Multicomponent seismic surveys in a complex setting: Catatumbo, Colombia

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ABSTRACT

Compared with single component seismic data, multicomponent data have potentially higher information content even in structurally complex areas. Converted wave data are an obvious potential added value, but also important are the sensitivity of the 3C sensors to the vector properties of the data, which may improve the P-wave information. Data processing which takes into account the topography illustrates these points. Multicomponent seismic surveys acquired in a Northern Andes foothills setting are presented here. The survey is in a location that includes rough topography and folded geology. The seismic data were acquired with the 3C sensors oriented vertically, and it can be assumed that waves arrived normal to the surface. Consequently, the rotation of the radial and vertical data into a direction normal to the topography would better estimate the P-waves. Radial filtering was used to attenuate coherent noise, Gabor deconvolution was applied, and finally, a rotation was carried out to obtain the P-wave normal to topography. Differences can be observed in the stacked sections with and without correction; however, the result can not be considered definitive. Information about the near surface layer suggests the possibility of non-normal wavefront incidence, which implies the need to consider the free surface effect on this wave-mode separation. Converted waves mustl also be given similar consideration. Besides the usual difficulties related to converted wave processing, such as static corrections, velocity analysis and trace binning, the geologic structure presents a particular challenge for converted waves, which was illustrated by another multicomponent data set previously acquired in the area. Prestack depth migration appears to be an appropriate tool to overcome these shortcomings of converted wave imaging.

INTRODUCTION

Since many geologically simple locations have been thoroughly explored, much effort has recently been directed to complex areas. In these types of terrain, many of the usual useful assumptions, which have been successfully used in simpler zones, are no longer applicable. Perhaps the multicomponent method, with its higher information content, can add value. The multicomponent method has previously been applied to relatively simple geological settings; however its potential for obtaining information from more complex zones, which are challenging for the current state of the technology, has not been explored widely.

Multicomponent exploration to improve P data in complex areas have been subject of recent publications, (e. g. Behr, 2005, and Ronen *et al.* 2005), and new acquisition methods have been developed (e. g. Gibson et al., 2005). New processing techniques have been proposed, that consider specific properties of multicomponent data. Developments in that direction would allow us to exploit the well known potential information content of converted waves for describing lithological properties in more complex settings. In another approach Stewart and Marsichio (1991) proposed to take advantage of the vector properties of off-line energy to obtain information from 2-D multicomponent data. As an application, this off-line energy is related to complex 3D settings and could contribute to improved 3D images.

An experiment with vector detection of the incident P-wave is presented in this work, together with some other aspects of multicomponent data in complex media, and applied to a case study in the Northern Andes in Colombia.

In the multicomponent method, usually the vertical component is assumed to be equivalent to the P-wave, and the horizontal radial component is assumed to correspond to the converted S-wave. However, these assumptions are not necessarily true. P-waves may not be limited to the vertical component, since the waves may not arrive normal to the surface (as in the case of a high-velocity near surface), or the sensors may not be normal to the surface (dipping surface, as in rough terrain). The latter case is investigated here.

Some other issues related to obtaining seismic images from multicomponent data are noise attenuation and imaging in complex velocity media. In addition to the potential of the multicomponent method to improve P data quality in a complex setting, processing issues for converted waves are also considered. The conventional processing of P-waves, based on simple geometrical models, is not as appropriate for converted waves, since even simple binning already depends on the velocity field, that is to say, on the geological properties.

DATA AND METHODOLOGY

The setting and the data

The data used were acquired in the Catatumbo Area, a Northern Andean setting in Colombia. The geology at this place includes shales and sandstone from the Tertiary and shales, sandstone and limestone, from the Cretaceous. Prospective reservoirs are in permeable sandstones, and also in fractured limestones. Structures include folding and faulting from moderate to severe. There are hills in this area, which stand out about 400 m over the alluvial valleys, and usually correspond to outcrops of older rocks. The location of the Basin in the Andes is illustrated by Figure 1.

A multicomponent survey, using MEMS technology sensors, and dynamite as the source of energy was acquired in this area in 2005. The acquisition design included a symmetrical split-spread with 800 channels per shot, 15 m between receivers and 60 m between sources.. The nominal fold was 100.

