Converted wave prestack depth migration from topography: a comparison

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ABSTRACT

Pre-stack depth migration is applied to PP and PS waves of a synthetic dataset, obtained using 2D elastic finite difference modeling with a geological model having structural features and topography. Two methods of migration, Kirchhoff and PSPI are applied directly from the topography. Correct depths were obtained however with different character in the images, which can be related to the migration algorithm and to the wave mode used. Also, statics correction to a horizontal datum followed by migration was compared with migration directly from topography, which showed that the statics significantly degrades the images.

INTRODUCTION

Converted-waves have promise to contribute important information to the hydrocarbon resources industry, as shown by many authors (e.g. Stewart et al., 2002). Simultaneously, structurally complex areas are of increasing interest to the industry. This work is intended to explore the improvement of the subsurface information content provided by imaging converted waves (known as PS waves or C-waves, and in the following identified with this last term)., which are recorded with the multicomponent method.

Methods used currently by the industry for C-wave processing in time domain are based in relatively simple approximations (e. g. Tessmer and Behle, 1988); however, these have allowed successful applications (Stewart et al., 2002). Experience has shown that although it is possible to obtain a time image of the PP wave without too much knowledge of the geology, it is not so easy with C-waves. Thus, some authors have identified the close relation between the geological properties and the C-wave image, even for simple models (e.g. Thomsen, 1999). Besides that, identification of events of P- and C-waves coming from the same reflector is required, which can be easier in the depth domain. Therefore the depth migration methods present very attractive features for C-waves. Additionally prestack depth migration has been identified as more appropriate in complex areas and it has interesting properties related to AVO analysis.

On the other hand many processing algorithms assume a flat surface. Elevation static corrections has been an usual method applied to approximatly adjust the data to a flat datum, however it has an implicit error and is less accurate in rough topography areas (Cox, 1999). Instead of static corrections, methods like migration from the rough surface or wave equation datuming (e. g. Beasley and Lynn, 1992) have been developed..

A test of migration algorithms is presented in this work. Synthetic data from a geological model with topography and complex structure are analysed. Methods specific to elastic wave migration have been proposed in the literature (e. g. Hokstad, 2000), however this work is an extension of the methods used for P-waves. Two depth migration methods for C-waves from the topography are shown, corresponding to the Kirchhoff and PSPI approaches. The data are related to the results of P wave migration. A test on the effect of the statics correction is also presented.

THEORY

General

Two popular options for prestack depth migration are shot-profile and source-receiver backpropagation. In this work we applied two C-wave prestack depth migration methods in the shot-profile domain, Kirchhoff and Phase Shift plus Interpolation (known as PSPI), which have shown many successful results and have a sound theoretical basis. A brief explanation about them follows.

Kirchhoff method

The Kirchhoff method was first proposed by Schneider (1978), based in a high frequency approximation to the wave equation. Many developments about it have folloed, e. g. Wiggins (1984) who developed an application in the case of prestack data and irregular surfaces.

According to Biondi (2006), the Kichhoff method of prestack migration in 2D can be represented as follows:

$$I(x_\varepsilon, z_\varepsilon) = \int_\delta W(x_\varepsilon, z_\varepsilon, m, h)\psi[t = t_\psi(x_\varepsilon, z_\varepsilon, m, h), m, h]\, dm\, dh, \quad (1)$$

where $I(x_\varepsilon, z_\varepsilon) \equiv$ the migrated image, x_ε , $z_\varepsilon \equiv$ coordinates of the image point, $\psi[t, m, h]$ $\equiv$ the input wavefield (which is a data gather that can be in the midpoint (m) offset (h) domain), $W(x_\varepsilon, z_\varepsilon, m, h)$ a weight factor, and δ represents the migration aperture.

In this equation t_ψ is the total time delay accumulated by the wave while propagating from the source to the image point and back to the receiver. An eikonal calculator, coded at CREWES, was used in this work. In the case of C-waves different velocities are used for each trajectory related to the image point (i.e. P-wave velocities are used for source to image point and S-wave velocities are used for receiver to image point).

PSPI

The PSPI (Phase Shift plus Interpolation) method, proposed by Gazdag and Sguazzero (1984), is based on the representation of wave propagation in the Fourier domain, which allows results consistent with properties of the wave equation and to take advantage of efficient numerical algorithms. It is based on the phase shift property of the Fourier transform, which allows the extrapolation of the wavefield in depth z, such that:

$$\varphi(k_x, f, z_0 + \Delta z) = \varphi(k_x, f, z_0)e^{2\pi i k_z \Delta z}.$$

where $\varphi(k_x, f, z_0)$ is the Fourier Transform in time and horizontal space (x-space) of the seismic record $\psi[t, x, z]$..

