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Interval anisotropic parameters estimation in a least squares sense – Case histories from West Africa

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Summary

In this study we describe a different approach from the unconstrained Dix transform to convert the effective anisotropic parameters V_{nmo} and η_{eff} coming from the nonhyperbolic velocity analysis, into interval ones. The method is designed for building and refining the velocity models for the Anisotropic PSDM (PreStack Depth Migration). The objective of this algorithm (based on a new Eni proprietary approach) is to prevent the nonrealistic and highly oscillating interval velocity and anellipticity η_{int} parameter, which can be easily obtained with Dix inversion from relatively small variations in the stacking or effective values. The resulting model can be considered geologically reasonable and more stable, using a combination of constraints and analytical trend.

The work has been completed evaluating the benefits and improvements by taking anisotropy into account, applying the methodology to a real field dataset.

Introduction

The methodology proposed in this paper leads to a stable and geologically plausible anisotropic model for imaging procedure. The objective of this study is to obtain the best anisotropic parameters estimation as input for the PSDM in order to improve the imaging in terms of better focusing and structural positioning.

The algorithm seeks to create no-oscillatory instantaneous velocity and anisotropic parameter η_{int} from conventional estimates.

The main idea is to find a constrained model that best fits the effective NMO velocities and η_{eff} in a least-squares sense, considering some internal constraints that aim to overcome the uncertainties and not realistic parameters obtainable from conventional Dix inversion, Toldi (1989). In fact small variations in the stacking velocities and η_{eff} can easily produce unstable parameters.

The method can be applied to create a new model which can be refined by more advanced methods, such as anisotropic depth tomography.

The reconstruction of the interval values of anisotropic parameters from the effective ones is done by a numerical inversion, based on conjugate-gradient method, respecting the forward Dix equations and exploiting geological information of the examined area. This represents a new Eni approach for the anisotropy evaluation in the PSDM velocity model building. In this way we can generate instantaneous velocity and interval η_{int} with more geological sense, honoring the stacking estimates.

The methodology is applicable on 2D and 3D seismic data. In the 2D case the estimation of seismic anisotropy is done on CMP (Common Mid Point) time-gathers from the nonhyperbolic moveout described by two parameters, the normal moveout velocity (V_{nmo}) responsible for short-offset propagation and the anisotropic parameter η_{eff} responsible for long-offset propagation.

In the 3D case, the anisotropic parameters can be obtained from the azimuthal variation of P-wave normal moveout velocity, as suggested by Grechka and Tsvankin (1999).

The estimation of effective values is not treated in this paper, because the analysis has already been extensively studied in literature.



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The study has been focused on the inverted interval parameters, which should not only match the given effective estimates, but also the trend of the geological model.

The methodology has been applied on 2 different areas in off shore West Africa.

Constrained anisotropic analysis

The methodology is based on the use of the normal moveout velocity and the effective anisotropic parameter η_{eff} estimated for the CMP time gathers.

Considering the 2D case, the anisotropic effective parameters are obtained using a two-dimensional semblance, which describes a non-hyperbolic summation trajectory. The objective is to improve the flattening of the time gathers after the Normal Move Out (NMO) procedure and to reconstruct the interval values for the Anisotropic PSDM, in order to get the best result in terms of seismic imaging. Differently from the 2D case, the 3D case includes another methodology for the estimation of effective anisotropic parameters and different equation for the Dix forward.

