

Interval anisotropic parameter estimation using velocity-independent layer stripping

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SUMMARY

Moveout analysis of long-spread P-wave data is widely used to estimate the key time-processing parameter η in layered VTI (transversely isotropic with a vertical symmetry axis) media. Inversion for interval η values, however, suffers from instability caused by the tradeoff between the effective moveout parameters and by the subsequent error amplification during Dix-type layer stripping. Here, we propose an alternative approach to interval parameter estimation based on the velocity-independent layer-stripping (VILS) method of Dewangan and Tsvankin (2006). This method makes it possible to compute the interval moveout in a layer of interest without knowledge of the medium parameters in the overburden. Thus, the layer stripping of moveout parameters in the conventional method is replaced by the much more stable stripping of reflection traveltimes. We also develop the 3D version of the layer-stripping method and apply it to interval parameter estimation for orthorhombic media using wide-azimuth P-wave data.

The superior accuracy and stability of our algorithm is illustrated on noise-contaminated ray-traced synthetic data for typical layered VTI and orthorhombic models. The algorithm is also tested on wide-azimuth P-wave reflection data recorded above a fractured reservoir at Rulison field in Colorado. The interval η values estimated by VILS are more plausible and stable than those obtained by the Dix-type method.

INTRODUCTION

Traveltime analysis of reflection data yields effective moveout parameters for the whole section above the reflector. For purposes of velocity model-building, AVO (amplitude-variation-with-offset) inversion, and seismic fracture characterization, it is necessary to estimate interval parameters, which is done using tomographic techniques or Dix-type layer stripping (e.g., Dix, 1955; Grechka and Tsvankin, 1998; Grechka *et al.*, 1999). In particular, Dix-type formalism is often used to invert P-wave nonhyperbolic moveout from layered VTI media for the interval parameter η , which is responsible for time processing of P-wave data (Alkhalifah, 1997; Grechka and Tsvankin, 1998). An extension of this methodology to orthorhombic media makes it possible to estimate the interval parameters $\eta^{(1,2,3)}$ from azimuthally varying long-spread P-wave traveltimes (Vasconcelos and Tsvankin, 2006).

Nonhyperbolic moveout inversion, however, is hampered by the tradeoff between the normal-moveout (NMO) velocity and the quartic moveout coefficient, which causes instability in η estimation (Grechka and Tsvankin, 1998). The error in the effective parameter η may get greatly amplified in the layer-stripping process, which causes unacceptable distortions in the interval values.

Here, we develop 2D and 3D moveout-inversion algorithms

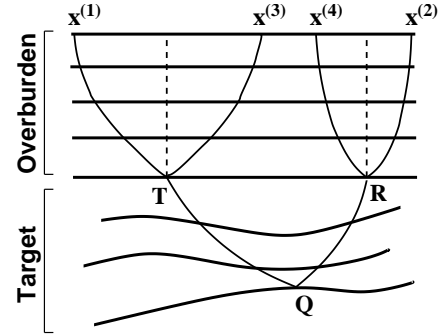


Figure 1: 2D diagram of VILS for pure-mode reflections (after Dewangan and Tsvankin, 2006). Points T and R are located at the bottom of the laterally homogeneous overburden. The leg $x^{(1)}T$ is shared by the target reflection $x^{(1)}TQRx^{(2)}$ and the overburden event $x^{(1)}Tx^{(3)}$; the leg $Rx^{(2)}$ is shared by the reflections $x^{(1)}TQRx^{(2)}$ and $x^{(2)}Rx^{(4)}$.

for VTI and orthorhombic media based on the velocity-independent layer-stripping (VILS) method of Dewangan and Tsvankin (2006). Application to synthetic and field data demonstrates that the interval parameter estimates produced by our technique remain accurate in the presence of typical correlated noise in reflection traveltimes.

