Some seismic reflections on 3C-3D and anisotropy

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ABSTRACT

In this short note I consider some of the features of different 3-D surveys – P-P, S-S and P-SV – that make them more or less advantageous for anisotropy analysis. The implications of survey type, that is, source and receiver polarizations, upon phenomena such as shear-wave splitting and moveout variation with offset and azimuth are considered. There are apparently many benefits to be derived from the 3C-3D survey with a single (P) source type, both in terms of data acquired and of cost.

INTRODUCTION

A significant potential advantage of 3-D seismic over 2-D with respect to anisotropy analysis is provided by the range of azimuthal coverage of the 3-D survey, in contrast to the single azimuth of the 2-D line. In general, to determine anisotropic parameters of a subsurface formation, the more directions in which observations are made, the better constrained the determination will be.

In this note, I speculate on some of the possibilities that 3-D seismic data provide in terms of extracting information about anisotropic parameters. P-P, SV-SV and SH-SH surveys are considered and, in addition, the 3-C P-SV converted-wave survey is given particular attention. Here it is assumed, unless otherwise stated, that the subsurface is made up of homogeneous layers bounded by horizontal interfaces.

AZIMUTHAL ANISOTROPY

Without loss of generality, consider that the azimuthal anisotropy is caused by an aligned set of vertical fractures or cracks. Azimuth, θ, is measured relative to the strike of the fractures.

The P-P case

For a shot-receiver azimuth of $\theta = 0°$, parallel to fracture strike, the moveout (MO) will be normal, i.e., unaffected by the anisotropy, and the reflection traveltime curve, $t(x)$ (loosely referred to here as the MO) will retain its near-hyperbolic form (hyperbolic in the short-spread approximation or in the single-layer case; see e.g. Yilmaz, 1987, for a review of isotropic NMO). For a shot-receiver azimuth of $\theta = 90°$, perpendicular to fracture strike, $t(x)$ will have the same functional behaviour as in the case of transverse isotropy (TI), taking due account of the different geometries. MO in this case has been dealt with by, among others, Thomsen (1986, 1988), Dellinger and Muir (1993) and Tsvankin and Thomsen (1994) and, in general, is nonhyperbolic. In addition to that, the moveout velocity in the short-spread or zero-offset limit, defined by:

$$V_{\mathrm{MO}}^2 = \lim_{x \to 0} \left[\frac{\mathrm{d}(x^2)}{\mathrm{d}(t^2)} \right] \tag{1}$$

is different for the parallel (||) and perpendicular ($\perp$) cases. For the NMO of the parallel case,

$$V_{\mathrm{NMO}} = V_{\mathrm{P}_0} \tag{2}$$

and for the abnormal MO of the perpendicular case,

$$V_{\mathrm{MO}} = V_{\mathrm{P}_0}(1-\delta) \tag{3}$$

where V_{P_0} is the vertical P-wave velocity and δ is one of the Thomsen (1986) anisotropy parameters. For azimuths between 0° and 90°, the moveout situation is much more complex but tractable. In general, the reflection traveltime will depend on x, V_{P_0}, θ, δ and ε. However, the dependence on ε, another of the Thomsen (1986) anisotropy parameters, is very weak for short spreads.

In order to estimate values for some of these parameters, one could take either a full 3-D approach or a 2-D approach (still utilizing the 3-D dataset). In a 2-D approach, for example, one could observe the MO (i.e. the traveltime curve) along two perpendicular azimuths, say 0° and 90°; and the process could be repeated for say 5° and 95°, and so on. Where the two perpendicular MO curves are the most different will be the principal directions or natural axes of the anisotropy, one in this case being the fracture strike direction. Then one could estimate V_{P_0} and δ from equations (2) and (3).

In a full 3-D approach, one tack would be to derive the full functional form of $t(x, V_{\mathrm{P}_0}, \theta, \delta)$, initially probably as a short- to intermediate-spread approximation. Then, one could invert the observed traveltimes to estimate V_{P_0}, δ, and the $\theta = 0°$ direction by some appropriate inversion procedure, such as generalized linear inversion (GLI) (see e.g. Twomey, 1977; Vestrum and Brown, 1994).

In cases where the azimuthal anisotropy does not extend to the surface but is confined to an interval at depth, some layer-stripping technique will have to be applied in order to isolate the parameters of the anisotropic interval.

The 4-C shear-wave case

For shear waves at near-vertical incidence in a vertically fractured medium, shear-wave splitting is a much more diagnostic parameter than MO variation. In this situation, consider a four-component shear-wave survey shot with shear waves generated and recorded with polarizations in two perpendicular directions, say parallel to the sides of a rectangular 3-D grid. For this case, one does not gain any significant new information than is obtainable with a 2-D four-component shear-wave survey because the shot-receiver azimuth plays no role in what is recorded, only the source and receiver polarization directions. Given these, the shear-wave time delay will be a function only of $V_{||}$ (or $V_{\perp}$) and γ, where $V_{||}$ and $V_{\perp}$ are the velocities of vertically propagating S waves polarized parallel and perpendicular to fracture strike and γ is the third Thomsen parameter (the shear-wave anisotropy).

