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Integration of crosswell seismic data for simulating porosity in a heterogeneous carbonate aquifer

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ABSTRACT

A challenge for the geostatistical simulation of subsurface properties in mining, petroleum and groundwater applications is the integration of well logs and seismic measurements, which can provide information on geological heterogeneities at a wide range of scales. This paper presents a case study conducted at the Port Mayaca aquifer, located in western Martin County, Florida, in which it is of interest to simulate porosity, based on porosity logs at two wells and high-resolution crosswell seismic measurements of P-wave impedance. To this end, porosity and impedance are transformed into cross-correlated Gaussian random fields, using local transformations. The model parameters (transformation functions, mean values and correlation structure of the transformed fields) are inferred and checked against the data. Multiple realizations of porosity can then be constructed conditionally to the impedance information in the interwell region, which allow identifying one low-porosity structure and two to three flow units that connect the two wells, mapping heterogeneities within these units and visually assessing fluid paths in the aquifer. In particular, the results suggest that the paths in the lower flow units, formed by a network of heterogeneous conduits, are not as smooth as in the upper flow unit.

1. Introduction

Seismic measurements and well logs are commonly used to characterize rock properties and geological heterogeneities in the subsurface. Examples of applications include mining and petroleum exploration, in which it is of interest to describe heterogeneous ore deposits and reservoirs at multiple scales. These applications are usually focused on understanding the nature of the heterogeneity and on improving algorithms to produce reliable deposit or reservoir models. Such models, which integrate cores, well logs, seismic and production data are used to identify mineral resources, to locate unswept oil in reservoirs under waterflood, or to forecast oil reservoir performance (Ikelle and Amundsen, 2005; Jennings et al., 2000; Kerans et al., 1994; Malehmir et al., 2012).

In groundwater applications, the integration of seismic data and well logs can provide information at a wide range of scales in order to predict the rock physical properties and the geological heterogeneities of an aquifer, which is essential for flow transport modeling and for designing cost-effective aquifer remediation and water management procedures (Dafflon et al., 2009). The geophysical attributes capture the geological structures and their physical properties, allowing mapping and characterizing flow units at large well separations to minimize the number of wells, thus avoiding unnecessary disruptions of the environment. Although a combination of surface reflection seismic and well log data can help to delineate large scale heterogeneities and structural features in aquifers (Parra et al., 2006), it is also important to conduct high-resolution crosswell seismic measurements to predict rock physical properties such as permeability and porosity at local scales in the region between wells.

To relate the geological units or the lithology of an aquifer to its petrophysics, it is imperative to have a standard suite of well logs (e.g., porosity, permeability, resistivity, gamma ray). For limestone aquifers, formation micro-imager (FMI) logs are recommended to provide the microstructure characteristics of the formation at the well location. In carbonate aquifers, the FMI logs allow estimation of primary (matrix) and secondary porosities. Processing the FMI logs also yields vuggy and crack porosity logs. The primary or matrix porosity can contain interconnected pores to create a water flow path, and the secondary porosity can be formed by isolated or connected vugs. Connected vugs in the matrix form good water conduits, while isolated vugs form low-permeability flow paths (Kazatchenko et al., 2006). Cores and well logs provide relevant information about the rock-fabric facies, which is used to describe heterogeneities and to predict fluid paths in the aquifer at the well scale. By using porosity and permeability data captured

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by seismic waves, as well as seismic data acquired between wells, one can relate the seismic attributes with petrophysical data at the well scale to characterize the aquifer between wells. The most common attributes extracted from seismic data are P-wave velocity, impedance and attenuation.

Geostatistical techniques such as kriging and cokriging have been widely used to integrate seismic data with well log data (Doyen, 1988; Dubrule, 2003; Parra and Emery, 2013). These techniques allow mapping or delineating flow units but do not provide information about pore structure variability (or heterogeneities) within these units. Although the relationship between total porosity and the lithological units at the well scale are generally understood, there is a need to identify and to visualize the distribution of small-scale heterogeneities in aquifers at the interwell region, which can be achieved by means of stochastic simulation (Belina et al., 2009; Dafflon and Barrash, 2012; Dafflon et al., 2009; Dubreuil-Boisclair et al., 2011).

In this paper, we describe a work conducted at the Port Mayaca aquifer in western Martin County, Florida, in which stochastic simulation is used to visualize the small-scale aquifer heterogeneity. Our study incorporates previous well examinations at the site (Parra et al., 2009), in which tight limestone features are clearly observed at several FMI depths. These features are correlated with elemental log analysis (ELAN, Schlumberger propriety software) porosity logs. Several thinner resistive streaks shown in the FMI logs are not resolved by the ELAN porosity logs, but lower porosity in a permeability barrier interval (Bennett and Recrenwald, 2002). Between these resistive streaks are thin, conductive limestone zones corresponding to isolated secondary porosity.