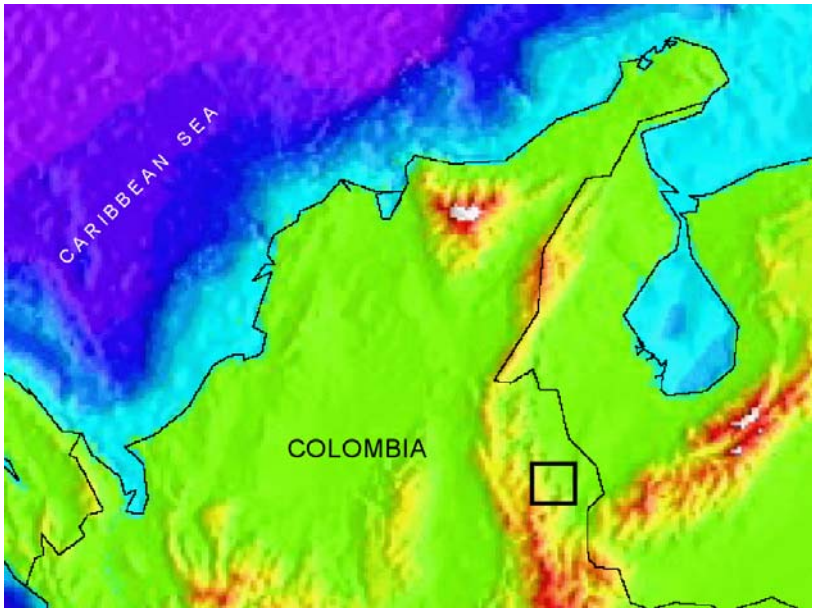

FIG. 1. Location of the study area (square). Colors correspond to elevations, from green (lower) to white (higher). For example the reddish color shows elevations between 1500 and 3500 meters above the medium sea level..

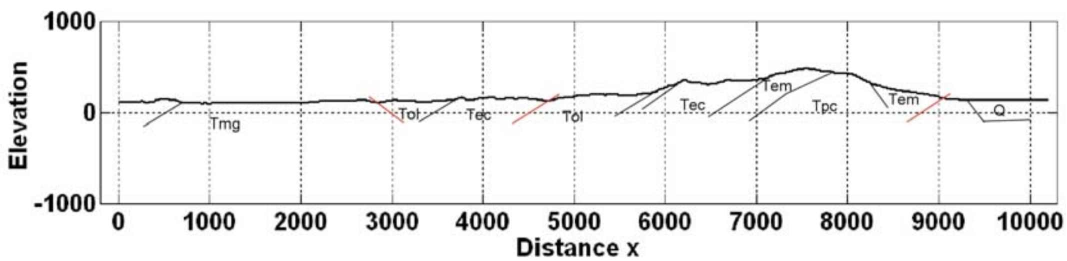

FIG. 2. Section showing the surface geology and topography at an aspect ratio of one to one.

A seismic line identified as U-1065 in the following, was selected for the experiments presented here. This line is oriented approximately EW, following the main dip trend. Figure 2 is a section that illustrates the topography and the near surface geology of the area selected. A total of 678 receiver locations along a 10.2 km line were selected. The nominal fold was reduced to about 70 since each shot had a lower number of receivers, and there were missing shots and bad traces.

Figure 4 illustrates the vertical and radial components of a raw shot gather. The strong ground-roll can be observed in both (1), with some additional events in the radial component (2). Hyperbolic-shaped events in the vertical component can be observed (3), corresponding to P-wave reflections. It is a bit harder to identify similar events in the radial component, and they appear weaker and show lower frequencies (4). Some topographic effects are evident in both gathers (5).

Another piece of information was an uphole survey acquired approximately 2 km south of the middle location of the U-1065 line study zone, with the purpose of investigating near-surface properties. This survey will be considered in the discussion section.

