Variable Depth Streamer: Benefit for Rock Property Inversion

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Abstract

The lack of low frequencies in conventional seismic data means that a low frequency model must be incorporated in seismic inversion process in order to recover absolute elastic attribute values. Typically, low frequency models are obtained from low-pass filtered impedance logs. If well-logs are sparse and the geology complex, the derived low frequency model may be inaccurate and cause biased inversion results. One option to improve the low frequency model is to use seismic velocities. Seismic velocities provide information at very low frequencies, they are not providing information for all missing frequencies. Seismic data acquired using variable depth streamers (VDS) are suited for inversion as they provide directly the missing low frequencies, hence removing the need to build low frequency models from well data. In order to quantify the impact of the low frequency content on seismic inversion, comparative elastic inversion tests were conducted using 2-D seismic data from Constant Depth Streamer (CDS) and VDS acquisitions. Both datasets from offshore NW Australia were acquired simultaneously. Both data sets were processed using PSTM sequences and inverted. Two gas-bearing sand reservoirs are identified. Delineation of reservoirs is improved with VDS seismic inversion which shows lower impedance and Poisson ratio values in the gas-bearing interval. The inversion results were subsequently interpreted in terms of facies using a supervised Bayesian classification procedure. Three litho-classes were considered: gas-sand, water-sand and shale.

Introduction

Quantitative interpretation teams need to solve two problems when using model-based inversion: extracting meaningful wavelets and building accurate low frequency models. Conventional seismic data are band limited and a low frequency model must be incorporated in the inversion process in order to recover absolute impedance values. Typically, low frequency models are obtained from low-pass filtered impedance logs. If well-logs are sparse and the geology complex, the well-derived low frequency model will be inaccurate and cause biased inversion results. One commonly used method to improve the low frequency model is to use seismic velocities. However, while seismic velocities provide information at very low frequencies [0-4 Hz], they are not usually providing information for the missing frequencies in the range from 4 to 10 Hz. Seismic data acquired using variable depth streamers are ideally suited for inversion as they provide directly the missing low frequencies, hence removing the need to build low frequency models from well data. In order to quantify the impact of the low frequency content on seismic inversion, comparative elastic inversion tests have been conducted using 2-D seismic data from Constant Depth Streamer (CDS) and Variable Depth Streamer (VDS) acquisitions.

Variable depth streamer and reservoir characterization

The development of new marine acquisition techniques (optimised streamer steering) associated with new processing techniques is aiming to enhance frequency content of seismic data. It has led to seismic data with broader frequency content for a better vertical resolution and more detailed seismic interpretation. At the same time low frequencies are also enhanced. Soubaras and Lafet (2011) demonstrated that variable depth streamer acquisition with a joint deconvolution provides true seismic spectrum with a bandwidth [2.5-150Hz]. More information is available in variable depth streamer seismic due the broadband spectrum. This information can to be used for quantitative interpretation thus to derive accurate rock properties.

Desirability of broad bandwidth

Broad bandwidth is desirable because it produces sharper wavelets for better resolution of important features such as thin beds and stratigraphic traps. Low frequencies provide better penetration for deep targets, as well as better stability for inversion. At least two octaves of signal are required for seismic imaging and more are better. Contrary to intuition, the main effect of increasing the low frequency content of data is to decrease the side lobes of the wavelet, thus making accurate interpretation easier, as shown in Figure 1. Increasing the high frequency content sharpens the central peak of the wavelet, yet still leaves reverberating side lobes making precise interpretation difficult. The sharpest wavelets, and therefore the best resolution, is produced by extending the bandwidth in both the low and high frequency directions. It is now possible to record a full six octaves of signal by using BroadSeis, a proprietary broadband solution that combines state-of-the-art equipment with novel acquisition geometries and proprietary processing algorithms to produce the broadest possible bandwidth (Soubaras et. al. 2011).