For the current study, ELAN porosity logs are integrated with crosswell P-wave seismic impedance. We selected a high water production zone in the interwell region, and ELAN porosity logs from Port Mayaca wells MF-37 and EXPM-1 were used to acquire the crosswell data. Basic statistics of the data are provided in Table 1. The ELAN porosity, available along the wells with a resolution of 0.15 m (0.5 ft), represents the lithological variability of the aquifer at the well scale, while P-wave impedance data are obtained by inverting crosswell seismic reflection measurements, with a resolution of 3.05 m (10 ft) in the east–west direction and 0.61 m (2 ft) in depth (Parra et al., 2006, 2009).

2. Joint modeling of ELAN porosity and P-wave impedance

2.1. Basic hypotheses

In the following, we will work in the two-dimensional space formed by the cross-section between wells MF-37 and EXPM-1. A generic location in this space will be represented by a vector $\mathbf{x} = (x_1,x_2)$ indicating the east and depth coordinates. ELAN porosity and P-wave impedance are viewed as realizations of two cross-correlated spatial random fields, which will be denoted by Z_1 and Z_2, respectively.

Modeling the joint distribution of these random fields faces two main difficulties:

1) ELAN porosity is known only at wells MF-37 and EXPM-1, in the edges of the region of interest, so that there is little direct information about the spatial continuity of this variable along the east–west direction.

Table 1
Statistics of ELAN porosity (dimensionless) at wells MF-37 and EXPM-1 and P-wave impedance ((g/cm^3) (ft/s)) in the interwell region.

	ELAN porosity	P-wave impedance
Number of data	1070	17,145
Minimum	0.1946	7253.2
Maximum	0.4896	23,824.6
Mean	0.3921	15,943.9
Standard deviation	0.0435	2119.9

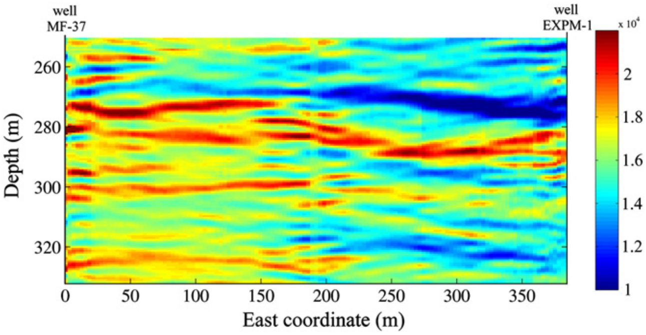

Fig. 1. Map of P-wave impedance in the interwell region.

2) The distributions of ELAN porosity and P-wave impedance are likely not to be the same everywhere in the interwell region. In particular, the map of P-wave impedance (Fig. 1) and the scatter plots of P-wave impedance along each coordinate axis (Fig. 2) suggest the presence of a systematic trend along the east coordinate (with greater impedance values to the west and lower values to the east), whereas no obvious trend is perceptible along the vertical direction (well direction). One therefore expects the random fields associated with ELAN porosity and P-wave impedance to be non-stationary, with distributions that vary along the east–west direction.

The key idea of the model that will be proposed is to transform the ELAN porosity and P-wave impedance into two cross-correlated Gaussian random fields. The non-stationarity of ELAN porosity and P-wave impedance will be modeled through the use of local transformations, which vary along the east–west direction, while the transformed (Gaussian) random fields will be considered as stationary (i.e., with distributions invariant under a translation in space), in order to ease the inference of their spatial correlation structure and to achieve their simulation subject to conditioning data. In the following subsections, we will determine the local transformations at the well locations and in the interwell region, then we will turn to the modeling of the spatial correlation structure.

2.2. Transforming ELAN porosity data into normally distributed data

Let $\mathbf{x} = (x_1,x_2)$ be a location in the interwell region. It is assumed that the ELAN porosity at this location, $Z_1(\mathbf{x})$, is the transform of a standard Gaussian random variable, $Y_1(\mathbf{x})$:

$$Z_1(\mathbf{x}) = \phi_{\mathbf{x}}(Y_1(\mathbf{x})), \tag{1}$$

where $\phi_{\mathbf{x}}$ is a non-decreasing function called Gaussian anamorphosis (Chilès and Delfiner, 2012). This function characterizes the distribution of ELAN porosity at location $\mathbf{x}$. It depends on $\mathbf{x}$ or, more precisely, on its first coordinate x_1, because of the assumed non-stationarity along the east–west direction. To model the anamorphosis, let us consider its expansion into Hermite polynomials (Rivoirard, 1994; Wackernagel, 2003):

$$\forall y \in \mathbb{R}, \phi_{\mathbf{x}}(y) = \sum_{p=0}^{+\infty} \phi_p(x_1) H_p(y), \tag{2}$$

where $\{\phi_p(x_1)\colon\ p \in \mathbb{N}\}$ are real coefficients (functions of x_1) and $\{H_p\colon\ p \in \mathbb{N}\}$ are the normalized Hermite polynomials. These polynomials are defined as:

$$H_p(y) = \frac{1}{\sqrt{p!}\,g(y)} \frac{d^p g(y)}{dy^p}, \tag{3}$$