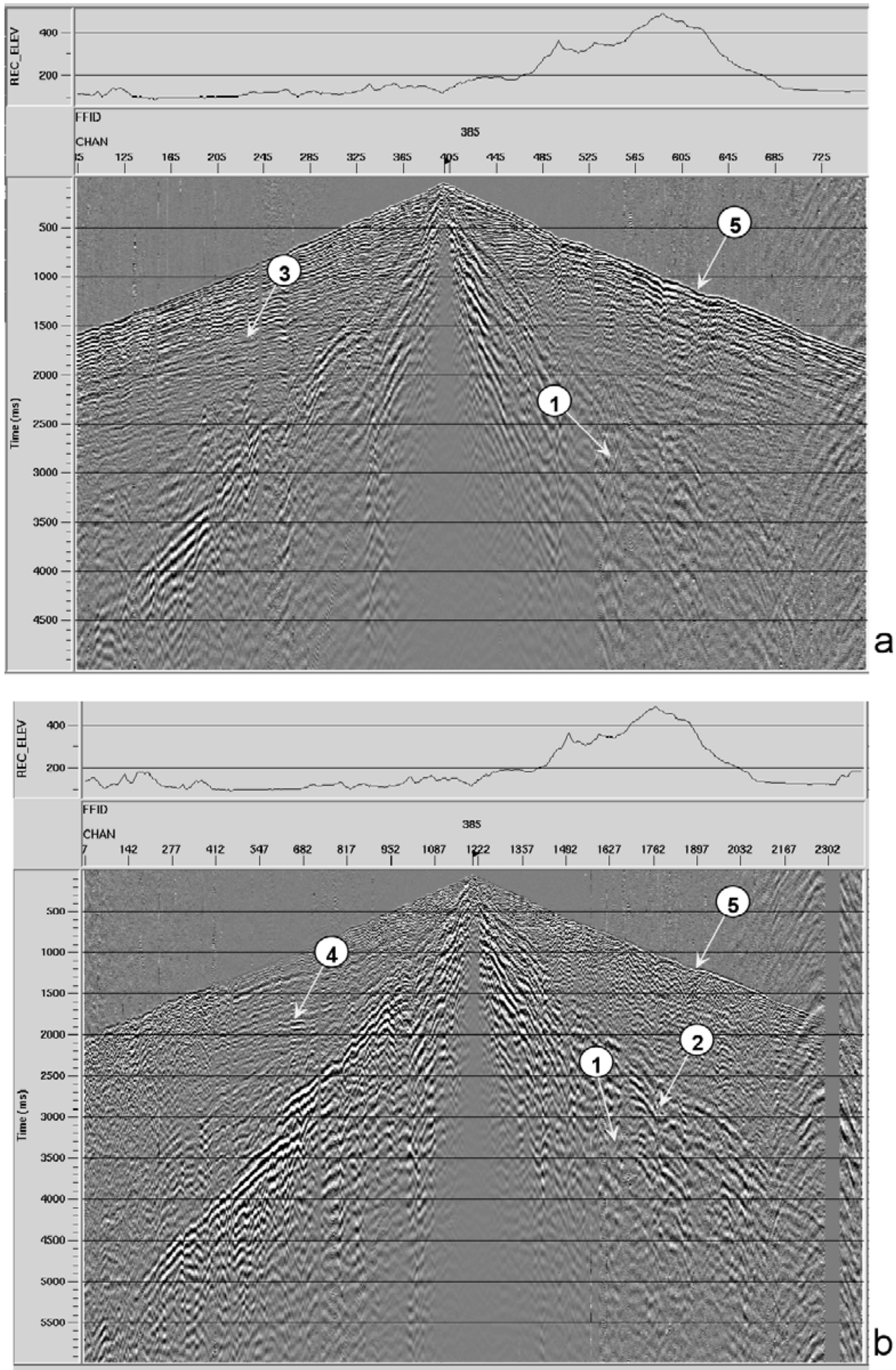

FIG. 3. Raw shot. a) Vertical component b) Radial component.

Another dataset which will be considered was acquired in the year 2000 in a nearby area, about 30 km north of line U-1065. This was an experimental 3C survey, identified as L-99. Partial results and processing issues were presented at the 2002 CSEG meeting (Guevara and Cary, 2002), and some information about L-99 will be also reviewed here. In that survey, the spread was made up of 3C geophones along three 7 km seismic lines crossing each other at their center. The geophones were deployed 30 m apart, and there was 60 m between each source. The processing applied included converted-wave stacked sections and fracture analysis.

On vector incidence at the surface

Multicomponent sensors are designed to detect vertical and horizontal displacements. The sensors used in line U-1065 (I/O VectorSeis) have a mechanism to adjust the vertical direction, according to gravity (Gibson et al 2005). In the case of a low velocity near surface layer, P- and S-wave rays tend to arrive normal to the surface, so their corresponding displacement for a horizontal terrain would be vertical for the P-wave and horizontal for the S-wave. In this case it is possible to identify vertical component with P-wave and horizontal component with S-wave without too much error. However, in the presence of topography with vertically oriented sensors, the wave arrival direction for a similar case would be at an angle to the sensor direction.

Modeling shown in Figure 4 illustrates this point. It was carried out with Norsar2D based on real topography from the Andes, in the Colombia Eastern foothills. A 50 m thick low-velocity layer, with a velocity of 800 m/s was assumed. It can be observed that the rays arrive almost normal to the surface.

As a consequence, each wave-mode would be recorded on both the vertical and radial components. Figure 5 illustrates the components and their relation to the arriving waves. A geometrical relation can be found between each wave-mode and each component assuming that the incidence is normal to the surface. So, in principle, it would be possible to obtain the wave modes from the horizontal and vertical component gathers, given a known incidence angle, which would be calculated from the topographic slope.

In this way it would be possible to improve the imaging of P and S waves. This correction would be more important when the topography is steeper and the assumptions about the large thickness and low velocity in the near surface are closely approximated. It is remarkable that this effect can happen at any sloping location, and that it cannot be detected with the conventional 1-C geophones.