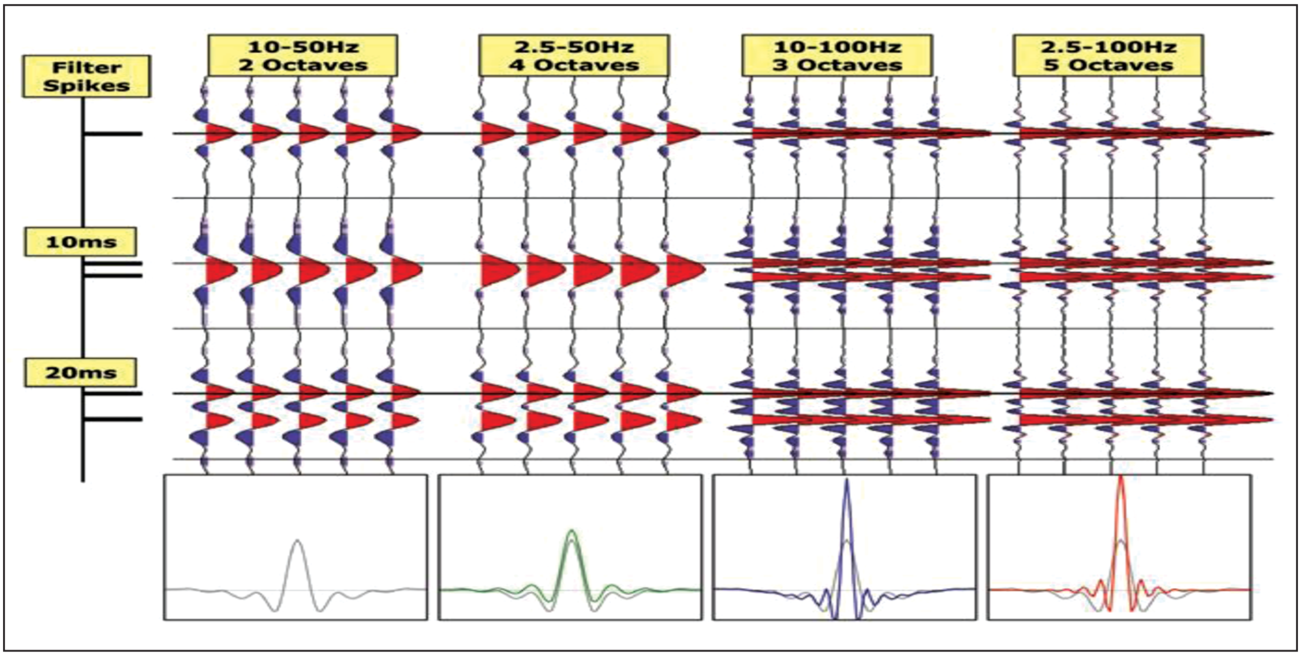

Fig. 1**:** Increasing the number of octaves in a seismic wavelet provides better resolution and more precise interpretation

Equipment

Central to this new broadband solution is the use of proprietary solid streamers, as these have outstanding lowfrequency and low noise performance as well as the ability to be towed at greater depths than industry norms. New generation electronics allow such streamers to record data down to 2 Hz, adding an extra one or two octaves to the low frequency end of the spectrum; the challenge is to record signal rather than noise at these frequencies. Dowle (2006) describes some of the advances in streamer technology that address this issue. Solid streamers are specifically designed to reduce noise (particularly sea state noise), as the cylindrical hydrophone assembly, containing 32 noise-cancelling piezoelectric elements per group, is embedded in the foam flotation jacket and isolated from the strain member, thus reducing vibration noise sensitivity (Figure 2). Using a solid foam fill inhibits the transmission of noise wave modes, such as bulge waves along the streamer, making the streamer inherently quieter than either fluid or gel cables as shown in Figure 3. This combination of low frequency hydrophone recording and reduced noise provided by solid streamers is the basis ofthe new broadband solution. An additional advantage is that the solid streamer has a uniform density, stable buoyancy, and is robust enough to operate at extreme depths (down to 60 m). This deep tow capability facilitates streamer depthprofiles which allow the recording of significant ghost-notch diversity and optimal low frequency signal (Soubaras et. al. 2011).