However the Fourier transformed data in the horizontal space domain prevents for property variations in this direction. Margrave and Ferguson, (1999) developed a method to address this issue using non-stationary phase shift. It allows variations in the horizontal direction such as velocity and topography. After these developments, Al-Saleh et al. (2009) established a method for downward continuation from topography, which is applied in this work. The PSPI code used here is described in Ferguson and Margrave (2005) and implemented in the MATLAB codes pspi_shot and pspi_cwave. These codes were adapted to topography as described Al-Saleh et al. (2009).

DATA GENERATION

The first step was the generation of synthetic seismic data over a geological model. The migration methods are applied to the resulting data, P- and C-waves, assuming they correspond to the vertical and horizontal components respectively.

Finite difference (FD) was the method used to generate the synthetic data. The FD code is 2D, elastic and isotropic, based in the method proposed by Hayashi et al. (2001). It uses a staggered grid scheme, second order in time and fourth order in space, and allows implementing an irregular surface.

Geological Model

A simple model with topography and geological structures was generated, whose characteristics are illustrated in Figure 1. It is relatively simple however with key features such as a structural fault, dipping interfaces and a topographic recording surface. The target corresponds to the dipping layer with Vp of 2500 m/s separated by the inverse fault. This layer has a dip of 11º. The fault has a dip of 63º. The peak of the hill is 135 m over the flat level.

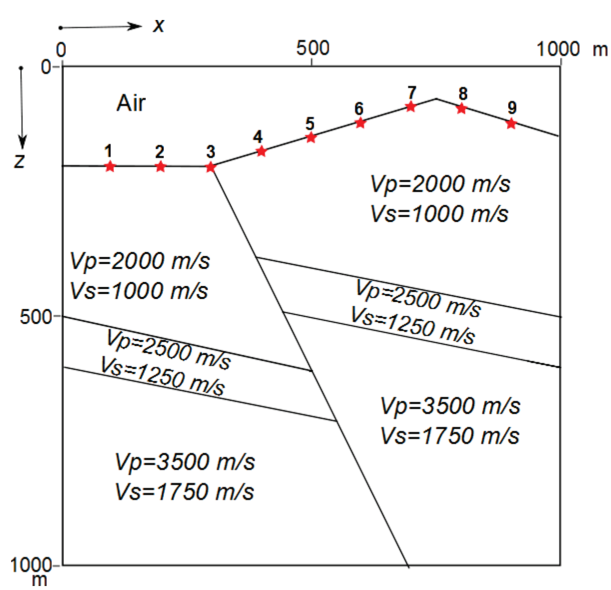


FIG.1. Geological Model. The left and right hand sides are separated by an inverse fault. The surface shows a hill with 135 m high. The shot points are indicated by stars on the surface and identified with numbers. The target is the dipping layer with Vp 2500 m/s separated by the inverse fault.

