Sub-salt velocity prediction with a look-ahead AVO walkaway
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Summary
Drilling through salt in deep water is expensive and risky. Abnormally high pore pressure just underneath salt is a common problem, and one of the essential inputs to pore pressure prediction is seismic velocity. Estimating velocity beneath salt using even the most sophisticated surface seismic techniques is difficult due to poor and irregular illumination. In this paper we explore the possibility of using a walkaway VSP survey to predict seismic velocities just below the base salt interface.

The idea is to acquire a walkaway survey with an array of three component receivers clamped in the salt just above the base salt interface. As with walkaways acquired for AVO calibration, the similarity of the downgoing path for direct and reflected arrivals is exploited together with true amplitude processing to produce a multiple-free, zero phase seismic AVO response just beneath the receivers. We pick the base salt P-p and P-s reflection amplitudes versus offset, transform to incidence angle using measured polarizations and invert for sub-salt elastic parameters. Salt properties are assumed constant and the base of salt interface is assumed to be locally planar. The AVA inversion is Bayesian and Monte Carlo, providing posterior uncertainty estimates in estimated parameters. Given realistic noise we find that a soft constraint on density is required as it is poorly constrained by the data. Using this look-ahead AVO walkaway approach the uncertainty in Vp should be significantly reduced from pre-drill bounds. A good estimate of Vshear is also provided, opening up new opportunities for sub-salt pore pressure work.

Introduction
In the Gulf of Mexico severe drilling problems are sometimes encountered underneath salt, but P-wave velocities, essential to pore pressure prediction models, have large uncertainties due to complex seismic propagation through and around salt. Consequently, any predictive technique that can reduce sub-salt velocity uncertainties is of interest.

A VSP acquired for look-ahead purposes is a fairly common survey (E.G. Payne (1994)). The procedure is usually to invert the processed upgoing reflections to acoustic impedance to identify target boundaries or drops in acoustic impedance associated with excess pore pressure. Justification for such surveys comes from the fact that the VSP information often helps to reduce the risk associated with drilling decisions, for example determining the safe distance to drill before setting the next string of casing. Malinverno and Leaney (2002) extended the look-ahead VSP to the multi-offset (walkaway) case, exploiting both moveout information (Leaney (2000)) and reflected amplitudes (AVO) in a Monte Carlo Bayesian inversion. In that approach effective VTI (polar anisotropic) 1D modelling was iterated to estimate profiles of Vp, Vs and density ahead of the receivers.

Figure 1. Sub-salt predictive walkaway schematic showing the similarity of downgoing ray paths for direct and reflected arrivals.

If one’s attention is limited to the layer just beneath the salt rather than to a sequence of layers then a complex overburden is much less of a problem and the AVO of the base salt reflection may be exploited to estimate the elastic parameters of the sub-salt layer. The base salt converted wave AVO response has also been modeled in the context of sub-salt overpressure (Miley and Kessinger (1999)) and so we make use of the converted wave AVO as well.

Walkaways designed for anisotropy and AVO (Leaney (1994)) have the receiver array clamped just above the target reflector(s). In such a survey the reflection points are close to the receivers so the downgoing path for direct and reflected arrivals is virtually the same (see Figure 1.). True amplitude processing with deterministic “up-by-down” deconvolution removes the overburden and wavelet leaving the zero phase, bandlimited AVO response of reflectors just under the receivers. In the context of the sub-salt problem the base salt event would be picked, amplitudes extracted...
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and mapped from offset to incidence angle using measured polarizations. These would feed into an inversion for sub-salt elastic parameters which would in turn be used to develop pore pressure models for drilling. Obviously the walkaway data must be acquired, processed and analyzed in a time frame relevant for drilling decisions, possibly only a few hours, so the workflow must be efficient and reliable. In the remainder of this paper we describe the processing sequence and demonstrate the inversion of AVA data for sub-salt elastic parameters on synthetic data.

