ORIGINAL ARTICLE

A raypath-consistent receiver correction in PS converted wave processing through seismic interferometry: New application for tropical zones

Andrés Salamanca[1,*], Luis Montes[2]

1. Servicio Geológico Colombiano, Diagonal 53 # 34 - 53, Bogotá, Colombia, 111321

2. Universidad Nacional de Colombia, Sciences Faculty, Geosciences Department, Group of Geophysics, 30th Avenue and 45th Street, Bogotá, Colombia, 111321

* afsalamancas@unal.edu.co

Electronic supplementary material:
N.A.

OPEN ACCESS

Abstract

The estimation of static corrections is an issue still unsolved for PS converted wave processing. Due to the PS converted wave usually arriving at the surface at non-zero angles, the surface consistent approach is no longer valid, and corrections become non-stationary, i.e. the correction is not static. Seismic interferometry is used in receiver gathers transformed to the radial domain to estimate functions that contain the delay caused by the weathered layer, considering the emergence angle of the PS converted wave. Inverse filters, derived from these functions, are applied by convolution to the raw traces to supply traces corrected for weathering layer effects. Seismic interferometry was satisfactorily tested in two synthetic models and then applied to a 2C seismic line from the Llanos Basin (Colombia). This is the first application of the technique in Colombia, initially developed for permafrost zones, with different assumptions and surface complexity; and it resulted in an improved PS converted wave image.

Keywords: seismic interferometry; image processing; PS converted-waves

Introduction

Static corrections, which can reach up to 100 ms for receivers, are an inherent problem of PS converted wave (PS-CW) processing that has not been completely solved. The difficulties related to receiver corrections include the masking of the first arrivals of the refracted PS-CW by surface waves, and the low energy of the refracted PS-CW, which prevents the use of refraction methods. Due to several factors such as water level, permafrost, and calcareous soils, among others, the V_p / V_s relation in the weathered layer can be non-uniform and as high as 10, that makes the P wave statics less useful for the correction of PS-CW statics.

There are two main approaches to the calculation of PS-CW statics. The first one requires a known shear velocity model, usually obtained by direct measurements (borehole data, refraction, Rayleigh wave inversion). The second

one assumes a surface consistent model, as in the statics correction methods available for acoustic wave processing (Guevara *et al.*, 2015). However, the surface consistent assumption is not always valid, and, in the case of PS-CW, it causes error during processing. Seismic interferometry, an adaptation of optical interferometry (Wapenaar *et al.*, 2010a; Wapenaar *et al.*, 2010b), creates new seismic data from recorded wave fields through the correlation of seismic traces. Seismic interferometry has been used to find and apply receiver corrections in zones with complex weathering (Bakulin & Calvert, 2006). To avoid the surface consistent assumptions, an adaption of seismic interferometry, referred as raypath interferometry uses constrained common emerging angle gathers instead of common converted point gathers - CCP gather for correcting the PS-CW image (Henley, 2012).

Henley (2012) developed raypath interferometry for zones with permafrost layer (high velocity). In this research, seismic interferometry was applied to a PS-CW dataset acquired in the Llanos Basin, Colombia, where different conditions are present. For example, the near-surface has a low-velocity layer composed of clay matrix and sand channels, typical of tropical soils. As a matter of experience, the available static methods do not properly correct the distortion caused by the weathered layer in PS-CW images in the Llanos basin.

Materials and methods

The stability and robustness of raypath interferometry was validated by testing two models that simulated the geological features of the Llanos Basin, e.g.: a weathered layer with water level at depths between 20 m and 50 m, sand channels with low seismic velocity in a clay matrix (Guayabo Formation) and different values of thickness and depth for the weathered layer. From now on, the weathered layer will be called LVL because it is generally a Low-Velocity Layer. As shown in **Fig. 1 A**, the first model contains an LVL with a thickness between 180 m to 250 m, and two flat reflectors at depths of 400 m and 700 m. The LVL of Model 2, which is shown on **Fig. 1 B**, has a water level at 50 m of depth with a thickness between 110 m to 160 m and lateral velocity variations represented by sand channels, whose shear velocity and acoustic velocity are 400 m/s and 900 m/s, respectively. There are two reflectors cut by a fault in the middle of the section below the LVL. Fig. 1 A and 1 B indicate the velocity values $V_s(x, z)$ and $V_p(x, z)$ for both models.

