RAY-BASED 2D ANISOTROPIC PRE-STACK DEPTH MIGRATION ON SYNTHETIC AND REAL DATA

J. MISPEL

Elf Geoscience Research Centre[1]
Imperial College[2]

P. WILLIAMSON

Elf Geoscience Research Centre[1]

P. BERTHET

Elf Exploration Production[3]

MIGRATION PROFONDEUR AVANT SOMMATION ANISOTROPE EN 2D BASÉE SUR LE TRACÉ DES RAYONS. ÉTUDE SUR DES DONNÉES SYNTHÉTIQUES ET RÉELLES

La migration profondeur avant sommation (PSDM), bien que coûteuse, est un outil puissant d'imagerie et d'analyse de vitesse. On pense maintenant que l'anisotropie de la vitesse sismique est largement répandue dans les roches sédimentaires, et plus particulièrement dans les argiles. Nous avons écrit un code de migration profondeur avant sommation en 2D à des fins d'utilisation dans les milieux à isotropie plane avec un axe de symétrie vertical (TIV). Nous l'utilisons afin d'étudier les effets de l'anisotropie sur la migration isotrope avant sommation au moyen d'un exemple synthétique simple. Les résultats suggèrent qu'il est difficile de trouver des modèles isotropes plausibles qui donnent des images correctes des réflecteurs sur tous les pendages. Nous appliquons en plus notre code PSDM à un profil en 2D de données réelles provenant d'un champ offshore d'Afrique occidentale, où il y a une épaisse série argileuse, en utilisant des modèles de vitesse anisotropes et isotropes. Un plan de faille incliné est mis en images plus clairement avec le modèle anisotrope, mais certains miroirs presque horizontaux sont moins bien représentés, suggérant par là que ce modèle pourrait être amélioré et confirmant la sensibilité de la migration profondeur avant sommation à tous les aspects du modèle de vitesse.

RAY-BASED 2D ANISOTROPIC PRE-STACK DEPTH MIGRATION ON SYNTHETIC AND REAL DATA

Pre-stack depth migration (PSDM), while costly, is a powerful tool for imaging and velocity analysis. Seismic velocity anisotropy is now thought to be widespread in sedimentary rocks, particularly shales. We have written a 2D pre-stack depth migration code for use in transversely isotropic media with a vertical symmetry axis (TIV). We use it to investigate the effects of anisotropy on isotropic pre-stack migration by means of a simple synthetic example. Results suggest that it is difficult to find plausible isotropic models which give good images of reflectors at all dips. We further apply our PSDM code to a 2D line of real data from offshore West Africa, where there is a thick shale sequence, using isotropic and anisotropic velocity models. A dipping fault plane is imaged more clearly with the anisotropic model, but some of the near horizontal reflectors are less well imaged suggesting that this model could be improved and confirming the sensitivity of pre-stack depth migration to all aspects of the velocity model.

(1) Department of Geology,
Prince Consort Rd.,
London SW7 2BP - United Kingdom

(2) 30 Buckingham Gate,
London SW1E 6NN - United Kingdom

(3) CSTJF,
Avenue Larribau,
64018 Pau Cedex - France

MIGRACIÓN EN PROFUNDIDAD
DE PRE-ACUMULACIONES ANISOTRÓPICAS
BIDIMENSIONALES EN BASE A RAYOS
CON DATOS SINTÉTICOS Y REALES

La migración en profundidad pre-acumulativa (PSDM), a pesar de su costo, constituye una poderosa herramienta para la obtención de imágenes y para el análisis de velocidad. La anisotropía de velocidad sísmica es considerada actualmente muy frecuente en rocas sedimentarias, y en particular en esquistos. Hemos escrito un código de desplazamiento en profundidad pre-acumulativo bidimensional para utilizarlo en medios transversalmente isotrópicos con un eje de simetría vertical (TIV). Habitualmente, investigábamos los efectos de la anisotropía sobre la migración isotrópica pre-acumulativa mediante un ejemplo sintético simple. Los resultados sugieren que resulta difícil encontrar modelos isotrópicos plausibles que proporcionen buenas imágenes de reflectores con cualquier buzamiento. Aplicamos entonces nuestro código PSDM a una línea bidimensional de datos reales obtenidos frente a la costa de Africa Occidental, donde existe una gruesa secuencia de esquistos, utilizando modelos de velocidad isotrópicos y anisotrópicos. Un plano de falla inclinado es más claramente representado en imágenes con el modelo anisotrópico, pero algunos reflectores cercanos a la horizontal proporcionan imágenes menos claras, sugiriendo que este modelo puede mejorarse y confirmando la sensibilidad del desplazamiento en profundidad pre-acumulativo a todos los aspectos del modelo de velocidad.

INTRODUCTION

Pre-stack depth migration (PSDM) is a very powerful seismic imaging tool. In regions of seismic velocity complexity the alignment of energy from different offsets or shot records which has come from the same reflection point allows optimal stacking, assuming a good approximation to the real velocity field has been obtained. Converse PSDM is very sensitive to the accuracy of the input velocity model due to the requirement that a given reflection event appears in the same position in all the pre-stack migrated images, i.e., that common image gathers (CIGs) be flat. PSDM is therefore also a powerful tool for refining and/or validating velocity models in depth when other methods have proved inadequate. Anisotropy is one aspect of velocity complexity which has so far been relatively neglected in this context (see Dong and McMechan, 1993; Ball, 1995; Kosloff, pers. comm. 1997). Although workers at the *Center for Wave Phenomena* at the CSM have demonstrated methods for parameter estimation in layered media (e.g., Alkhalifah and Tsvankin, 1995) and recent work has extended this for mild lateral variations (Grechka and Tsvankin, 1998), these methods work mainly within the time domain.

In this paper we present a 2D Kirchhoff-type PSDM code for imaging in anisotropic background models which are transversely isotropic with a vertical symmetry axis (TIV). We illustrate the impact of anisotropy on PSDM by considering various isotropic migrations of a synthetic reflection profile from a model containing a TIV layer with a range of dips. Next we apply our 2D PSDM to a real data case study from offshore Africa, using isotropic and anisotropic background models, built with a method based on inversion of stacking velocities described in Williamson *et al.* (1996). Finally we discuss our results and attempt to draw some conclusions.

