Practical inversion of anisotropy parameters from surface *P*-wave seismic data

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Summary

A structure located beneath a tilted transversely isotropic (TTI) overburden will be laterally mispositioned on *P*-wave surface seismic data if isotropic velocities are assumed during processing. Since the seismic velocity is fastest in the bedding-parallel direction, the processed image is shifted laterally in the updip direction. This lateral shift can be on the order of hundreds of meters and may have serious consequences in the targetting of hydrocarbon prospects. The magnitude of the shift depends on the source-receiver offset and five independent parameters: the TTI layer thickness, layer dip, slow velocity and the Thomsen anisotropy parameters ε and δ. We propose that ε and δ can be estimated successfully by inversion of three values measured for an event observed on seismic data at the base of a TTI sequence: the zero-offset arrival time, difference in arrival time between a near-offset and a far-offset and the difference in imaged location between these same offsets. Inversion of a numerical modelling data set produces parameters very close to those of the true model while inversion of field data from the Alberta Foothills results in reflectors being better imaged by TTI depth migration than by isotropic depth migration.

Introduction

Most work addressing the question of extracting anisotropy parameters (Thomsen, 1986) from surface seismic data has focussed primarily on the application of non-hyperbolic velocity analysis and traveltime inversion (e.g., Alkhalifah and Tsvankin, 1995; Grechka and Tsvankin, 1998a, 1998b, 1999). 2-D physical modelling data of a step target underlying a TTI overburden reveals a significant offset-dependent lateral shift of the imaged target from its true location and that this lateral shift updip is greater on near-offset gathers than on far-offset gathers (Isaac and Lawton, 1999). We used this observation to develop a new method for estimating the Thomsen parameters which utilises the measurement of offset-dependent imaged locations and arrival times (Isaac and Lawton, 2000). Three parameters associated with a selected event are measured from the seismic data: the zero-offset time from prestack time-migrated data, the arrival time difference between selected near and far offsets from poststack time-migrated common-offset gathers (with only residual NMO applied) and the imaged location difference between these same offsets from prestack time-migrated common-offset gathers. The other unknown factors, slow velocity, depth and dip, are estimated from the processing velocities and used as starting points for the inversion routine's iterations. We make the assumptions that Vp/Vs=2, that the TTI sequence has constant dip over the offset range under analysis and that the data are referenced to a flat datum. There is not a unique solution due to the CDP and time sampling intervals, so the results are averaged.

Numerical modelling data

A synthetic data set was generated using Norsar's TTI ray-tracing code. The model consists of a uniformly dipping TI overburden overlying horizontal isotropic layers to simulate a thrust sheet with footwall cut-offs. Interval velocities range from 3500 m/s to 6500 m/s. Shots are spaced at 100 m intervals along the flat surface and the receiver interval is 25 m, for a CDP interval of 12.5 m. Offsets range from -2000 m to 2000 m. The data were generated at a sampling rate of 4 ms with a zero-phase 30 Hz Ricker wavelet and imported into ProMAX for processing using isotropic velocities determined by standard time processing techniques. We also used GX Technology's Sirius program to determine an isotropic depth velocity model by iterative focussing analysis of prestack depth migrated offset gathers. The velocities determined by this method are too high for the TTI layer by 400 m/s but very close to correct for the underlying isotropic layers, although the geometry of these layers is somewhat incorrect.

Initially we chose two footwall cut-off events for analysis but applied only the results from the shallowest event, as on field data there may often be only one event suitable for analysis. The zero-offset time was picked from the prestack time migrated data. We determined the optimum lateral shift by cross-correlating windows of data around the two selected events with the far offset gather being shifted in increments of one CDP. Similarly, the far-offset gather was shifted vertically by various time values for the time shift analysis (Figure 1). This analysis was performed on several pairs of offset gathers and values chosen that showed consistency. For our chosen offsets of 200 m and 1600 m, the measured location and time differences were -5 CDPs (far-offset image updip of near-offset image) and 0.084 ms, respectively. The accuracy of the measured time and location differences is limited by the sampling rates, which are 4 ms and 12.5 m, respectively.

In the inversion we tested velocity ranges of 4075 - 3300 m/s in steps of 25 m/s, dips of 23 - 18.5° in steps of 0.5° and depth ranges of 1725 - 1400 m in steps of 25 m. In the interests of decreased computer time, the inversion, which assumes that the shifts are accurate to one CDP and the time sampling rate, outputs only unique combinations of ε and δ for each value of $Vp(0)$, regardless of dip. The averaged results were $\varepsilon = 0.21$, $\delta = 0.12$, $Vp(0) = 3550$ m/s, dip = 21° and depth = 1525 m. These solutions compare very well with the true parameters of $\varepsilon = 0.20$, $\delta = 0.10$, $Vp(0) = 3500$ m/s, dip = 20° and depth = 1500 m.