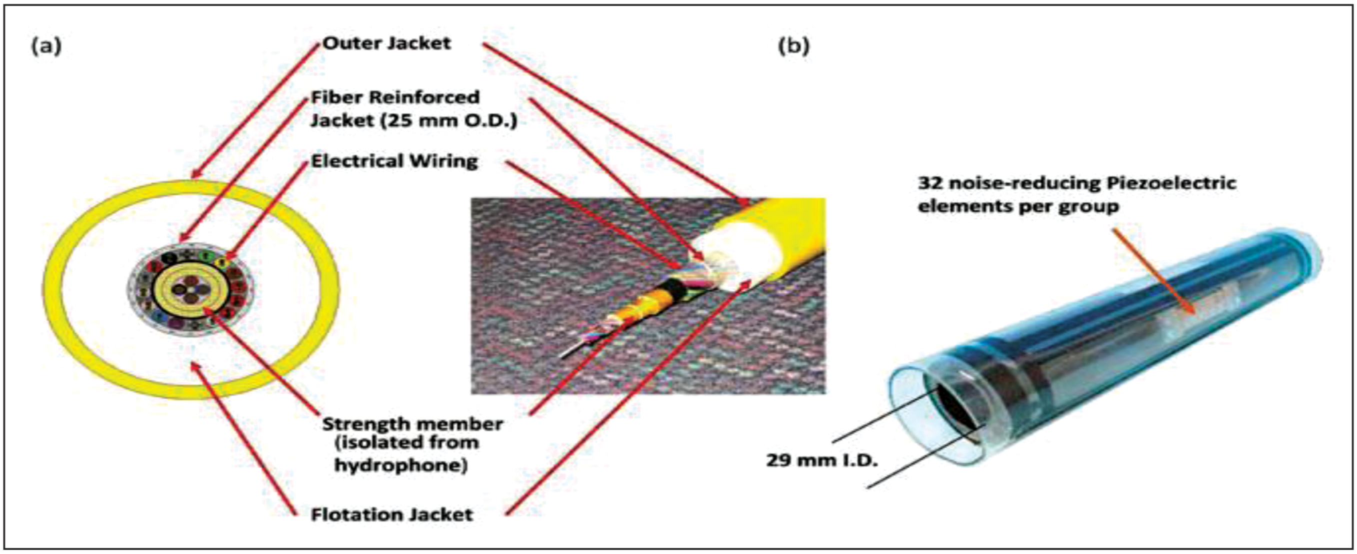

Fig. 2: (a) Image of cut-away solid streamer showing the solid foam fill which isolates the hydrophone from the strain member. (b) Image of the cylindrical hydrophone assembly which is embedded in the foam flotation jacket and contains 32 noise-cancelling piezoelectric elements per group.

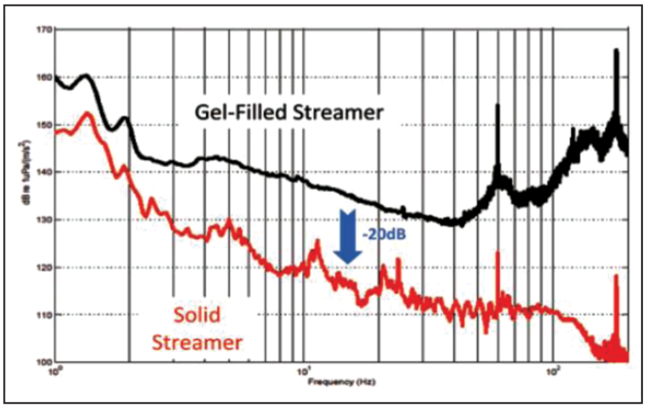

Fig. 3: Noise performance of a solid streamer compared with a gel-filled at different Streamer in a vibration tank test. The noise level of the solid streamer Is upto 20 dB below that of gel filled streamer.

Receiver ghosts

Towing cables at depth reduces the sea state noise recorded, but introduces streamer ghost notches in the amplitude spectrum within the seismic frequency range. These notches are caused by the sea surface reflected wave interfering with the direct arrival, with constructive and destructive interference creating the ghost effect. For vertical incidence the ghost time is computed as $t=2z/v$, where z = streamer (or source) depth and v = velocity. The notches in the spectrum are found at frequencies of $c/2z$, where c = water velocity, so approximately *750/cable depth* Hz (Soubaras et. al. 2011).

In conventional acquisition, it is necessary to tow the streamer close to the sea surface so that the first ghost notch occurs beyond the frequency range required for imaging. However, this choice also results in attenuation of lower frequencies (Figure 4) and increases the noise recorded at the low frequency end.