1 METHOD

In common with most pre-stack methods, our migration is Kirchhoff-type. Amplitudes and traveltimes for the Green's functions are calculated by a dynamic ray-tracing algorithm which uses the wavefront construction (WFC) ideas of Vinje *et al.* (1993). These ideas allow us to trace rays so as to cover a smoothly heterogeneous region completely and efficiently, thus avoiding explicit two-point ray-tracing; it also calculates multiple arrivals, so that, e.g., the most energetic arrival can be selected for migration. Lambare *et al.* (1996) improved the method by intro-ducing a better sampling criterion, based on paraxial ray theory, so that the ray field samples phase space more uniformly, even in the vicinity of caustics. We have extended their code by changing the isotropic dynamic ray-tracing kernel to allow for TIV media. This gives us a tool for computing traveltimes and amplitudes of *qP* arrivals efficiently in smoothly heterogeneous TIV media. The calculated information is then passed to the pre-stack migration; the migration itself works on common offset data sections.

When the structure is not too complex we typically obtain the background velocity models for the migration using the stacking velocity inversion method described in Williamson *et al.* (1996, 1997). This builds a layered model from interpreted interfaces by map demigration and migration, and seeks interval parameters which optimise the fit between modeled and observed data. In general, stacking velocities are insufficient to specify even a TIV anisotropic model, so additional data such as well seismic traveltimes and well marker depths may be used in the inversion. Alternatively, as in the case described here, stacking velocities may be replaced by NMO velocities and the parameter, η, which can be obtained by non-hyperbolic moveout analysis (Alkhalifah and Tsvankin, 1995). Parameters may also be constrained directly to reflect a priori information from cores, logs or other local studies.

2 SYNTHETIC DATA EXPERIMENT

In order to test the migration and investigate the effects of anisotropy we created a synthetic dataset using the Atrak ray-tracing software written by M. Kendall of *Leeds University*. The model, shown in Figure 1a, contains three reflecting interfaces; all of the layers are homogeneous; the third layer is TIV with anisotropy parameters $\varepsilon = 0.20$, $\delta = 0.05$ (Thomsen, 1986), but the other layers are isotropic. We expected that the range of dips (from sub-horizontal up to 38 degrees) in the third reflector would clearly demonstrate the effects of the anisotropy. Shots were located every 25 m between $X = 4$ km and $X = 11$ km; the receiver spread was from 0 m to 4000 m offset, also at 25 m intervals, in the direction of decreasing X. Only *qP-qP* arrivals were modeled. The zero-offset section is shown in Figure 1b.

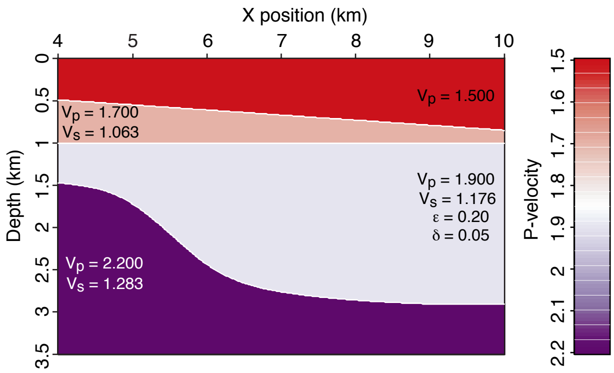

Figure 1a

Velocity model used to generate the synthetic dataset. The maximum dip of the curved interface below the anisotropic layer is 38°.

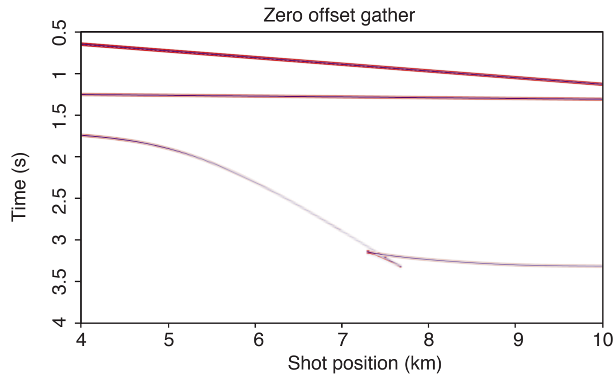

Figure 1b

Synthetic *qP-qP* reflection seismogram generated by ray tracing through the velocity model of Figure 1a.

Figures 2a, 2b and 3a, 3b show results from two migrations with homogeneous isotropic velocities in the third layer, chosen to optimally flatten the CIGs at $X = 5.5$ km and $X = 9.0$ km, respectively. These posi-tions were chosen to sample both the sub-horizontal and dipping portions of the third reflector. The difference in these velocities is similar to that predicted by the “abnormal DMO” factor for NMO velocities in Tsvankin (1995). It is sufficient to produce significant curvature in the respective “other” CIGs, so that the corresponding part of the stacked image is poorly focussed. In both cases the depth of the third reflector is significantly too large. We note also that even in the

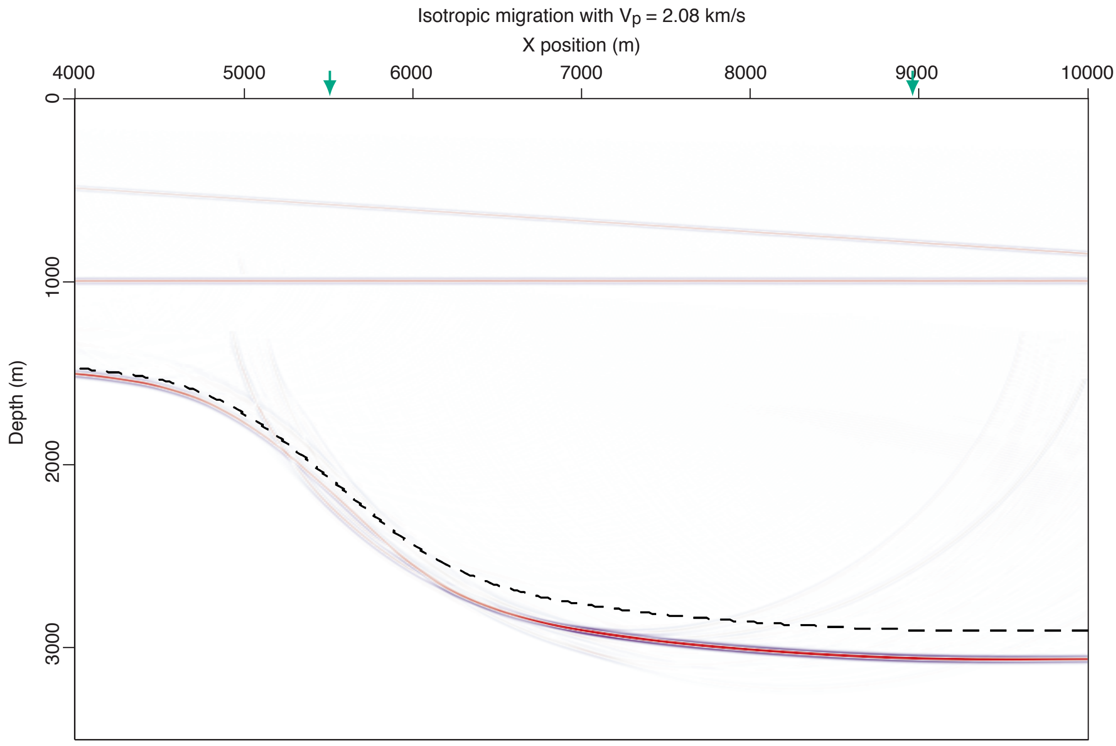

Figure 2a

Stacked image after isotropic PSDM using V_p = 2.080 km/s in the third layer. The dashed black line indicates the true position of the third interface. The arrows mark the position of the CIGs shown in Figure 2b.

