Orthorhombic Migrations for Imaging Fractured Reservoirs

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Abstract

The combined effects of horizontal layering and vertical fracturing in the reservoir produce orthorhombic anisotropy. In order to properly image these kinds of reservoirs, we need to abandon the simple assumption of VTI and HTI as independent effects, used in current migration algorithms, and adopt new simultaneous accountings of both effects in the form of an orthorhombic time migration.

In this paper we will describe the theoretical underpinning of orthorhombic symmetry, how we use it in migration and then show some results on real data.

A discussion about the challenges associated with doing velocity updating will be briefly discussed at the end of the article

Introduction

Wide azimuth geometries are becoming the norm in modern land acquisition surveys. Amongst the motivations for this more complex and expensive process lays the desire to increase subsurface illumination of a given reflector. An added benefit comes from the fact that these geometries don't only increase the total illumination, but allow the independent study of the illumination as function of the acquisition azimuth, i.e. source-receiver vector.

Since there is now a good azimuthal coverage of the input data, it is important that we develop processing techniques than can preserve and utilize this information after the migration. A suite of tools and technologies have been developed for this purpose and we will describe a few of them in this paper, mainly those connected with the imaging and velocity determination step.

Several of these have been described elsewhere by us and others so we will simply refer the reader to the relevant publications (Tsvankin 1997, Jenner et al 2001, Xu and Tsvankin 2006, Roende et al 2008, Stein et al 2010).

Offset Vector Tiles and Offset Migrated Gathers

The starting point in the processing is the formation of Offset Vector Tiles (OVT). These have been covered extensively in the references above so we will simply remind the reader that OVT are data sets with offset & azimuth in a narrow range. These are the input to our migrations.

Before going any further we would like to introduce a job flow (figure 1) that explains the basic methodology followed.

The critical point of this workflow is the necessity to do two migrations (not an iteration loop). The first migration is an isotropic OVT migration (described below in figure 2). This migration produces Offset Migrated Gathers (OMG). These are vector versions of our traditional migrated gathers. They represent the migrated data as function of offset and azimuthal orientation. If there is any kind of anisotropy present they will not be flat.

The non-flatness of the gathers comes from a combination of (at least) two separate effects, one is vertical anisotropy or VTI (Vertical Transverse Isotropy) from the natural horizontal depositional layering process, and the second one is the horizontal anisotropy or HTI (Horizontal Transverse Isotropy) produced by the presence of fractures (here assumed to be vertical penny shape).

A good way to describe the combined effect of these two anisotropies is with an orthorhombic symmetry model (Tsvankin 1997, Stein 2010).

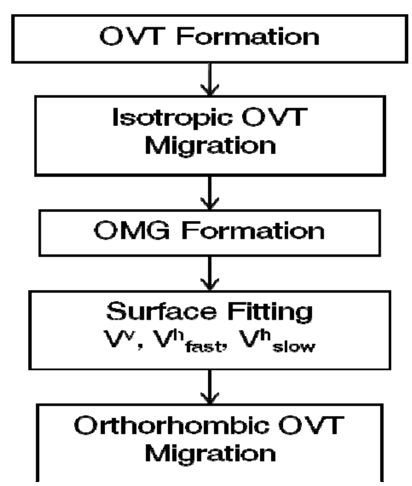

Figure 1: Basic Orthorombic Migration Flow.

Before getting into the orthorhombic parameter determination, let us pause for a minute to understand the first isotropic migration. The individual OVT are migrated and binned on output to generate Offset Migrated Gathers or OMG as exemplified in figure 2. The migration is

carried out with a spatially varying velocity model that has no azimuthal variation (or vertical anisotropy for that matter). There is only one velocity field at this stage regardless of the source-receiver geometry.
The isotropic assumption produces OMG that are not flat. However, flatness now means something a little bit more complicated that an effect in the offset direction (figure 3), it now contains an azimuthal component as well.