In the past, the ghost notches dictated the depths at which sources and streamers were towed. As the cable is moved deeper, a better low frequency response is obtained, with a lower noise level, but the ghost notches affect the seismic passband. For low frequencies, and especially for deep penetration in challenging geological environments such as basalt or very deep layers, it is beneficial to tow the streamer deep. However, unless the notches are removed, the higher frequencies will suffer. In cases where only low frequencies are of interest, for example up to 25 Hz, and it is acceptable to sacrifice the high frequencies, a tow-depth of 25 m depth could be ideal.

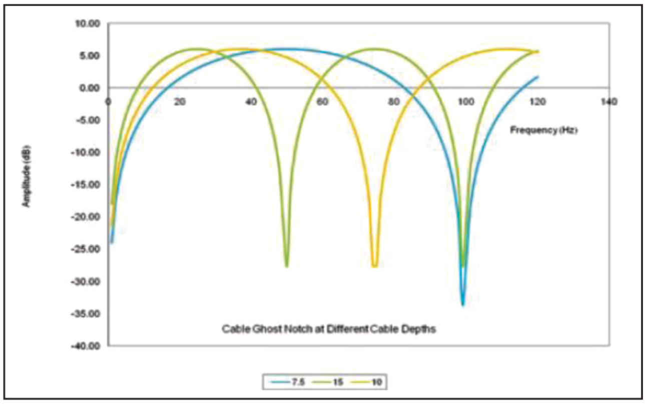

Fig. 4: Notches in the amplitude spectrum caused by ghosts streamer depths lead to compromises in data quality during survey design.

This dilemma has led to compromises in the bandwidth recorded for most surveys. Because of their inherent resistance to sea state noise, solid streamers can be towed shallow to record the high frequencies without causing undue noise contamination to the low frequencies, but still need to be towed deep to record the full low frequency signal. Different acquisition techniques have been proposed to overcome this problem, including deep-towed dualsensor streamers, with the upgoing waves, recorded by the geophone, being used to infill the notch in the hydrophone data, or towing pairs of streamers at different depths to yield a fuller frequency range by combination and deghosting.

The broadband marine datasets described in this paper acquired with both the low and high frequencies with the same set of solid streamers and a variable depth towing configuration to deliver an elegantly simple solution with a vastly improved bandwidth in the final image. With this configuration (patent pending), the receiver ghost notch varies along the cable and this 'notch diversity' is exploited by new proprietary deghosting and imaging techniques (patent pending). The wavelet produced yields both a high signal-to-noise ratio and maximum bandwidth, which provide the clearest images of the subsurface for any target depth.

The variability of the streamer depth and shape of the cable, and hence the diversity of the streamer ghost notch, can be tuned for different targets so that the notch diversity and output spectra are optimized for each survey. This cable shape is designed according to the water depth, target depth, and velocity profile of the survey area (Soubaras et. al. 2011).

Background

In seismic inversion workflow, one has to access two main “unknowns” using a band limited input seismic. The first one is to estimate representative wavelets. The most commonly used technique is based on the comparison of seismic amplitudes and well data reflectivity series (which give us an independent measurement). This can be complex due to the band limited nature of input seismic data and depend on the availability of good quality sonic logs (compressional and shear). The second “unknown” is to create an initial model (also called low frequency model) which is representative of the elastic 3D variations in the subsurface. At this stage, attempted to fill the low frequency gap we observe on conventional seismic [0-10Hz]. Most of initial model building workflows are based on interpolation of well data together with interpreted horizon as a stratigraphic guide. Interpolation techniques using calibrated seismic velocities as secondary property is commonly used. This exercise is becoming more complex as sparse information (well data) available and may require a lot of input from interpreters and geologists to properly interpolate well data. The main risk would be to over constrain the inversion initial model and final results. Moreover the seismic velocity are usually providing frequency information for very low frequencies [~04Hz] and cannot totally fill the missing frequencies for conventional seismic when no well data is available.

Variable depth streamer technique is maximizing the spatial and temporal resolution of seismic data. A broader frequency spectrum leads to minimized wavelet side lobes and bringing more high and low frequencies. In other words, one has more stable wavelets and less missing frequencies in the lower end of the spectrum. The lower frequency content will simplify the initial model workflow, seismic velocities can be used directly.