Method

Before describing the walkaway processing and analysis sequence a few comments on survey design are warranted. The array of downhole (3C) receivers should be clamped as close to the base salt drilling logistics and the well plan permit. This is important to assure that the fundamental requisite of the technique is satisfied – that the downgoing path for direct and reflected events is the same. Secondly, the walkaway line should follow a direction over the simplest overburden and base salt structure. We expect that an important part of the workflow will include data transmission from the well site, perhaps with some data compression, to enable computing center processing. Well site processing may be necessary in some cases.

The processing sequence is essentially that as described in Leaney (1994), comprising data orientation, wavefield separation and deterministic deconvolution. The main difference is that in addition to parametric wavefield decomposition (Leaney and Esmersoy (1989)) which we use to get salt velocities and reflected polarization angles we use the related technique of anisotropic vector plane wave decomposition (Leaney (2002)) to separate wavefields. This latter technique is better suited to complex wavefields as it is model-based rather than data-driven and includes a broader angular spectrum of plane waves. Wavefield separation and deconvolution are carried out in the common-shot domain to maintain shot independence and effectively remove shot-to-shot variations in signature and down wave propagation characteristics.

Diffractions and multi-pathing are prevalent in walkaway surveys shot through salt, but since the same complicated events are present on downgoing as well as reflected wavefields they are removed by the deconvolution step. After deconvolution we pick the base salt event on all receivers, extract the amplitude and use data redundancy to form robust estimates of reflectivity versus offset.

A residual spreading and constant Q gain are applied to picked amplitudes. This correction is offset dependent and although small can be significant for the shallowest receivers. The final step before inversion is to map these data from offset to incidence angle. The offset-to-angle transform comes from direct P and reflected P and Sv polarizations, a by-product of the parametric inversion.

The simultaneous inversion of P-P and P-Sv AVA data is superior to that using P-P data alone as it provides reduced uncertainty of both shear velocity and density estimates (e.g. Larsen (1999)). We fix salt (top layer) elastic parameters and invert only for sub-salt (lower layer) parameters. Salt velocities come from the walkaway data via parametric inversion. Vp, Vs and density may come from LWD, wireline logs or other prior information.

We demonstrate the inversion on noisy synthetic data. To generate the synthetic AVA data we chose isotropic elastic parameters for the salt as: Vp=14.7kft/s, Vs=8.2kft/sec, rho=2.15gm/cc. The sub-salt layer elastic parameters were chosen to be: Vp=8.5kft/sec, Vs=3.5kft/sec, rho=2.40gm/cc. Gaussian noise was added to both amplitudes and angles with standard deviations of .05 and 3 degrees, respectively. The synthetic data are shown in Figure 2. The results of the inversion are shown in Figures 3 and 4. In Figure 3 the posterior is plotted versus velocity. The inversion results are shown in crossplot form in Figure 4 with the posterior color coded Vs versus Vp. The
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distributions have peaks centered on the correct model values; standard deviations are 550ft/sec for Vp and 320ft/sec for Vs. The uncertainties depend on the level of noise in the data but we believe the selected noise level to be representative of real data. The information provided about Vs is important and opens up new possibilities for pore pressure prediction (Ebrom (2002)).

Figure 3. Posterior versus velocity showing Vs and Vp for 10000 models. Velocity units are kft/sec.

Figure 4. Color-coded posterior, Vs versus Vp. Velocity units are kft/sec.

Conclusions

A borehole seismic survey design, processing workflow and inversion procedure has been described for the prediction of P and S velocities just beneath salt. The proposed survey is a walkaway designed to measure the AVO of the base salt reflector where the receiver array is clamped just above the base salt. True amplitude processing including scalar-from-vector wavefield separation and specially tailored deterministic deconvolution are used, together with an offset-to-angle transform coming from polarizations to produce P-P and P-Sv AVA data. The inversion is Monte Carlo and Bayesian and delivers posterior uncertainties.

Predicting elastic velocities just beneath salt with a look-ahead AVO walkaway should significantly reduce uncertainties in seismic velocities. Due to the vector recording at depth converted waves can be included which provide a reliable estimate of Vshear sub-salt. This provides a new measurement to improve pore pressure predictions for (expensive) sub-salt GOM wells.

References