Figure 6 illustrates the slopes along the line, calculated for each receiver location from the topography information. It can be observed that at some places the slope goes to 20°, and that these locations are correlated to the mountainous sectors (see Fig. 2).

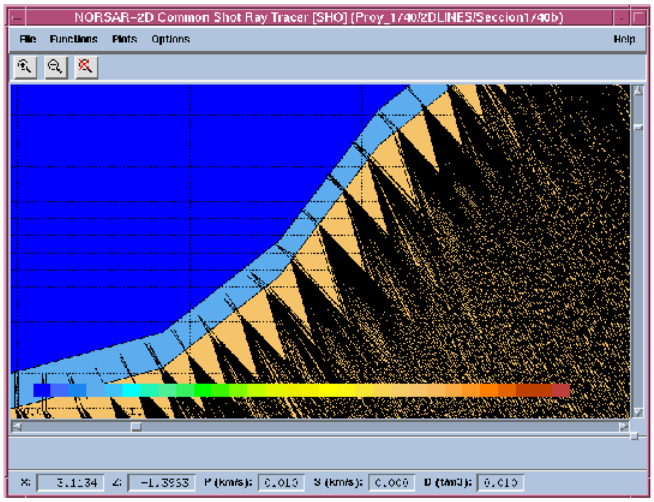

FIG. 4. Ray tracing with a low velocity layer and topography.

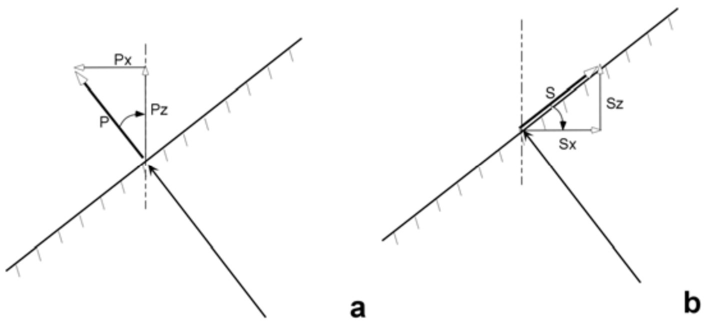

FIG. 5. Arrival direction and multicomponent detection in a steep slope area. a) Components of the P-wave. b) Components of the S-wave.

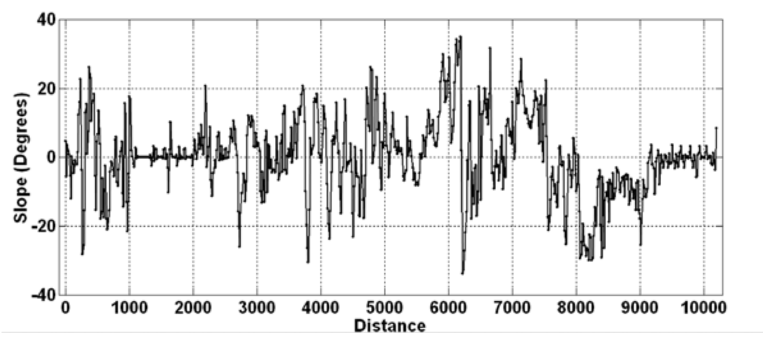

FIG. 6. Slope in degrees along the line, calculated for each receiver.

Processing Test

The processing flow included filtering, wave mode correction for topography, statics correction, velocity analysis and stacking. .The radial transform was applied for coherent noise filtering (Henley, 2003), and Gabor deconvolution, instead of the conventional deconvolution, for recovering the frequency spectrum and for amplitude correction (Margrave et al, 2002).

Figure 7. illustrates radial transform filtering and Gabor Deconvolution applied to the shot of Figure 3. The reflections are improved, and attenuation of the ground-roll and other type of noise can be observed in the vertical component. In the horizontal component there is more continuity, so reflections are more clearly identified, and the spectrum has been whitened.