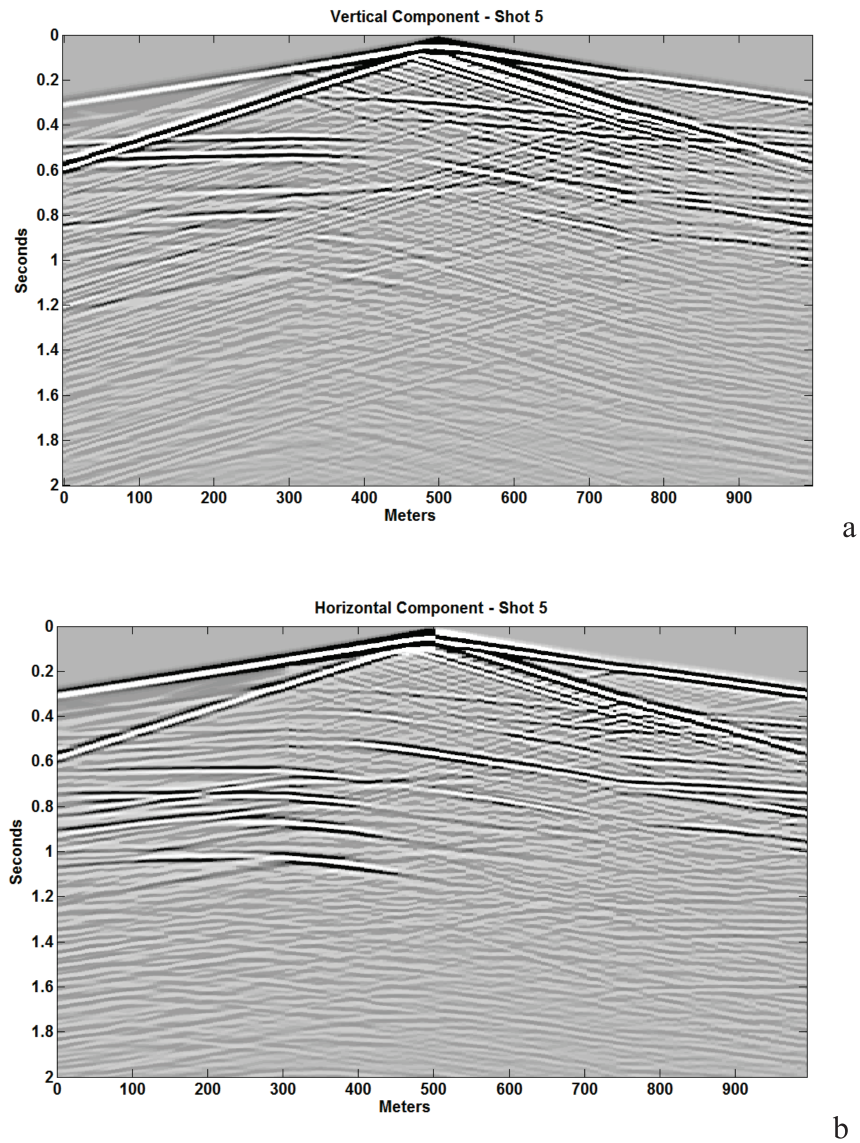


FIG. 2. Shot gather resulting from modeling corresponding to the shot location number 5. a) Vertical component and b). Horizontal component It can be observed strong energy in the first linear events. Many events can also be observed in both components.

The sources of energy were located almost at the free surface, and are identified by a number and a star in this Figure 1. Nine shot gathers were generated, separated by 100 to each other. The receiver interval is 5 m, and the time sampling 2 ms. The record length was 2 s. A Ricker wavelet with a center frequency of 20 Hz was used. It had a length of 100 ms. The wavelet is symmetrical and starts at zero time. Care was taken to choose a receiver interval such that S-waves are not aliased at the receivers.

Typical shot records are illustrated in Figure 3. These records correspond to the shot number 5 in Figure 1. In the vertical component (Figure 2a) there are more events at shorter times, which can correspond to the higher velocity P waves (whose polarization trends to vertical) and in the horizontal component there are more events arriving later, which corresponds most probably to S-waves (since their polarization trends to horizontal). However many events can be observed in both components ("wave leakage"), which for linear polarization is caused by not exactly vertical or horizontal angle of incidence. However this behavior is not frequent in real data, since, due to the low velocity of the near surface layer, the wave incidence trends to the vertical.

Data Migration

The source waveform was a delayed zero phase wavelet (with 100 ms length, symmetrical and maximum at 50ms) delays the data by 50 ms. The PSPI code assumes a zero phase wavelet that is not delayed so a 50ms shift was applied to the data before migration.

The migration methods were applied to the *PP* and to the C –wave, assuming that the vertical component corresponds to the *PP* and the horizontal to the *PS* mode, as used in the industry for real data. No previous processing or noise attenuation was applied to the data before migration, so the original amplitudes and multiple events were preserved. No aperture limitation was defined, so the migration included all the traces for each case.

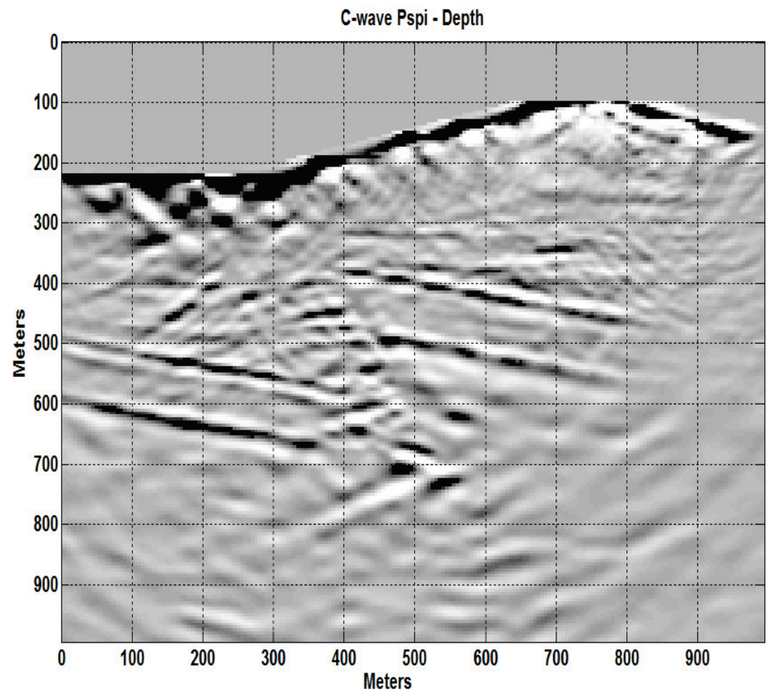
RESULTS

PSPI migrations:

Figure 3 shows the resulting migrated data using the PSPI method. These are stacks of the nine shot gathers migrated using the PSPI method. Figure 3a corresponds to the C-wave and Figure 3b to the P-wave. The depth location of the events is in agreement with the original geological model (Figure 1). An event can be used to check the accuracy of the geometry reconstruction carried out by the migration: at the top of the target the horizontal coordinate of 600 m has a vertical coordinate of 420 m. Both migrated sections correspond quite closely to this expectation.

However there are apparent differences between the two migrated sections. Notice the higher frequency content and the noisier record for the C-wave. This can be explained by the lower velocity of the S-wave compared with the P wave, which means a shorter wavelength. Also, the C-wave section is noisier while the P-wave data appear quite clean. The longer incidence time of the C-wave and the presence of many events in the horizontal component (mostly multi-modes P-waves) can explain this noise on the C-wave migrated section (see Figure 2b). Compared with the P-wave section, the C-wave section is noticeably noisier in the fault shadow, where it is not possible to observe the target interface contacting the fault.

Figure 4 is an example of the PSPI migration of one shot, corresponding to source 5 (whose raw data is illustrated in Figure 2). It can be observed that the reflector depths correspond closely to the geological model, as expected. The relatively limited illumination of this shot can be identified by the length of the target interface images. The C-wave illumination appears wider, as can be expected due to the smaller reflection angle of the S-wave compared to the reflection angle of the P-wave. Strong noise can be also identified in both gathers, probably stronger that in the case of the stack (Figure 3).



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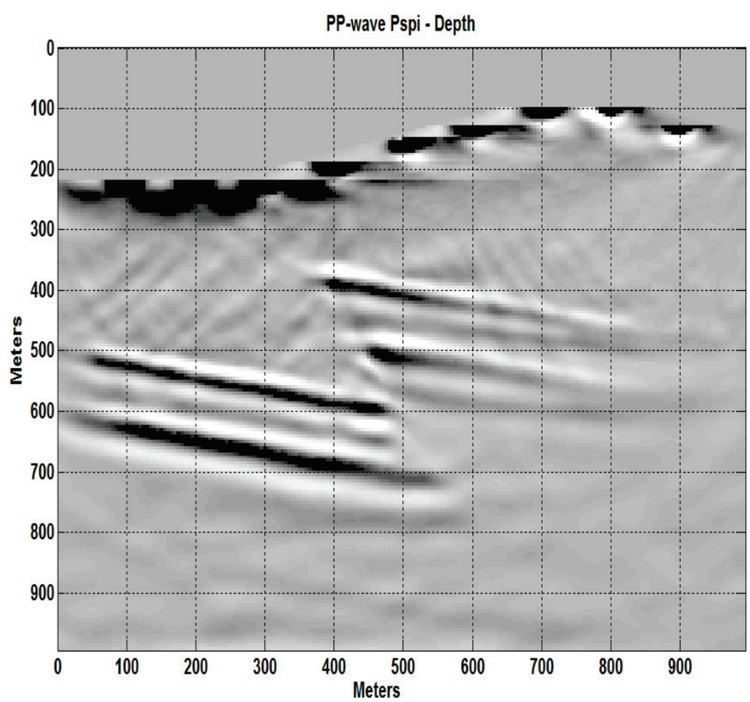

