Trend-kriged seismic velocities to predict pore pressure and to model effective stress for reservoir characterization in a deepwater basin

Summary

To optimize drilling decisions and well planning in overpressured areas, predrill pore pressure predictions are essential. Knowledge of pore pressure implies knowledge of the effective stress, which is one of the key inputs for 3D and 4D seismic reservoir characterization. This case study focuses on how high-resolution seismic velocities (Banik et al., 2003) were used to predict pore pressure and effective stress in a deepwater environment. The velocity to pore pressure transform was calibrated using existing well log data. To allow for consistency between well and seismic data and stratigraphic layers, geostatistical mapping (trend-kriging) techniques were applied using several key horizons. Thus, the final trend-kriged model is constrained by the structural framework and the geology of the basin.

Introduction

Pore pressure prediction from seismic data can be used for both exploration (e.g., fluid behavior and seal integrity) and drilling purposes. Accurate predrill pore pressure estimates are essential for safe and cost-effective drilling. Elastic wave velocities in rocks normally increase during compaction due to a reduction in porosity and the associated area increase in grain boundary contacts. The pore pressure in overpressured sediments inhibits compaction. Thus, elastic wave velocities may be used for pore pressure prediction (e.g., Hottman and Johnson, 1965; Pennebaker, 1970). An accurate predrill pore pressure prediction can be obtained from fit-for-purpose seismic velocities using an empirical velocity-to-pore pressure transform. This paper describes techniques used to build accurate velocity models and to predict pore pressure and effective stress in a deepwater basin. Geology and well-data consistent velocity models were needed to build low-frequency background elastic impedance models for multi-attribute seismic inversion (McWhorter et al., 2005) and for high-resolution reservoir characterization, which uses effective stress in a Bayesian statistical formalism for lithofacies classification (Bachrach et al., 2004). The effective stress based lithofacies classification in the study area is the subject of a separate presentation (Bachrach et al., this meeting).

Methodology

Most methods for pore pressure prediction are based on Terzaghi’s effective stress principle (Terzaghi, 1943), which implies that elastic wave velocities are a function of the effective stress tensor, which is defined as the difference between the total stress tensor and the pore pressure \( p \). In the study presented here, it is assumed that the elastic wave velocity is a function only of the vertical effective stress \( \sigma \). Then Terzaghi’s relationship can be written as

\[
\sigma = S - p \tag{1}
\]

The vertical component \( S \) of the total stress is assumed to be the weight of the rock matrix and the fluids in the pore space overlying the interval of interest. \( S \) is calculated by integrating the bulk density from the surface to the specific depth:

\[
S = g \int_0^z \rho(z) dz \tag{2}
\]

where \( \rho(z) \) is the density at depth \( z \) below the surface and \( g \) is the acceleration due to gravity.

Effective-stress methods used to predict pore pressures include the methods of Bowers (1995) and Eaton (1975). For this study, Eaton’s approach was used following the inversion methodology of Sayers et al. (2002a, 2002b). Eaton’s method estimates the deviation of the velocity from the velocity in normally pressured sediments (normal velocity). An inversion using offset well data allows the normal velocity to be accurately defined such that possible shallow overpressures can be identified: this contrasts with current methods that fit a normal trend line to velocity data as a function of depth below mudline. The calibration of the transform is based on evaluating the misfit between the predicted pore pressure and the measured pore pressure and is quantified by the root mean square of the residuals (Sayers et al., 2002a). An estimate of the inherent uncertainty is given by minimizing and mapping the root mean square with respect to the parameters that define the pore pressure transform.

Pore pressure data used for calibration were obtained from an analysis of mudweights and formation pressure test data. The overburden stress \( S \) is calculated from equation 2. To estimate overburden stress at the depth of interest, an
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The normal velocity derived by inversion (Sayers et al. (2002a, b) and shown in Figure 1 was then used in an Eaton approach to calculate effective stress and to determine pore pressure. Figure 2 shows an example for a calibrated well.

The calibrated velocity-to-effective stress transform was then applied to the velocities. To apply the pore pressure transform, it is necessary to determine density at all locations so that a 3D volume of total vertical stress can be calculated. To do this, a density cube was built by geostatistically mapping the available well log data in the area, constrained by depth horizons and a 3D trend. Figure 3 shows the structural framework of the study area.

analytical form calculated over the depth range for which density information was not available was used.

Figure 1 shows the upscaled sonic log velocities for the offset wells versus the effective stress calculated from the relevant mudweights. The curve shown is a fit based on an Eaton-type normal velocity plotted versus effective stress and shows a good fit to the well data. The deviations from the curve represent possible variations in porosity and clay content.

The geostatistical mapping (trend-kriging) of the upscaled density log data is guided by a 3D density-trend volume, which was built by applying a locally-calibrated Gardner relationship (Gardner et al., 1965) to the seismic velocity cube. This density-trend cube was resampled into 3D curvilinear stratigraphic grids representing stratigraphic layers for use as a 3D trend (local mean). The upscaled density log data were then kriged in each layer (Figure 4),
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assumining a geostatistical model consisting of a single spherical structure with a given vertical correlation length and an isotropic lateral correlation length (parallel to bedding). Integration of the density cube using equation 2 thus allows the total vertical stress to be determined anywhere in the model.

The interval velocities used in the present study were obtained using a method that maximizes the stacking power of spatially continuous events in prestack gathers. The initial interval velocity model was built using a velocity model builder that inverts stacking velocity functions for interval velocity profiles using a singular value decomposition method. Since the inversion of interval velocity is non-unique, the initial velocity model is regularized using a semblance-based interactive velocity analysis system. This fit-for-purpose velocity analysis method was successfully used previously for pore pressure and effective stress prediction. (e.g., Banik et al., 2003).

The velocity model, thus obtained, went through geostatistical mapping (trend-kriging) using the upscaled well log velocities within several key stratigraphic layers, similar to the method applied in creating the density model. The use of horizons helped to maintain consistency of the well data and the geological structure. The velocity-to-pore pressure transform, which is established from offset well data, is then applied to this trend-kriged velocity volume.

Results and discussion

Figures 5 - 8 show volume slices of high resolution seismic velocity, the kriged velocity, and the predicted pore pressure and effective stress volumes using the kriged velocity results. The kriging was done with available wells and four key horizons. The choice of horizons is the key to building a velocity model consistent with geology. The results are presented and discussed in a separate session. In Figure 9 we present an example of the effective stress with corresponding hydrocarbon sandstone probability values along an inline in the reservoir zone. We note that high quality reservoir sandstones occur in zones with relatively high effective pressure.

Conclusion

The application of trend-kriging, a statistical mapping process, using well data and geologic horizons successfully predicts pore pressure and effective stress. The results were used successfully in low-frequency background model building for multi-attribute seismic inversion and for high-quality lithofacies prediction using effective stress as an attribute with elastic impedance. The success of the work depended on developing a suitable velocity-to-pore pressure transform and applying this to a fit-for-purpose velocity volume using statistical mapping methodologies that honor the structural framework and geology of the basin.

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Figure 5: Final high-resolution seismic velocity (in units of ft/s).

Figure 6: Final high-resolution velocity after kriging (in units of ft/s).

Figure 7: Final pore pressure volume (in units of psi).

Figure 8: Final effective stress volume in units of psi.

Figure 9: Effective stress (left) and hydrocarbon probability values (right) on an inline section.
EDITED REFERENCES
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