Low-frequency Source Field Test in the Kerala Konkan Basin

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Abstract

In recent years, low-frequency sources have been developed to provide the optimum data for processes such as full waveform inversion. In addition, these sources provide valuable lows for AVO Inversion. In some basins with very high-absorption and deep targets, such as the Santos pre-salt, a benefit is also being investigated through field trials. Another scenario where low-frequency sources could be useful in exploring the sub-basalt -here, the frequency attenuation is not as severe as the Brazilian pre-salt but still substantial enough that extending the lows, and thus penetration, could have some benefits. Applying new geophysics should be based on a series of tests to ensure the objective is met and that the data quality has been improved. The first simple test of a low-frequency source was carried out in Q2 2023 to evaluate the effectiveness by acquiring two 2D lines and comparing these to the standard production source. The test was acquired in the Kerala Konkan basin, where the mapping of the basalt, especially its thickness, and the structures and extents of the sub-basalt sediments. The results show an uplift in most cases and suggest that we should consider these sources as an enhancement, especially when used in conjunction with a conventional source, where the sources flip-flop. Further filed tests may show that in 3D that the conventional source is not needed.

Introduction

Since the initial offshore drilling operations in India in the early 1960s, over 3500 wells have been drilled. With nearly two out of every three wells encountering some form of hydrocarbon, it demonstrates the continent's substantial prospective potential. However, a relevant majority of these discoveries are concentrated on a few basins, leaving others largely unexplored.

The fundamental reason behind this exploration asymmetry lies in the sub-crop geological complexity, exemplified by the presence of the Late Cretaceous Deccan volcanic province along most of the western margin. The most extensive LIP ever recorded highly impacts exploration activities, particularly when the seismic signal requires penetration underneath the flood basalts to illuminate deeper in the unexplored Mesozoic target.

The Deccan volcanics were accumulated as a consequence of the burst of the Reunion mantle plume around 65 M.a ago, producing an excess of 3000 meters of flood basalts accumulated, particularly along the western margin.

With only 23 exploratory wells, the Kerala Konkan Basin is the classic example of a frontier basin. No commercial discoveries have been reported so far. However, four wells have encountered some sort of hydrocarbon, making this province attractive for testing new acquisition methods to unravel new working petroleum plays.

Marine seismic acquisition has had a history of looking at the source of the seismic waves since its beginnings in the 1960s. Initially, dynamite was used in 2D surveys. Later, there was a period in the '70s and '80s when the desire to generate sound waves more often, more reliably, and more safely came about, especially for the new development of 3D surveys. Systems using dynamite, steam, air, sparkers, boomers, and even marine vibrators were developed and sometimes commercialised. However, airguns became the most successful marine seismic sources and are now the industry standard for several geophysical and operational reasons: repeatability, predictability, reliability, flexibility and safety. Since these early developments in sources, not much changed over the next thirty years other than getting larger on average. However, recently several factors have combined to drive a new raft of seismic source design: The development of broadband streamer data, so low-frequency rich data could be acquired; the rise of quantitative interpretation, where low-frequencies improve the inversion result; and finally, the coming-of-age of full-waveform inversion.

This paper discusses the idea of frequency locking first described by Lawset.al in 1990[1], the field trials that led to the commercialisation, and some initial processing results from a field test carried in the Kerala Konkan basin where the sub-basalt presents a formidable geophysical challenge that will require many solutions to overcome fully. The starting signal may prove to be an important part in this process.

Drivers of low-frequency sources

Extending the bandwidth of seismic data is useful for several reasons - it improves resolution, seismic inversions and full-waveform inversion.

A significant development in seismic acquisition was the development of broadband seismic. In this method, we try to tune the acquisition design of the tow depths of the streamers and sources such that the data can be "deghosted" -either by estimating the ghost from the pressure (hydrophone) data or by summing complementary pressure and velocity data (hydrophone and accelerometer). The tuning depends on the ratio of the depths of the source and streamers, which changes the frequency of the ghost notch. The way to create broadband, mainly by increasing the lows, is to tow the streamer as deep as possible (say 15-20m), as this reduces the effect of the zero notch and the noise from the sea swell. But there is an operational limit for how deep streamers can go without harming the sensitivity of the hydrophone. Additionally, the deeper the streamer lower the frequency of the first ghost notch and the more notches there are in the seismic bandwidth. Extending lows further must therefore rely on improving the low-frequency output of the source.

The Physics of Frequency-locked Sources

In a typical source array, we have the situation where we have airguns close together (clusters), such that their bubble coalesce and far enough apart so that there is no interaction and the tuning of the array elements can be accomplished. However, between these two extremes, there is a point where the pressure fields interact, but not their bubbles, and this is the process described as frequency locking [1]. The modelling and field tests performed by Hatton et al. showed that two different gun volumes that are frequency locked create an oscillation frequency proportional to the combined volume of the guns and is distinct from that of coalescing bubbles in a cluster.

