. Tryggvason, L.B. Pedersen, and A. Revil, 2006, Improved hydrogeophysical characterization using joint inversion of cross-hole electrical resistance and ground-penetrating radar travel time data: Water Resour. Res., v. 42, W12404, doi:10.1029/2006WR005131.

Rabaute, A., A. Revil, and E. Brosse, 2003, In situ mineralogy and permeability logs from downhole measurements: Application to a case study in clay-coated sandstone formations: Journal of Geophysical Research, v. 108, 2414, doi: 10.1029/2002JB002178.

Woodruff, W.F., A. Revil, A. Jardani, D. Nummedal, and S. Cumella, 2010, Stochastic inverse modeling of self-potential data in boreholes: Geophysical Journal International, v. 183, p. 748–764.

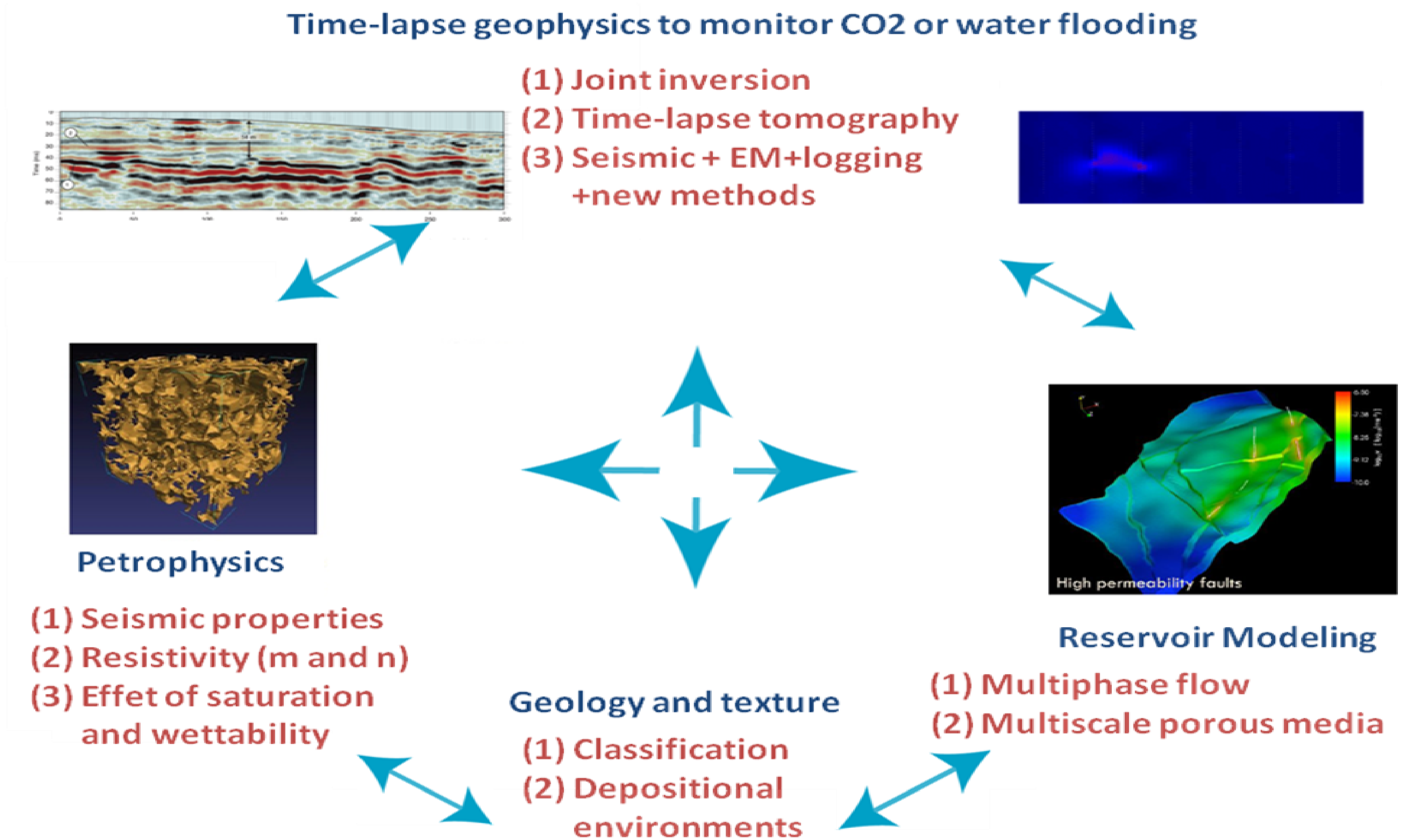

Figure 1. Interaction between geophysics, petrophysics, and reactive transport modeling to assess the production of oil in carbonate rocks during CO_2 or water flooding.

