SBGf39199

Measurements of Anisotropy in West Africa

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ABSTRACT

Seismic data from West Africa shows strong evidence of the effects of seismic anisotropy. In this paper we show an estimation scheme based on the measurement of nonhyperbolic moveout. Although nonhyperbolic moveout can be caused by various effects (rapid vertical or lateral velocity variations), the smoothness of the velocity field, as well as the spatial consistency of the measurements, indicates that seismic anisotropy is the primary cause of the moveout behaviour of this dataset.

INTRODUCTION

Seismic data from West Africa has been known for some time to be significantly influenced by seismic *P*-wave anisotropy (Ball, 1995, Alkhalifah et al., 1996). This influence takes three forms:

- DMO corrections fail to properly allow simultaneous imaging of flat and dipping reflectors;
- non-hyperbolic moveout is evident at moderate offset-to-depth ratios (1);
- Significant misties (10-15%) between seismically derived velocities and well-based checkshot velocities are routinely observed.

Because of the magnitude of these effects, correction factors in DMO and depth conversion are routinely applied. More recently, based on the work of Tsvankin and Alkhalifah, the industry has turned to a more theoretically correct set of processing methods. This paper presents a case history of the application of these new methods to estimate the seismic anisotropy in offshore West Africa. The work shown here is a collaborative effort between workers in our respective companies.

In several of their papers, Tsvankin and Alkhalifah have presented a robust and reliable DMO-based estimation scheme. Their scheme derives estimates of the VTI parameters by looking at the failure of conventional DMO to correct for the effects of dip on velocity. Key to the success of that approach is the geometry of the dipping and flat beds: both should be positioned to sample the same segment of the subsurface. For some geometries, particularly where a series of relatively unfaulted, low-dip reflectors overly the region of interest for imaging or depth conversion, we must turn to another estimation procedure. In these cases, a second approach, based on the nonhyperbolic moveout equation of Tsvankin and Thomsen (1994), and then further developed by Alkhalifah (1997), becomes quite attractive.

Schemes for measuring and interpreting nonhyperbolic moveout have been around since the early days of reflection seismology. In turning to this type of approach, we recognize significant potential pitfalls: the basic measurement is both weak (fourth-order moveout, instead of the robust second-order moveout we usually face with NMO) and is subject to ambiguous interpretation (vertical or lateral heterogeneity, or anisotropy). Nonetheless for the very high quality data we find in the Tertiary section in West Africa, we can make reliable measurements of non-hyperbolic moveout, and then reliably interpret those measurements as being due to anisotropy.

MEASUREMENT OF P-WAVE ANISOTROPY: NONHYPERBOLIC SCANS

The analysis presented here consists of two main steps: 1) measure nonhyperbolic moveout through a modified semblance-scan procedure, then 2) through some form of an inversion procedure, transform those measurements into interval values. For the dataset presented here, the nonhyperbolic moveout is not a subtle effect. Nonetheless, to provide the inversion step with reliable measurements we must take care in devising the nonhyperbolic scans. In particular, we precede the two-dimensional search for zero-offset curvature ($V_{nmo}(0)$) and nonhyperbolic parameter (η) with a standard short-offset hyperbolic scan. These hyperbolic-moveout parameters serve to anchor and stabilize the nonhyperbolic analysis.

Figure 1 shows a set of these nonhyperbolic-moveout measurements (η), displayed as a color overlay on the DMO stack for a 2D line. These measurements show a general tendency to increase with time, with magnitudes ranging from 0 to .15. Although these measurements are influenced by noise, they show good consistency over this section of consistent geology.

Not only are these measurements spatially consistent, but we can clearly see the same pattern of moveout expressed on the underlying CMP gathers. Figures 2 and 3 show two different sets of CMP gathers, corrected according to three sets of moveout formulae:

- hyperbolic moveout using $V_{nmo}(0)$ (near-offset curvature).
- hyperbolic moveout using V_{stack} (best-fit hyperbola over the full range of offsets)
- nonhyperbolic moveout using $V_{nmo}(0)$ and η

The curves shown in the first two panels of each figure are the $V_{nmo}(0)$ and η values, both in measured (green) and in interval (red) forms.

As is the case with standard moveout analysis, any one of these measured values represents an average of effects from all of the overlying layers. Beginning with the CMP gather shown in Figure 2a, note the generally smooth character of the green V_{nmo} curve. Note also that the green η curve shows a significant increase from η =.08 at 2 seconds, to η =.2 at 2.5 seconds. Returning to our section view of Figure 1, we see this increase occurs across the section at this same level. The CMP gather displays of figure 2a show the cause of this strong increase: the residual moveout (after the hyperbolic corrections) increases from moderate at 2 seconds, to very large at the mid-offset range at 2.5 seconds. The nonhyperbolic corrections applied to the CMP gather shown in Figure 2 have clearly succeeded at flattening the gather for all offsets and times.