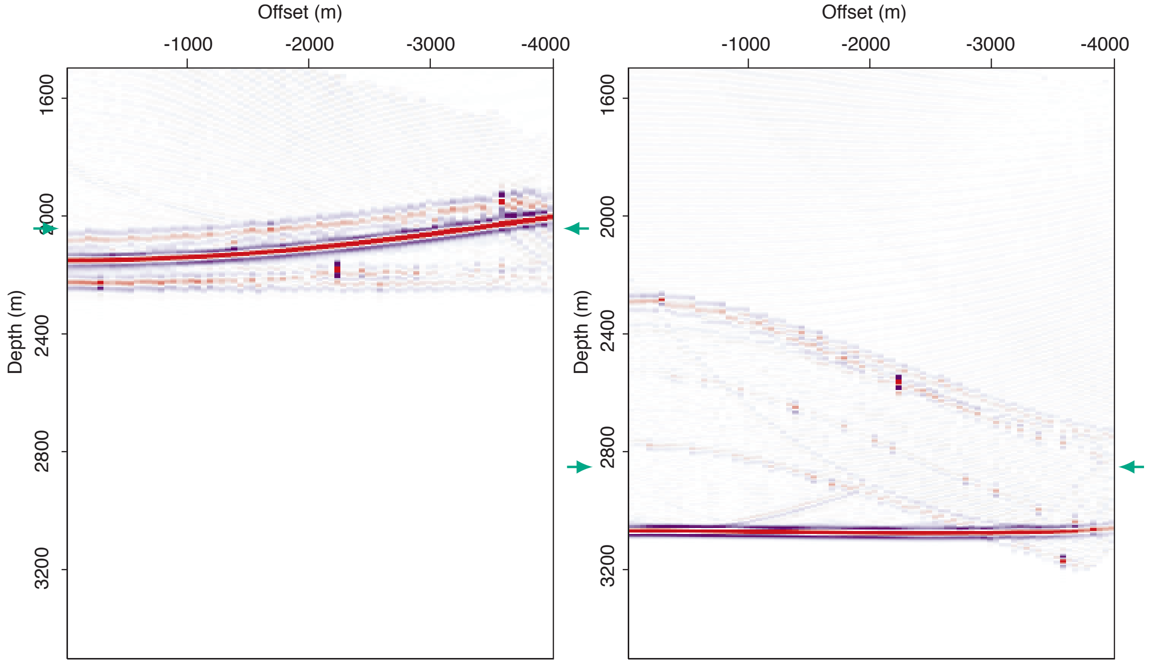

Figure 2b

Common image gathers at X positions 5.5 km and 9.0 km for the isotropic migration of Figure 2a. The arrows indicate the depth of the third interface at the selected X positions.

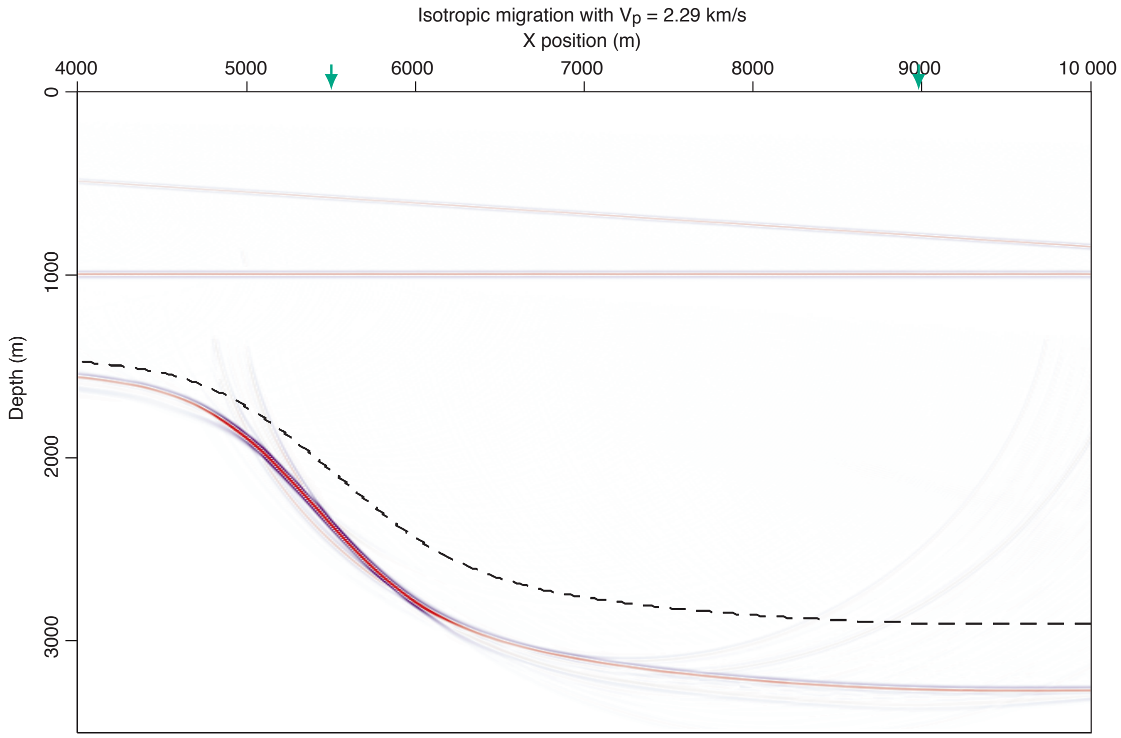

Figure 3a

Stacked image after isotropic PSDM using V_p = 2.290 km/s in the third layer.

