VELOCITY-INDEPENDENT LAYER STRIPPING OF PP AND PS REFLECTION TRAVELTIMES

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Abstract

Building accurate interval velocity models is critically important for seismic imaging and amplitude inversion. Here, we adapt the so-called "PP+PS=SS" method to devise an exact technique for constructing the interval traveltime-offset function in a target zone beneath a horizontally layered overburden. The algorithm is designed for arbitrarily anisotropic target layers, but the overburden is assumed to have a horizontal symmetry plane (i.e., up-down symmetry). Important advantages of this layer-stripping technique compared to the existing Dix-type equations include the ability to handle the asymmetric moveout of mode-converted waves and laterally heterogeneous target layers with multiple curved reflectors. Also, our method is entirely data-driven and does not require knowledge of the velocity field anywhere in the medium.

The computed interval moveouts of PP- and PS-waves can be used to estimate the interval parameters of transversely isotropic layers with a tilted symmetry axis (TTI), which is essential for accurate imaging in fold-and-thrust belts (e.g., the Canadian Foothills) and near flanks of salt domes. Other applications include the dip-moveout inversion for the P-wave time-processing parameter η and stable computation of interval long-spread (nonhyperbolic) moveout for purposes of anisotropic velocity analysis.

Introduction

Interval parameter estimation using seismic reflection data requires application of layer-stripping (e.g., Grechka et al., 1999; Ursin and Stovas, 2005) or tomographic (e.g., Stork, 1991; Grechka et al., 2002) methods. In horizontally layered isotropic media, the normal-moveout (NMO) velocity of reflected waves is equal to the root-mean-square of the interval velocities. This relationship (Dix equation) helps to obtain the interval velocity using the NMO velocities for the reflections from the top and bottom of the layer.

Dix-type averaging of the interval NMO velocities remains valid even for reflections from dipping interfaces in anisotropic media, if the common-midpoint (CMP) line is confined to a vertical symmetry plane and the overburden is laterally homogeneous (Alkhalifah and Tsvankin, 1995). A 3D extension of this result to the NMO ellipses of horizontal and dipping events is given by Grechka et al. (1999) and Grechka and Tsvankin (2002a). However, if the reflector is dipping, the interval NMO velocity no longer corresponds to any physical interface and has to be computed for an imaginary reflector orthogonal to the slowness vector of the zero-offset ray. Therefore, anisotropic layer-stripping algorithms based on this formalism involve interval parameter estimation for the whole overburden (Tsvankin, 2005). Also, although Dix-type averaging expressions have been extended to long-offset data, they are largely limited to horizontally layered models (e.g., Tsvankin, 2005; Ursin and Stovas, 2005). Finally, existing methodologies cannot be applied to mode-converted waves when their moveout becomes asymmetric (i.e., traveltimes of converted waves do not necessarily remain the same when the source and receiver are interchanged).

Here, we present a technique for computing exact interval traveltimes and the corresponding offsets of pure-mode and converted waves in a heterogeneous target zone overlaid by a laterally homogeneous overburden. Our approach is based on the "PP+PS=SS" method originally designed for generating pure-mode SS reflection data from PP- and PS-waves (Grechka and Tsvankin, 2002b).

Layer-stripping methodology

We consider a PS-wave converted at the target reflector beneath an anisotropic medium (Figure 1). Note that layer stripping for pure modes (PP or SS) can be treated as a special case of the algorithm for PS-waves. In the 2D version of the method discussed here, the acquisition line is supposed to be confined to a vertical symmetry plane in all layers. The target zone (i.e., the layer between the reflector and the bottom of the overburden) can be arbitrarily heterogeneous in the incidence plane and can include multiple curved interfaces above the reflector. The only restriction on the type of anisotropy in the target zone is that the incidence plane has to be a plane of symmetry; this restriction can be lifted in the 3D version of our method operating with wide-azimuth data.

Each layer in the overburden, however, is assumed to be laterally homogeneous with a horizontal symmetry plane. Then any reflection point at the bottom of the overburden (e.g., points T and R in Figure 1) coincides with the common midpoint for the corresponding source-receiver pair, and the traveltimes along the downgoing and upgoing segments of the reflected ray are equal to each other.

