The Elastic Look-ahead

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Introduction

Determination of the variation of velocity in the earth is critical to imaging but also to time-to-depth conversion and pore pressure prediction. Vertical Seismic Profiles (VSPs) have been used for predictive purposes for many years. The common approach is to correlate the corridor stack with surface data to place the well within the seismic volume and thereby determine its location relative to interpreted drilling targets or hazards. Inversion of the corridor stack to acoustic impedance can provide improved vertical resolution and predictive capabilities (e.g. Payne (1994)), but as with all trace inversions the low frequency or long wavelength component must come from an external source as it is not present in the bandlimited trace amplitudes. Additionally, since velocity determination is the ultimate goal an assumption about density is required to convert acoustic impedance values to velocities. Prior to drilling a well and acquiring check shot or VSP t(z) measurements this information generally comes from the moveout of reflections in surface seismic recordings – velocities are estimated using either stacking coherency or reflection tomography. But these velocity estimates may still be too inaccurate to reduce drilling risks to the desired level. Typical problems associated with surface seismic –derived velocities are: bias due to anisotropy, ambiguities due to multiple contamination or illumination issues and limited resolution or bandwidth (limited that is compared to what is achievable with borehole seismic). What is needed is a borehole seismic survey that contains reflection moveout – enter the multi-offset VSP or walkaway.

Walkaways have been used extensively for imaging, anisotropy estimation and AVO calibration but have seen limited use for predictive drilling applications. This is undoubtedly due to the larger volume of data (relative to zero offset VSP data) and more complex processing. Being able to turn around a walkaway data set in a time frame relevant for drilling decisions requires efficient acquisition, data transfer, processing and analysis. The latest borehole seismic technology provides quality 3C data with reliable, efficient acquisition, and rapid data transfer from rig to computing center is now possible (possibly with some data compression), but what of automated processing and analysis ? This is the focus of this paper: to review our approaches to look-ahead walkaway data analysis, to show supporting synthetic and real data examples and to discuss present imitations and the way forward to expand the range of applicability of this very promising technology.

Look-ahead walkaways: Moveout inversion

Offset VSPs have been used for predictive drilling applications by imaging target formations or structures (e.g. Sorotka (1996), Meyer and Tittle (1998)) and images from walkaways have been used, albeit rarely in a similar way (Blanco, personal communication), but velocity analysis using walkaways is a relatively recent proposal (Leaney (2000)). The idea is to transform the asymmetric walkaway reflection ray path into half of a symmetric CMP ray path by mirroring the layered medium about the reflecting layer as shown in Figure 1. This idea together with effective VTI modelling and direct times non-hyperbolic fitting permits the efficient computation of reflection moveout trajectories accurate to very long offsets. To determine velocities a multi-parameter inverse problem was formulated by constructing a smooth velocity profile as the sum of a gradient plus harmonic terms. Calibrated effective VTI modelling provides fast computation of reflection travel times for NMO correction and a coherency functional is optimized to yield the velocity-depth profile beneath the receivers.

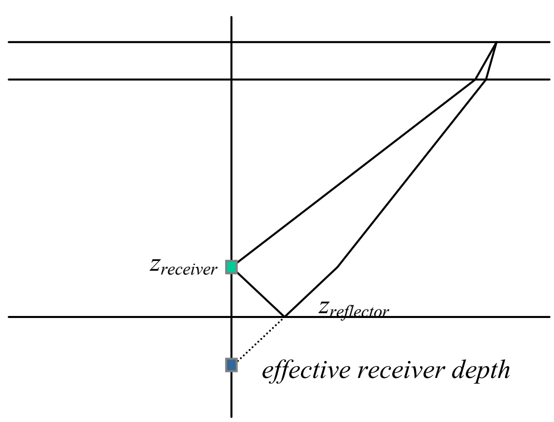

Figure 1. Schematic of the procedure to transform an offset VSP reflection ray path into a direct ray-path so that effective VTI theory can be used. Layered model parameters are mirrored about the reflector depth and the actual receiver depth is replaced by a new effective receiver depth.