VELOCITY-INDEPENDENT LAYER STRIPPING

The VILS algorithm of Dewangan and Tsvankin (2006) is designed to compute the interval traveltimes in an anisotropic heterogeneous target zone from surface reflection data. Each layer in the overburden has to be laterally homogeneous with a horizontal symmetry plane, so that the raypath of any reflection from the top of the target zone is symmetric with respect to the reflection point (e.g., points T and R in Figure 1). The target zone, however, can be heterogeneous and can include interval curved interfaces. By equalizing time slopes on common-receiver gathers, we identify the overburden reflections that share the downgoing and upgoing ray segments with the target event (Figure 1). Then the interval reflection traveltime t^{int} in the target zone can be computed as

$$t^{\text{int}}(T, R) = t^{\text{eff}}(x^{(1)}, x^{(2)}) - \frac{1}{2} \left[t^{\text{ovr}}(x^{(1)}, x^{(3)}) + t^{\text{ovr}}(x^{(2)}, x^{(4)}) \right], \quad (1)$$

where the superscripts *eff* and *ovr* refer to the reflection traveltimes from the target reflector and the bottom of the overburden, respectively. The corresponding source-receiver pair (T,R) has the following horizontal coordinates:

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

	Layer 1	Layer 2	Layer 3 (target)
Thickness (km)	0.7	0.3	0.5
t_0 (s)	0.70	0.25	0.39
V_{nmo} (km/s)	2.10	2.52	2.78
η	0	0.10	0.20

Table 1: Interval parameters of a three-layer VTI model (model 1).

For 3D wide-azimuth data, identifying the target and overburden reflections with the same ray segments requires estimating two orthogonal horizontal slowness components. Thus, the VILS algorithm makes it possible to construct the interval moveout function, which can then be used for interval parameter estimation. Since effective traveltimes are better constrained by reflection data than the corresponding effective moveout parameters, VILS produces more accurate interval parameter estimates than Dix-type techniques.

2D INVERSION FOR VTI MEDIA

Nonhyperbolic moveout of P-waves in a single horizontal VTI layer can be accurately described by the following equation (Alkhalifah and Tsvankin, 1995; Tsvankin, 2005):

$$t^2 = t_0^2 + \frac{x^2}{V_{\text{nmo}}^2} - \frac{2\eta x^4}{V_{\text{nmo}}^2 [t_0^2 V_{\text{nmo}}^2 + (1 + 2\eta)x^2]}, \quad (3)$$

where x is the offset and t_0 is the zero-offset traveltime. For layer-cake VTI media, the NMO velocity (V_{nmo}) and parameter η become effective quantities, and the interval value of η can be obtained from Dix-type equations (Alkhalifah, 1997; Tsvankin, 2005). The effective parameters V_{nmo} and η are usually estimated from a 2D semblance scan on long-spread data.

Although equation 3 provides a close approximation for nonhyperbolic moveout in VTI media, the estimated η is sensitive to small errors in V_{nmo} , even if the maximum offset-to-depth ratio (x_{max}/h) is between two and three. The tradeoff between the effective V_{nmo} and η (along with the slight bias of the nonhyperbolic moveout equation) in the presence of correlated noise may cause large errors in η , which are amplified in the Dix-type layer stripping (Grechka and Tsvankin, 1998).

Synthetic testing

Here, we apply VILS and the Dix-type method to long-spread P-wave data generated by anisotropic ray tracing (Gajewski and Pšenčík, 1987) for a three-layer VTI model (Table 1). For noise-free data, the absolute error in the interval η estimated by VILS is 0.02, while it reaches 0.06 when the Dix-type method is used. The error of VILS is mostly caused by the small bias of the single-layer moveout equation 3.

To study the influence of realistic noise on the interval parameter estimation, we added linear and sinusoidal time errors to the reflection moveout from the bottom of the target layer. The traveltimes from the top of the target were left unchanged. (Since both methods are based on semblance analysis, they remain stable in the presence of random noise.)

Linear noise can simulate long-period static errors. For a linear noise function that varies from 6 ms at zero offset to -6 ms at the maximum offset, VILS estimates the interval V_{nmo} with an error of 4% and η with an absolute error of 0.07. The distortions in V_{nmo} and η after the Dix-type layer stripping are much larger (15% and 0.34, respectively), which makes the inversion results practically useless.

Sinusoidal time errors, which can be associated with short-period statics, are described by the function $t = A \sin(n\pi x/x_{\text{max}})$. While the Dix-type method breaks down for $A > 3$ ms, VILS remains accurate for noise of much higher magnitude. When $A = 8$ ms and $n = 3$, the errors in the interval V_{nmo} and η produced by VILS are only 2% and 0.08, respectively, while they reach 21% and 0.41 for the Dix-type method.