Both synthetic models were simulated, based on a finite difference modeling algorithm, with a split-spread pattern with 480 channels, a maximum offset of 2 400 m, a receiver interval of 5 m, and a source interval of 20 m. A 35-Hz Ricker impulse was used as wavelet with a sample interval of 2 ms. Raypath interferometry was then applied to a two-component seismic line located at Quifa Project and acquired by Pacific E&P Corporation. The Quifa area of the
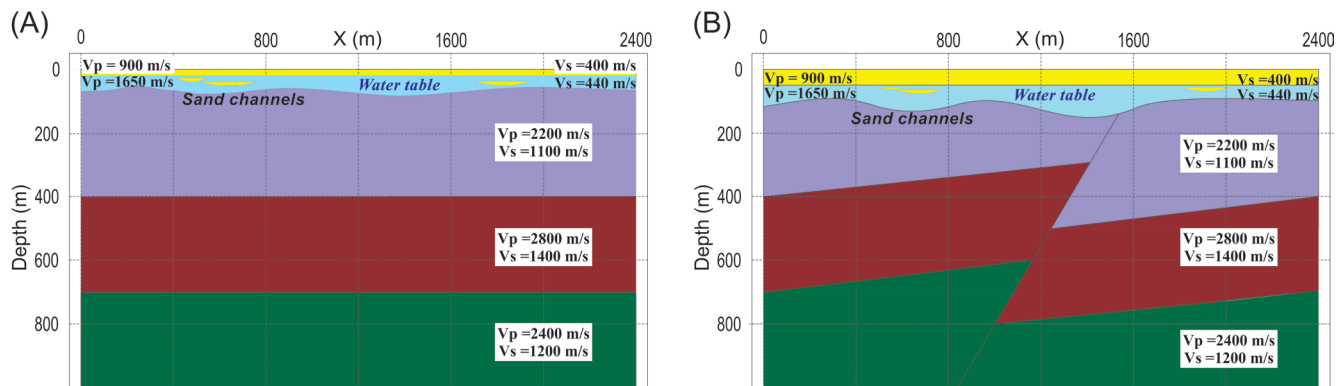
Figure 1. Synthetic models. **A)** Model 1 consists of 3 layers under a weathered layer with an undulating base, a water table and some sand lenses. **B)** Model 2 has a thicker weathered layer, a deeper water table, and three dipping layers cut by a fault.

Llanos Basin features Late Eocene to Oligocene formations where heavy oil deposits have been found, and the presence of hydrocarbons is associated with channel deposits. The provided PS-CW image was compared with a previous image obtained (Buitrago, 2016) through a conventional PS-CW processing sequence (Lu & Hall, 2003).

Theoretical framework

A static correction is a vertical time shift applied to a seismic trace to correct the LVL effects associated with its changes in composition, elevation, thickness and lateral facies (Sheriff, 1991). The surface consistent correction procedure assumes that the raypaths through the LVL layer are near vertical, an approximation that is only valid when the velocity of the LVL layer is much smaller than the velocity of the underlying layer. This condition is unusual in the Llanos Basin, where the path followed by PS converted waves across the LVL can reach emergence angles higher than twenty degrees, due to smooth velocity variations. In this case, the surface consistent approximation is no longer valid, and the receiver correction becomes non-stationary, i.e. a static correction cannot correct distortions along the whole PS-CW trace (Cova *et al.*, 2017). The raypath consistent assumption, which replaces the surface consistent constraint, is implemented through the radial trace transform (Claerbout, 1975), which extracts the plane wave components of the wavefield and provides common ray parameter gathers. Common shot gathers $S(x, t)$ are mapped from the offset-time domain (x, t') to common emergence angle gathers $S'(v, t')$ in the radial domain (θ, t) through the

transform: $R\{S(x,t)\} = S'(v,t')$, $t = t'$, $\theta = Tan^{-1}(x/t)$ or $t = t'$, $v = x/t$.
Fig. 2 A illustrates the raypaths for a common shot gather and **Fig. 2 B** shows the raypaths for a common ray parameter gather, where rays emerge at the same angle. Fig. 2 C illustrates the process of extracting radial traces from a shot gather where the amplitude of each sample is represented by a color. The process includes a) straight lines with different slopes or velocities are traced from the origin, b) the travel times and amplitudes that each line intercepts constitute the new trace in the radial domain with a constant velocity established by the slope. The mapping is well-behaved everywhere except at the origin, but the discrete sampling is not the same in both domains, and interpolation is required from one domain to the other to avoid aliasing.

Fig. 3 shows the reflection seismogram recorded on an LVL that overlays the second layer. To remove the travel time across the LVL, the g trace is shifted by time T(ACB) and the resulting trace is kinematically equivalent to the h trace recorded as if a virtual source and receiver were redatumed to the base of the LVL. Similarly, this process is obtained by means of cross-correlation, a key concept for interferometry. The cross-correlation of the f trace with the g trace is equal to the h trace. For raypath interferometry, the uncorrected trace represents the g trace. The trace f is an operator obtained by the cross-correlation of the g trace with a pilot trace. Applying the operator by cross-correlation (or its time-reverse version by convolution), it corrects the g trace.
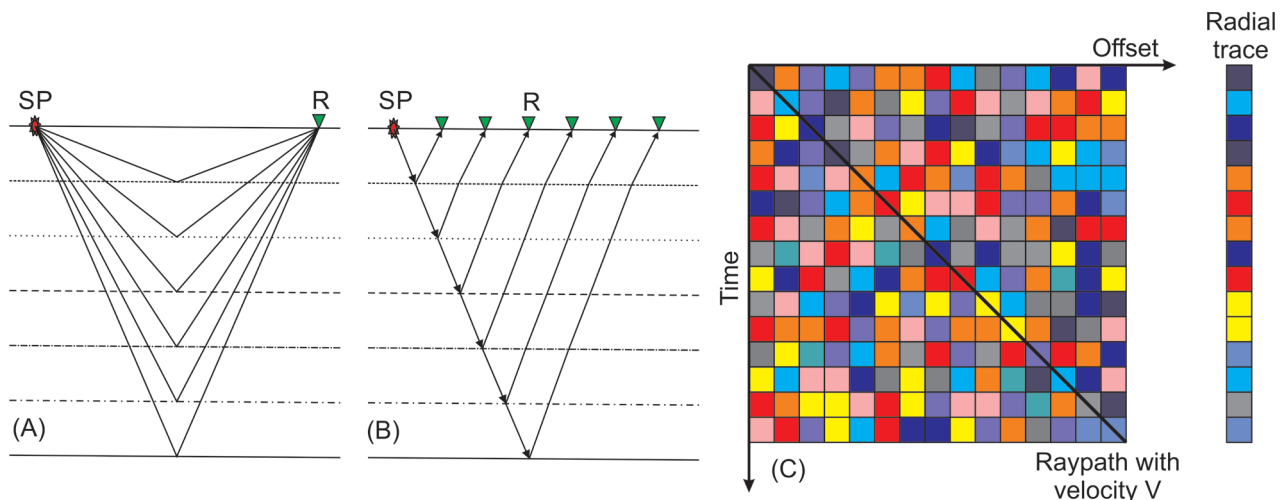