For the VTI (Vertical Transverse Isotropy) media the relation between effective and interval values are described by the Dix forward equations 1 and 2, T. Alkhalifah (1997), where the variable V_{nmo} corresponds to interval velocity value and the integration is over time for the vertical raypath. $\eta_{\text{int}}(\tau)$ is the instantaneous value of the anisotropy parameter η_{eff} as a function of the vertical reflection time.

$$V_{\text{nmo}}^2(t_0) = \frac{1}{t_0} \int_0^{t_0} v_{\text{nmo}}^2(\tau) d\tau \quad (1)$$

$$\eta_{\text{eff}}(t_0) = \frac{1}{8} \left\{ \frac{1}{t_0 V_{\text{nmo}}^4(t_0)} \int_0^{t_0} v_{\text{nmo}}^4(\tau) [1 + 8\eta_{\text{int}}(\tau)] d\tau - 1 \right\} \quad (2)$$

The inversion is done individually for each vertical function and the main scope of the minimization problem is to find a constrained interval model that matches the stacking profiles. The cost function includes the NMO velocity and effective η_{eff} misfit and a priori information about the model. The algorithm seeks to directly maximize

the objective function, matching also the trend of the geological model. The a priori information is easily incorporated into the inversion through an additional constraint; in this case we considered the interpreted time horizons. It is a different approach from the standard unconstrained Dix inversion that can produce highly oscillating values, even for small variations in the vertical profiles.

For each layer it is assumed an interval velocity varying linearly (gradient) and a constant parameter η_{eff} , permitting lateral variation through the investigated section. This choice is convenient for a PSDM study, but it is possible to approximate the instantaneous values (V_{nmo} , η_{int}) with any vertical functions, such as exponential, quadratic, cubic, etc. The model can be subsequently refined by other advanced methods, according to the scope of work.

Real data example

Case History 1

The methodology has been performed on a 3D seismic dataset about 200 km from the coast. In an Ultra Deep Water exploration block, with water depth ranging from 2000 to over 3000 m, some shallow layers have been investigated. The scope of the work was the estimation of the seismic anisotropy in these layers, around the well location, evaluating the benefits and improvements on the Pre-Stack Depth Migration.

Initially, the estimation of the effective anisotropic parameters was computed for the CMP-gather near the well location, from the non-hyperbolic moveout, using a two-dimensional semblance. For this area we considered a transversely isotropic medium with vertical symmetry axis (VTI). In Figure 1 the vertical profiles for isotropic and anisotropic V_{nmo} and the anellipticity parameter η_{eff} extracted from the estimation are displayed in a 3D plot. In Figure 2, some hockey-sticks can be identified after the isotropic NMO, typical behavior of seismic anisotropy presence.

Taking into account the anisotropy, we can observe on the right the correct flattening of the time gather after the Normal Move Out procedure.



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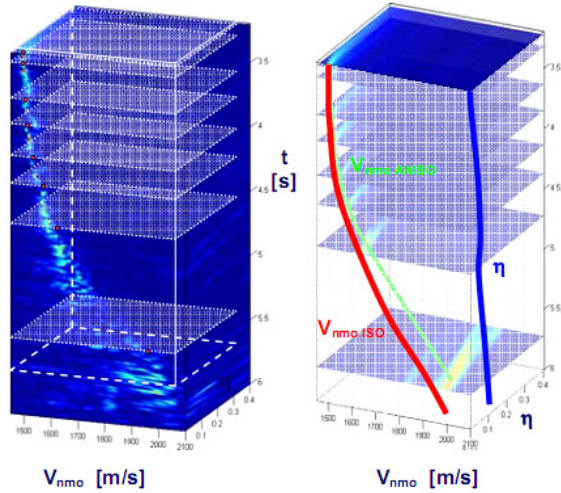


Figure 1: Semblance cube - Anisotropy estimation procedure for a CMP time gather. RED - Isotropy NMO Velocity. GREEN ANIsotropic NMO Velocity. BLUE – Eta.