3D INVERSION FOR ORTHORHOMBIC MEDIA

The azimuthally-dependent P-wave reflection moveout in a single orthorhombic layer can be well-approximated by equation 3 with azimuthally varying parameters V_{nmo} and η (Xu and Tsvankin, 2006; Vasconcelos and Tsvankin, 2006):

$$t^2(x, \alpha) = t_0^2 + \frac{x^2}{V_{\text{nmo}}^2(\alpha)} - \frac{2\eta(\alpha)x^4}{V_{\text{nmo}}^2(\alpha)[t_0^2 V_{\text{nmo}}^2(\alpha) + (1 + 2\eta(\alpha))x^2]}. \quad (4)$$

V_{nmo} is obtained from the equation of the NMO ellipse:

$$V_{\text{nmo}}^{-2}(\alpha) = \frac{\sin^2(\alpha - \varphi)}{[V_{\text{nmo}}^{(1)}]^2} + \frac{\cos^2(\alpha - \varphi)}{[V_{\text{nmo}}^{(2)}]^2}, \quad (5)$$

where φ is the azimuth of the $[x_1, x_3]$ symmetry plane, and $V_{\text{nmo}}^{(1)}$ and $V_{\text{nmo}}^{(2)}$ are the NMO velocities in the vertical symmetry planes. The parameter η is approximately given by

$$\eta(\alpha) = \eta^{(1)} \sin^2(\alpha - \varphi) + \eta^{(2)} \cos^2(\alpha - \varphi) - \eta^{(3)} \sin^2(\alpha - \varphi) \cos^2(\alpha - \varphi), \quad (6)$$

where $\eta^{(1,2,3)}$ are the anellipticity parameters defined in the symmetry planes of the model.

For layered orthorhombic media, all moveout parameters become effective quantities. If the vertical symmetry planes in different layers are misaligned, the principal directions for the effective η are described by a separate azimuth, φ_1 (Xu and Tsvankin, 2006):

$$\eta(\alpha) = \eta^{(1)} \sin^2(\alpha - \varphi_1) + \eta^{(2)} \cos^2(\alpha - \varphi_1) - \eta^{(3)} \cos^2(\alpha - \varphi_1) \sin^2(\alpha - \varphi_1). \quad (7)$$

We use the semblance-based 3D nonhyperbolic moveout inversion algorithm of Vasconcelos and Tsvankin (2006) to estimate the best-fit effective moveout parameters $V_{\text{nmo}}^{(1,2)}$, $\eta^{(1,2,3)}$, φ and φ_1 for the top and bottom of the target layer. To implement the Dix-type methodology, we obtain the interval NMO ellipse

	Layer 1	Layer 2	Layer 3 (target)
Symmetry type	ISO	VTI	ORTH
Thickness (km)	0.5	0.5	0.5
t_0 (s)	0.50	0.41	0.39
$V_{\text{nmo}}^{(1)}$ (km/s)	2	2.49	3.18
$V_{\text{nmo}}^{(2)}$ (km/s)	2	2.49	2.64
$\eta^{(1)}$	0	0.05	0.2
$\eta^{(2)}$	0	0.05	0.06
$\eta^{(3)}$	0	0	0.13
φ ($^\circ$)	-	-	30

Table 2: Interval parameters of a three-layer model that includes an orthorhombic layer (model 2).

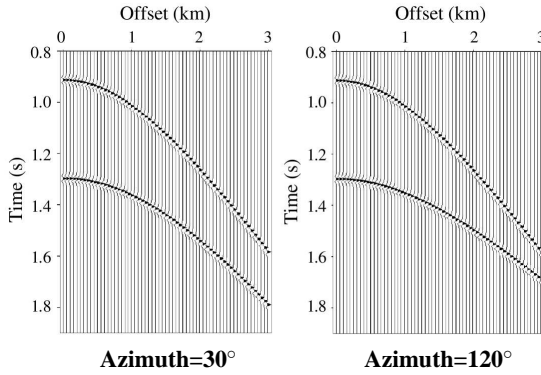


Figure 2: Synthetic long-spread reflections from the top and bottom of layer 3 (target) in model 2 (Table 2). The seismograms are computed in the two orthogonal vertical symmetry planes of the target orthorhombic layer.

from the generalized Dix equation (Grechka *et al.*, 1999). The interval parameter η for each azimuth is approximately computed from the corresponding VTI expression (Grechka and Tsvankin, 1998; Tsvankin, 2005). Finally, the interval parameters $\eta^{(1,2,3)}$ are obtained by fitting the azimuthally varying η values to equation 6.