Figure 2. The radial domain. **A)** Paths followed by rays from the source to a unique receiver. **B)** Paths followed by rays with a ray constant parameter. **C)** Common shot gathers where each sample is represented by a color and the slope of the traced line defines a velocity V. The samples defined by the line compose the new radial trace.
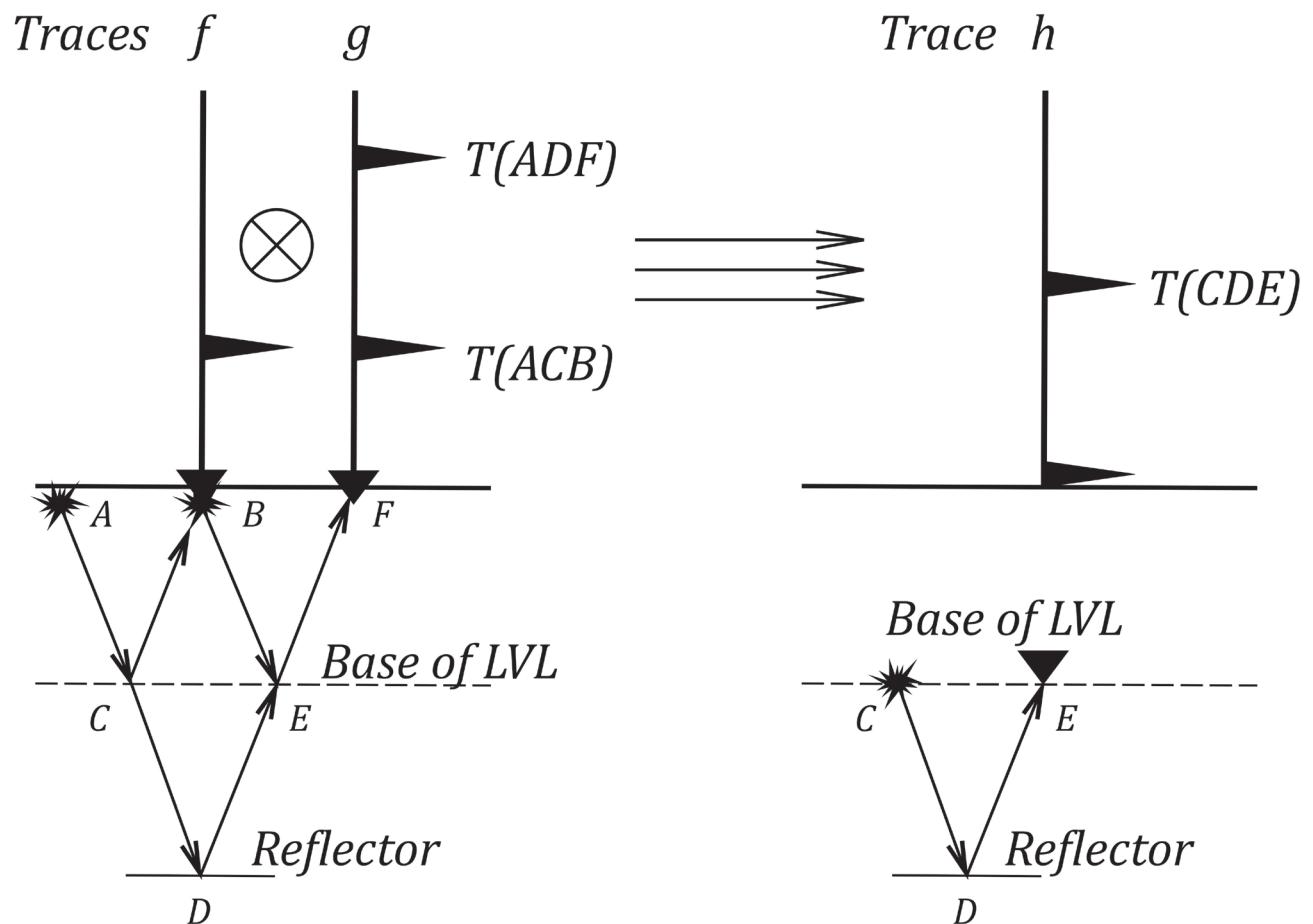
Figure 3. The cross-correlation of the f trace with g trace provides the h trace, that results from time shifting the g trace the time interval T(ACB), a static correction process. Adapted from Schuster (2009).