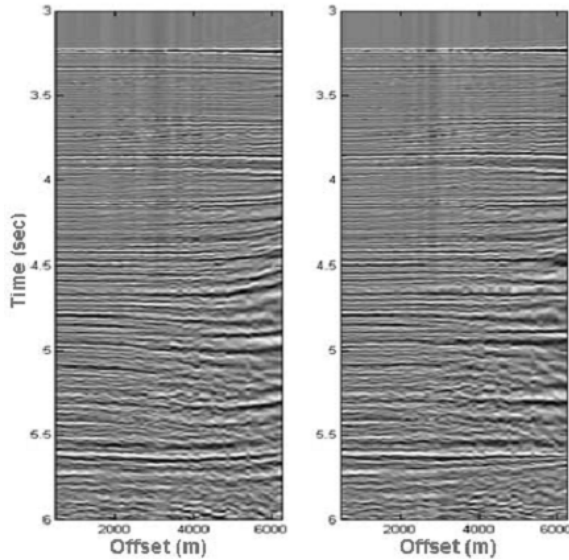


Figure 2: Isotropic and Anisotropic CMP time-gather with NMO applied. The CMP location is near the well location

The effective values are converted to interval ones with the proposed approach, different from conventional Dix layer stripping procedure. Instead of applying the Dix equation, the reconstruction of the instantaneous values is done with a numerical inversion, based on conjugate-gradient method, respecting the estimated stacking values and exploiting the information of the interpreted time horizons. In Figure 3 an example of this inversion is shown for the CMP time gather near the well location. On the left, the interval NMO velocity (green), the estimated effective NMO velocity (blue) and the NMO velocity reconstructed by the inversion (pink) are displayed. On the right, the same for the anisotropic parameter η .

A good match between the estimated and reconstructed values (blue and pink curves in the figure) can be observed, denoting the quality of the results.

The procedure has been applied for the entire section crossing the well, in order to observe the lateral variation of the estimated parameters, as we can see in Figure 4. The interpreted time horizons are displayed on this section. For evaluations and observations regarding the hockey sticks presence and comparison between isotropic and anisotropic normal moveout velocity, the anisotropy was considered between the horizons *Hor 2* and *Hor 4*. The non-hyperbolic moveout was not taking into account in the zone below the *Hor 4* for the lack of long offset in the pre-stack data. In fact the estimation of seismic anisotropy becomes less stable when the X/D ratio is less than about 1.3, where X is the maximum offset of geometry acquisition and D the approximate depth of the horizon.



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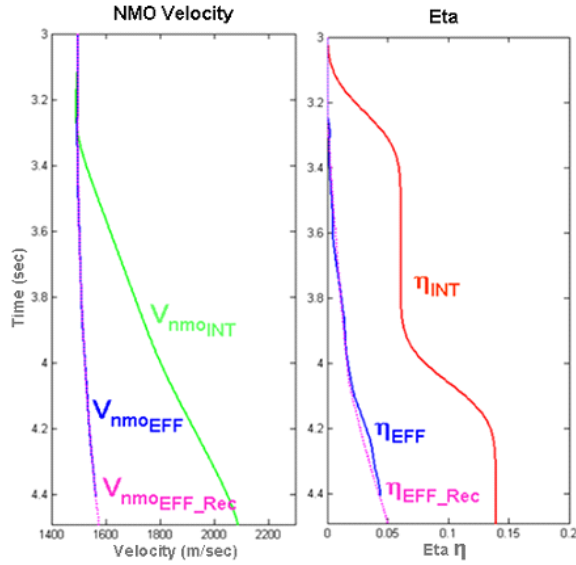


Figure 3: Interval estimated values for the CMP time gather near the well location and reconstructed effective parameters with the inversion.