Workflow

To illustrate the benefit of variable depth streamer acquisition for rock property inversion, a comparative pre-stack inversion was done and Bayesian lithoclassification using two seismic datasets from offshore NW Australia. Two 2D seismic lines were acquired simultaneously using one seismic boat, with a constant streamer depth of 7m for the conventional acquisition and streamer's depth ranging from 7.5 to 58 m for the VDS acquisition.

We observe the difference in the frequency content, VDS is showing a lower frequency content with a similar vertical resolution in the reservoir interval (3 to 4s).

There are 3 wells next to the lines, compressional and shear sonic logs are available for the three wells. Four angle stacks (5, 15, 25 and 35 degrees) were generated after seismic conditioning for both datasets. Independent well based wavelets were extracted for each angle stack of each dataset (four wavelets for CDS and four wavelets for VDS).

After interpretation of the seismic lines, one initial model was built and used to invert both seismic datasets. Low frequency elastic model for density, compressional and shear velocities was built using seismic velocities. To derive density Gardner's relation was used (a and b values were calibrated using well data). Shear velocity was derived from seismic velocity and *Poisson ratio* trend. *Poisson ratio* trend was defined using well data. This technique was preferred to Greenberg-Castagna equation. Observed significant decrease of *Poisson ratio* with depth that could not be properly reproduced with a linear relationship between compressional and shear velocities.This initial model only contains very low frequencies [0-3Hz].

At this stage, one can argue the low frequency model is not representative of constant depth streamer seismic frequency content. We initially wanted to build two low frequency models, and we have realized it would not enable a direct comparison of the results. So was decided to apply a pure blind well configuration in which there is no direct well control.

Pre-stack inversion workflow is layer based (Coulon et al. 2006). It inverts elastic properties directly in a stratigraphic framework. The initial model is perturbated to find a global solution that optimizes the match between the input angle stacks and the corresponding synthetic angle stacks. Synthetic angle stacks are derived from the convolution of input wavelets with full Zoeppritz reflectivity equations. The optimization strategy is using a multi-terms objective function minimized using Simulated Annealing procedure. In addition to a data mismatch term, the objective function contains 3-D spatial continuity constraints that are used to attenuate the effects of random noise.

During the inversion compressional, shear velocities and density are perturbated indepedantly in each cell of the stratigraphic framework.

Pre-stack inversion was followed by a Bayesian litho-classification (Silverman, 1986, Doyen, 2007). The workflow can be divided into three main steps: a training set is build from elastic properties (log data or inversion results) where the lithology is known. This training set is a two or three dimension crossplot of elastic properties color coded by lithoclass. Then, probability distribution functions (PDFs) are modeled for each lithoclass. Finally, Bayesian classification is applied point by point to the seismic volume by computing the local posterio probalility of each lithoclass. The posterior probability can be expressed as $p(C_i|Z_1,Z_2)$, C_i being one lithoclass and Z_1,Z_2 being the elastic properties.

Inversion Results

From well analysis, reservoir intervals are consisting of good quality gas-bearing sands with porosities of 16-25 % and thickness up to 122 m. The main reservoir intervals are ranging from 3s to 3.4s. Figures 5(a) to 5(f) show the absolute acoustic impedance, Ip, and the *Poisson ratio* profile inverted from the CDS and VDS data between wells B and C. Two gas-bearing sand reservoirs (R1 and R2) are identified. Delineation of the R1 reservoir is much improved with the VDS inversion results which show lower impedance and Poisson values in the gas-bearing interval. The inversion well tie is also significantly improved with the VDS data. Small size reservoirs are delinated on both inversion, whereas thicker reservoirs are not correctly predicted using CDS seismic. Between well locations, we observe significant differences in reservoir prediction. As prediction at the wells is improved with VDS seismic we can anticipate that elastic prediction between wells is also significantly improved.