To apply VILS to 3D wide-azimuth data, we have to estimate both horizontal slowness components, which can be computed by traveltim differentiation on common-shot or common-receiver gathers. A more convenient and numerically stable option employed in our algorithm is to obtain the horizontal slownesses using equation 4 with the best-fit parameters. Despite the tradeoffs between the effective moveout parameters, equation 4 provides sufficient accuracy for long-spread P-wave moveout and, therefore, for the horizontal slowness components.

Synthetic testing

We generated synthetic wide-azimuth data for a model that includes the target orthorhombic layer beneath the overburden composed of isotropic and VTI layers (Table 2). Note that the traveltimes from the bottom of the target layer (Figure 2) noticeably vary with azimuth.

Without traveltim noise, both methods give similar accuracy

	Layer 1	Layer 2	Layer 3 (target)
Symmetry type	ISO	ORTH	ORTH
Thickness (km)	0.3	0.7	0.5
t_0 (s)	0.30	0.58	0.39
$V_{\text{nmo}}^{(1)}$ (km/s)	2	2.56	3.68
$V_{\text{nmo}}^{(2)}$ (km/s)	2	3.06	2.73
$\eta^{(1)}$	0	0.05	0.24
$\eta^{(2)}$	0	0.07	0.12
$\eta^{(3)}$	0	0.02	-0.10
φ ($^\circ$)	-	30	70

Table 3: Interval parameters of a three-layer model that includes two orthorhombic layers with misaligned vertical symmetry planes (model 3).

in the interval moveout parameters. As before, we added linear and sinusoidal time errors to the reflection moveout from the bottom of the target layer in model 2. For a linear error that changes from 6 ms to -6 ms over the spread for each azimuth, the maximum errors in the interval parameters $V_{\text{nmo}}^{(1,2)}$ and $\eta^{(1,2,3)}$ estimated by VILS are 3% and 0.06, respectively, while they reach 9% and 0.16 for the Dix-type method. The errors in the azimuth φ for both methods are negligible. Similar results were obtained by contaminating the traveltimes with an azimuthally varying sinusoidal function of the form $A \sin(n\pi x/x_{\text{max}}) \sin m\alpha$.

We also tested VILS on a more complicated model that includes orthorhombic layers with misaligned vertical symmetry planes (Table 3). Estimation of the effective parameters $\eta^{(1,2,3)}$ in such a case is carried out using equation 7. The sinusoidal error $t = A \sin(n\pi x/x_{\text{max}})$ applied to the traveltimes from the bottom of the target layer produces much more significant distortions in the output of the Dix-type method compared to VILS. For instance, when $A = 6$ ms and $n = 3$, the maximum errors of the interval $V_{\text{nmo}}^{(1,2)}$ and $\eta^{(1,2,3)}$ estimated by VILS are 4% and 0.09, respectively, while the errors of the Dix-type method reach 13% and 0.25.

FIELD-DATA EXAMPLE

We applied the 3D VILS algorithm to wide-azimuth P-wave data acquired at Rulison field, a basin-centered gas accumulation located in South Piceance Basin, Colorado. The reservoir (Williams Fork formation) is capped by the UMV shale (Figure 3), which served as the target layer in our study. Since the subsurface structure is close to layer-cake (Figure 4), the moveout equations discussed above should give an accurate description of reflection traveltimes. To increase the azimuth and offset coverage, we combined CMP gathers into 5x5 superbins, as suggested by Xu and Tsvankin (2007).

We carried out the moveout inversion in the center of the survey area. Because the average offset-to-depth ratio at the bottom of the reservoir is close to unity, nonhyperbolic moveout inversion cannot be applied to the reservoir formation. Therefore, the target layer is chosen to be the UMV shale (cap rock).

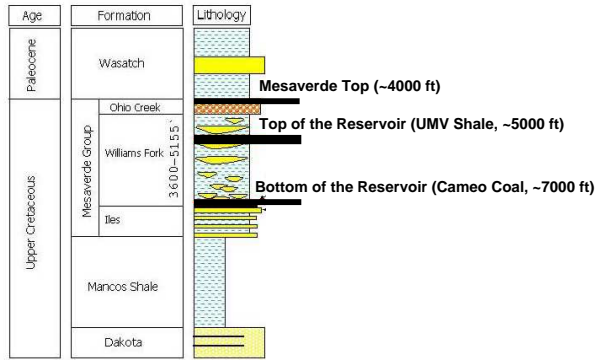


Figure 3: Stratigraphic column of Rulison field (after Xu and Tsvankin, 2007). The gas-producing reservoir is bounded by the UMV shale (the target layer in this study) and the Cameo coal.