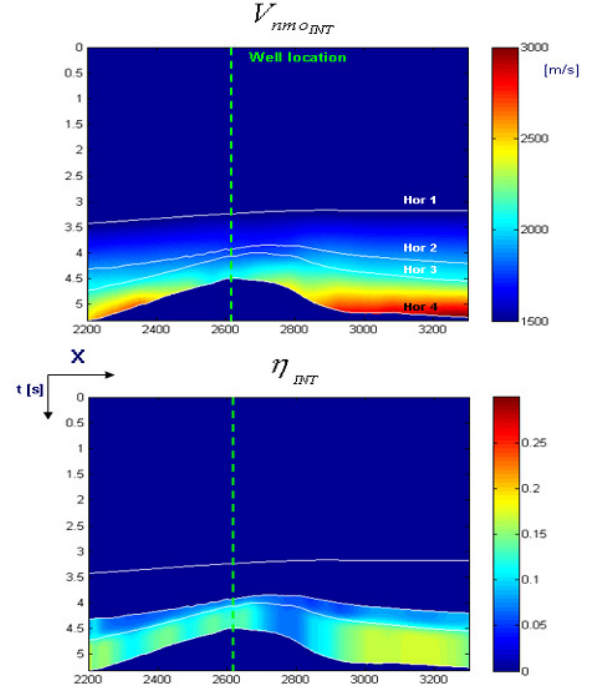


Figure 4: Interval V_{nmo} and η_{int} obtained with the constrained inversion, for the section crossing the well location.

The next step of the anisotropy analysis is the determination of the two Thomsen's dimensionless anisotropic parameter ϵ and δ , starting from the previous interval parameters V_{nmo} and η_{int} .

The parameter δ is indicative of the velocity variation near the symmetry axis direction, while the parameter ϵ is indicative of the difference between the vertical and horizontal propagation velocity. The parameter η , whose departure from zero indicates anisotropy, and the normal moveout velocity are related to the Thomsen's parameters, as described in the equations 3 and 4 (Alkhalifah, 1997), valid for VTI media:



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$$\eta = \frac{\varepsilon - \delta}{1 + 2\delta} \quad (3)$$

$$v_{nmo} = V_{p0} \sqrt{1 + 2\delta} \quad (4)$$

where V_{p0} is the P-wave vertical velocity.

Using these relationships and the information coming from the sonic log of the well, we obtained the best values of ε and δ through the section, adopting an inversion procedure similar to the previous one used for the interval parameters V_{nmo} and η_{int} . We completed the study with the estimation of the anisotropic parameters in the area around the well location, observing the 3D variation and the effect of the geological structure on the results.

Ignoring the outlier values, especially in the more complex zones, such as faults or strong dips, we got a trend along the line smoothing the values of ε and δ , in order to describe the anisotropy in the investigated layers.

After the evaluation of the instantaneous values in the survey area, the 3D volumes for ε and δ were generated and the anisotropic VTI Pre-Stack Depth Migration was

performed. In order to evaluate the benefits and improvements gained by taking anisotropy into account, we compared the Isotropic and Anisotropic Migration, respectively in Figure 5 and Figure 6, in terms of Depth Migrated Stack section, semblance and CRP gathers.

As regards the isotropic case, we forced to Zero the anisotropic parameters ε and δ , while in the anisotropic case we used the constrained inversion results.

Two different positions have been considered to study the effect near and far from the well location, where the thickness of the sediments is different.

Comparing the Isotropic and Anisotropic Pre-Stack Depth Migration, we can observe that the introduction of anisotropy improves the imaging in terms of better focusing in stack depth section.

The events in depth domain (CRP gathers) are correctly flattened and the semblance is properly aligned to the zero reference line, indicative of the quality for the adopted velocity model.

The benefits are visible both near and far from the well location.

