SBGf15299

Reservoir characterization using AVO attributes from multi-component data

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Abstract

Traditionally, AVO analysis is mainly performed on P-wave data because of poor quality of S-wave data. Although the P-wave analysis is a valuable tool, its results are sometimes too ambiguous to interpret. The recent development in ocean bottom seismic technology makes it possible to acquire high quality S-wave data in marine environment. The use of S-waves for AVO analysis can give a more reliable solution for reservoir characterization. In this paper, I present a real data example using jointly P- and S-wave in AVO analysis. S-wave data give the opportunity to get an estimate of S-wave velocity and density variations. The real data example illustrates that the obtained elastic parameters allow indeed to detect the fluid contacts and delineate the extent of reservoir sand. Some special prestack processing techniques for the success of S-wave AVO inversion are also illustrated with this example.

INTRODUCTION

Seismically derived elastic parameters of subsurface materials play an important role in seismic reservoir detection and characterization. These parameters can be related to lithology and fluid content using empirically derived relationships (Castagna *et al*., 1985). AVO analysis is one of the techniques for evaluating rock elastic properties from seismic data (Ostrander, 1984). It is usually performed on P-waves. To describe an isotropic elastic Earth, three parameters are needed. There are a number of choices for these parameters (Forgues and Lambare, 1997), but among those, the most geophysically significant are P-wave velocity, S-wave velocity and density. The amplitude of P-wave data is a function of all three parameters. Unfortunately, using offset limited data, the two velocities and density can not be unambiguously resolved (Tarantola 1986; Debski and Tarantola, 1995). In fact, many theoretical and numerical studies (Ursin and Tjaland, 1992; Jin *et al*., 1993) have demonstrated that only two parameters can be determined from P-wave AVO data. Thus, in practice, one usually chooses a parameterization in which only two parameters influence most the seismic amplitude, and the other parameter can be neglected in the incidence angle range of recorded seismic data. The two parameters are generally P-wave and S-wave impedances (Fatti *et al*., 1994) or intercept and gradient (Shuey, 1985). However, in certain circumstances, these parameters are not adequate for hydrocarbon detection. For example, the detection is difficult when there are near-zero impedance contrasts between the sands and encasing media. In these cases, the use of velocity and density may be a remedy because they can have detectable polarity-reversed contrasts for zero impedance. Unfortunately, even if the impedances are well resolved from P-wave data, it is not possible to accurately convert them to velocities because of the poor resolution - or absence - of density.

S-waves have been used in seismic exploration for several decades. Recent developments in ocean bottom multi-component recording technology can provide high quality P- and S-wave data. The use of S-wave data allows new opportunities for AVO analysis to resolve elastic parameters. The amplitude of S-wave depends only on two parameters for an isotropic elastic medium, so the numerical singularity for the parameter resolution may be less severe than in the P-wave 3-parameter case, and S-wave velocity and density may be more reliably estimated from S-wave AVO analysis.

Multi-component field records from an explosive source contain converted and non-converted P-wave and S-wave reflections. The converted PS-wave is one of the S-waves which are generally of good quality and easy to acquire. Since I only focus on PS-wave in this paper, S-wave will from now on refer to PS-wave, unless otherwise specified. Real data examples are shown to illustrate the benefits of joint P- and S-wave AVO analysis for reservoir characterization.

THEORY

REFLECTION COEFFICIENTS

Following Aki and Richards (1980), when the jumps in elastic properties at the boundary of two layers are small and the angle of incidence does not approach 90 degrees, the reflection coefficients of P-P and P-SV waves can be approximated as

$$R_{pp} = 0.5\,(1+\tan^2\alpha)\frac{\Delta I_p}{I_p} - 4\gamma^2\sin^2\alpha\,\frac{\Delta I_s}{I_s} - (0.5\,\tan^2\alpha - 2\gamma^2\sin^2\alpha)\frac{\Delta\rho}{\rho}, \qquad (1)$$

$$R_{ps} = 0.5\,\frac{\sin\alpha}{\cos\beta}[4(\sin^2\beta - \gamma\cos\alpha\cos\beta)\frac{\Delta V_s}{V_s} - (\cos 2\beta + 2\gamma\cos\alpha\cos\beta)\frac{\Delta\rho}{\rho}], \qquad (2)$$

where α the is angle of incidence of P-wave and β the angle of reflection of S-wave. β can be calculated from α using Snell's law. V_p, V_s , I_p, I_s and ρ represent respectively the average P-wave velocity, S-wave velocity, P-wave impedance, S-wave impedance and density. ΔV_p , ΔV_s , ΔI_p , ΔI_s and $\Delta\rho$ are their jumps at the boundary of two layers. γ is the velocity ratio V_s/V_p. Unlike the P-wave reflection coefficient, the P-S reflection coefficient does not depend on the P-wave velocity contrast.

STABLE ROCK PHYSICAL PROPERTY ESTIMATION

One of important objectives of AVO analysis is to estimate the subsurface physical parameters from amplitude variations of seismic data. This can be done by least-squares curve fitting using equation (1) and (2). Smith and Gidlow (1987) used such technique for P-wave data and introduced the "fluid factor" concept to highlight the gas-bearing sandstones.