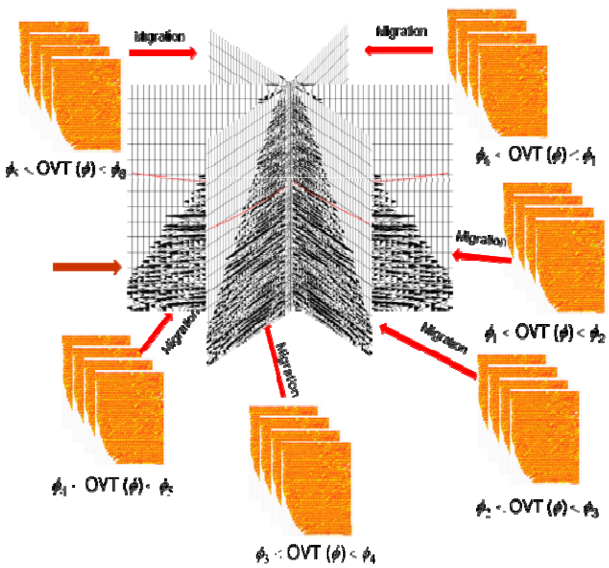

Figure 2: OVT are migrated independently to form an OMG

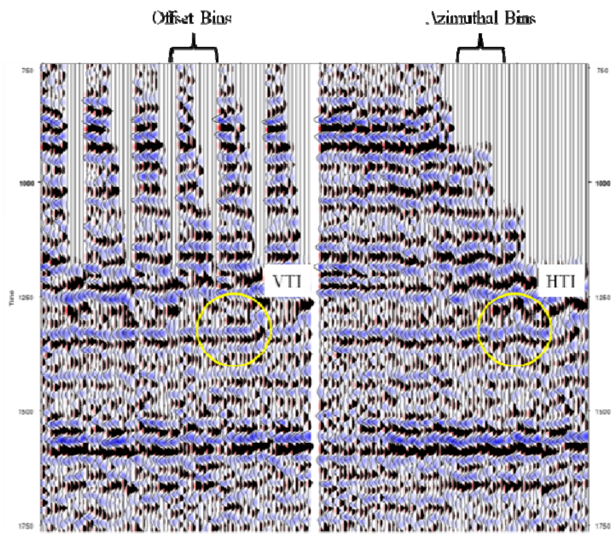

Figure 3: Offset Migrated Gathers afetr isotropic Migration

Surface Fitting for Anisotropy Parameter Extraction

The presence of these two effects, calls for a simultaneous accounting in the traveltime equation. This topic has been covered extensively in the literature (Tsvankin 1997, Jenner et al 2001, Xu and Tsvankin 2006, Roende et al 2008) so we will simply use the results and refer the reader to the original papers for the details of the formulation.

The standard formulation for the traveltime equation in an orthorhombic environment is given by:

$$T^2 = T_0^2 + 4\left(w_{11}\cos^2\alpha + 2w_{12}\cos\alpha\sin\alpha + w_{22}\sin^2\alpha\right)X^2 + F(\eta,\alpha,V^v)X^4 \quad (1)$$

Where T_0^2 is the zero offset traveltime, w_{ij} represent the matrix coefficients to be determined in an LSQ inversion, η is the VTI anisotropic parameter, α is the azimuthal angle and F(η, α, V^v) describes the higher order correction due to the orthorhombic (VTI + HTI) correction (Xu & Tsvankin 2006). After fitting the ellipsoid we obtain an expression for the horizontal velocities in terms of w_{ij}

$$V^h{}_{slow} = \sqrt{2}\left[w_{11} + w_{22} + \sqrt{(w_{11} - w_{22})^2 + 4w_{12}^2}\right]^{-\frac{1}{2}} \quad (2)$$

$$V^h{}_{fast} = \sqrt{2}\left[w_{11} + w_{22} - \sqrt{(w_{11} - w_{22})^2 + 4w_{12}^2}\right]^{-\frac{1}{2}} \quad (3)$$

For every OMG and for every sample and using eq. (1) it is possible to (surface) fit (in a least square sense) a "velocity" (or anisotropy) ellipsoid whose axes are the vertical velocity and two horizontal velocities (figure 4).

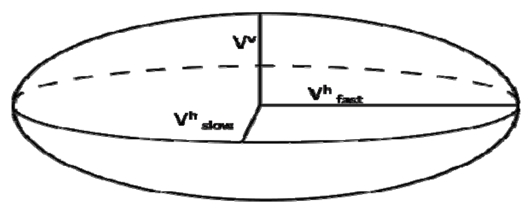

Figure 4: Velocity Ellipsoid used in orthrhombic migration

These ellipsoids vary in size and orientation, depending on the magnitude of the anisotropy and the direction of maximum propagation at every point in the survey and they account for both the VTI and the HTI effect simultaneously. .These ellipsoids form a 4D vector field of coordinates (V^v, $V^h{}_{fast}$ $V^h{}_{slow}$, Φ) called FracMaps.

Figure 5 shows a time slice from a FracMap clearly indicating the direction of the anisotropy ellipsoids. The observation that these vectors form swarms confined to thin layers has led us to interpret them as fractures.

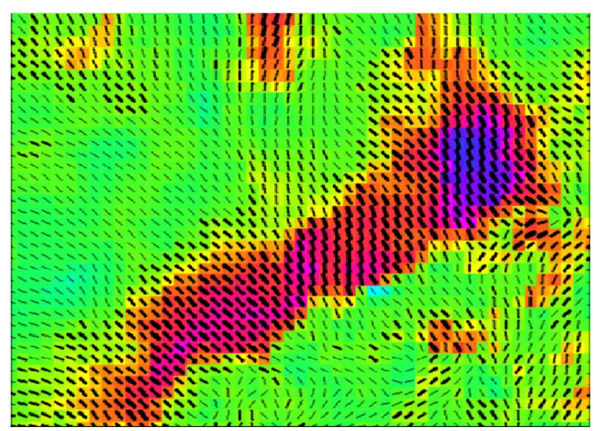
Figure 5: FracMap showing a the fast propagation direction

Orthorhombic Migrations

The surface fitting program generated a vector field of horizontal and vertical anisotropic parameters necessary to construct travel times according to eq. (1) (Tsvankin, 1997).