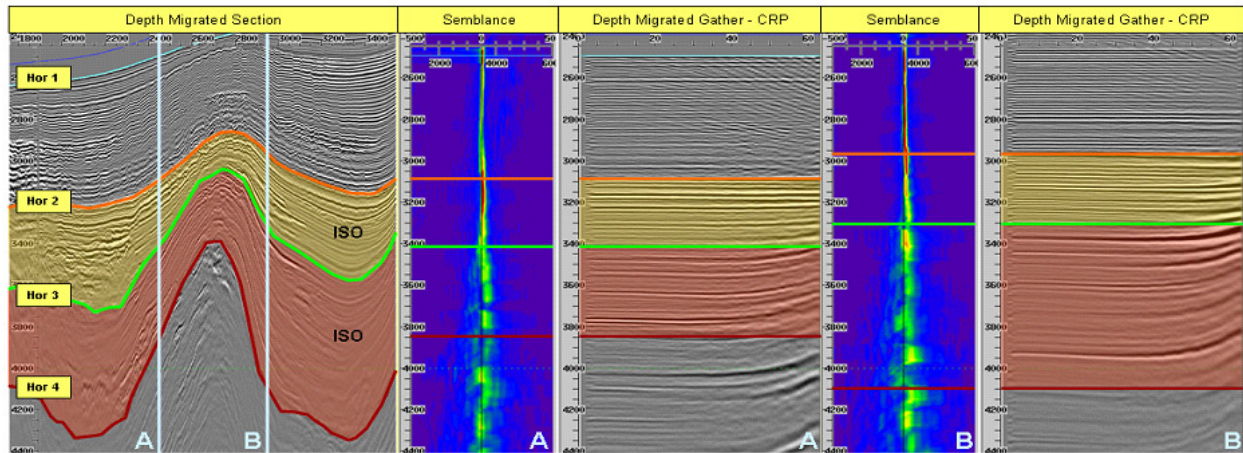


Figure 5: Isotropic PSDM – Depth Migrated Section near (A) and far (B) from the well location, Semblance and CRP gather



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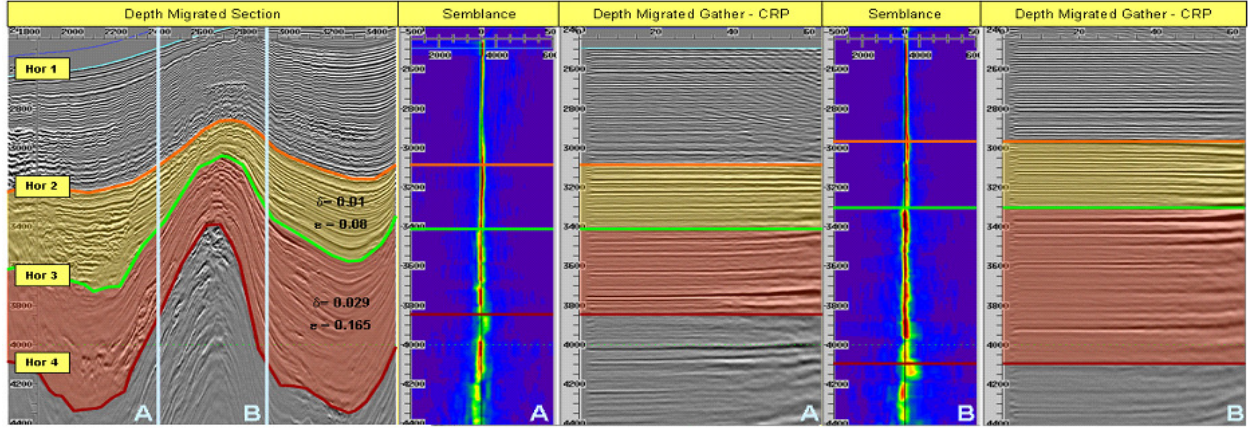


Figure 6: Anisotropic PSDM – Depth Migrated Section near (A) and far (B) from the well location, Semblance and CRP gather

Case History 2

For the Case History 2 the same methodology described before has been applied on layers where the presence of VTI anisotropy, due to the presence of thin layered shales is a hypothesis quite probable. The anisotropy has been estimated in a deep water area (Sea Bottom at about 25003000 m) in the 2 shallower layers: Sea Bottom – Horizon 300 until 4500m and Horizon 300 – Horizon 500 until 5500 m. In Figure 7, a set of 5 CMPs time gathers is showed with Isotropic and ANisotropic NMO applied using vertical profile of Isotropic or Anisotropic normal moveout velocity.