Figure 2b tells the same story of a strong increase in nonhyperbolic moveout between 2 and 2.5 seconds for a second CMP gather. This figure also shows the difference between flattening the gather at zero-offset, that is, using $V_{nmo}(0)$ in the hyperbolic corrections, and flattening the gather using a hyperbola fit over all offsets, that is using V_{stack}. This difference is particularly apparent in the strong event at 3.2 seconds: the stacking-velocity parameter, a faster velocity than $V_{nmo}(0)$, has created an overall flatter event by allowing some gentle downward curvature at zero offset to “hold the tail down” at the far offsets. This gentle downward, then upward curvature is most evident in comparison to the completely flat event shown on the nonhyperbolically corrected data.

INVERSION: DETERMINATION OF INTERVAL PROPERTIES

By feeding the moveout measurement parameters from a set of gathers to an inversion program, we can derive an estimate of the interval property that is causing the nonhyperbolic moveout. Using a 1D Dix-type inversion, based on the work of Alkhalifah, the Chevron group has derived a set of continuous 1D-interval estimates. Returning to the gathers shown in Figure 2, we now understand the meaning of the red curves: they are the interval values corresponding to the inversion of the measured η and $V_{nmo}(0)$ centered on those locations. The interval η values show the large values of anisotropy (>.15) that we expected from the moveout behavior of the CMP gathers. Note also the generally smooth character of the interval-velocity curves. Sonic logs from this area show the same smooth increase of velocity with depth.

Over the last several years, researchers at Elf have developed a 3D velocity-inversion tool, known as SuperDix, that iteratively builds a depth/interval-velocity model to explain the measured stacking velocities and zero-offset times (Robein et al., 1995). More recently, this same tool was extended to include anisotropy (Williamson et al., 1996). The inputs to the program consist of measured $V_{nmo}(0)$ and η picks (of the kind we have been describing in this paper), along with 3D time migrated maps and depth picks in wells. SuperDix iteratively models these effects through raytrace-based modeling and data fitting. At the same time, the program is evaluating what value of δ will be required to make the computed depths agree with the depths provided from the well picks.

In summary, Figure 3 shows a comparison between the two approaches. The interval values from the 1D continuous approach are taken at four locations along the line and the block-interval values are computed through SuperDix. The two approaches have found fundamentally the same character of anisotropy: low values (5%) from water bottom to 2 seconds, then increasing to 10-20% in the interval from 2 to 3 seconds. The largest differences appear to be in the 2 – 2.6 second layer, where the 1D approach is finding consistently higher η values. Overall, the 1D continuous approach finds more vertical detail and some locally extreme values, whereas the 3D-block approach smoothes through some of that detail, but provides solid average values. We are currently gaining more experience with both approaches, in particular developing an understanding of how to reliably make the necessary tradeoffs between accuracy and resolution.

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ACKNOWLEDGMENTS

The authors thank Elf Exploration Production, Elf Exploration UK and Chevron Overseas Petroleum for permission to present this paper. This work was first presented at the Eighth International Workshop on Seismic Anisotropy, and has been included in an upcoming article in the May 1999 issue of The Leading Edge.

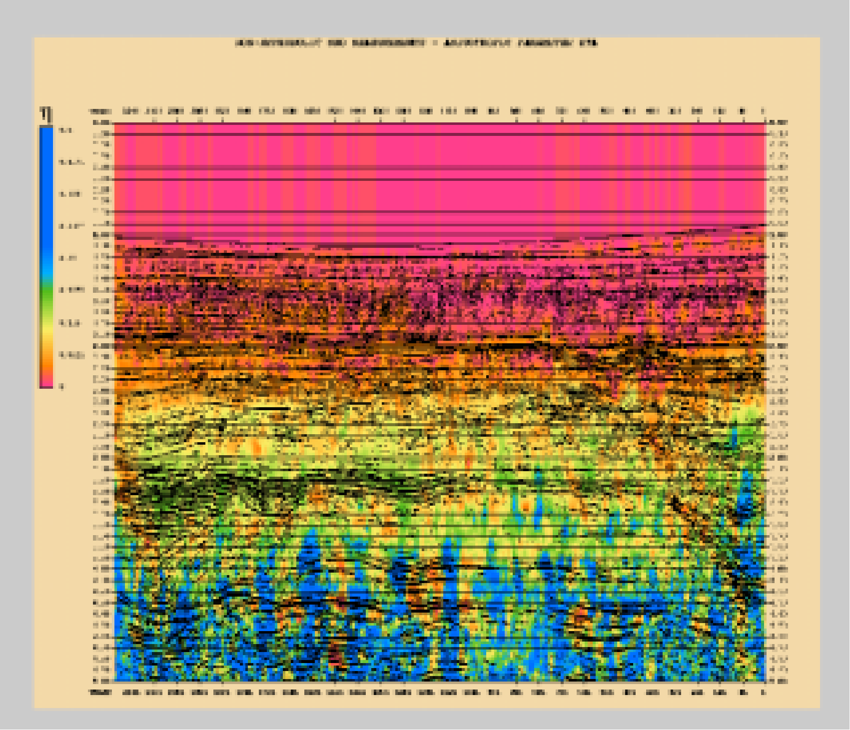

Figure 1: Nonhyperbolic moveout measurements displayed as a color overlay on the DMO stack for a 2D line.

