Seismic lithology discrimination in complex fluvial stratigraphy: Tenerife 3D 3C Survey, Middle Magdalena Valley (Colombia).

Summary
Middle Magdalena Basin is an active producing region in Colombia, that in last years has been chosen to be developed by water and steam flooding. However complex stratigraphy has prevented to have detailed reservoir static models. Tenerife 3D3C experiment was conducted in 2009 as a first integral (from acquisition design to interpretation) application of multicomponent technology to discriminate lithology (sand and clays) in a Colombian field. Acquisition design resulted in a 480,000 traces/Km² density, 22.3 Km² survey. Petrophysics showed that density is the best Vclay discriminant so the main objective was to obtain a good density estimation from surface seismic. Density from PP+PS joint inversion was more detailed and stable than density derived from PP simultaneous inversion and is currently guiding the location of new wells in the oilfield.

Introduction
Middle Magdalena Basin (Colombia) is a 34,000 km² intermontane area with 1900 Mbls discovered oil reserves that pioneered oil production in Colombia. Reservoir units are Paleocene-Miocene sandstones deposited in braided to meandric rapidly varying fluvial systems (Barrero et al, 2007). More than 40 oil fields in this basin produce mainly black oil (19°-28° API) and marginally heavy oil and gas. Most of fields have been exploited by primary production, but currently water flooding and steam injection is beginning to be proved in several oil fields. With the beginning of secondary production and the rapid production declining in some of oil fields, a better characterization of reservoir architecture is needed all over the basin. One of the common problems to all oilfields is lithological classification. To take advantage of the difference in reflection response of clays and sands, a multicomponent (3D3C) seismic pilot experiment was proposed having as main objective lithology discrimination.

A dozen 3D3C surveys have been acquired in Colombia, with little success. In most cases horizontal components were not processed nor interpreted and a posterior evaluation has shown that survey acquisition parameters were not suited to converted waves, but gave acceptable results for P waves. The Tenerife 3D3C survey was acquired in 2009 as a first converted-wave oriented (from acquisition design to interpretation) experiment in Colombia.

Tenerife Oilfield
Tenerife is a small (OOIP 20 Mbls) producing field located in roughly flat terrane 10 Km SW from the giant La Cira Infantas field and being a miniature representative of the stratigraphical complexity of all Middle Magdalena Valley productive units. This field includes two producing oil wells and one dry well.

Reservoir units are the sandstones deposited during the Paleogene in channel systems in the Mugrosa Formation (7000 ft deep). Reservoir rocks were deformed by a transpressive fault system that generated a compartmentalized, mixed structural-stratigraphic trap. As in all basin, a detailed description of the complex distribution and connectivity of fluvial sandstones is a key component of the reservoir characterization. Sand units average thickness is 5 m, well below seismic resolution. However amalgamated sand bodies can reach locally 30 m.

Figure 1: Location of Tenerife seismic experiment (red square). In green are presented the main oilfields in Middle Magdalena Valley Basin, all producing from fluvial reservoir, stratigraphically complex units.

Acquisition Design
Survey design followed closely the methodology described by Galbraith (2004). One key point at this approach is that detectability of petrophysical properties controls the required signal to noise ratio (S/N) and subsequently the recommended trace density. The steering petrophysical properties for survey design were clay content, porosity and fluid saturation. Elastic modeling showed that PP-wave AVO was sensitive to porosity changes. Clay content at wells required multi-log analysis due to the difficulty to interpret gamma-ray in producing intervals. The main clay
content discriminant parameter resulted to be density. Interestingly, elastic modeling from well logs showed a clear advantage for joint PP+PS density inversion compared with PP prestack density inversion which justified the use of multicomponent data. Fluid substitution analysis showed that neither PP nor PS waves could distinguish oil saturation unless non economical high trace density were used in the survey.

Density log data was unavailable for all Tenerife wells, thus a big effort was performed by the petrophysics group to find a plausible synthetic density log by using modified Gardner or Neural Network approaches.

Middle Magdalena Valley is known for near surface complexity due to laterally varying thick recent fluvial deposits, conglomerates presence, dense vegetation and intense weathering. Near surface conditions were crucial in receiver interval definition. Source generated noise modeling show that to optimally attenuate ground-roll a 15m - 20m receiver interval was required. In a conservative manner, use of polarization filters that could allow increase receiver spacing was dismissed during the acquisition design stage, due to the uncertainty of its success in complex near surface conditions.

In an orthogonal geometry, receivers were planned WNW-ESE and sources NNE-SSW both with 20 m spacing. A 280m and 360m receiver line and source line interval respectively were defined. A patch including 12 receiver lines (3000 active receiver stations) allowed reaching a 480,000 traces/Km² density and 3.4 Km as maximum effective offset. An acquisition area of 22.6 Km² illuminated the zone of interest including the two producing wells. Ray-tracing modeling at target horizon showed that footprint could be especially strong for PS wave (Duarte et al., 2011). To mitigate this effect we displaced source positions randomly on a 5m radius as determined by wavefront modeling.