The effective values (in Figure 8 the V_{nmo} and η sections are showed) are converted to interval ones with a new approach (Ferla M., 2009), different from the conventional interval DIX layer stripping procedure. Instead of applying the DIX equation, we obtained the section of V_{nmo_INT} and η_{INT} with a numerical inversion, based on conjugate-gradient method, which reconstructs the best interval anisotropic parameters in every layer, respecting the previous estimated effective values and exploiting the information of the time interpreted horizons.

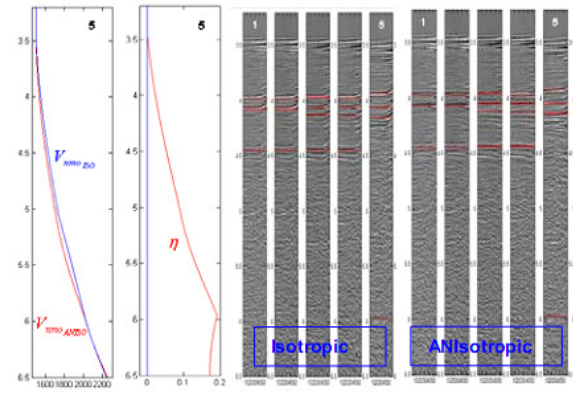


Figure 7: Isotropic NMO and Anisotropic NMO with the estimated effective values of V_{nmo} and η on 1 of 5 CMPs time-gathers with Isotropic (on the left) and ANisotropic (on the right) NMO applied.

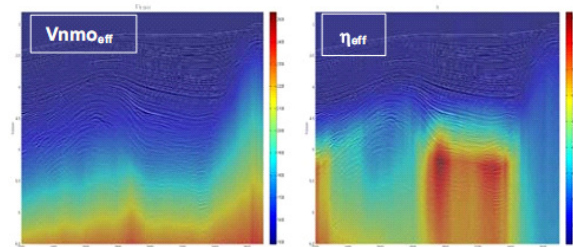


Figure 8: Effective V_{nmo} and η sections



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For the anisotropic parameter η , we assumed a constant vertical value in every layer, but permitting lateral variation through the section. While for the anisotropic parameter V_{nmo} we assumed a linear variable velocity (gradient velocity).

On the bases of the Anisotropic Semblance Coherence section (Figure 9) the Interval Velocity and Eta section are inverted applying the least square method and compared with the section obtained by Dix (Figure 10).

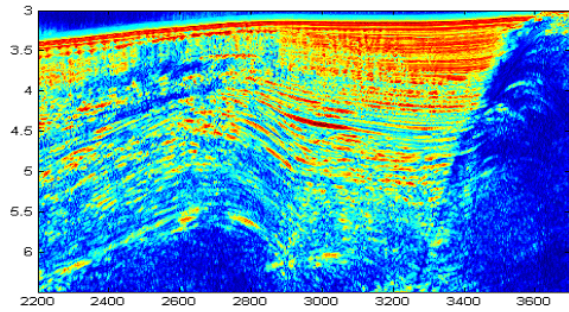


Figure 9: Anisotropic Semblance Coherence section

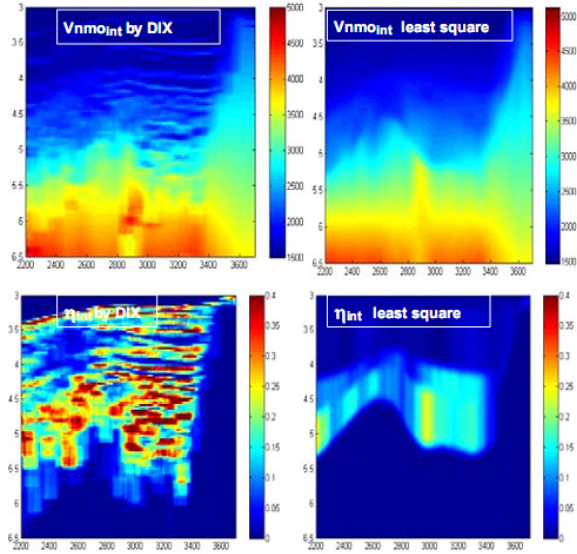


Figure 10: Interval Vnmo and Eta computed by DIX (on the left) and with the proposed methodology based on least square technique (on the right)