The inversion results were subsequently interpreted in terms of facies using a supervised Bayesian classification procedure. Three litho-classes were considered in classification: gas-sand, water-sand and shale. For each class, a training set of Ip and *Poisson ratio* (PR) values was constructed using well log data. The different litho-probabilities, p(Ci|Ip,PR), were computed at each sample point from the inverted attributes and the attribute PDFs displayed in Figure 6. Figures 7(a) and 7(b) show the gas-sand probabilities for CDS and VDS data respectively. The thickness of the gas-bearing interval in R1 is much better delineated from the VDS data, due to their improved low frequency content.

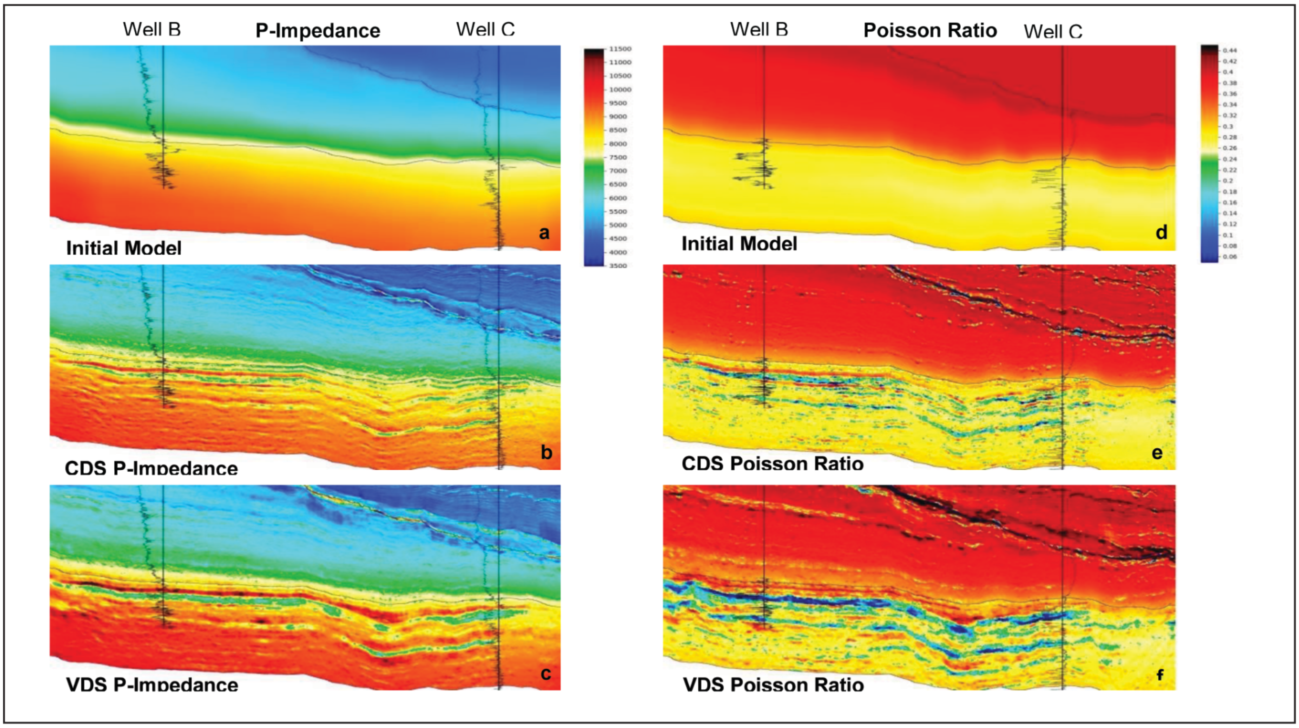

Fig. 5: Elastic Inversion results: (a) P-Impedance initial model, (b) CDS Inverted P-impedance, (c) VDS Inverted P-impedance, (d) Poisson ratio initial model, (e) CDS Inverted Poisson ratio, (f) VDS Inverted P-impedance