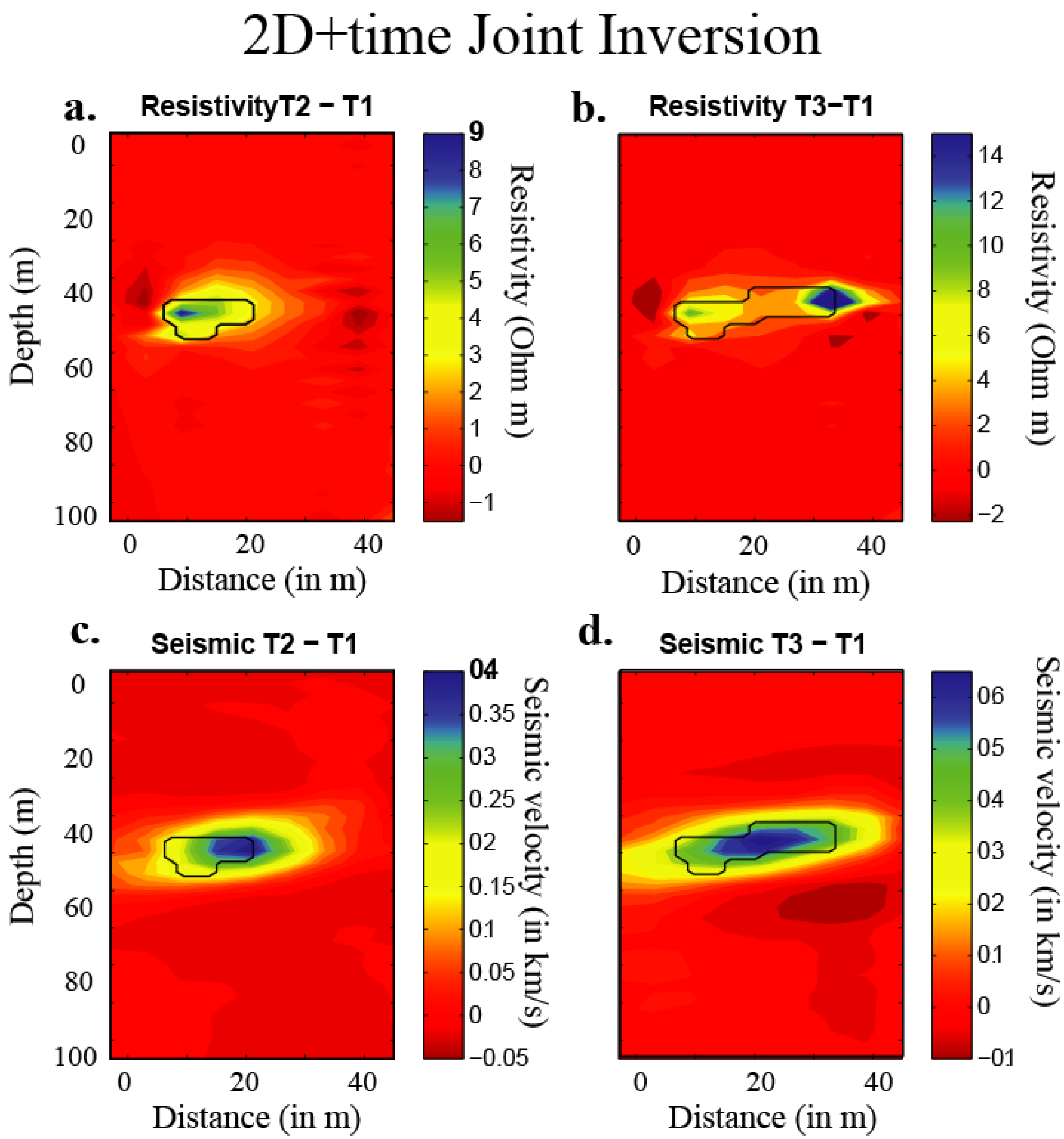

Figure 2. Joint time-lapse inversion. a. b. Time-lapse joint inversion of the resistivity and seismic data and display of the resistivity changes between time T2 and time T1 (a) and between time T3 and time T2 (b) at iteration 5. c. d. Same for the seismic data. The thin black line denotes the true position of the change in seismic velocity and resistivity.