Thus, the same sort of analysis that one would use in the 2-D case will do equally well in the 3-D case, for example, Alford (1986) rotation or some similar method. Thomsen (1988) presents equations that can be used to determine the principal directions (fracture strike). These may be solved explicitly but, in practice, this is done by calculating these expressions for a range of azimuths, θ (of polarization to fracture strike), in effect rotating the horizontal components, then looking for nulled cross-components and diagonal components with single, time-delayed, shear arrivals.

Thomsen (1988) also gives expressions for shear-wave MO in the case of azimuthal anisotropy for the short-spread and weak-anisotropy approximation. For a survey line parallel to fracture strike, V_{MO} in SV and SH surveys is simply equal to the corresponding vertical velocity, $V_{\parallel}$ and $V_{\perp}$, respectively. For a survey line perpendicular to fracture strike, for an SV survey,

$$V_{\mathrm{MO}} = V_{\parallel}\left[1-\gamma+\left(V_{\mathrm{P}_0}/V_{\parallel}\right)^2(\varepsilon-\delta)\right] \tag{4}$$

and for an SH survey,

$$V_{\mathrm{MO}} = V_{\perp} = V_{\parallel}(1-\gamma). \tag{5}$$

The 3-C P-SV case

In the converted-wave case, the situation is quite different from the other shear-wave cases. At the point of conversion from P to SV, this shear wave will be polarized (nearly horizontally for small offsets) in the vertical plane of propagation (sagittal plane) of the P and SV waves, whose azimuth is identical to the source receiver azimuth. Consequently, receivers at a range of azimuths will record varying degrees of fast and slow shear waves. For a source-receiver azimuth aligned with fracture strike $\theta = 0^\circ$, there will only be one (fast) shear arrival, S1. For a source-receiver azimuth aligned perpendicular to fracture strike $\theta = 90^\circ$, there will also be just one (slow) shear arrival, S2. At any other azimuth, however, there will be an S1 and an S2 recorded, whose relative amplitudes will depend on θ. Various rotation methods, for example modified Alford rotation (Thomsen, 1988) or Harrison rotation (Harrison, 1992), can be applied to the two horizontal-component records to enable determination of the direction $\theta = 0^\circ$ and rotation into these natural axes.

This feature of the 3C-3D P-SV survey – the wide range of "source" shear-wave polarizations – is particularly advantageous in acquiring split shear-wave data for anisotropic analysis compared with the 4-C, 3-D S-S survey where the source polarizations are usually restricted to two perpendicular directions. Besides that, the reduced cost of using only vertical-component or P-wave sources is an added bonus.

TRANSVERSE ISOTROPY

A subsurface that exhibits transverse isotropy with a vertical symmetry axis may be thought of, without loss of generality, as arising from a stack of thin horizontal layers. For P-P, S-S and P-SV surveys, the situation is essentially of a 2-D nature. The P-wave MO is the same at all azimuths and is a function of x, V_{P_0}, δ and ε, the ε-dependence again being significant only for long spreads. Shear-wave splitting will be the same at all azimuths and depend only on x, V_{S_0}, and γ. However, this lack of dependence on azimuth in itself may be useful as a check on the proposition that the subsurface is indeed transversely isotropic. The other main benefit of 3-D, in the TI case, is the large multiplicity of data.

Expressions for V_{MO} for TI media are given by Thomsen (1986), again, for the short-spread and weak-anisotropy approximation. For a survey line of any azimuth, for a P survey,

$$V_{\mathrm{MO}} = V_{\mathrm{P}_0}(1+\delta) \tag{6}$$

for an SV survey,

$$V_{\mathrm{MO}} = V_{\mathrm{S}_0}\left[1+\left(V_{\mathrm{P}_0}/V_{\mathrm{S}_0}\right)^2(\varepsilon-\delta)\right] \tag{7}$$

and for an SH survey,

$$V_{\mathrm{MO}} = V_{\mathrm{S}_0}(1+\gamma). \tag{8}$$

where V_{S_0} is the (single) vertical S-wave velocity.

ORTHORHOMBIC ANISOTROPY

The case of orthorhombic symmetry, with one of the symmetry axes vertical, may be considered to be caused by a superposition of thin horizontal layering and aligned vertical fractures or cracks. The situation will be similar to that for azimuthal anisotropy with the TI effect, which is the same for all azimuths, superposed.

The P-P case

The situation with respect to P-wave MO is similar to that for azimuthal anisotropy. The TI (thin-layering) anisotropy will give rise to a different MO variation with offset but this effect will be the same for all azimuths; so azimuthal MO variation will be due only to the aligned vertical fractures. A 3-D dataset will again in this case be a significant improvement over 2-D data by virtue of the data redundancy and the azimuthal coverage.

The S-S and P-SV cases

Here also the situation follows the discussion for azimuthal anisotropy. If observations are confined to small offsets, the variation with offset introduced by the thin layering will have little effect.

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