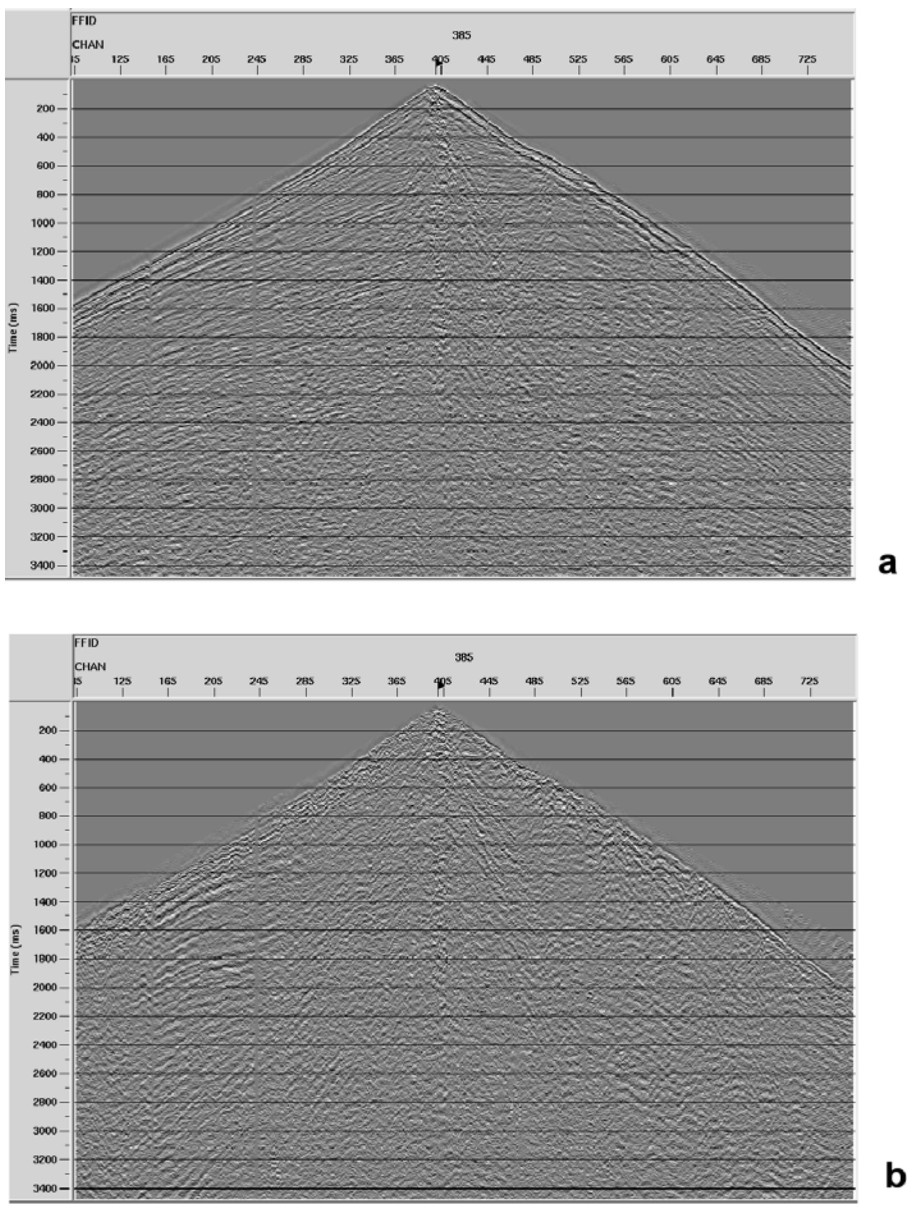

FIG. 7. Components after radial transform filtering and Gabor Decon a) Vertical component, b) Radial component.

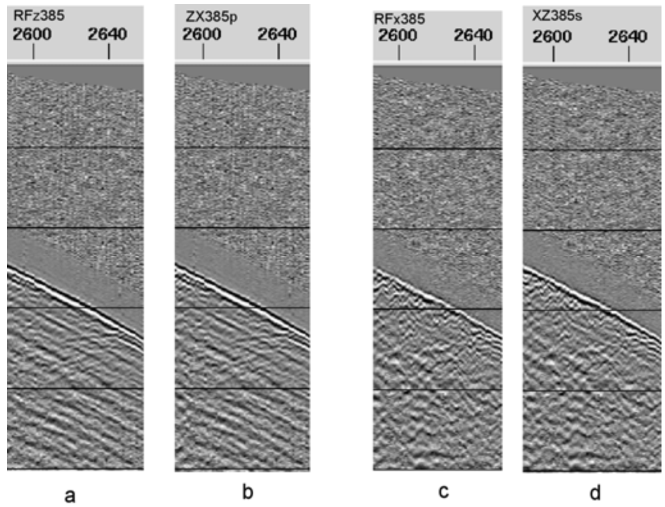

FIG. 8. Comparison of the two components before (left) and after (right) rotation. A) and b), vertical, (c) and (d) horizontal.

The correction for each one of the wave modes was investigated according to the angle of incidence analysis described previously. Figure 8 illustrates this result for a shot gather in a close-up corresponding to rough terrain surface zones. Figure 8a and 8c shows the data without correction for the vertical and horizontal components, and Figures 8b and 8d the data after the correction. .Improved signal appears in the horizontal component; but in the vertical, it is hard to identify any difference.

A stacked section after applying the slope correction was also obtained for the P-wave, which is illustrated in Figure 9. Figure 10 shows a close-up of this stacked section, compared with a previous stacked section, which included RT filtering and Gabor decon. This close-up corresponds to CDPs under a rough part of the terrain. Some subtle differences can be observed.