PS converted wave processing

The input for the receiver correction of the LVL effects for PS-CW is the NMO corrected set of common receivers (CR) gathers with source statics provided previously by acoustic wave processing. The PS-CW processing sequence applied follows the guidelines proposed by Lu & Hall (2003), but the receiver statics module is replaced by the interferometry approach, whose workflow is depicted in Fig. 4. On the other hand, the PS-CW image obtained by Buitrago (2016) followed a modified Lu & Hall (2003) sequence. The traces of CR gathers (including a deconvolution and band pass and f-k filters to attenuate the coherent noise) are sorted by ascending offsets and then transformed to the radial domain. Later, the radial traces are sorted by ray parameter and receiver to create common angle (CA) gathers, where each ray parameter represents an exit angle. The traces of CA gathers contain the seismic response associated with rays emerging with the same angle and transforming the LVL distortion into a stationary one. Now, the cross-correlation is used to identify the effects

caused by LVL. The pilot traces that compose the reference wavefield are generated by a partial running stack of the original traces over an aperture to create a smoothed model of the section. Subsequently, all the traces are correlated with their corresponding pilot traces to capture the delay times and
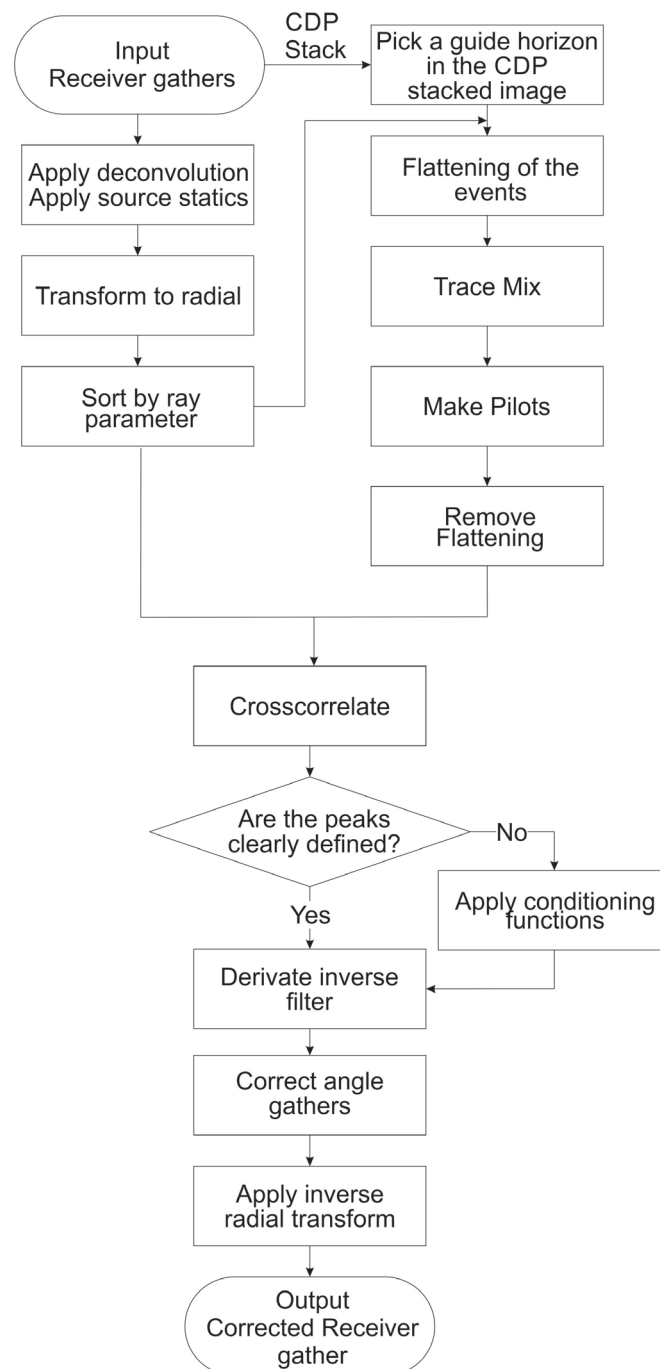

Figure 4. Workflow of seismic interferometry to correct the effect of the LVL for the PS converted wave.

phase distortions produced by travel through the LVL. The time length of the correlation should be at least twice the largest expected static of the survey. Conditioning functions can be applied to the cross-correlations to emphasize the strongest correlations and to deemphasize correlations lying farthest from zero shift.

Additionally, inverse filters derived from final correlation functions are applied to each trace in the original common angle gathers by convolution to remove the delays and phase distortions caused by LVL. Each inverse filter corrects a single trace in a CA gather, which produces a significant improvement in the continuity of reflectors. During the interferometric process, the entire correlation function is used because it includes the differences in phase and amplitude associated with the travel through the LVL. Finally, the CA gather is sorted and transformed to the $x - t$ domain by the Inverse Radial Transform in order to produce a CR gather. The final PS-CW stacked section is obtained by stacking all the resulting CR gathers.