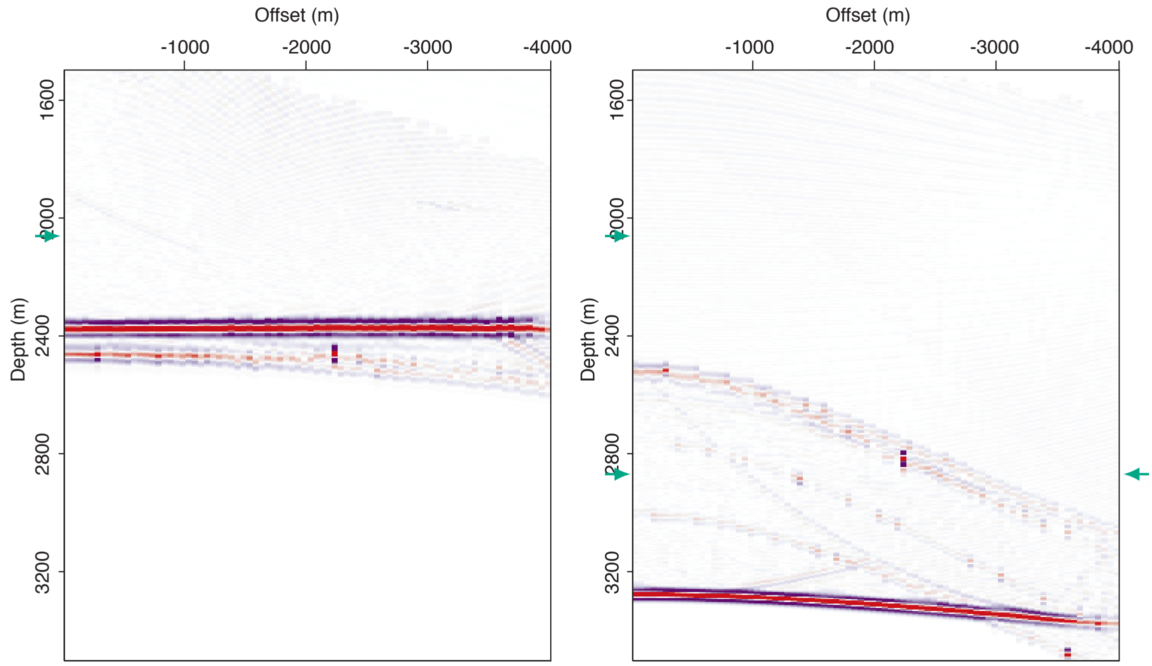

Figure 3b

Common image gathers at *X* positions 5.5 km and 9.0 km for the isotropic migration of Figure 3a.

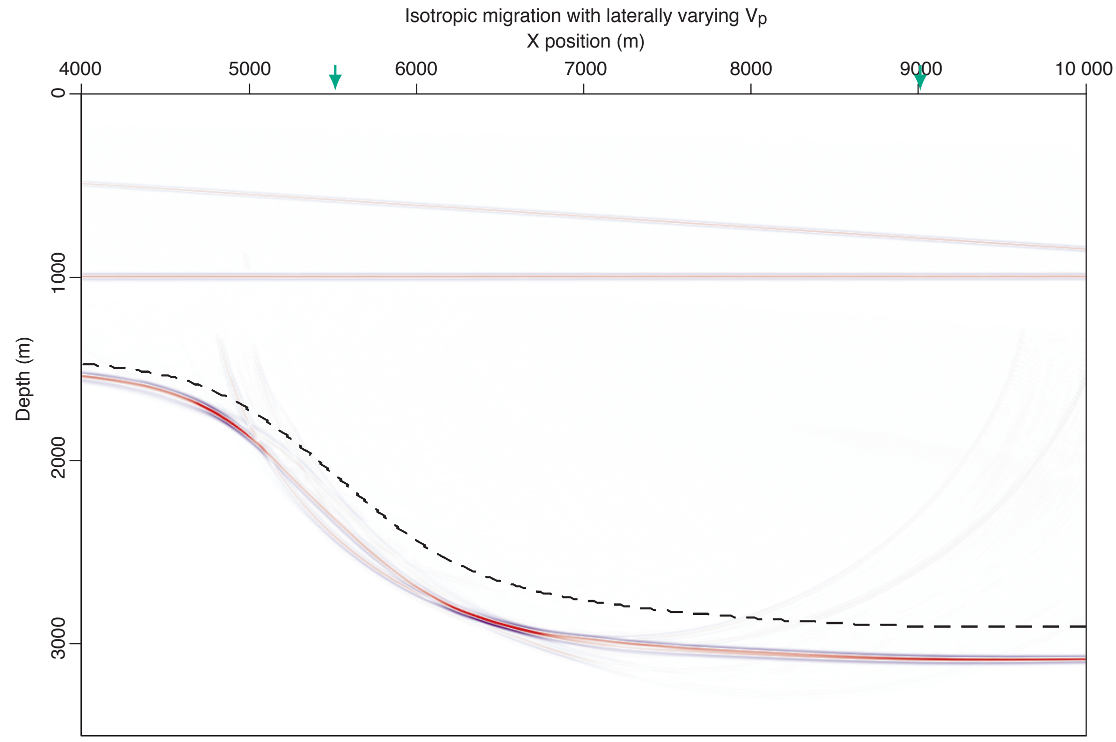

Figure 4a

Stacked image after isotropic PSDM using a laterally varying V_p (see Figure 5) in the third layer.