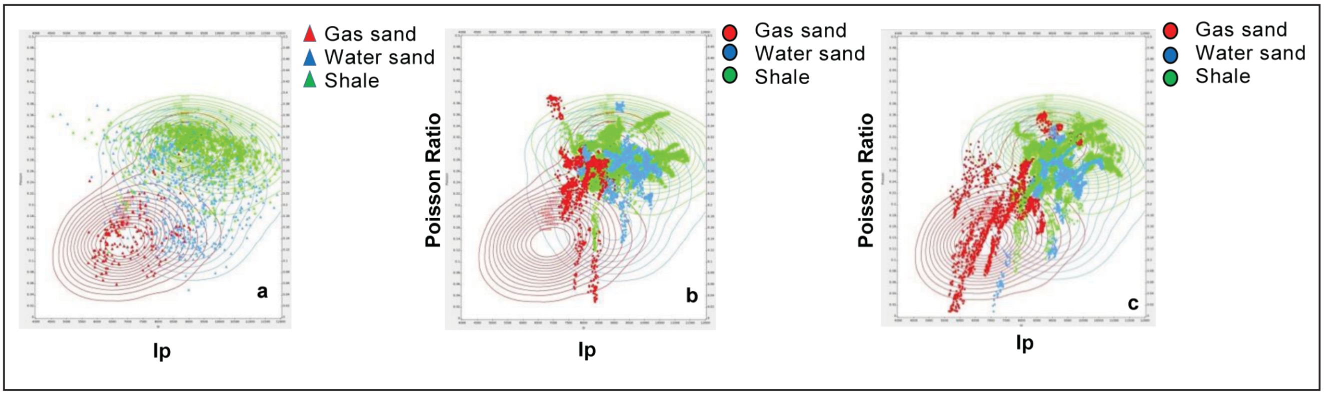

Fig. 6: Bayesian classification (Ip[m/s x gr/cm^3] versus Poisson ratio: (a) PDFs computed from three well data, (b) PDFs computed from wells, points from CDS data, (c) PDFs computed from wells, points from VDS data

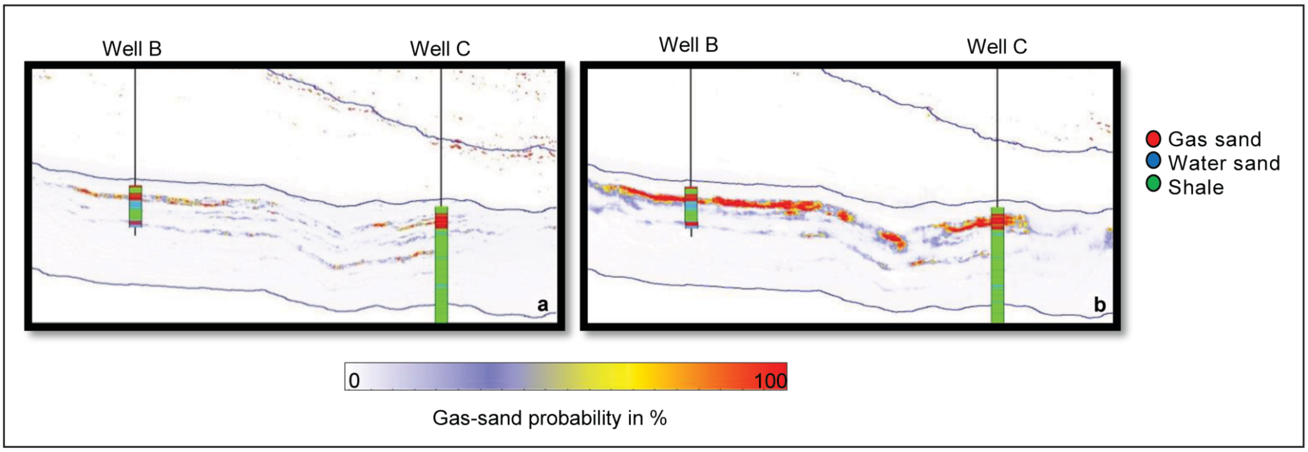

Fig. 7: Gas sand probability section: (a) CDS data, (b) VDS data

Conclusions

The lack of low frequencies in conventional seismic data means that seismic inversion relies traditionally on a well-derived low frequency model to recover estimates of absolute acoustic impedances. The accuracy of this low frequency model is often questionable when well data are sparse. Low frequency acquisition using variable depth streamers provides valuable information to constrain the inversion process and obtain accurate impedance estimates without using a log-derived low frequency model. Comparative inversion study shows that the extended frequency content achieved using the VDS acquisition yields significantly improved inversion results, better delineation of the gas-bearing reservoir and reduced uncertainty for facies classification.

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