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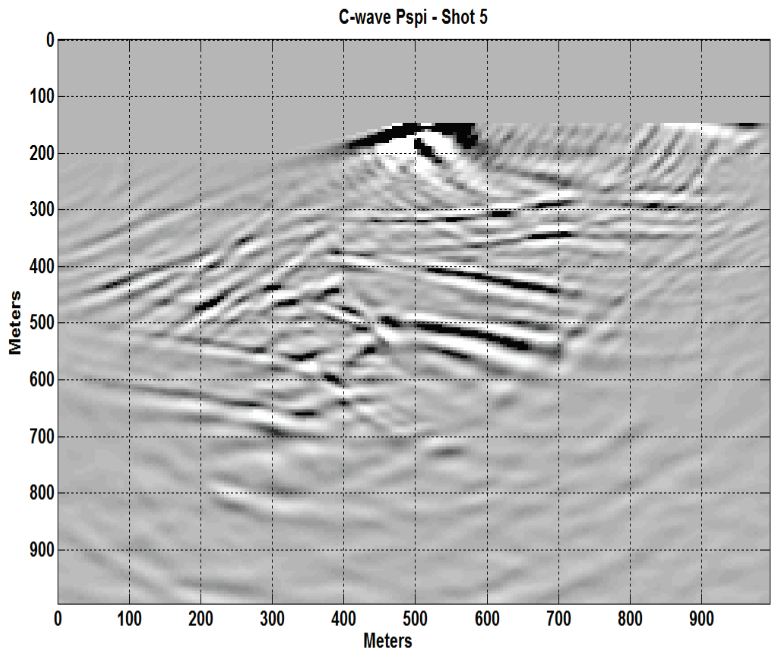
FIG. 3. Depth PSPI migration results (a) C-wave (b) P-wave. The top of the target at the distance of 600 m, is close to 420 m as expected according to the geological model (Figure 2).



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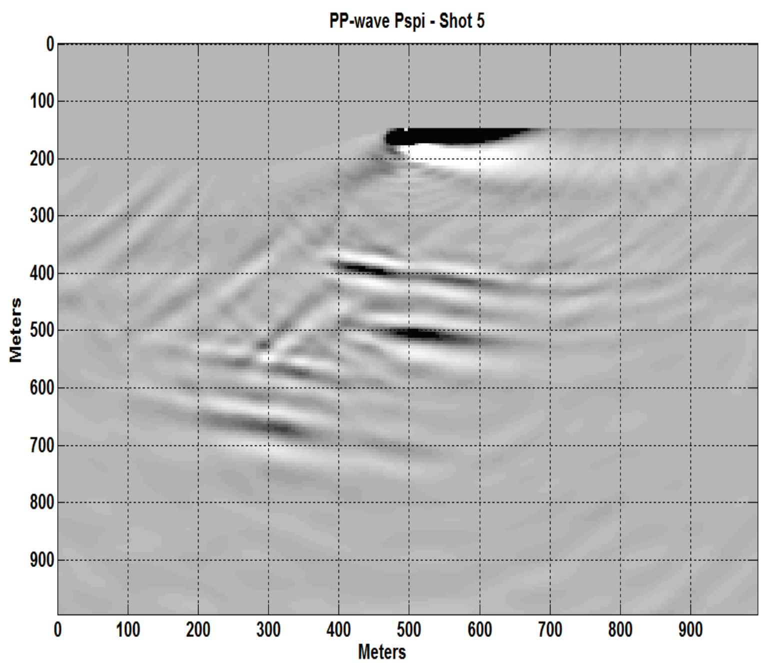

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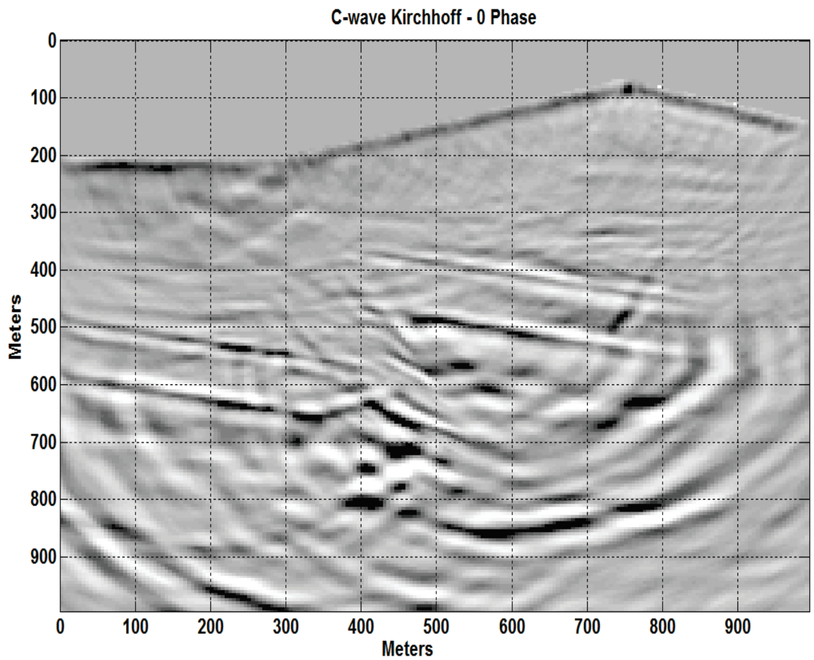
FIG. 4. Migrated shot gathers with the PSPI method for the Shot gather 5. (a) C-wave. (b) P-wave.