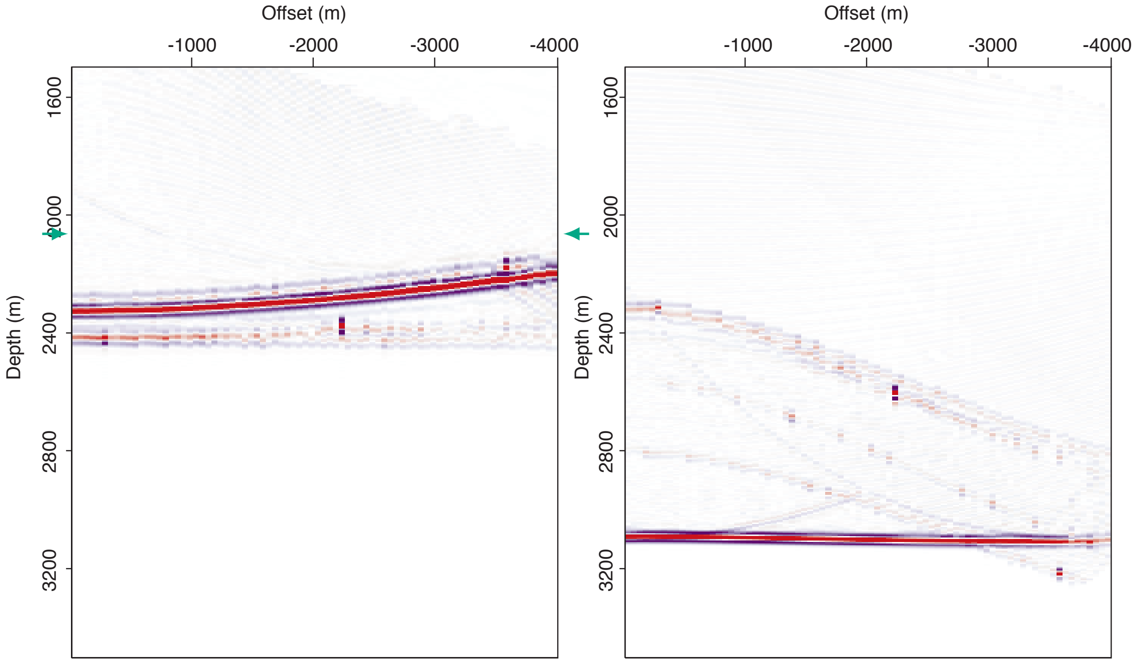

Figure 4b

Common image gathers at *X* positions 5.5 km and 9.0 km for the isotropic migration of Figure 4a.

optimised CIGs the event is not quite flat, which corresponds to non-hyperbolic moveout in the data arising from the non-ellipticity of the anisotropy. The artefacts in the images are due to the incorrect amplitudes given for the caustics associated with the triplication by asymptotic ray theory.

We made a naive attempt to create an "improved" isotropic model by interpolation based on the above results. The laterally inhomogeneous velocity field for the third layer which resulted from this attempt, is shown in Figure 5; the migration result is shown in Figures 4a and 4b. There is little overall improvement on the previous results. We suspect that it may not be possible to compensate for the anisotropy in this model with only lateral variation because of the way in which the rays corresponding to different parts of the reflector cross at different propagation angles. A tomographic approach (allowing for variations in both lateral and vertical directions) might yield a velocity model which flattens the gathers everywhere (cf., Bube and Meadows, 1998), but this model might well contain geologically implausible artefacts.

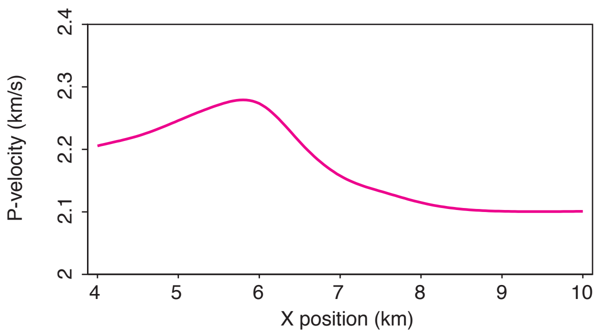

Figure 5

Laterally varying *P*-velocity in the third layer used for migration in Figure 4. The maximum lies above the dipping part of the third interface.

As expected, using the true anisotropic model gives flat CIGs at all locations and a well-focused image at the correct depth (Fig. 6).

3 APPLICATION TO REAL DATA

We have also applied our PSDM code to a 2D dip line from offshore West Africa which contains a dipping fault generating a strong reflection. We used smoothed isotropic and anisotropic (TIV) velocity models (see Figure 7), created using the stacking velocity inversion method with a priori information from neighbouring studies. The anisotropic inversion used the NMO velocities and η values obtained from non-hyperbolic moveout analysis instead of stacking velocities. In fact the models were only explicitly built above (to the right of) the main fault. The parameters for the region below it were not inverted, so we do not concern ourselves with the results there. The image from the isotropic migration (Fig. 8), for which offsets out to 2.5 km were stacked, gives clear images of the sub-horizontal reflectors, and, by inference from their terminations, minor faults dipping downwards from right to left. The main fault plane reflection is visible, but poorly focussed. This is clearer in the enlarged section at the top of Figure 9; the CIGs show that whereas the events corresponding to the sub-horizontal reflectors appear flat, there is residual "moveout" for the fault plane event, at least at $X = 8.5$ km (at depth c. 2150 m).

For the PSDM with the anisotropic model, the part of the fault plane reflection between depths 1950 m and 2300 m appears to be better focussed in the stacked image than for the isotropic model, and is clearly better flattened in the CIG at 8.5 km (Fig. 10). We can also see a slight lateral displacement of the fault characterized by, for example, the intersection with the prominent sub-horizontal reflector at depth around 2300 m. However the sub-horizontal events around $X = 9.0$ km and 2500 m depth and the minor faults in this area are less clear than before. This is partly due to some additional migration artefacts, but it is certainly the case that the velocity model is sub-optimal here, possibly because the a priori information used in building the model is inappropriate. This suggests that further work is needed to refine the anisotropic model.

4 DISCUSSION

We have presented a method for 2D PSDM of *P*-waves in TIV media, and used it to demonstrate the sensitivity of PSDM to anisotropy in a synthetic study. The results suggest that in anisotropic regions with a range of dips, it is probably not possible to find a smooth isotropic velocity model, which would flatten the gathers everywhere and produce a well-focussed image. Even if the gathers are flattened for a small range of dips, the estimated depth of the reflectors will be incorrect. Therefore PSDM, in conjunction with a