Results

Stacked PS-CW sections of Models 1 and 2 obtained using interferometry were compared with stacked PS-CW sections with a simple correction based on the Vp/Vs average ratio for the weathered layer. Initially, long-period statics were observed for Model 1 due to the thickness and lateral velocity variations in the weathered layer. Moreover, short-period statics were added intentionally during processing. **Fig. 5 A** depicts the result after a correction based on P wave statics multiplied by a Vp/Vs ratio. Fig. 5 B shows the stacked PS-CW image of Model 1, after raypath interferometry, where the removal of short-period and long-period statics can be observed.

The initially corrected PS-CW stacked section of Model 2 shows mild undulations that are still affecting the reflectors (**Fig. 6 A**). These undulations are related to changes in depth and thickness, a lateral variation of velocity produced by some channels, and the water table in the weathered layer. Fig. 6 B shows the stacked section corrected by interferometry, where the geometry of the reflectors and the fault plane is improved. A depth migration was necessary to locate both reflectors in the right position and attenuate the fault shadow effects.

Fig. 7 A shows the P wave stacked section of the real data obtained using a conventional process of static correction where weathering effects are partially corrected. Some residual effects are observed in the Carbonera Formation reflectors (indicated by the arrows), and in the lack of continuity of some reflectors in the same formation. Fig. 7 B shows the PS-CW stacked section without any correction (neither source nor receiver) and indicates large weathered level effects (more than 100 ms).
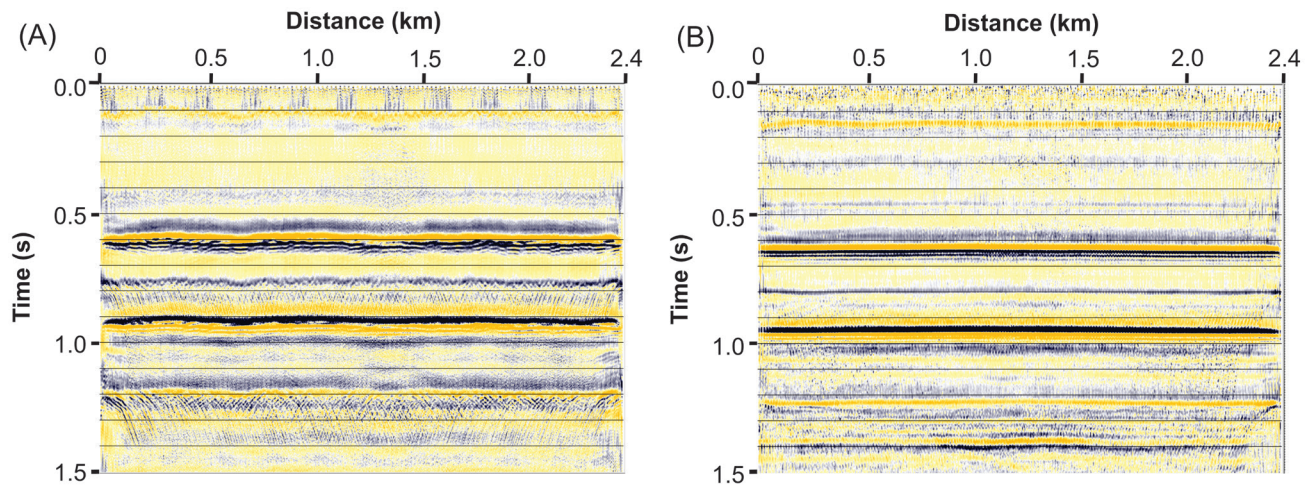
Figure 5. Model 1 results. **A)** PS-CW stacked section of Model 1 obtained after conventional static correction process. **B)** PS-CW stacked section obtained by interferometry showing the real structure of the reflectors.

As illustrated in **Fig. 8 A**, the PS-CW stacked image obtained by the conventional static correction, a modification of Lu & Hall (2003) sequence that uses the P wave receiver statics at the receiver statics calculation onset,
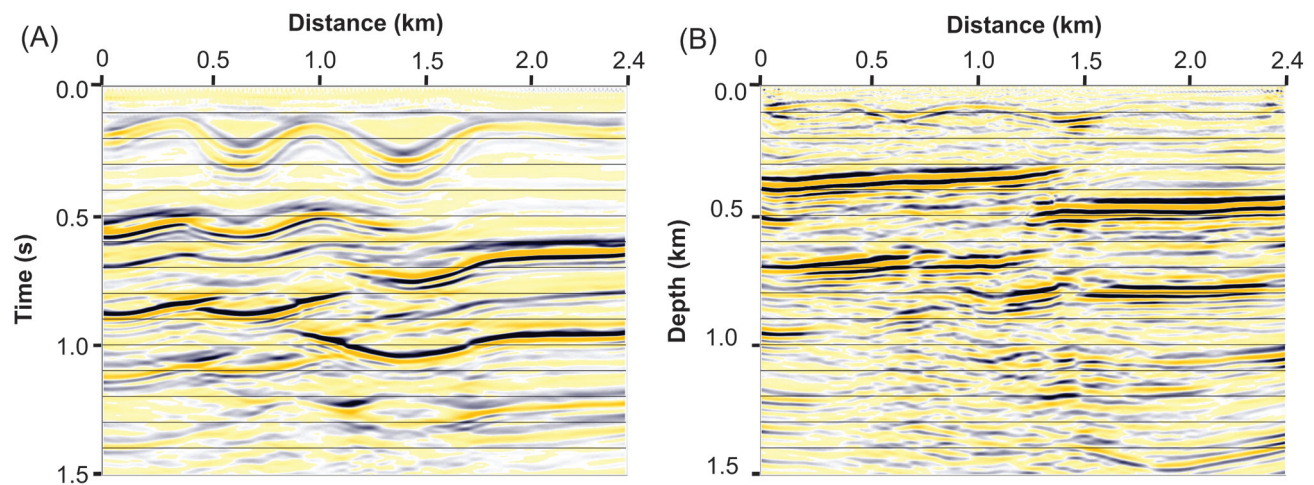