Here, we demonstrate that a variation of the "PP+PS=SS" method (Grechka and Tsvankin, 2002b) can be used to construct the exact interval traveltime-offset function in the target layer without knowledge of the velocity field. This is accomplished by combining the target event with reflections from the bottom of the overburden in such a way that they share the same ray segments in the overburden (Figure 1). Following the algorithm of Grechka and Tsvankin (2002b), we form a common-receiver gather of the target event $x^{(1)}\,\mathrm{TQR}\,x^{(2)}$ at point $x^{(2)}$ and determine the time slope on this gather at point $x^{(1)}$. Since the slowness vector is equal to the gradient of the travelime surface, the estimated time slope yields the ray parameter (horizontal slowness) of the reflection $x^{(1)}\,\mathrm{TQR}\,x^{(2)}$ at the source location $x^{(1)}$. We then use the same algorithm to evaluate the time slopes of the overburden PP reflections excited at $x^{(1)}$ and recorded at different locations along the line. For a certain receiver location $x^{(3)}$, the time slope (ray parameter) of the overburden reflection from $x^{(1)}$ to $x^{(3)}$ coincides with that of the target event,

$$\frac{\partial t_{PS}^{\mathrm{eff}}(x^{(1)},x^{(2)})}{\partial x^{(1)}} = \frac{\partial t_{PP}^{\mathrm{ovr}}(x^{(1)},x^{(3)})}{\partial x^{(1)}}\,, \tag{1}$$

where the superscripts "eff" (effective) and "ovr" (overburden) refer, respectively, to the PS reflection traveltime from the target and the PP time from the bottom of the overburden. The identical ray parameters mean that the overburden PP reflection $x^{(1)}\,\mathrm{T}\,x^{(3)}$ shares the segment $x^{(1)}\,\mathrm{T}$ with the target PS event.

Repeating this procedure at point $x^{(2)}$ allows us to identify the reflected SS-wave $x^{(2)}\,\mathrm{R}\,x^{(4)}$ that has the same shear-wave segment $\mathrm{R}\,x^{(2)}$ in the overburden as the PS-wave. Therefore, the algorithm has to operate with both PP- and SS-waves reflected from the bottom of the overburden. In the absence of shear-wave excitation, the needed reflection moveout of SS-waves can be obtained by applying the PP+PS=SS method to the overburden PP and PS reflections.

Both events (PP and SS) from the bottom of the overburden have symmetric raypaths with respect to their reflection points. Hence, the interval PS traveltime in the target layer and the corresponding source/receiver coordinates (i.e., the horizontal coordinates of points T and R) can be found as

$$t_{PS}^{\mathrm{int}}(T,R) \,=\, t_{PS}^{\mathrm{eff}}(x^{(1)},x^{(2)}) \,-\frac{1}{2}\,\left[t_{PP}^{\mathrm{ovr}}(x^{(1)},x^{(3)}) \,+\, t_{SS}^{\mathrm{ovr}}(x^{(2)},x^{(4)})\right]\,, \tag{2}$$

$$x_T \,=\, \frac{\left(x^{(1)}+x^{(3)}\right)}{2}\,,\quad x_R \,=\, \frac{\left(x^{(2)}+x^{(4)}\right)}{2}\,. \tag{3}$$

Synthetic example

The layer-stripping algorithm was tested on PP and PS reflection data generated for the layered anisotropic model in Figure 2, where the target zone is represented by the dipping TI layer with a tilted symmetry axis. The traveltimes from the plane dipping reflector and the bottom of the overburden (i.e., from the top of the TTI layer) were computed by anisotropic ray tracing with a shot spacing of 25 m and a receiver spacing of 50 m (Figure 3). Note that the PS-wave moveout is asymmetric (i.e., the traveltime is different for positive and negative offsets) because of the combined influence of reflector dip ($\phi = 20^\circ$) and the tilt of the symmetry axis ($\nu = 35^\circ$) in the target TTI layer. The complexity of the target event, however, does not pose a problem for our layer-stripping method that relies only on the up-down symmetry of the reflection raypaths in the overburden.

The layer-stripped interval PS traveltimes and the corresponding source/receiver coordinates are close to the exact values computed directly by ray tracing (Figure 4). The minor deviations from the ray-tracing results are caused by interpolation errors related to the finite source and receiver sampling. This and other synthetic tests performed for a representative set of layered anisotropic models confirm the accuracy of the algorithm for any source-receiver offset. We have also verified that the interval moveout remains unbiased when the input traveltimes are contaminated by significant Gaussian noise with the standard deviation reaching 10 ms.