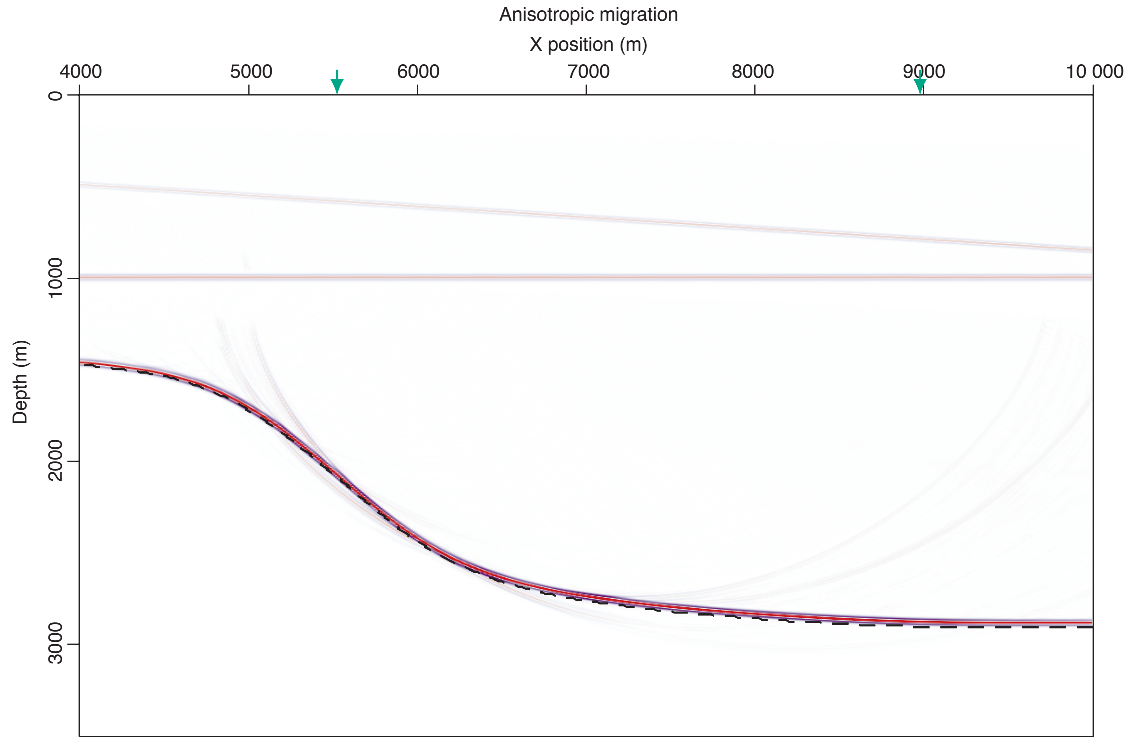

Figure 6a

Stacked image after PSDM using the true anisotropic velocity in the third layer.

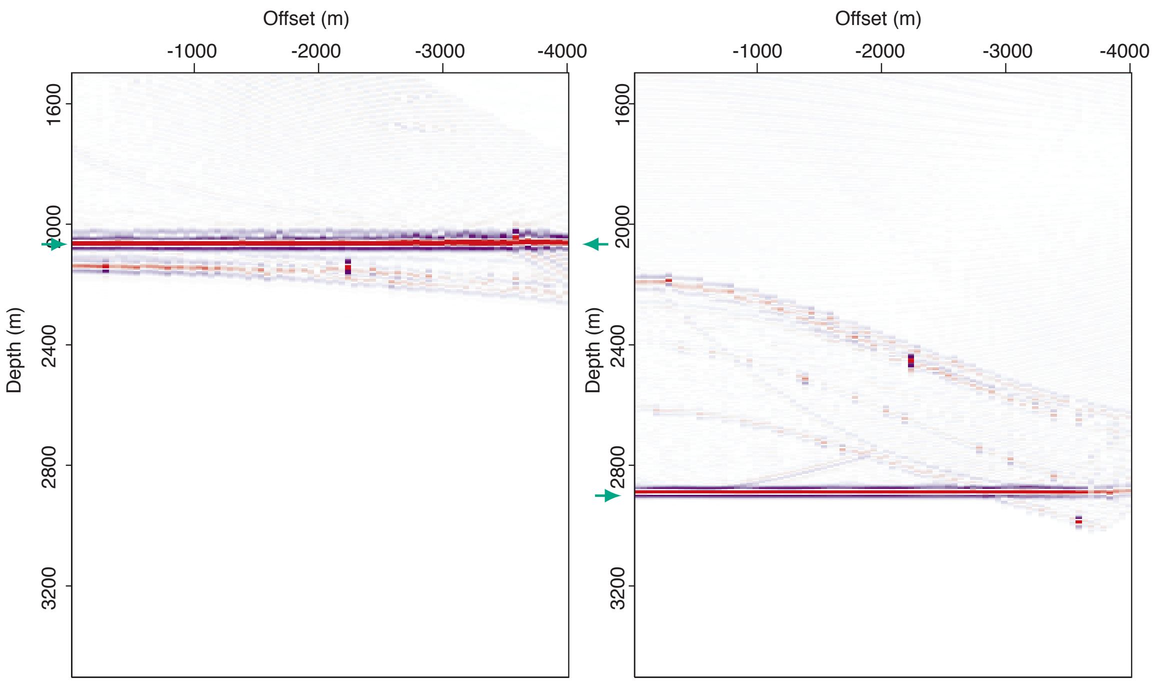

Figure 6b

Common image gathers at *X* positions 5.5 km and 9.0 km for the anisotropic migration of Figure 6a.

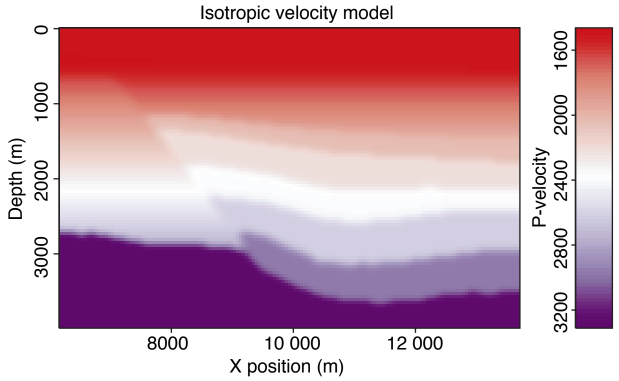

Figure 7a

Smooth isotropic velocity model for the migration of the real data.

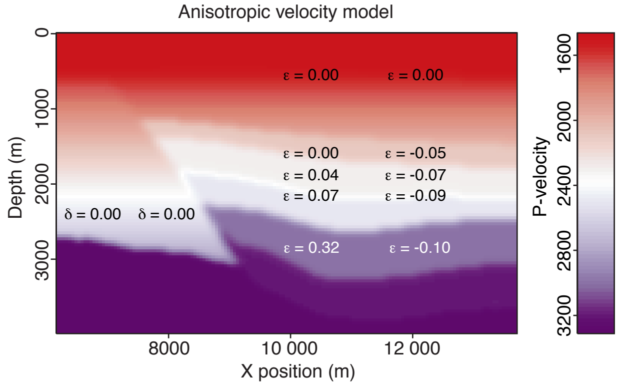

Figure 7b

Smooth anisotropic (TIV) velocity model. Vertical V_p is shown with Thomsen anisotropy parameters for relevant layers.