The inversion results were tested using a 2-D Kirchhoff prestack depth migration algorithm in Veritas' SAGE software. We migrated the data set three times, using (1) the exact velocity field with TTI parameters, (2) the velocity field derived from the isotropic PSDM analysis and (3) the same velocity field as (2) but with the TTI layer parameters derived from the inversion (Figures 2a, c and e, respectively). The base of the shallowest isotropic velocity layer (green) in Figure 2c is altered in Figure 2e to account for the depth of the footwall cut-off as derived from the inversion. The migrations from the true and inverted velocity models (Figures 2b and 2f, respectively) are very similar, having the base of the TTI layer at the correct location and depth and the positions of the footwall cut-offs in the correct positions. The flat reflectors are not quite imaged properly in Figure 2f because we used the velocities derived from the PSDM analysis for the isotropic layers, since in real life the exact velocities would be unknown. Migration with the isotropic velocity model results in errors in the position and depth of the image. The analysed shallow footwall cut-off event is shifted 175 m updip and is too deep by 150 m, which is 10% of the TTI layer thickness. Also, the dip at the base of the TTI overburden is incorrect.

Real data case

The inversion routine and TTI PSDM were tested on a field data set from the Shaw-Basing area of the Alberta foothills donated by the former Mobil Canada. The velocity model used to prestack migrate the data was obtained through GX's isotropic PSDM focussing analysis and the processing was performed using ProMAX. A consistent lateral shift of -1 CDP and time shift of 0.028 ms were measured over a number of consecutive traces underneath a clastic section having fairly consistent dip, while the zero-offset arrival time was measured as 0.882 s. The solutions of the inversion averaged to $\varepsilon = 0.07$, $\delta = 0.02$, depth = 1550 m, *Vp(0)* = 3500 m/s and dip = 31.5°.

The data were prestack depth migrated using Veritas' SAGE program. For the ray-tracing from topography we used the velocity model derived from Sirius with and without the TTI parameters determined by the inversion. Figure 3 shows the results of (a) isotropic migration and (b) TTI migration for the analysed part of the line. The TTI migration has shifted events under the sequence slightly in the downdip direction and, in general, there is an improvement in reflector continuity on the TTI section, especially where indicated by arrows. The geology is very complex here and the quality of the imaging results is, of course, not only a function of the velocity model but also of the field acquisition parameters and residual statics applied to the data.

Discussion

Seismic data processed under the assumption of isotropy will not image correctly a target located beneath a dipping anisotropic overburden. Determination of the Thomsen anisotropy parameters for use in anisotropic data processing will become more important as the inadequacies of isotropic data processing become better understood. We have developed an inversion method for obtaining an approximation to the Thomsen parameters from surface *P*-wave data alone, with the assumptions that the *Vp/Vs* ratio is two, that the dip of the TTI sequence is constant and that the data are referenced to a flat surface. To apply this method to real data there has to be a suitable event below the TTI layer and we assume that the measured times and shifts are accurate to the sampling interval. The solution is constrained considerably when two events are used together in the analysis, although field data may not provide two suitable events. For a data set generated using TTI numerical modelling, the inversion results were very close to the true model. For data from the Southern Alberta foothills, where the geology is complicated, the complex part of the section is not terribly well resolved with either isotropic or TTI migration. However, those parts of the line where the reflectors have less complex geometry are imaged better on the TTI section. This inversion scheme appears to hold promise for use on field data but will not work miracles on highly complex structures with complicated velocity models that are hard to determine. However, the parameters estimated by this method offer an optimum starting point for anisotropic data processing.

Acknowledgements

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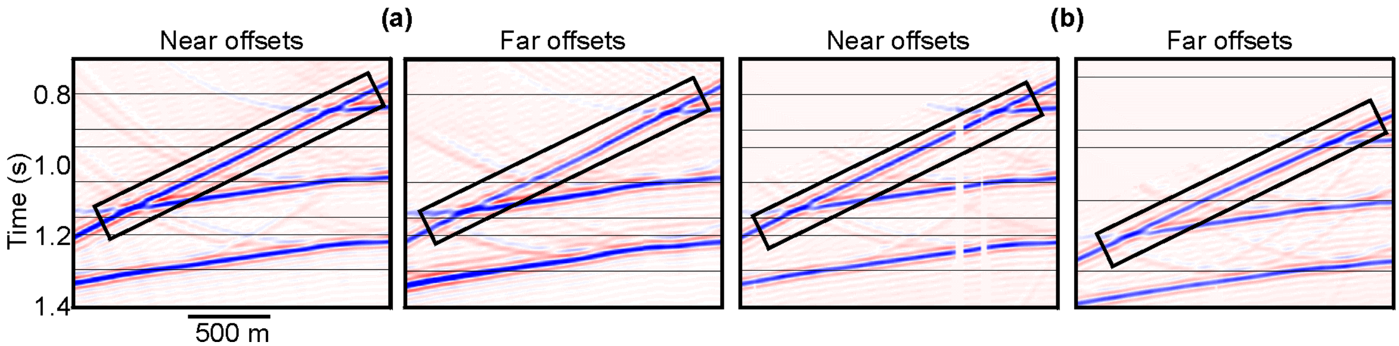