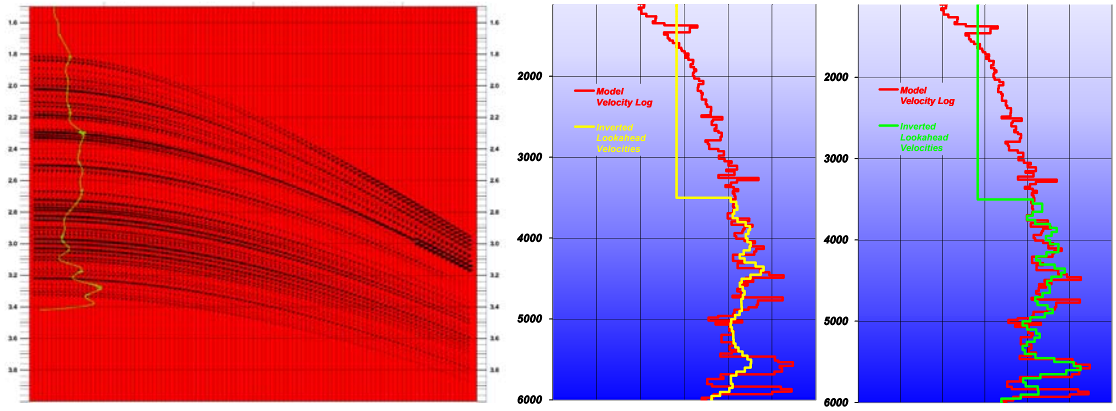

Figure 2. East coast synthetic walkaway with moveout inversion results showing smoothly varying velocity trends. Sufficient offset aperture is important for velocity sensitivity.

This velocity prediction procedure was recently tested on a synthetic data set generated from a 1D elastic model built from Nova Scotia well data. Figure 2 shows the synthetic walkaway data with smooth velocity profile and two inversions in depth, one using limited offset data and the other using the full offset range corresponding to a maximum offset/depth ratio of 2. When sufficient offsets (angles) are available the moveout inversion is able to accurately recover the velocity profile, in particular the velocity decrease at the onset of overpressure.

Look-ahead walkaways: AVO inversion

Given the long wavelength variation in velocity from the moveout inversion above, one could use this to constrain an amplitude inversion such as a conventional VSP inversion to acoustic impedance. After all, the walkaway data set contains as a subset the zero offset VSP trace. But the walkaway also contains angle dependent reflection amplitude information (AVA), all that is required is a model to supply the offset-to-angle transform. This comes from the long wavelength velocity profile determined in the previous section, and effective VTI modeling. We have developed two approaches to the walkaway AVO inversion problem. A time domain approach (Malinverno and Leaney (2001)) wherein the long wavelength velocity background is held fixed while perturbations in Vp, Vs and density are sought, and a one-step depth domain inversion (Malinverno and Leaney (2002)) wherein a simple compaction trend serves as the prior model and layer depths as well as elastic parameter contrasts are determined. Both of these approaches employ a primaries-only convolutional model and use a Bayesian formulation with a Monte Carlo exploration of model space.

Figure 3 shows the results of the second, depth domain approach on a real data set from deep offshore West Africa. Darker areas indicate greater probability that a parameter will take on that value at that depth, meaning that more models that fit the data took on those parameter values. The prior model in Vp came from a simple compaction trend with a generous uncertainty. Log measurements (LWD) from above the receivers were used to define correlations between Vp, Vs and density which were used to map the Vp prior to the Vs and density priors. The log correlations also supplied model covariance during the inversion. The middle result in Figure 3 uses only the zero offset or VSP trace so only variations in acoustic impedance are recoverable. The variations in Vp and density arise from the prior correlations. The "down-to-the-right" trends in the dark clouds are due to higher velocities corresponding to larger depths for the given time of a reflection event. When the full offset range is used the elastic parameters come into focus, with the reflection moveout providing the long wavelength variation in Vp (and time-to-depth conversion) and the AVO in the data supplying the rapidly varying information about elastic contrasts. Also shown in red are the wireline log values.