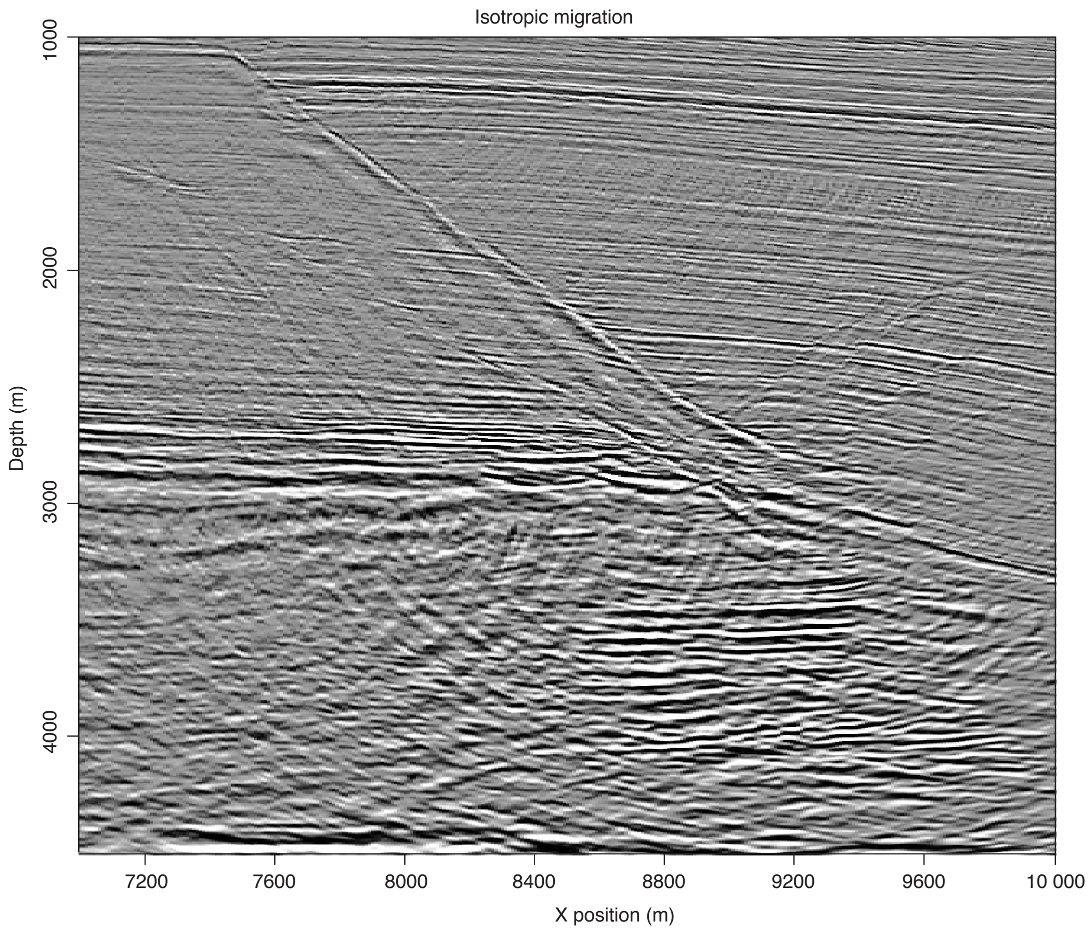

Figure 8

Stacked image of the real data after PSDM using the isotropic velocity field in Figure 7a.

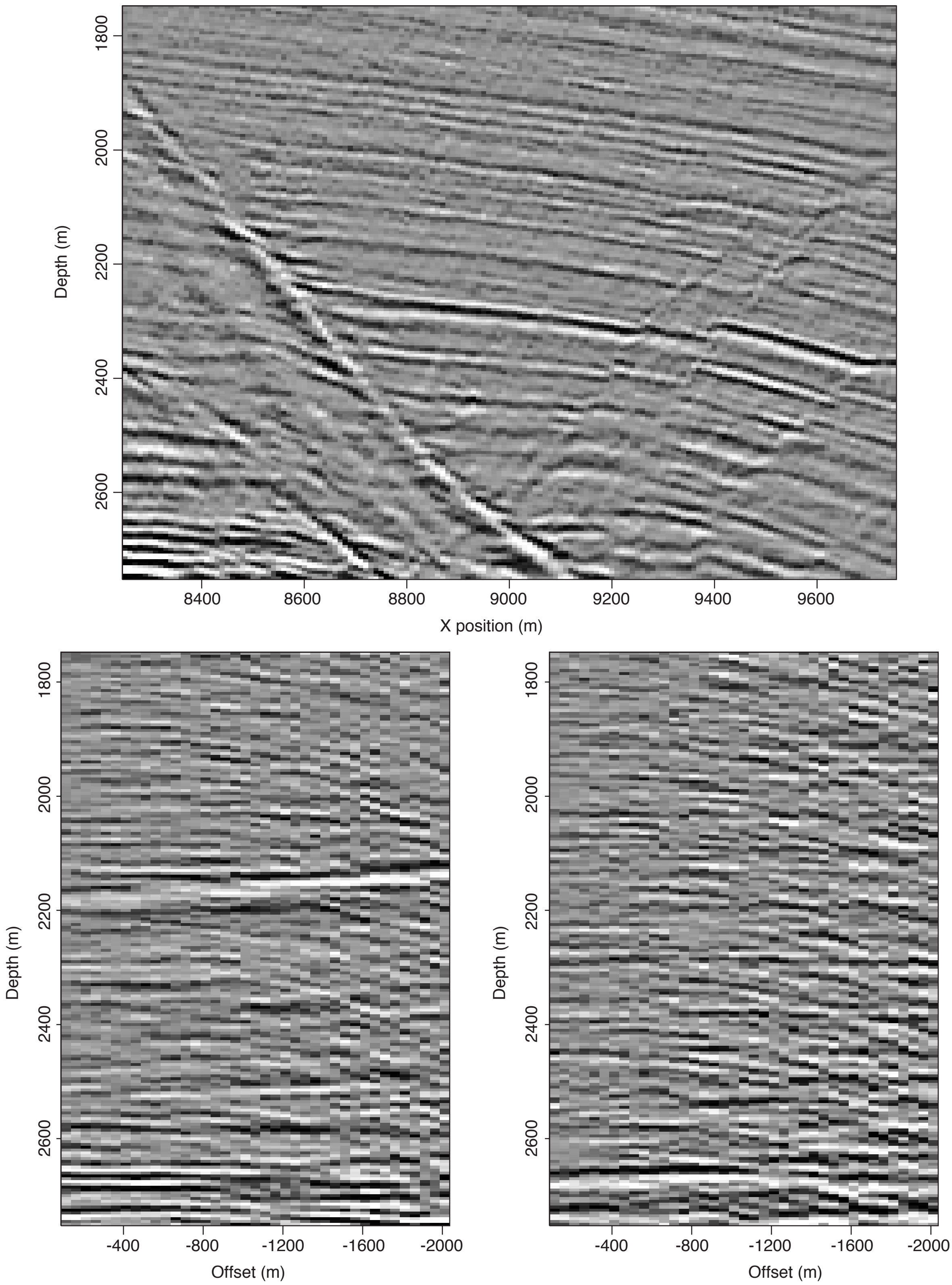

Figure 9

(Top) enlarged section of Figure 8; (bottom) two common image gathers at *X* positions 8500 m and 9000 m.