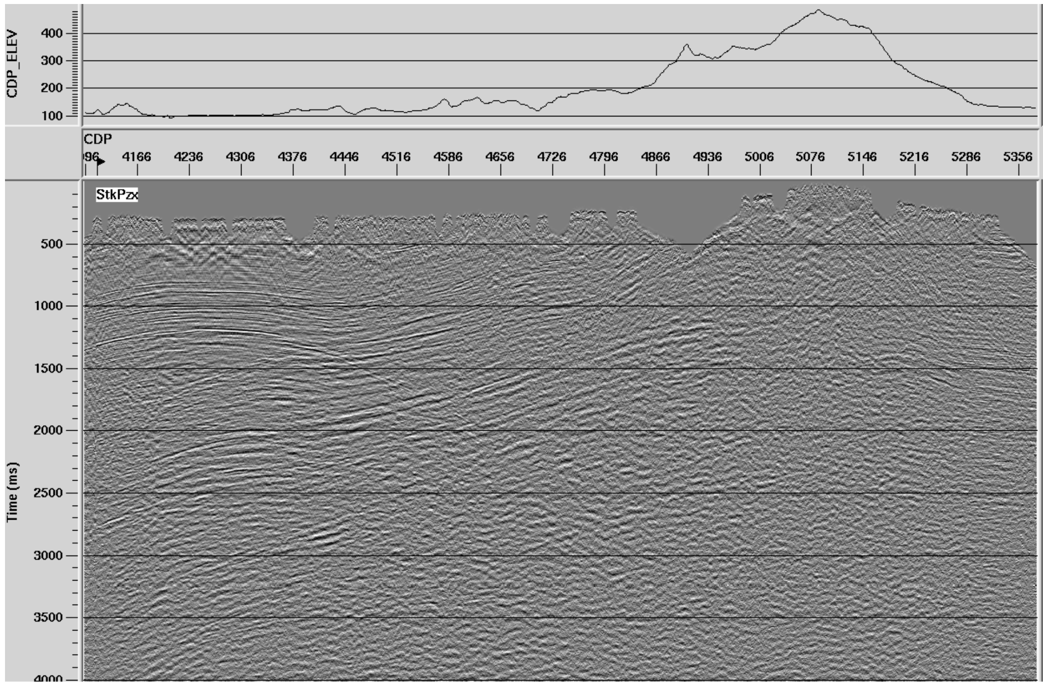

FIG. 9. Stacked section after mode-wave separation taking into account the topography.

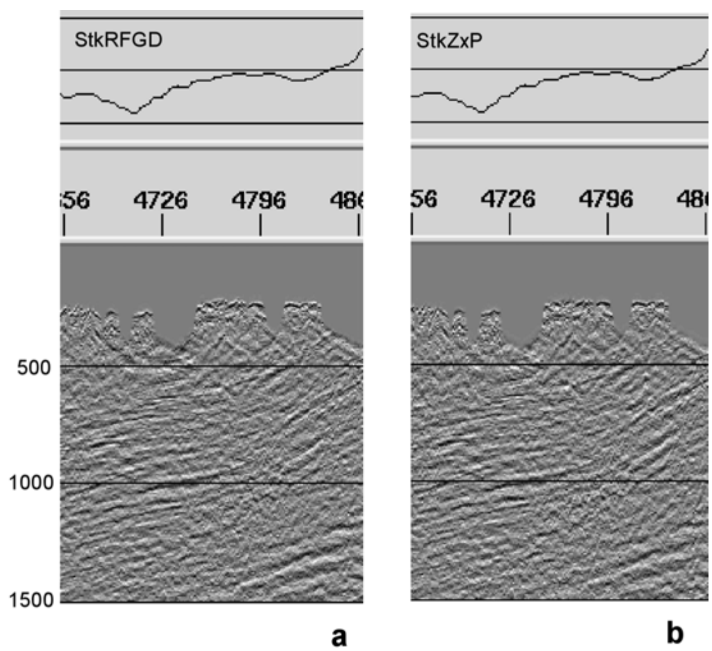

FIG. 10. Close-up of stacked sections (a) before wave mode separation and (b) after wave mode separation. Subtle differences can be observed.

DISCUSSION

The near surface model

Basic assumptions for this experiment include the near surface characteristics, thickness and velocity. A model of these characteristics is usually obtained from refraction data, or perhaps using tomography, during the statics correction process. Figure 11 shows the near velocity model obtained using tomography. A low velocity layer with a velocity of about 900 m/s and a thickness of about 10 to 20 m can be observed along the line. An uphole survey was also acquired close (2 km) to this line, for studying the near surface. The arrival data of the uphole is shown in Figure 12. In this case the velocities appear higher than in the tomography result, and the low velocity layer appears to have less than 10 m thickness.