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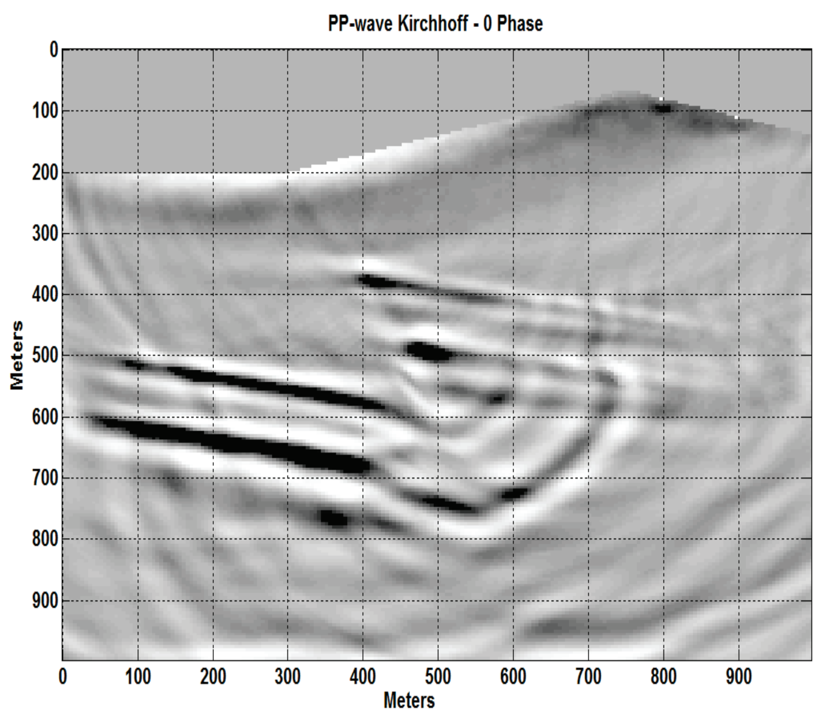

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FIG: 5. Kirchhoff migration (a) C-wave. (b) P-wave.

Kirchhoff migration

Figure 5 illustrates the results of Kirchhoff migration. The depth of events also correspond closely to the expected depth of the geological model. Similarly to the PSPI result, higher resolution can be observed in the C-wave which is also noisier than the P-wave. However the noise has different characteristics: is concentrated at deeper depths and its shape correspond to migration “smiles”.

Migration with static corrections applied

Static correction has been a method used by the industry to correct for near surface properties and topography A test using this method follows. The basic principles of this method are the following: a flat datum is assumed, and then the seismic data is shifted as if the sources and receivers were located at the flat datum. A vertical wave trajectory and a velocity called replacement velocity (close to the velocity of the near surface) are assumed.

The datum assumed here was 200 m, corresponding to the elevation of the flat free surface to the left hand side in Figure 1. The replacement velocities to shift the seismic data of the hill to the right hand side on Figure 1 were 2000 m/s for the P-wave and 1000 m/s for the S-wave.

Figure 6 shows the resulting migration stack for the data after application of the statics correction using the PSPI method. Figure 7 corresponds to the migration of shot 5. Therefore Figure 6 can be compared with Figure 3 and Figure 7 with Figure 4. A general decrease in the quality of the image can be observed. The extreme deterioration happens on the C-wave stack, since the image of the target to the left hand side of the fault almost disappears (Figure 3a compared with Figure 6a).

Looking at the migrated shot, the difference is not as strong. Similar events appear, even if they are noisier (Figure 4 vs. Figure 7). However looking more carefully, image displacement of the reflectors after statics can be observed. An example is the top of the target at the x of 600 m, whose z coordinate is different of the expected 420 m. This observation can give an explanation to the decrease in the quality of the stacks: the error from one shot to another after statics can be different, therefore the migrated stack would be worse than the individual migrated shot.