Figure 1. Panels of near and far offset data used to determine the lateral shift difference (a) and arrival time difference (b) between these offsets for the two footwall cut-off events. The rectangle shows the window of data used in the cross-correlations. In the migrations we applied only the results obtained for the shallowest footwall cut-off in the upper right of the figures.

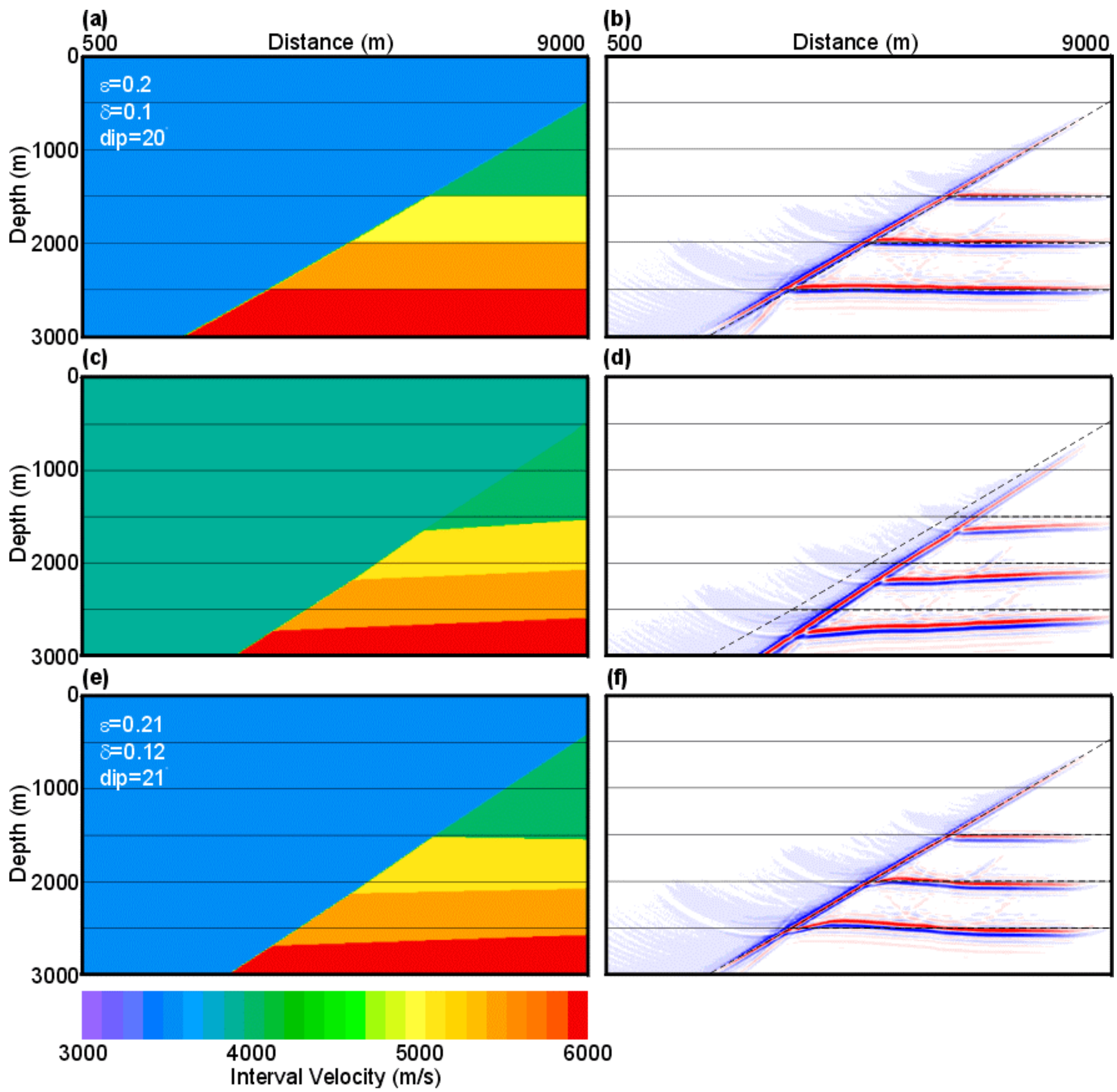

Figure 2. The velocity models (a, c, e) and corresponding prestack depth migrated numerical modelling data (b, d, f). Velocity model (a) is the exact TTI model, (c) is the isotropic model derived through depth velocity model building and (e) is the model of (c) but with the TTI parameters derived by inversion applied to the TTI layer. The dashed lines on the sections indicate the true positions of the reflectors.