From the events observed, the dominant frequency could be around 40 Hz, which would mean a wavelength of 20 m for 800 m/s and 40 m for 1600 m/s. It would mean that the thin layer probably wouldn't affect the incoming wave. If this is the case for our data, the effect of vertical incidence to the surface would probably be diminished or disappear, since the velocity contrast would be small for wavelength greater than 10 m and the wavelength would be too big for this low velocity layer. Consequently we possibly would have a non-normal incidence to the surface.

In this case, there would be an angle between wave and surface, and recording would be affected by the free surface effect, which depends on the angle on incidence to the surface and the near surface properties (Kahler and Meissner, 1983, Evans, 1984). Both wave modes would be merged at each trace on both components once again, but in a different way. Wave mode separation should be tried with other methods that take account of this effect, e. g the proposals by Dankbaar (1983) or by Donati (1996). Behr (2005) proposed first breaks polarization analysis to detect the orientation of the incoming wave, which would be useful in this case.

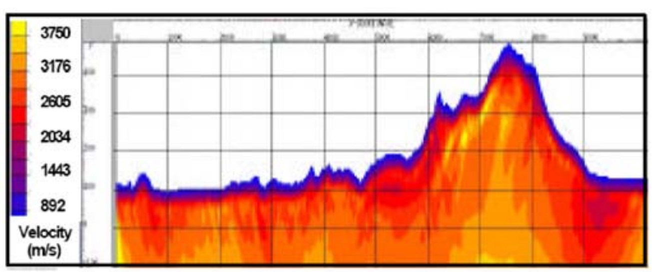

FIG. 11. Near surface velocity model from tomography (From Acevedo et al., 2006).

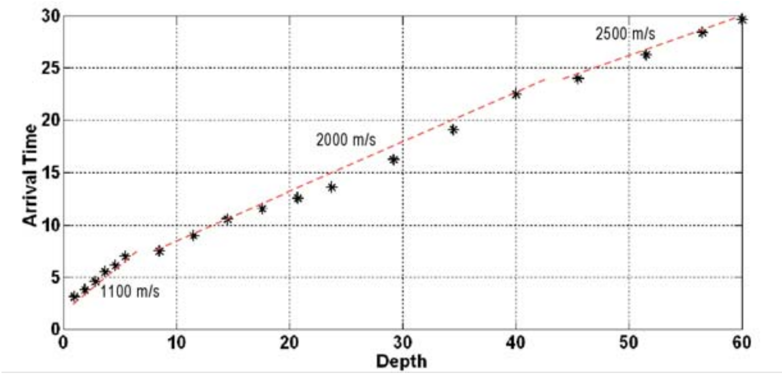

FIG. 12. Arrival times for the Uphole. Notice high velocities close to the surface.

Issues of converted wave processing in complex areas

Converted waves have information about elastic properties which would be useful in prospecting complex areas. However PS wave processing for this type of terrain is difficult. Examples of the L-99 survey data of Catatumbo area (Guevara and Cary, 2002) illustrate this point. Two approximately orthogonal lines will be considered, one in the geological strike direction and the other one in the dip direction. For the strike line, after some effort specially related to ad-hoc processes for statics correction and velocity analysis, an image was obtained. Use of a VTI anisotropy model (after Thomsen. 1999) greatly improved the image focusing, and a fracture analysis could be carried out.

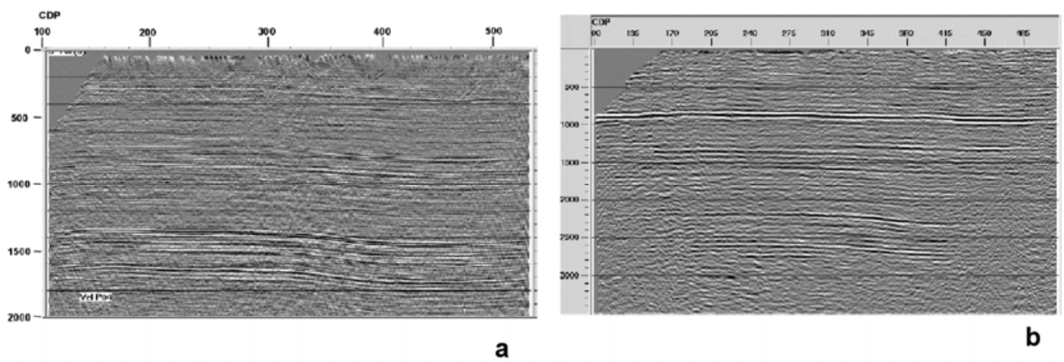

FIG. 13. Strike line of L-99. (a) P-wave stack, (b) PS-wave stack.