The least-squares fitting of equation (1) and (2) results in two equation systems of dimension 3x3 and 2x2 at every depth point. Solving for $\{\Delta I_p/I_p,\ \Delta I_s/I_s,\ \Delta\rho/\rho\}$ and $\{\Delta V_s/V_s,\ \Delta\rho/\rho\}$ requires the inversion of the systems. Seismic data are always offset limited and noisy. The range of incidence angles for deep points can become very small and lead the systems to be severely ill conditioned. Even though the inversion concerns only the systems of small dimension, it suffers from numerical instability (Jin *et al*., 1993). A simple way to stabilize the inversion is to solve the systems by Singular Value Decomposition (SVD). In the following example section, the elastic parameters are estimated using the SVD technique. I refer to Lines and Treitel (1984) and Jin *et al*., (1993) for a detailed description of system resolution by SVD .

APPLICATION TO AN EXAMPLE FROM THE NORTH SEA

In this section, I give an example of the joint use of P- and S-wave AVO analyses for reservoir characterization. The data were acquired by placing multi-component sensors on the bottom of the ocean, which ensures a good coupling with the sea bed. The water depth is in the range of 120 meters. The reservoir is a late Paleocene oil-bearing sand which is hardly observable on conventional sections of streamer data. The purpose of this AVO study is to detect fluid contacts and delineate the extent of the oil-bearing sand using P- and S-wave derived elastic parameters.

PRESTACK PROCESSING

The data was carefully processed for AVO purposes. The amplitude-preserving processing scheme includes mode converted wavefield separation, geometrical spreading correction, NMO and wavelet calibration taking into account well information. For the converted P-S waves, the other specific operations, such as Common Conversion Point (CCP) gathering and overburden anisotropy compensation, were applied. I refer to Vuillermoz and Granger (1998) for more data acquisition and processing information. Here I briefly describe the overburden anisotropy compensation and residual NMO correction, which are of the utmost importance for the success of the presented shear AVO inversion.

Equations (1) and (2) are based on the assumption of an isotropic Earth. However, the subsurface materials are usually anisotropic. Direct inversion of the anisotropy parameters such as elastic stiffnesses is unpractical because it increases unknowns and thus makes the problem severely ill conditioned. In order to apply the presented inversion method, the overburden anisotropy effect must be compensated for. The most prominent anisotropy effect is shear wave splitting. In the processing of the data, the shear wave splitting was investigated by the rotation analysis of multi-component data, similar to the techniques proposed by Thomsen (1988). This analysis is able to find the anisotropy principal axes and delay time of split shear waves. The anisotropy overburden compensation is then achieved by applying to the data the obtained delay time, amplitude and rotation corrections which simulate the reverse of the shear wave splitting effect of the overburden.

The final prestack processing step is residual NMO correction. Slight NMO errors can drastically contaminate the results. To prevent this happens, a horizon-oriented statistical correction was applied on CDP and CCP gathers
to make the strong reflection events at reservoir level perfectly aligned.

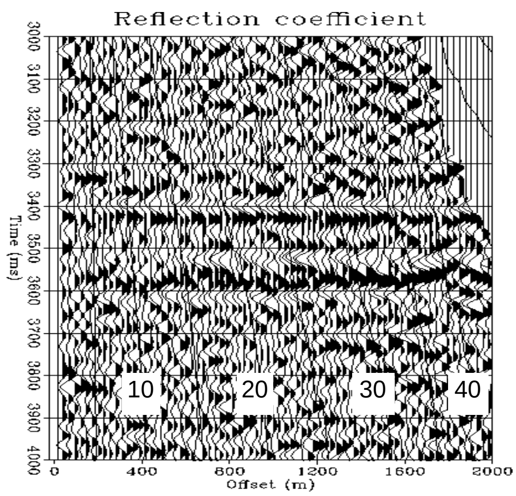

Figure 2: One of processed CCP gathers of P-S horizontal component data. The offset-angle curves are overlaid. The unit of the curve label is degree.

AVO INVERSION

The prestack processing produces CDP gathers for P-P waves and CCP gathers for P-S waves. As an example, Figure 2 shows one of CCP (Common Conversion Point) gathers of P-S horizontal component data used in this study. The Vs/Vp ratio is found to be 0.3 from velocity analysis of PP and PS data. A smoothed interval velocity model was derived from PP data (Jin, 1999). The offset-angle relationship is determined by ray tracing: a P-wave ray is firstly traced to the surface from a depth point with an angle of incidence, then a P-wave ray and a S-wave ray are traced from the same depth point using a departing angle determined by Snell's law. The offset corresponding to the incidence angle is the distance between the two emerging points of the rays at the surface. The procedure is repeated several times with different incidence angles and the offset-angle relationship is thus obtained. The offset angle curves are plotted on the CCP gather in Figure 2 after depth/time conversion. The maximum angle of incidence at the reservoir level is around 30 degrees for P-P waves and 45 degrees for P-S waves. The condition analysis (Jin *et al*., 1993) has shown that, with this maximum angle, it is possible to extract with a good accuracy the impedance contrasts $\{\Delta I_p/I_p, \Delta I_s/I_s\}$ from P-P data. Although not shown in this paper, the condition analysis on P-S data predicts also that it is possible to get a good estimate of $\{\Delta V_s/V_s, \Delta\rho/\rho\}$. Due to asymmetrical ray paths, the incidence angle is larger for PS wave reflection than PP reflection for a given offset. Figure 4 shows the contrasts of the P-wave impedance, S-wave impedance, S-wave velocity and density obtained from the SVD stabilized AVO inversion of the CDP and CCP gathers. A damping factor of 2 % of the first eigenvalue is applied to the second one (see Jin *et al*., 1993).