Field acquisition

The Tenerife experiment included the acquisition of surface seismic, well seismic, shallow up-holes and new well logs. Surface seismic consisted in a 22.6 Km² 3D3C survey and a 9 Km long 2D3C test line, both using Sercel DSU3-428 accelerometers. Field operations started at September 2009 and finished at January 2010. Well seismic acquired in Tenerife included vertical and offset VSP and shear wave logs at Tenerife-1 and Tenerife-2 wells.

Due to government regulations, only explosive sources are permitted in 3D seismic surveys in Colombia. Complexity in the near surface encouraged us to perform the lithological description of about 500 shot holes (ranging from 10m to 20m depth), to complete a detailed 1:10,000 surface geology cartography and to acquire two 60 m depth multi-azimuth walk-away 3C up-holes (Guevara et al., 2011).

Tenerife 3D3C survey was twice as expensive as conventional surveys in the same region, so one of our challenges was to show its value-added to our managers.

Converted wave data processing

Source generated noise was particularly challenging in Tenerife area. The appearance of refracted PS waves enlarged considerably the area of coherent noise in horizontal components. Additionally, strong back-scattered surface wave energy is present in most of shot records. Several coherent noise attenuation techniques were applied in shot, receiver and cross-spread domains. As converted waves dominant frequency is within the source generated noise bandwidth, the most effective methods were adaptive filters (Le Meur and Traomilin, 2008) and radial transform filters (Henley, 2003) in cross-spread domain. Some attempts were done to apply polarization filter on the data. However they were only locally successful and could not be applied in the whole data.

Statics were computed using five different methods: P-wave statics scaled by a constant, horizon guided, receiver functions, PS refraction statics and Montecarlo statics (Le Meur et al., 2011). All methods showed high static variability and values near 100 ms. For a comparison between different receiver statics methodologies in this
Two horizons were chosen as guide: first a shallow (1.0 s PS time) and strong reflector (Colorado Formation top) and the regional Eocene discordance (2.6 s PS time) which is the strongest reflector in PP and PS data. Vp/Vs varied from 2.8 for the shallower reflector to 2.2 for the discordance.

We followed the Li and Yuan (2001) approach for converted wave prestack time migration that includes three variables to define the converted wave velocity field: , or the hyperbolic CCP gathers "stack" velocity, or Vp/Vs ratio for "zero offset" PP and PS times and or anisotropy term that was computed comparing common features in positive and negative offsets. Figure 3 and Figure 4 compares the same in-line for PP-wave and PS-wave final PSTM images.

PP+PS Joint inversion: preliminary results

Structural interpretation obtained from PP wave image has allowed proposing a new development plan for the field with 22 new wells. PP data was used to extract intercept and gradient AVO attributes. Sands in Mugrosa formation behaves as Class 2, inverting polarity. We interpret the structure in the intercept volume rather than in the PSTM stack volume, allowing more details being interpreted.

PS gathers were also conditioned. Q compensation was done for PP and PS data using zero VSP and offset VSP data, with a Q value of 66. Dominant frequencies at target time are 40 - 60 Hz for PP-waves and 20-40 for PS waves. For PP+PS joint inversion (Russell et al., 2005) we decided to use frequencies ranging from 10 to 50 Hz.

Registration of PP and PS reflection events was very challenging due to deformation at target horizons. Because these two data sets have different frequency bands a matching filter was applied. Synthetic seismic traces based in P-wave and S-wave sonic logs and PSTM wavelets for each mode were used. When calibrating surface PS-wave seismic with offset VSP a 180° phase rotation was needed. Five main horizons were picked at PP volume. An intial Vp/Vs was used to squeeze the PS-volume to PP-times. Registration became increasingly difficult with the distance to the well zone.

To test parameters for joint PP and PS inversion a pilot in-line was inverted first using only PP data and later using PP and PS data. Three angle stacks were selected (0°-25°, 20°-40°, 35°-55°); in the first angle stack PS signal to noise ratio was very low, as expected from reflectivity of PS wave at near vertical incidence and as effect of coherent noise attenuation. Density inversion results for inline 6190 for PP simultaneous inversion and PP+PS joint inversion
are shown at Figure 5. PP+PS joint inversion shows more details and it is less dependent in the initial model.

![Figure 5](image)

**Figure 5**: (left) density inversion from PP AVO, (right) Density inversion from PP+PS joint inversion

**Conclusions**

Survey acquisition design was mainly controlled by source generated noise attenuation, that required 20 meters receiver spacing. High fold was also required to compensate for lower signal to noise ratio in PS waves.

Processing most challenging difficulties were: coherent noise attenuation, receiver statics and PSTM taking into account anisotropy. Cross-spread domain adaptive and radial transform filter were the most effective. Polarization filters showed only local success. Monte Carlo and horizon guided statics gave the best results.

Structural interpretation from PP data has allowed to place 22 new wells in Tenerife oilfield. These new wells are being relocated using the Vclay computed from density inverted from PP+PS data.

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EDITED REFERENCES
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REFERENCES