On the other hand the dip line was much more challenging. The statics correction method used for the strike line was harder to apply here. Even a simple dipping event creates some issues. A comparison of negative and positive offset in a preliminary stack of the L-99 dip line is shown in Figure 14. It can be observed that corresponding geological events (e. g. the top of the anticline) appear at different time and surface locations for each offset. As for comparison, Figure 15 illustrates the P-wave stack for the same line.

Statics are a main concern in the case of converted waves. More generally statics correction could be accomplished by datuming, using wave equation methods, since statics correction shows shortcoming for appropriate processing in the presence of rough topography. Prestack depth migration from surface would be the more appropriate method, since it takes into account wave propagation and earth properties. As mentioned in Gray *et al.* (2001), elastic migration is under research, and Gray (2001) suggests reverse time migration as the more appropriate for elastic field migration. However this method is not practical due to its huge demand on computer resources (at least nowadays). Backward propagation methods are an option that honor physical properties better than Kirchhoff migration and are also feasible in computation effort. Recently Margrave *et al.* (2006) and Al-Saleh (2006) presented an improved depth migration algorithm which shows appropriate features to be applied to this type of data. In a related development, Bale and Margrave (2004) and Bale (2006) presented anisotropic (HTI) elastic prestack migration, which honors vector properties of the data.

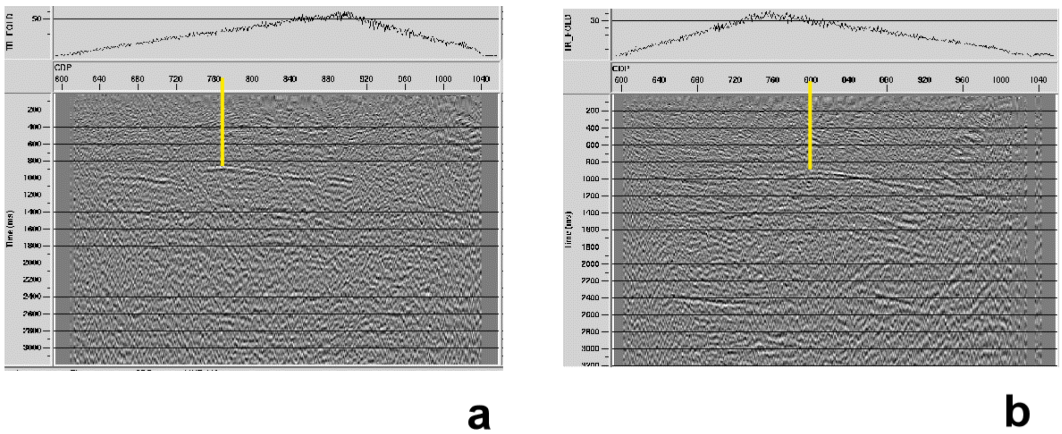

FIG. 14. Processing dip line converted wave, L-99 survey. (a) Positive offset. (b) Negative offset.

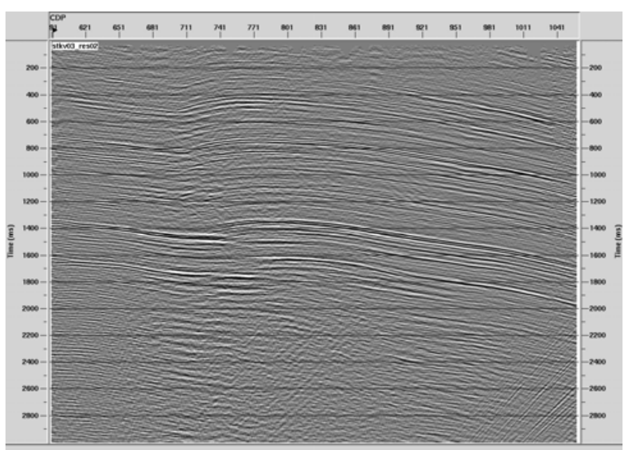

FIG. 15. P- wave section of the dip line of Figure 14.

CONCLUSIONS

The multicomponent method allows consideration of the orientation of the incident P-wave vector at the surface, so it should be possible to detect an improved P-wave signal. However, wave arrival at the surface appears more complicated than the simple model proposed, since it depends on near surface properties. It is also related to the presence of coherent noise.

Filtering of coherent noise is a mandatory first step. Methods such as radial transform, and Gabor deconvolution help with this purpose. Other authors have tested polarization filters with promising results.

The near surface velocity model for P and S waves is a basic input for processing in general and is more important in complex geology areas.

Converted wave processing in complex areas present additional challenges compared to converted wave processing in more quiet areas. The dependence of basic processing on geological properties is difficult to overcome with methods other than prestack depth migration.

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