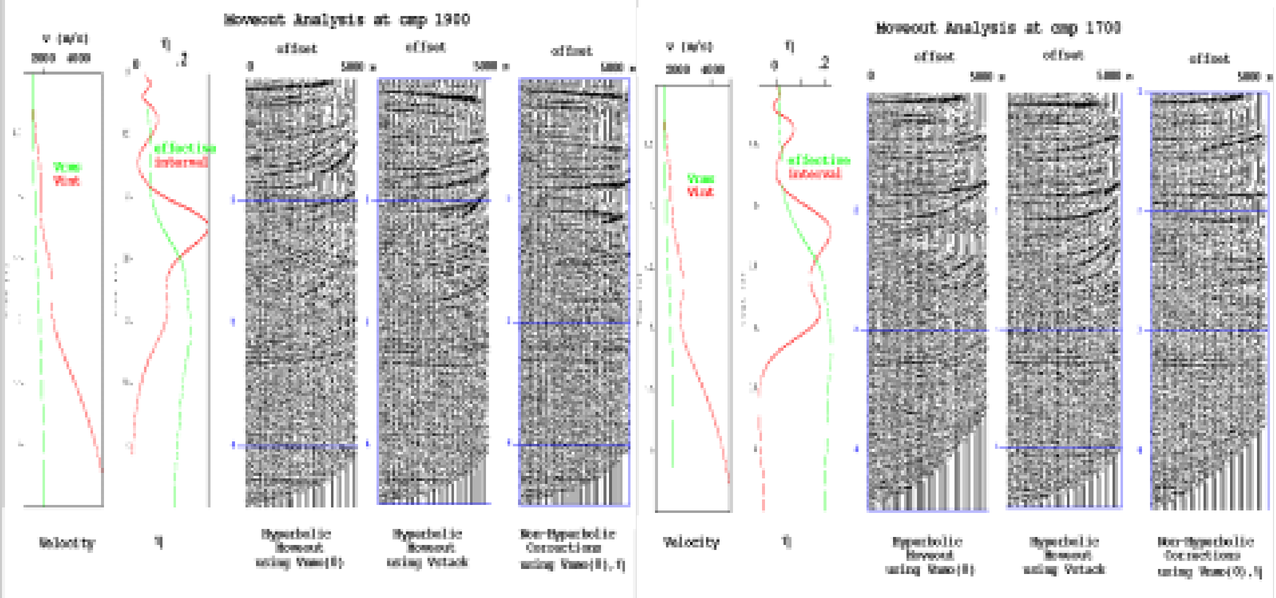

Figure 2: Moveout analysis at (a) cmp 1900 and (b) cmp 1700

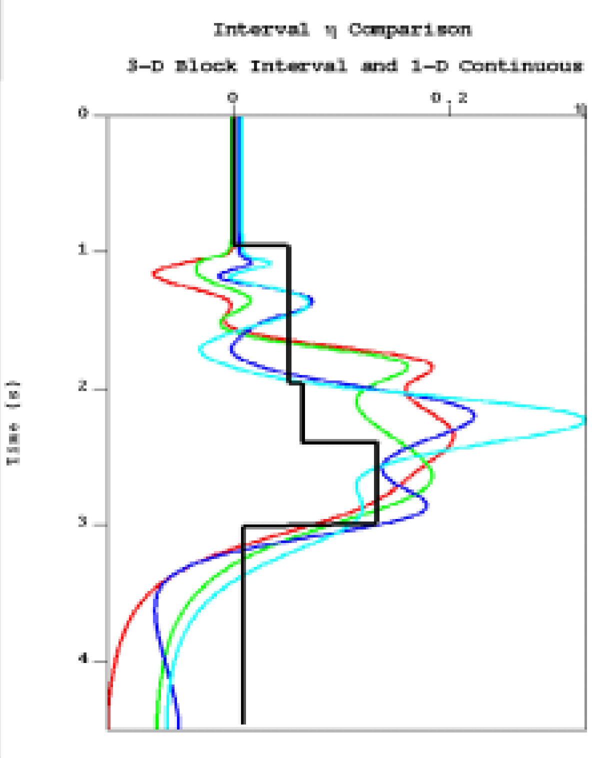

Figure 3: Comparison between interval anisotropy (η) derived through the 3-D block interval and 1-D continuous approaches.