Figure 6. Model 2 results. **A)** PS-CW stacked image of Model 2. It is affected by long-period statics due to changes in thickness and lateral velocity in the weathered layer, and fault shadow effects. **B)** PS-CW depth migrated image of Model 2 obtained by interferometry. The depth migration attenuates the fault shadow effects.
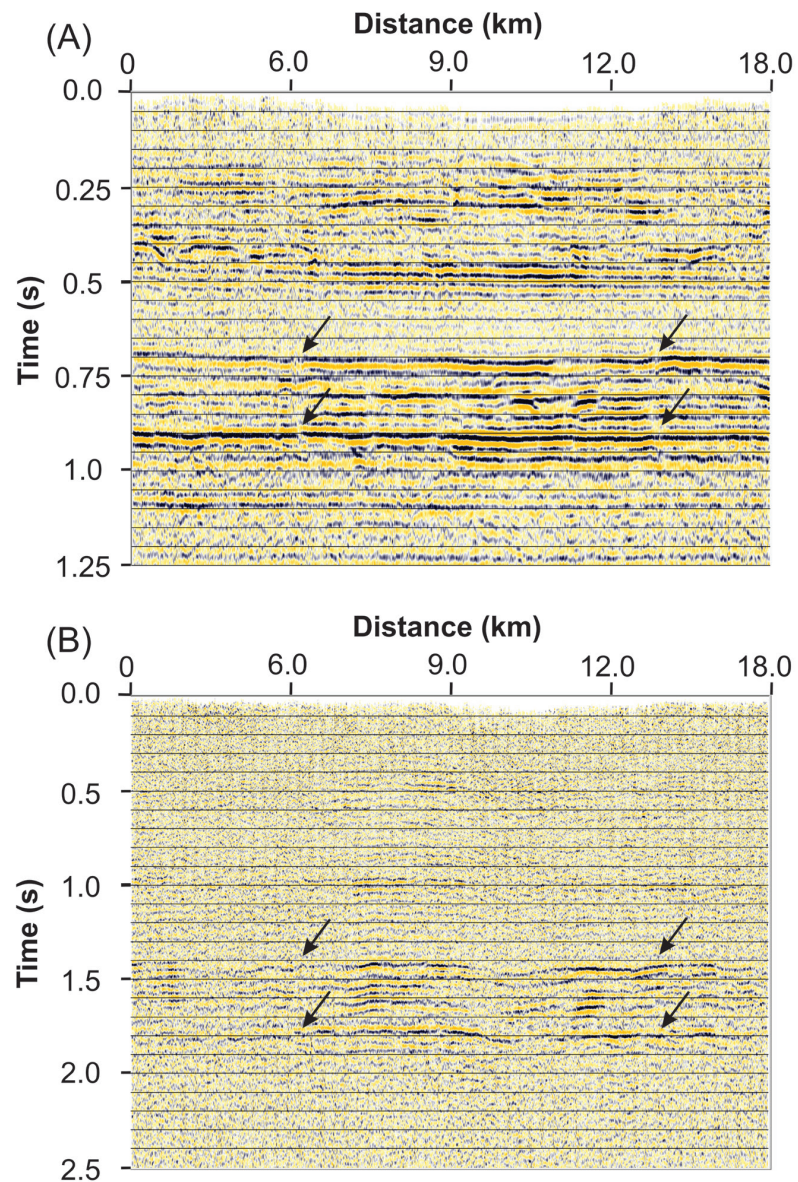
Figure 7. Field data prior the results. **A**) Stacked section of P wave for a set of field data acquired in the Llanos Basin (Colombia), obtained by Buitrago (2016). **B**) PS-CW stacked section without statics.