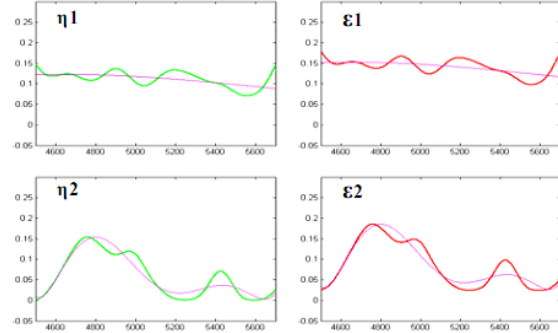


Figure 11: Eta and Epsilon profiles along the line for the 2 layers. The magenta lines are the smoothed versions.

The next step of the anisotropy estimation procedure is to determine the two Thomsen's dimensionless anisotropic parameter epsilon ϵ and δ , starting from the previous interval parameters V_{nmo} and η .

Using the Thomsen's relation of η , we obtained the section of ϵ for the 2 layers along the line here showed in Figure 11. Parameter δ has been considered constant through the section because it was difficult to get more detailed trend when the only available well is outside the area. Its value was set equal 0.024.

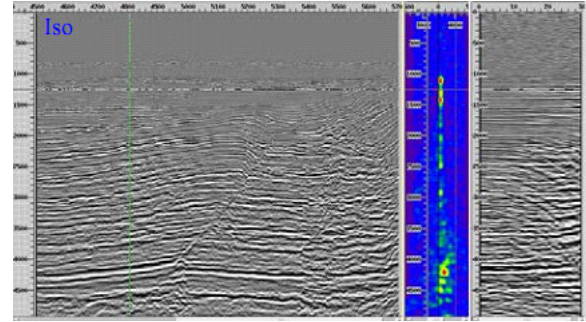


Figure 12a: Isotropic PSDM section with semblance panel and a CRP gather



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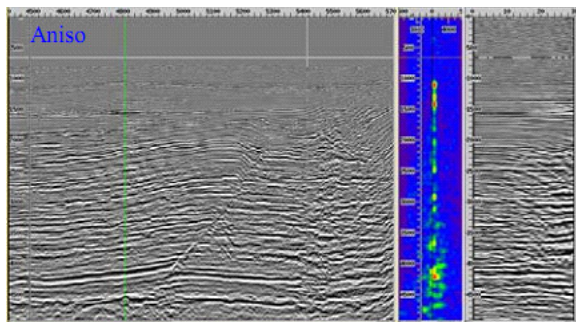


Figure 12b: ANIsotropic PSDM section with semblance panel and a CRP gather

Parameters ε and δ were then used to perform the Anisotropic Pre Stack Depth Migration and the result is compared with the Isotropic migration in Figure 12.

In the Anisotropic results the events in the CRP gathers are better aligned, semblance panels more focalized along the 0 delay line, given better imaged depth sections.

Conclusions

This paper describes a new methodology to convert the effective anisotropic values V_{nmo} and η_{eff} into interval ones. This represents a new Eni approach for the Anisotropic PSDM velocity model building. The objective of this algorithm is to prevent the nonrealistic and highly oscillating interval velocity and anellipticity η_{int} parameter, which can be easily obtained with the conventional unconstrained Dix inversion from relatively small variations in the stacking or effective values.

This approach reconstructs the interval values from the effective ones in a least-squares sense, based on conjugate gradient method, generating instantaneous velocity and interval η_{int} with geological sense and honoring the stacking estimates.

The methodology proposed in this paper leads to a stable and geologically plausible anisotropic model for PSDM procedure. The benefits and improvements are visible in both the real case histories presented, in terms of focusing and better imaging, indicative of the consistency of the results obtained with the inversion based on least square method.

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