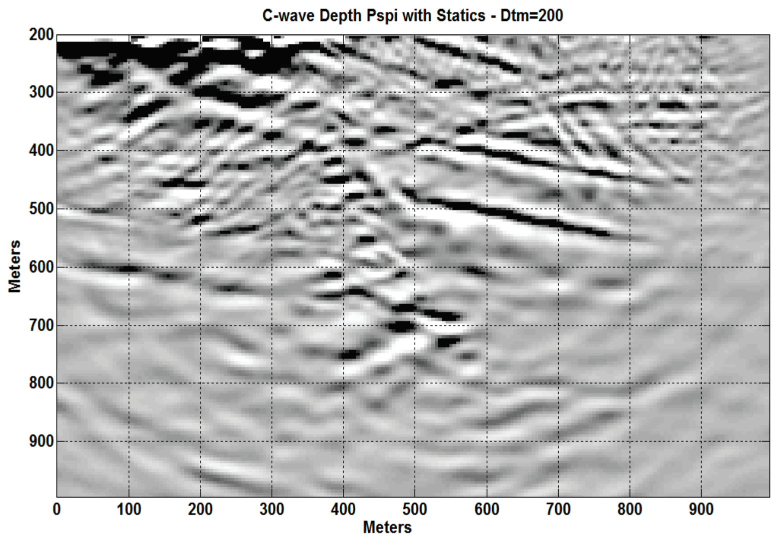
DISCUSSION

The data did not have any filtering or noise attenuation, neither wave mode separation, and there were only 9 shots. However both migration methods were applied successfully for P- and C-waves. .Real data are affected for many factors and uncertainties not taking into account here, such as attenuation, noise and heterogeneity, which requires specific methods. Despite that this is a simplified model, it illustrates properties of these technologies application to complex areas.

In this example there are specific differences in the results related to the noise, which can be attributed to properties of each algorithm. Kirchhoff appears noisier in general, especially related with artifacts generated at deeper depths. Other differences are related to the wave mode: the C-wave image is noisier than the P-wave.

Statics corrections also are shown to be inadequate for depth migration algorithms in the presence of topography, since the depth appears wrong. It can affect the velocity analysis, and contribute to the prevention in the identification of P-wave and C-wave events.

As for future work, the resulting migrated data can be an appropriate subject for amplitude investigation that can provide useful data on AVO of both wave modes.



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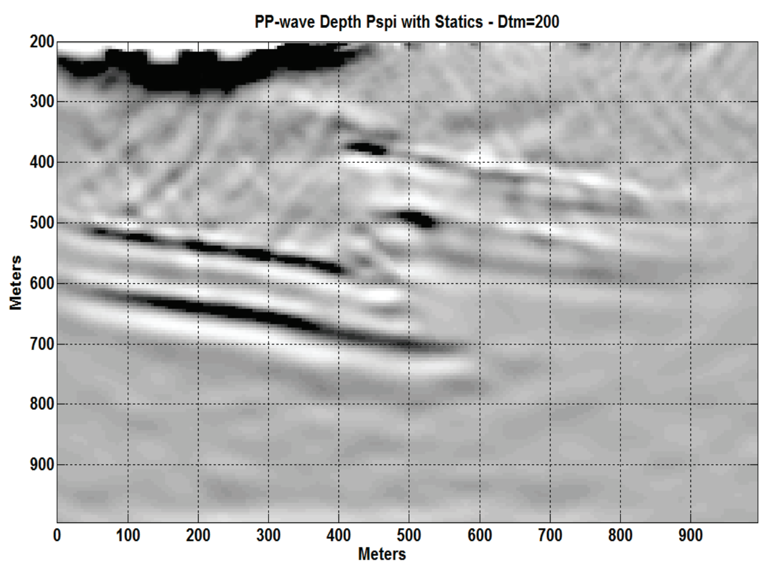

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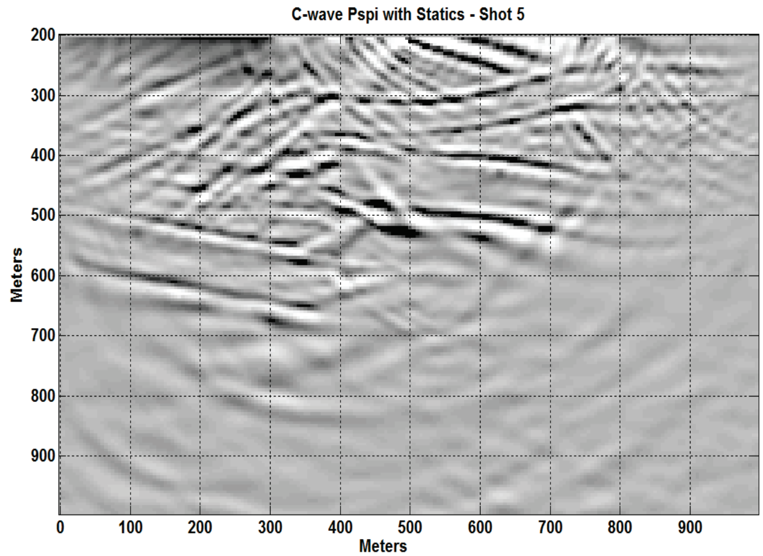
FIG. 6. Migration stack after conventional statics application. (a) C-wave. (b) P-wave.