In the center of the study area, the offset-to-depth ratio at the bottom of the shale is between 1.9 and 2.2. To estimate the interval moveout parameters, we used the 3D VILS and Dix-type algorithms for layered orthorhombic media.

Our tests show that the NMO ellipticity is small for both the top and bottom of the target layer over most of the area. Therefore, the principal directions of the effective and interval NMO ellipses are poorly constrained by the data. However, as long as the offset-to-depth ratio is close to two, the parameters $\eta^{(1,2,3)}$ can be estimated in a reliable fashion. The interval anellipticity parameters for two superbin gathers near the center of the area are listed in Table 4. Most values obtained by the Dix-type method are implausibly large for shale formations (Wang, 2002; Tsvankin, 2005), while VILS yields much smaller magnitudes of $\eta^{(1,2,3)}$.

To test the stability of both methods, we added a linear time error (from 4 ms at zero offset to -4 ms at the maximum offset for each azimuth) to the reflection moveout from the bottom of the target layer in the second superbin. The interval $\eta^{(1,2,3)}$ values estimated by VILS change by less than 0.07, while the deviations produced by the Dix-type method reach 0.2. Hence, VILS is much more stable than the Dix-type method in the presence of correlated time errors, as was established above for the synthetic data.

CONCLUSIONS

We applied the velocity-independent layer-stripping method (VILS) of Dewangan and Tsvankin (2006) to nonhyperbolic moveout inversion for layered VTI and orthorhombic media. If the overburden is laterally homogeneous and has a horizontal symmetry plane, VILS produces the exact interval traveltime without any information about the velocity field. Effective traveltimes are much better constrained by reflection data than effective moveout parameters employed in Dix-type algorithms. Therefore, VILS substantially increases the accuracy and stability of nonhyperbolic moveout inversion for the interval time-processing parameter η in VTI media, which is

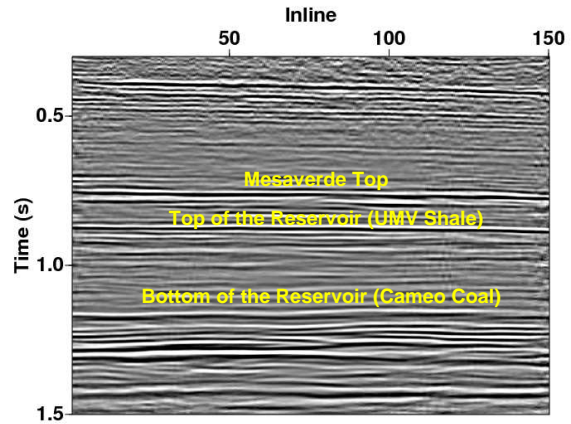


Figure 4: Seismic section across the middle of the survey area (after Xu and Tsvankin, 2007).

Superbin	1			2		
	$\eta^{(1)}$	$\eta^{(2)}$	$\eta^{(3)}$	$\eta^{(1)}$	$\eta^{(2)}$	$\eta^{(3)}$
VILS	0.38	0.47	-0.18	0.24	0.31	-0.15
Dix	0.74	1.24	-0.35	0.31	0.62	-0.19

Table 4: Interval parameters $\eta^{(1,2,3)}$ estimated for two superbin gathers in the center of the study area.

confirmed by our synthetic tests on noise-contaminated data.

We also presented an extension of VILS to 3D wide-azimuth P-wave data from orthorhombic media. To identify the target and overburden reflections that share the same ray segments, we compute the horizontal slowness components from the best-fit effective moveout parameters, which helps to avoid direct differentiation of traveltimes. Wide azimuthal coverage helps to increase the stability of η estimation using 3D Dix-type layer stripping. Still, our tests clearly demonstrate the superior performance of VILS for typical orthorhombic models, including those with the depth-varying azimuths of the vertical symmetry planes. The 3D version of the method was also successfully used to estimate the interval anellipticity parameters from wide-azimuth data acquired at Rulison field in Colorado.

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