As expected, the interval PS traveltimes in Figure 4 exhibit a much more significant asymmetry than the effective times in Figure 3. This asymmetric PS-wave moveout function for the target layer, supplemented by the interval PP-wave moveout, serves as the input to the inversion algorithm of Dewangan and Tsvankin (2004) designed to estimate the parameters of dipping TTI layers.

Extensions and applications

The 2D algorithm introduced here can be extended to wide-azimuth surveys using the 3D version of the PP+PS=SS method described by Grechka and Tsvankin (2002b). The 3D implementation of our method removes all restrictions on the anisotropy and heterogeneity of the target layer, and the overburden no longer needs to have a vertical symmetry plane.

An important application of our results is in velocity analysis for tilted TI layers using multicomponent (PP and PS) data. As shown by Dewangan and Tsvankin (2004), the combination of the asymmetry attributes of PS-waves with pure-mode moveout signatures can provide sufficient information for parameter estimation in a homogeneous TTI medium. The developed layer-stripping algorithm makes it possible to apply this inversion technique to realistic models with a stratified overburden above the target TTI layer.

Our method also overcomes the limitations of the Dix-type equations in the dip-moveout inversion for the P-wave time-processing parameter η in VTI media. Because of the need to compute the interval NMO velocities in the overburden for imaginary reflectors, η estimation using dipping events relies on the presence of both horizontal and dipping interfaces in each layer (Alkhalifah and Tsvankin, 1995; Tsvankin, 2005). This requirement, which is often difficult to satisfy in practice, is no longer needed if the interval moveout is computed by our velocity-independent technique. It can also be highly beneficial to apply our algorithm in the inversion of nonhyperbolic moveout. Whereas computation of the interval quartic moveout coefficient suffers from instability, our layer-stripping technique produces accurate interval long-offset traveltimes which can then be inverted for the anisotropy parameters (e.g., for the parameter η in VTI media).

Conclusions

The principle of the PP+PS=SS method can be employed to carry out exact layer stripping for both pure and mode-converted waves in anisotropic media. Estimation of reflection time slopes helps to identify the overburden events that share the upgoing and downgoing legs with the target reflection. This allows us to perform kinematic downward continuation of the wavefield and build the interval traveltime-offset function without knowledge of the medium parameters. Numerical testing for layered TI media above a dipping reflector confirms that the algorithm gives exact results for converted waves with asymmetric moveout and remains stable in the presence of noise. In contrast to tomographic methods that can also handle long-offset data from heterogeneous media, our layer stripping is velocity-independent, and the computed interval moveouts are not influenced by errors in the overburden parameters.

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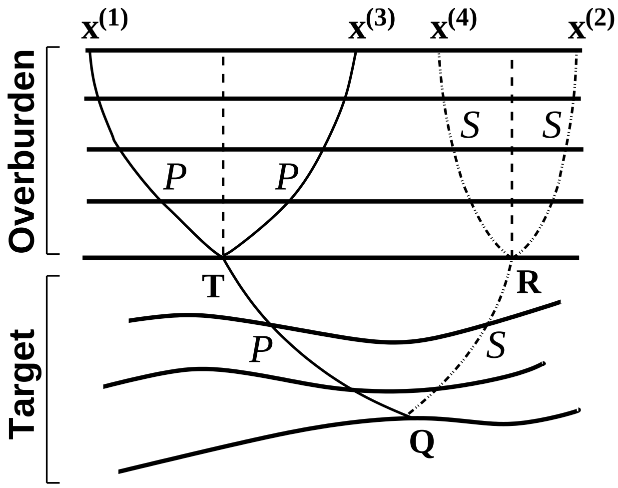

Figure 1: 2D ray diagram of the layer-stripping algorithm for PS-waves (italicized letters denote the wave mode). The target PS reflection ($x^{(1)}$ TQR $x^{(2)}$) and the PP reflection from the bottom of the overburden ($x^{(1)}$ T $x^{(3)}$) share the same downgoing leg ($x^{(1)}$ T). The upgoing leg of the target PS event in the overburden (R $x^{(2)}$) coincides with a leg of the SS reflection $x^{(2)}$ R $x^{(4)}$. The layer-stripping algorithm can be applied in the same way to any reflector in the target zone.