Before showing the results of the migration we would like to discuss the physics of the moveout equation and how the different "earth symmetries" affect the moveout of the data (figure 6).

Figure 6: Orthohrombic = VTI + HTI

VTI: Produced by the (horizontal) layering in the earth makes it a discrete set of values associated with the lithology. Unlike velocities, there is no compaction trend that produces an increase in anisotropy with depth. The compaction trend can be thought of as the low frequency component in the velocity with the high frequencies coming from the lithological and stratigraphic changes due to different materials making up the layers. Since anisotropy varies discreetly then it is can go from non-zero to zero at any interface. VTI produces the well known "hockey stick" moveout in the offset gathers. The deviation from flatness can be used to estimate the anisotropic parameter η.

HTI: Comes from the "vertical symmetry" imposed by the presence of (vertical) fractures. Waves propagating "along the grain", i.e. parallel to the fractures, will travel faster than waves propagating "against the grain" i.e. perpendicular to the fractures. This anisotropy produces a sinusoidal moveout. The shape and size of the moveout "hump" can be used to estimate three anisotropic parameters, in our case; we chose the fast and slow horizontal velocities and the direction of the fast one $(V^h_{fast}, V^h_{slow}, \Phi)$.

Orthorhombic: This symmetry arrives from the simultaneous presence of layering and fractures, i.e. VTI+HTI. The moveout produced, seen in figure 7, is a superposition of the two previously defined modes. It looks like a "hockey stick" (red) with an oscillating wave riding on top of it (yellow).

The result of using the orthorhombic migration is displayed in figure 8. On the left the isotropic migrated gathers and on the right the orthorhombic migrated ones. We have explicitly "picked" and decomposed the two degrees of freedom

Figure 8: Magnified version of a gather showing the VTI and HTI effect.

Finally, after correcting the gathers for the orthorhombic symetry, the data can be stacked to produce a final section. Note quality improvement on the stack due to the flattness (in all dimensions) of the gathers.

Figures 9 a,b show a stack section with an isotropic (a) and orthorombic(b) PSTM. Figure 9c shows the areas where the anispotrpy is large and the effect is maximal.

Figure 9a: Isotropic Migration

Figure 9b: Isotropic Migration

Figure 9c: Isotropic Migration

Layer Stripping

One particularly difficult challenge is the proper updating of the velocity field. If the waves go through a highly anisotropic fractured layer, then in order to obtain the proper velocity model we need to make sure that the effect of the shallow layers do not propagate into the deeper layers and produce an imprint.

In fact, we encountered this effect in this data as can be seen in figures below

Figure 10 shows the fracture intensity on a vertical section, derived from the first iteration of migration (no stripping). Large effects are seen in the middle section and one has to wonder if the deeper anomalies are real or an effect of the shallow one?

Figure 10: Fracture/Anisotropy indicator with no layer stripping

To answer this question we implemented a layer stripping mechanism (in the context of time migration) where the “moveout” of shallow events is removed, in an iterative fashion, from the deeper layers. The results are shown in figure 11. These indicate that some of the “fracture indicators” in the deeper section are not real but the results of shallow anomalies

Figure 11: Fracture/Anisotropy effect after layer stripping.

Conclusions

We have demonstrated how an orthorhombic prestack time migration algorithm can simultaneously account for vertical layering (VTI) and vertical fracturing (HTI) producing an orthorhombic anisotropy and non-hyperbolic moveout.

Along with this algorithm we have also introduced a methodology for deriving the necessary parameters and of using such parameters in the migration phase. This methodology requires two migrations to accomplish its task. The first one is isotropic, followed by a parameter derivation stage called surface fitting and followed by an orthorhombic migration.

The simultaneous treatment of HTI and VTI is important as was demonstrated in the body of the paper because the effect of azimuthal anisotropy comes into play before the vertical anisotropy becomes relevant.

Details have been presented that explain the mechanism for deriving the anisotropic parameter tetrad composed of a vertical velocity, two horizontal velocities and a direction of fastest propagation (V^v, V^h_{fast} V^h_{slow}, Φ)

Finally we have addressed the layer stripping conundrum. By removing the anisotropic (vertical and azimuthal) effect of shallow layers, it is possible to compute the true interval vertical and horizontal anisotropic parameters.

Acknowledgements
We would like to Geotrace for permission to publish

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