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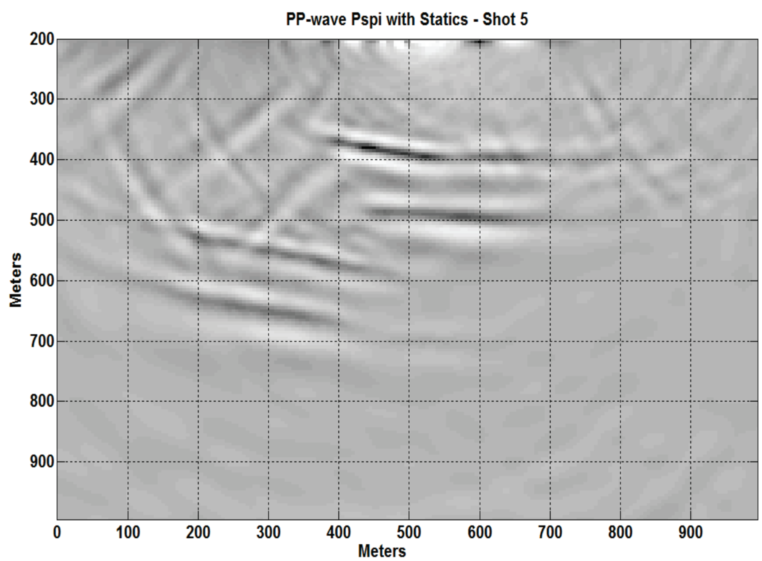

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FIG. 7. Shot 5 PSPI-migrated with statics. Notice depth shifting in the top of the target, since for x=600 m the depth should be 420 m.

CONCLUSIONS

- Both depth migration methods from the topography gave correct reflector depths.
- Both wave modes show the same structure, however with difference in the amplitudes and general features. These amplitude differences can also arise because of the differing PP and PS reflection coefficients and potentially allow an elastic inversion.
- Resolution of the C-wave appears higher but its result appears noisier.

- The Kirchhoff method appears noisier than PSPI.

- Statics can cause a systematic error in the depth and velocity of the image for cases of depth migration with rough surface.

ACKNOWLEDGEMENTS

We thank Ecopetrol SA, who allowed the use of the modeling software for the data generation and we also thank the CREWES sponsors for their support.

REFERENCES

Beasley, C. J., and Lynn, W:, 1992, The zero velocity layer: migration from irregular surfaces: Geophysics 57, 1435-1443.

Biondi, B., 2006, 3D seismic imaging: SEG Investigations in Geophysics No. 14.

Cox, M..,. 1990. Static corrections for seismic reflection surveys: SEG Geophysical References Vol. 9.

Ferguson, R. J., and Margrave, G. F., 2005, Planned seismic imaging using explicit one-way operators: Geophysics, Vol. 70, No. 5, pp S101-S109.

Gazdag and Sguazzero, 1984, Migration of seismic data by phase shift plus interpolation: Geophysics, 49, 124-131

Hayashi, K, Burns, D. R., and Tokzos, M. T., 2001, Discontinous-grid finite difference seismic modeling including surface topography: Bull. Seism. Soc. Am., 91, No. 6, 1750-1764.

Hokstad, K., 2000, Multicomponent Kirchhoff migration: Geophysics, v. 65, No. 3, p. 861-873.

Margrave, G. F., and Ferguson, R. J., 1999, Wavefield extrapolation by non-stationary phase shift: Geophysics 6, 1067-1078.

Al-Saleh, S. M., Margrave, G. F., and Gray, S. H., 2009, Direct downward continuation from topography using explicit wavefield extrapolation: Geophysics, Vol. 74, No. 6, pp S105-S112.

Schneider W. A., 1978, Integral formulation for migration in two and three dimensions: Geophysics, 43, 49-76.

Stewart, R. R:, Gaiser, J. E., Brown, R. J., and Lawton, D. C:, 2002, Converted-wave seismic exploration: methods: Geophysics, 6, 1348-1363. ´

Tessmer, G., and Behle, A., 1988, Common reflection point data stacking technique for converted waves: Geophys. Prosp. 36, 671-688.

Thomsen, L., 1999, Converted-wave reflection seismology over heterogeneous anisotropic media: Geophysics, 64, 678-690.

Wiggins, J. W., 1984, Kirchhoff integral extrapolation and migration of nonplanar data. Geophysics, , 1239-1248.