is still affected by some weathered level effects. This is caused using P wave statics that transfer the deficiencies of the P wave static correction process to the PS-CW image. This is indicated by the presence of the same statics of the P wave stacked image. Finally, the results of the interferometric application are shown in Fig. 8 B, where the residual effects have been removed and the continuity of the reflectors is improved.
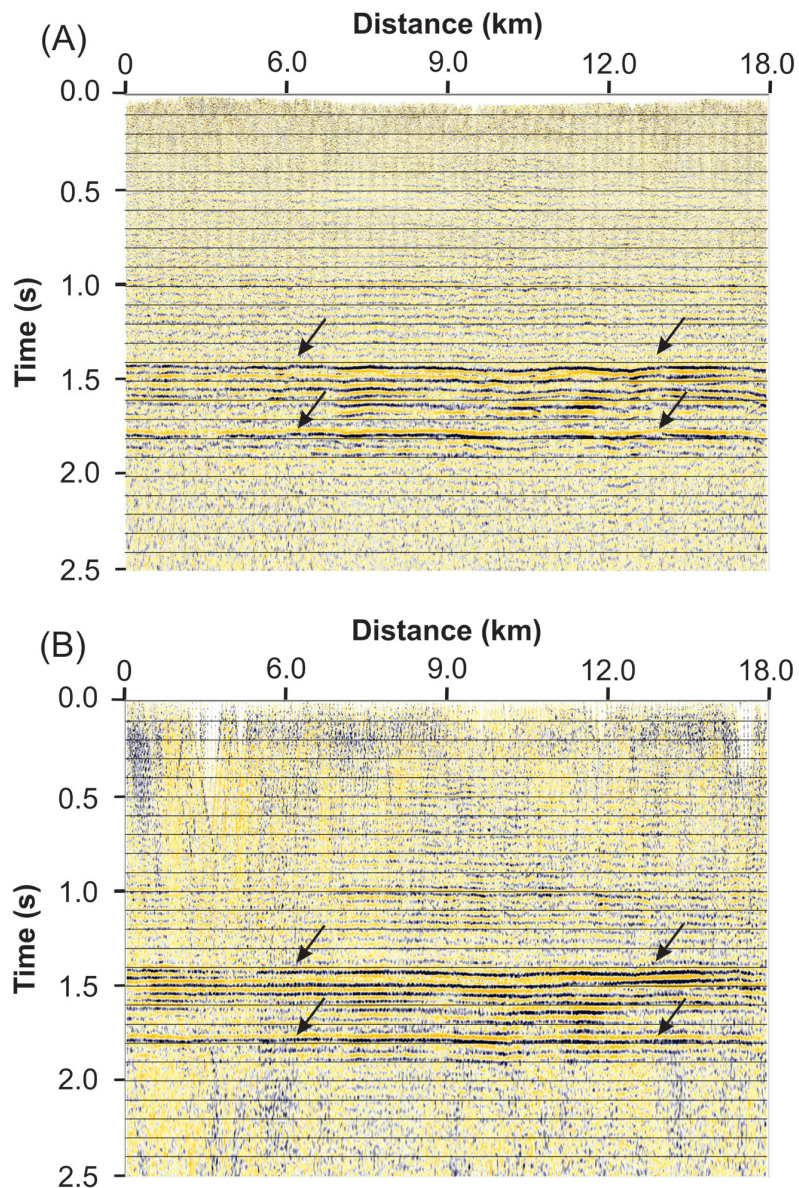
Figure 8. Interferometry results. **A**) PS-CW image corrected by the conventional process of Lu and Hall (2003) obtained by Buitrago (2016). **B**) Result of the Interferometry used to solve receiver statics for the PS-CW image.

Discussion

Interferometry is a good option to obtain a high-quality PS converted wave image for some problematic zones with gas-bearing layers or highly complex LVL, where it may be difficult to obtain a P wave image.

There are two weaknesses related to raypath interferometry. Firstly, the amplitude and phase changes produced by the application of the inverse filters to the raw seismic traces may make them inappropriate for seismic inversion procedures or amplitude attribute analysis. Cova *et al*. (2018) used a τ-p

transformation instead of the radial trace transformation, but they found a difficulty with the potential loss of data fidelity. Accordingly, other techniques that do not modify the amplitude and phase spectrum of the original data should be researched.

Secondly, interferometry, as used in this research, is not currently recommended for zones with faults and structural complexity (e.g. pinch-outs). The picking of the guide horizons becomes problematic in that case.

Conclusions

The reliable estimation of receiver statics during the PS converted wave processing improved the coherence and resolution of the stacked images. The seismic interferometry process improved the quality of the stacked section by removing the effects on the PS-wave horizons caused by the raypath's travel through the weathered layer. One advantage of this technique is that it does not require picking first breaks, which can be very subjective. This technique is appropriate for places where the surface consistent approximation is not satisfactory, like in the Llanos Orientales Basin. Finally, the results of this research depicted a new approach to solve the weathering effects for PS converted wave experiments not only for zones with permafrost but also with zones with tropical soils, which have much different conditions and physical properties.

Acknowledgements

Conflict of interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent arrangements), or non (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

References

Bakulin A, Calvert R. The virtual source method: Theory and case study, *Geophysics*, 71(4): SI139-SI150. 2006.

doi: 10.1190/1.2216190

Buitrago C. Caracterización de formación mediante relación Vp/Vs obtenidas con procesamiento de ondas P y PS. Ms. Thesis, Universidad Nacional de Colombia, Bogotá, Colombia. 2016.

http://www.bdigital.unal.edu.co/57059/7/CarolinaBuitragoTorres.2016.pdf

Claerbout J. Slant-stacks and radial traces. Technical report, Stanford Exploration Project report 5, Stanford University. 1-12. 1975.