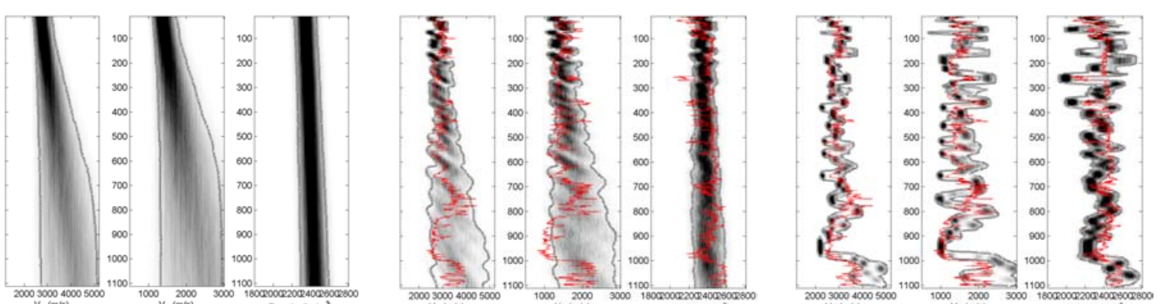

Figure 3. Bayesian inversion for Vp, Vs and density. Left: prior model with 95% uncertainties; middle: zero offset inversion; right: full offset walkaway inversion. The wireline logged values are overlain in red.

Discussion

Everything discussed and presented has made one very fundamental assumption – that the earth in the vicinity of the well is made up of flat layers. This obviously limits the applicability of these approaches on many real world problems. At a minimum regional dip must be handled. This can be included without difficulty by adding an odd term to the effective VTI model moveout equation. Variable reflector dip beneath the receivers can also be handled or reflector dip could even be treated as a free parameter, but more tests on synthetics need to be carried out to assess the best strategy.

Nothing has been said about data preparation for these inversions, but true amplitude 3C processing is of paramount importance. The processing sequence does not differ greatly from that used for walkaway AVO calibration as described (Leaney (1994)), although some improvements have been made, particularly in wavefield separation, deconvolution and propagation loss compensation.

Three component walkaways with elastic wavefield separation provide scalar shear (Sv) reflections as well. These have not yet been included in the inversions but would help to further constrain the determination of Vs and density.

Linearized (small contrast) AVO equations have been used in the inversion, so if contrasts are large then full Zoeppritz reflection coefficients should be used. Likewise, significant vertical velocity heterogeneity may necessitate replacing our effective VTI modeling approach with a more time consuming, exact VTI ray tracing. The ultimate goal is to incorporate 2D finite difference modeling as the forward engine in the inversion.

Conclusions

Deeper, riskier drilling puts the onus on getting accurate velocities for predictive drilling applications. Walkaways are a fit-for-purpose survey for velocity predictions because 1) like surface seismic data they contain the long wavelength velocity information in reflection moveout, 2) through three component recording they provide the raw material for extracting scalar elastic wavefields, 3) by measuring the downgoing wavelet at depth deterministic deconvolution delivers a virtually multiple free broadband zero phase AVO response and 4) since the recording is made at depth close to the target the prediction distance is smaller and thus errors are reduced.

The latest acquisition technology makes it possible to transfer a high quality walkaway data set of significant size from the rig onto the computing center hard disk minutes after the last shot. In gentle geologic settings the techniques discussed here can estimate elastic logs with uncertainties for drilling predictions but further developments in processing and analysis are needed and are ongoing with the goal of expanding the domain of applicability of the elastic look-ahead.

References

Leaney, W. S., 1994, Anisotropy and AVO from walkaways, 64th Ann. Internat. Mtg: Soc. of Expl. Geophys., 105-109.

Leaney, W. S., 2000, Look-ahead walkaways using effective VTI models, 70th Ann. Internat. Mtg: Soc. of Expl. Geophys., 1743-1747.

Malinverno, A. and Leaney, W.S., 2001, Bayesian Look-Ahead Inversion of Walkaway Vertical Seismic Profiles, 63rd Mtg.: Eur. Assn. Geosci. Eng., Session: N-35.

Malinverno, A. and Leaney, W.S., 2002, Monte Carlo Bayesian Look-Ahead Inversion of Walkaway Vertical Seismic Profiles, 64th Mtg.: Eur. Assn. Geosci. Eng.,B030.

Meyer, J. H. and Tittle, W., 1998, Exploration risk reduction using borehole seismic: East Texas pinnacle reef applications: 68th Annual Internat. Mtg. Soc. Expl. Geophys., Expanded Abstracts, 369-372.

Payne, M. A., 1994, Looking ahead with vertical seismic profiles: Geophysics, **59**, 1182-1191.

Soroka, W.L., 1996, Predicting Formation Target Depth Ahead of the Bit with High Accuracy : A Case Study from the Arun Field for a Deviated Well: Proceedings of the Indonesia petroleum Association, IPA96-2.5-028.