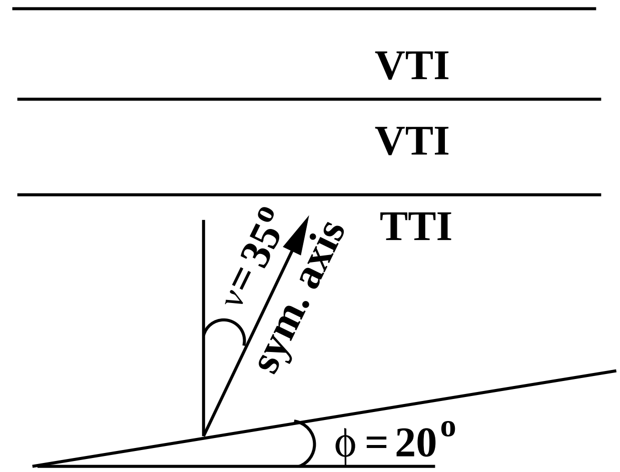

Figure 2: Transversely isotropic model used to test the layer-stripping algorithm. The first layer has a vertical symmetry axis (VTI) and the following parameters: the symmetry-direction P-wave velocity $V_{P0} = 2$ km/s, the symmetry-direction S-wave velocity $V_{S0} = 1$ km/s, the thickness $h = 0.25$ km, and Thomsen anisotropy parameters $\epsilon = 0.2$ and $\delta = 0.1$. The second layer is also VTI with $V_{P0} = 4$ km/s, $V_{S0} = 2$ km/s, $h = 0.25$ km, $\epsilon = 0.15$, and $\delta = 0.05$. The third (target) layer is dipping TTI with the symmetry axis tilted at $\nu = 35°$, the dip of the bottom $\phi = 20°$, $V_{P0} = 4$ km/s, $V_{S0} = 2$ km/s, $h = 0.5$ km, $\epsilon = 0.25$, and $\delta = -0.05$. The Thomsen parameters in the TTI layer are defined with respect to the symmetry axis.

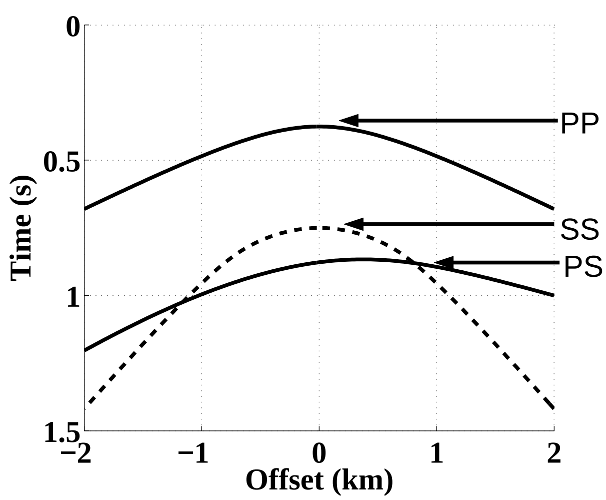

Figure 3: CMP gathers of reflected waves for the model in Figure 2 computed by anisotropic ray tracing. The PS-wave is converted at the dipping interface, while the PP- and SS-waves are reflected from the bottom of the overburden. The offset is positive when the source-to-receiver vector points downdip.

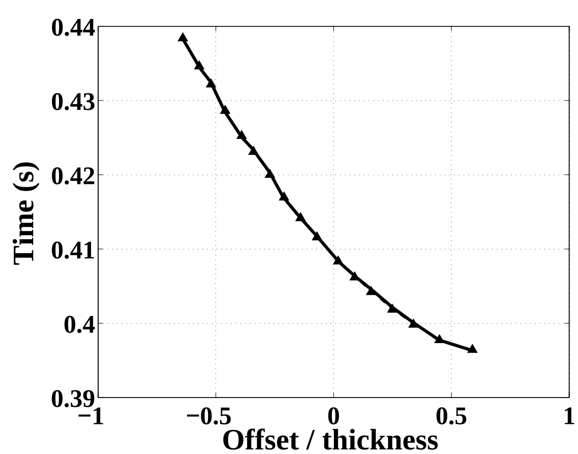

Figure 4: Interval PS-wave traveltime in the target layer as a function of offset for the model from Figure 2. The triangles mark the output of the layer-stripping algorithm; the solid line is the result of ray tracing.