Cova R, Henley D, Wei X, Innanen, K. Receiver-side near-surface corrections in the τ-p domain: A raypath-consistent solution for converted wave processing, *Geophysics*, 82(2): U13-U23. 2017.

doi: 10.1190/geo2016-0278.1

Cova R, Henley D, Innanen KA. Computing near-surface velocity models for S-wave static corrections using raypath interferometry, Geophysics, 83(3): U23-U34. 2018.

doi: 10.1190/geo2017-0340.1

Guevara S, Margrave G, Isaac H. A method for converted wave receiver statics correction in the CRG domain, *SEG Technical Program Expanded Abstracts*, 2134-2137, 2015.

doi: 10.1190/segam2015-5906814.1

Henley D. Interferometric application of static corrections, *Geophysics*, 77(1): Q1-Q13. 2012.

doi: 10.1190/geo2011-0082.1

Lu H, Hall K. Tutorial: Converted wave (2D PS) processing, *Crewes Research Report*, 15(1): 1-18. 2003.

Schuster G. Seismic Interferometry, Cambridge University Press, New York, United States of America, 274 pp. 2009.

Sheriff R. Encyclopedic Dictionary of Applied Geophysics. Tulsa, OK: Society of Exploration Geophysicists, 1991. First edition.

Wapenaar K, Draganov D, Snieder R, Campman X, Verdel A. Tutorial on seismic interferometry. Part I: Basic principles and applications, Geophysics, 75(5): 75A195-75A209. 2010a.

doi: 10.1190/1.3457445

Wapenaar K, Slob E, Snieder R, Curtis A. Tutorial on seismic interferometry: Part 2 - Underlying theory and new advances, Geophysics, 75(5): 75A211-75A227. 2010b.

doi: 10.1190/1.3463440

Corrección por receptor consistente con la trayectoria de rayo en el procesamiento de ondas convertidas PS a través de interferometría sísmica: nueva aplicación para zonas tropicales

Resumen: La estimación de las correcciones estáticas es un tema aún no resuelto en el procesamiento de ondas convertidas PS. Debido a que estas ondas usualmente llegan a superficie con ángulos diferentes a cero, la aproximación de consistencia en superficie no es válida, y las correcciones se convierten en no estacionarias, es decir, la corrección no es estática. La interferometría sísmica se usa en arreglos de receptores transformados al dominio radial para estimar funciones que contienen el retraso causado por la capa meteorizada, considerando el ángulo de emergencia de la onda convertida PS. Los filtros inversos, derivados de estas funciones, se aplican por convolución en las trazas crudas para suministrar trazas corregidas por los efectos de la capa meteorizada. La interferometría sísmica se probó satisfactoriamente en dos modelos sintéticos y fue después aplicada a una línea sísmica de dos componentes de la cuenca de Los Llanos Orientales (Colombia). Esta es la primera aplicación de la técnica en Colombia, inicialmente desarrollada para zonas con permafrost, con diferentes suposiciones y complejidad superficial, con la que finalmente se obtuvó una imagen mejorada de onda convertida PS.

Palabras clave: Interferometría sísmica; procesamiento de imágenes; ondas convertidas PS.

Correção por receptor consistente com a trajetória de raio no processamento de ondas convertidas PS por meio de interferometria sísmica: nova aplicação para zonas tropicais

Resumo: A estimação das correções estáticas é um tema ainda não solucionado no processamento de ondas convertidas PS. Devido a que essas ondas usualmente chegam a superfície com ângulos diferentes a zero, a aproximação de consistência na superfície não é válida, e as correlações se convertem em não estacionarias, ou seja, a correlação não é estática. A interferometria sísmica se usa em ajustes de receptores transformados ao domínio radial para estimular funções que contém o retraso causado pela capa meteorizada, considerando o ângulo de emergência da onda convertida PS. Os filtros inversos, derivados de essas funções, se aplicam por convolução nos traços brutos para fornecer traços corrigidos pelos efeitos da capa meteorizada. A interferometria sísmica provou-se satisfatoriamente em dois modelos sintéticos e depois foi aplicada a uma linha sísmica de dois componentes da bacia dos LLanos Orientales (Colômbia). Esta é a primeira aplicação da técnica na Colômbia, inicialmente desenvolvida para zonas com permafrost, com diferentes suposições e complexidade superficial, com a qual finalmente se obteve uma imagem melhorada da onda convertida PS.

Palavras-chave: Interferometria sísmica; processamento de imagem; ondas convertidas PS.

Luis Montes-Vides

Is a Physicist, and M.Sc. in Computer Science from the Universidad Nacional de Colombia, with a Ph.D. in Geophysics from the Universidade Federal do Pará (Brazil) and a post-doc stage at the ICP. He is an associate professor at the Universidad Nacional de Colombia, where supports the undergraduate program in Geology, the graduate programs in Geophysics and the Doctorate in Geosciences. Currently, his areas of research comprise seismic prospecting, seismic inversion, seismic modeling, and applied computing mathematics.

Andrés Felipe Salamanca
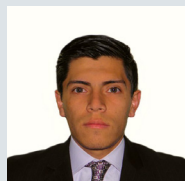
Is a Geologist, and M.Sc. in Geophysics from the Universidad Nacional de Colombia. He currently works at the Colombian Geological Survey as a researcher in the Geophysics Group. His areas of research are seismic processing, seismic inversion, potential methods, and near-surface methods. Andres is the CEO of GIDCO, a company of geophysics that prospects water resources, water pollution and geotechnical studies along Colombia.