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Accurate Detection and Spatial Delineation of Thin-Sand Sedimentary Sequences via Joint Stochastic Inversion of Well Logs and 3D Pre-Stack Seismic Amplitude Data

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Abstract

We describe the successful application of a new pre-stack stochastic inversion algorithm to the spatial delineation of thin reservoir units otherwise poorly defined with deterministic inversion procedures. The inversion algorithm effectively combines the high vertical resolution of wireline logs with the relatively dense horizontal coverage of 3D pre-stack seismic amplitude data. Multiple partial-angle stacks of seismic amplitude data provide the degrees of freedom necessary to estimate spatial distributions of lithotype and P- and S-wave velocities in a high-resolution stratigraphic/sedimentary grid. In turn, the estimated volumes of P- and S-wave velocity permit the statistical co-simulation of lithotype-dependent spatial distributions of porosity and permeability.

The new stochastic inversion algorithm uses a Bayesian maximization criterion to populate values of lithotype and P- and S-wave velocities in the 3D simulation grid between wells. Property values are accepted by the Bayesian selection criterion only when they increase the statistical correlation between the simulated and recorded seismic amplitudes of all partial-angle stacks. Furthermore, inversion results are conditioned by the predefined measures of spatial correlation (variograms) of the unknown properties, their statistical cross-correlation, and the assumed global lithotype proportions.

Using field data acquired in a fluvial-deltaic sedimentary rock sequence, we show that deterministic pre-stack seismic inversion techniques fail to delineate thin reservoir units (10-15m) penetrated by wells because of insufficient vertical resolution and low contrast of elastic properties. By comparison, the new stochastic inversion yields spatial distributions of lithotype and elastic properties with a vertical resolution between 10-15m that accurately describe spatial trends of clinoform sedimentary sequences and their associated reservoir units.

Blind-well tests and cross-validation of inversion results confirm the reliability of the estimated distributions of lithotype and P- and S-wave velocities. Inversion results provide new insight to the spatial and petrophysical character of existing flow units and enable the efficient planning of primary and secondary hydrocarbon recovery operations.

Introduction

Three-dimensional (3D) seismic amplitude data are commonly used to identify hydrocarbon reservoirs and to assess their spatial continuity. Modern seismic processing techniques ennable the interpretation of time-migrated common-midpoint (CMP) gathers in terms of amplitude-vs.-offset (AVO) variations to estimate subsurface petrophysical properties (Castagna and Backus, 1993). More sophisticated applications consist of directly determining spatial distributions of rock properties that best reproduce recorded seismic amplitudes (Sheriff and Geldart, 1982). These procedures make use of seismic inversion algorithms implemented in fully- or partially-stacked normal-moveout (NMO) corrected gathers. The latter approach, referred in this paper to as pre-stack inversion, attempts to capture enhanced degrees of freedom in the measurements to yield independent estimates of density, and P- and S-wave velocities (Contreras et al., 2005a) which can be used to estimate lithology-dependent petrophysical properties (Goodway et al., 1997).

Despite the fact that many variants of seismic inversion procedures have been reported in the open technical literature, in this paper we classify them into two main categories: deterministic and stochastic methods. Geoscientists commonly use deterministic inversion methods in their first attempt to interpret seismic amplitude reflection data in terms of quantitative rock properties. To accomplish this, deterministic inversion algorithms minimize an objective function that contains at least two additive terms (Debeye at al, 1990; Pendrel, 2001): one of these terms controls the misfit between recorded and synthetic seismic amplitudes and a second term controls the energy of the inverted reflectivities. The inversion includes a stabilization factor that places a differential weight between the metric of data misfit and the energy of the inverted reflectivities. Practical applications of pre-stack inversion indicate that S-wave velocity and bulk density are more difficult to estimate than P-wave velocity. Consequently, additional terms are often included in the objective function to enforce soft nonlinear relationships between elastic properties (Fowler et al., 2000). Deterministic inversion procedures do not honor well logs in a direct manner and hence the