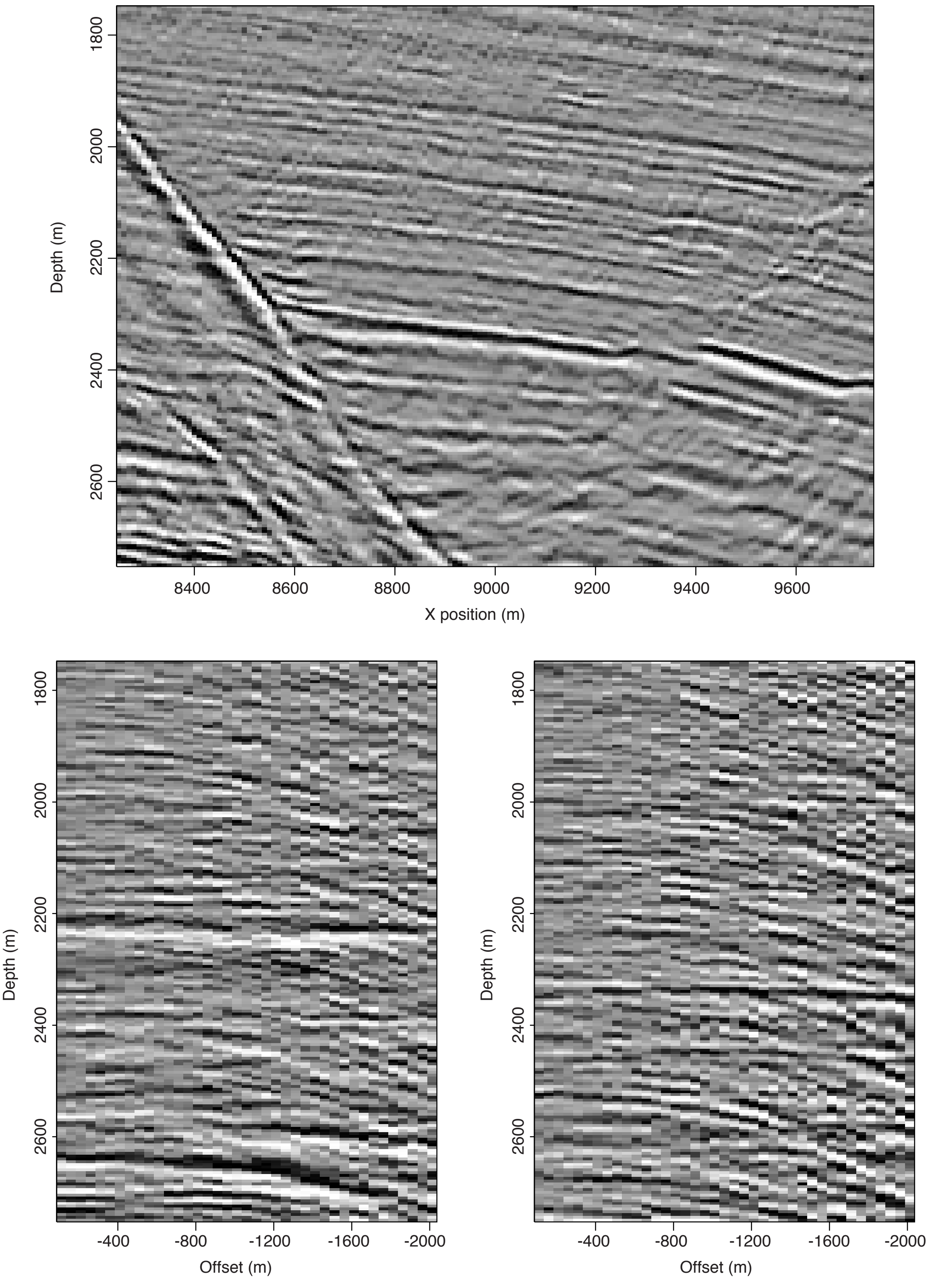

Figure 10

(Top) stacked image after PSDM using the anisotropic velocity model shown in Figure 7b; (bottom) two common image gathers at *X* positions 8500 m and 9000 m.

suitable scheme for updating the model, should allow estimation of at least some parameters describing the anisotropy. Application of the PSDM to a dip line from offshore West Africa using isotropic and anisotropic background models was inconclusive. Although it is clear that the isotropic result is less than ideal, the improvement, with the anisotropic model, of the image gathers around a dipping fault-plane reflection is offset by some degradation of the sub-horizontal events. We believe that anisotropy is important in this area, but these results highlight the necessity of obtaining an accurate background model for all PSDM imaging.

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REFERENCE

Ball G. (1995) Estimation of anisotropy and anisotropic 3-D prestack depth migration, offshore Zaire. *Geophysics*, 60, 1495-1513.

Bube K.P. and Meadows M.A. (1998) Characterization of the null space of a generally anisotropic medium in linearized cross-well tomography. *Geophys. J. Int.,* 133, 65-84.

Alkhalifah T. and Tsvankin I. (1995) Velocity analysis for transversely isotropic media. *Geophysics,* 60, 1550-1566.

Dong Z. and McMechan G.A. (1993) 3-D prestack migration in anisotropic media. *Geophysics,* 58, 79-90.

Grechka V. and Tsvankin I. (1998) 3-D moveout inversion in azimuthally anisotropic media with lateral velocity variation: Theory and a case study. *Proceedings of the 8th International Workshop on Seismic Anisotropy,* Boussens.

Lambare G., Lucio P.S. and Hanyga A. (1996) Two-dimensional multivalued traveltime and amplitude maps by uniform sampling of a ray field. *Geophys. J. Int.,* 125, 584-598.

Thomsen L. (1986) Weak elastic anisotropy. *Geophysics,* 51, 1954-1966.

Tsvankin I. (1995) Normal moveout from dipping reflectors in anisotropic media. *Geophysics,* 60, 268-284.

Vinje V., Iverson E. and Gjoystdal H. (1993) Traveltime and amplitude estimation using wavefront construction. *Geophysics,* 58, 1157-1166.

Williamson P.R., Sexton P.A., Robein E. and Berthet P. (1996) Stacking velocity inversion in anisotropic media. *Expanded Abstracts of the 58th EAGE Conference,* paper X010, Amsterdam.

Williamson P.R., Sexton P.A. and Xu S. (1997) Integrating observations of elastic anisotropy: constrained inversion of seismic kinematic data. *Expanded Abstracts of the 67th SEG Conference,* Paper ST 9.6, Dallas.

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