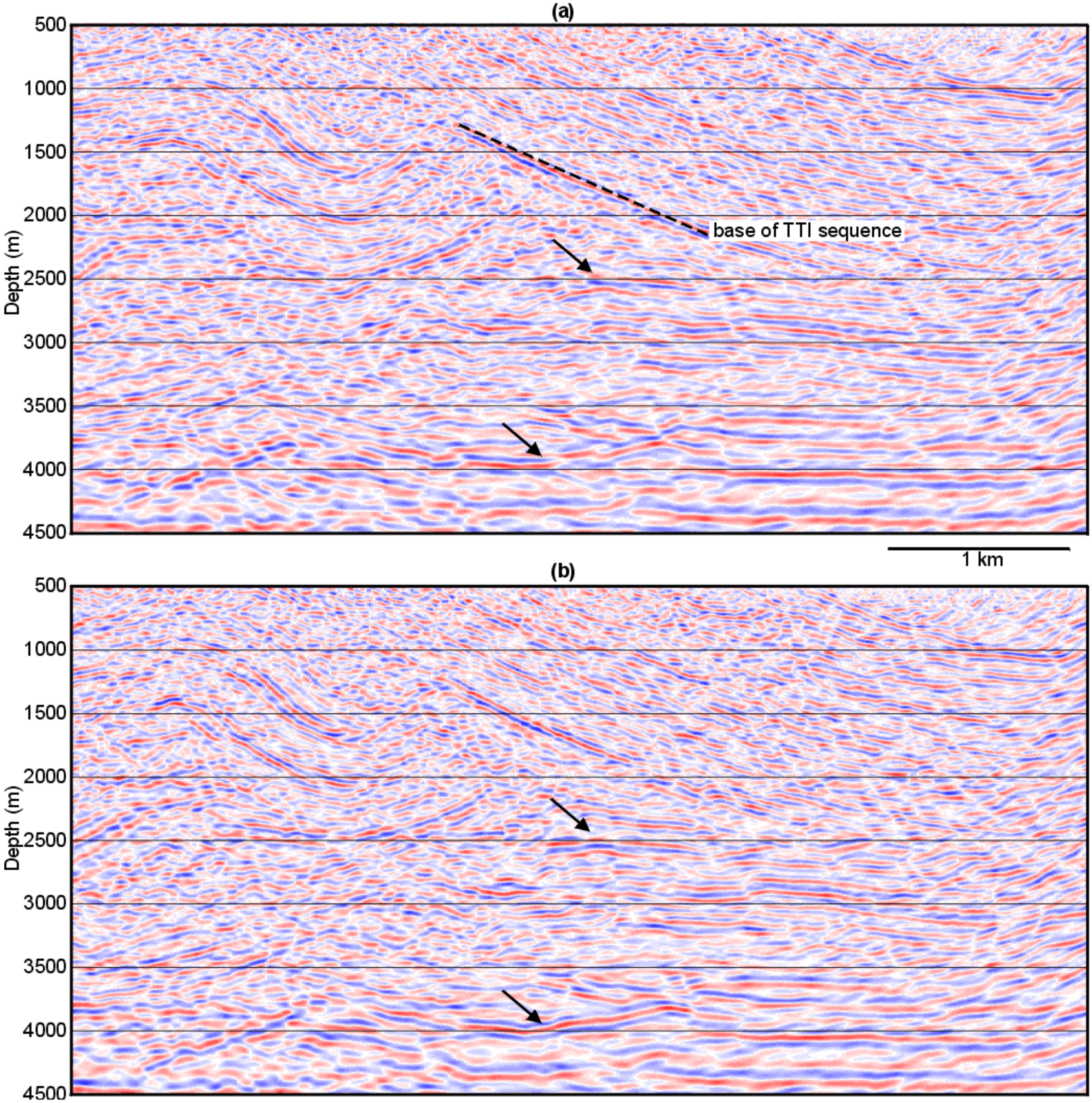

Figure 3. The Alberta Foothills data prestack depth migrated with an isotropic velocity field (a) and an anisotropic velocity field incorporating the TTI parameters derived by inversion (b). The arrows highlight some of the reflectors that are imaged better on the TTI section. The base of the TTI sequence we analysed is indicated.