INTERPRETATION

One reservoir sand was identified from well data. Arrows in Figure 3 indicate the bottom of the reservoir. The obtained elastic parameter contrasts reflect different nature of rock properties and respond differently to lithology and fluid content. The impedance contrasts convey mainly information about lithology changes. However, the P-wave data do not describe the reservoir geometry of the reservoir as good as S-wave data. The contrasts of S-wave velocity and density seem to be more informative about the reservoir.

Detailed analysis of the amplitude variations of S-wave velocity and density may reveal the fluid distribution within the reservoir. We can observe overall uniform amplitude of S-wave velocity contrast along the reservoir sand, except for some local variations due to remaining noise. However, we have not such observation for density contrast: CDP 476 (arrow position) separates the reservoir sand into two segments of different amplitudes. The density contrast is stronger on the left than on the right. Does this indicate fluid contact, or rather thin bed interference? The thin bed tuning effect does exist, but it is unlikely to be the cause of the amplitude difference because the structure is similar on both sides of this CDP point. Moreover, there is no reason why the tuning should not produce amplitude difference for S-wave velocity contrast as it does for density contrast. The interpretation that CDP 476 represents the separation between hydrocarbon-bearing sand and brine sand seems to be more reasonable. With this interpretation, we can easily explain why the density changes across this CPD point while S-wave velocity does not. In fact, S-wave is less sensitive to pore fill because it travels only through the rock matrix (Ensley, 1984). In contrast, the density depends on both the matrix and the material in the pore space of the rock.

CONCLUSIONS

Numerous theoretical and numerical studies have reported that neither velocity nor density can be well resolved from conventional marine data where the P-waves are dominant. One alternative is to use converted S-wave. With the recent developments in Ocean Bottom Seismic (OBS) technology, it is now possible to acquire high quality mode converted S-wave data in a marine environment, and use these measurements, comnbined with P-wave data, for rock property extraction.

Application to a carefully processed OBS data set analysis and the benefit of the combined use of obtained elastic parameters to seismic reservoir c illustrates the practical use of P- and S-wave AVO haracterization, especially for fluid contact detection and pore fill distinction.

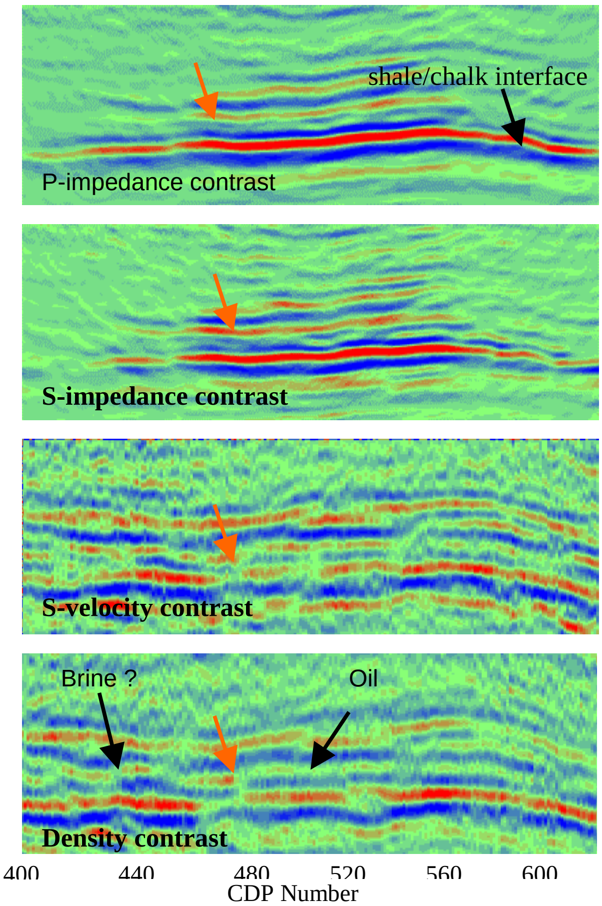

Figure 3: Contrasts of elastic parameters obtained from P-P and P-S AVO inversion. Orange arrows (CDP 476) indicate the fluid contact point.

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ACKNOWLEDGMENTS

I thank Guillaume Cambois, Renault Daures, Simon Spitz and Claude Vuillermoz for many helpful discussions.