Hopperstad et al. described using the effect of frequency locking to create low-frequency-rich sources. A central point made was that the low-frequency output is proportional to the total array volume and not how it was distributed within the array if the airguns (or clusters) are frequency locked. The resultant source design was called "hypercluster" in that paper. However, this design aimed to improve the low frequencies of smaller arrays, but not to extend the low frequencies. The volumes' size also meant that the airguns had to be physically close to each other, leading to operational problems.

To extend the idea of Hopperstad et al, a design was considered that would use larger airgun volumes, well above the norm of current arrays, so that lower frequencies could be achieved and be operationally reliable. In a relatively standard cluster formation, a larger airgun volume can be placed further apart to avoid damage during discharge. The resultant design achieves a dominant frequency of 4.1Hz, which extends half to a full octave of a typical production array. The overall amplitude output is high due to there being a number of elements, rather than a single large volume, and so in absolute terms, competes well with other low-frequency sources. This source is commercialised with the trade name "Harmony". Like all of the low-frequency sources, the spectral ripples caused by the bubble oscillations are there. It is difficult to tune such an array, which would involve smaller elements that would reduce the overall array volume, thus increasing the dominant frequency and negating the design's point. A better method would be to use such a source in combination with tuned arrays if the source de-signature is expected to be a concern; that is, the signal-to-noise is expected to be poor around the frequencies where there are deeper "notches".

Low-frequency Source Field Trial in the Kerala Konkan Basin

Development Field Trials

An early field trial of the source was conducted on Equninor's permanent reservoir monitoring system on Johan Sverdrup. This trial showed the source performed as expected with an uplift in the low-frequencies at 4.1 Hz. The spectra comparing the source to a conventional one is shown in figure 1.

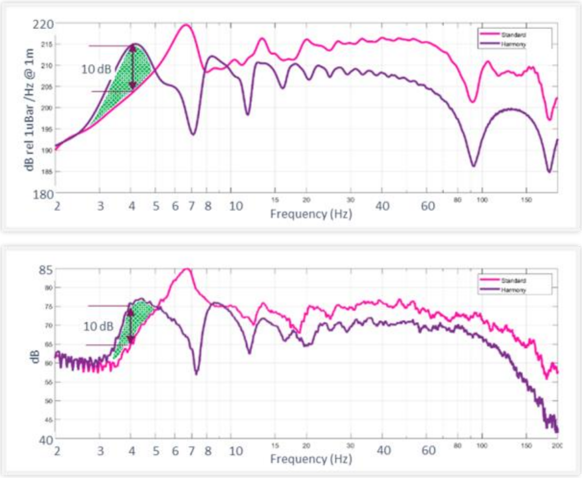

Figure 1 Top, Far-field signature spectra derived from the nearfield hydrophone data, and bottom, shot domain spectra from the PRM system on Johan Sverdrup. Conventional source in pink and low-frequency source in purple. Both spectra show an uplift of about 10dB at 4Hz over the conventional source. Data courtesy Equinor

Kerla Konkan Sub-Basalt Field Trial

In Q2 2023, a test was made of the low-frequency source on the coast of west India. The test was the first in a series to explore the potential for a low-frequency source to aid the interpretation of the basalt and sub-basalt geology. The idea would be that by improving the low-frequency content over a conventional source, there would be better penetration and improved continuity of reflectors. In addition, the test hoped to show that the shallow pre-basalt section was not impacted by the larger spectral ripple caused by the bubble effect of this type of source. Two 2D lines were shot with the source, covering recently acquired lines, as shown in figure 2

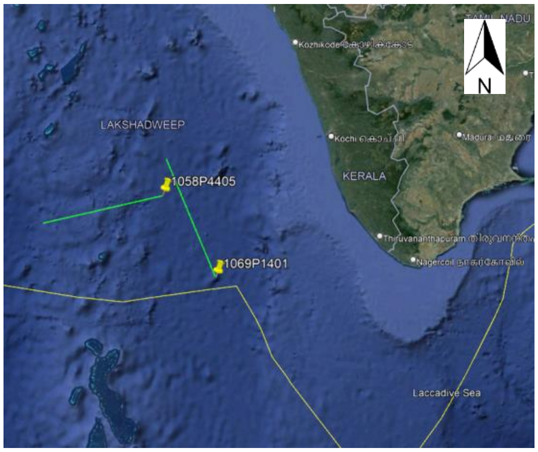

Figure 2 Two 2D lines acquired of the coast of Kerala, one dip and one strike

Processing

We want to compare the low-frequency response for the baseline and the low-frequency source. To do this, we applied processing with the same parameters and velocity fields for both source configurations so that any differences would be solely due to the variable acquisition. We removed incoherent noise, direct arrival, refractions and ghosts, then signature-matched both lines to a common target. Ghost elimination was done using Grion's phase-shift algorithm (Grion et al., 2016), which was assisted by the dipping cables. With the water depth much greater than the sedimentary extent, multiples arrived well below our target and were simply muted. Kirchhoff migration was used for the imaging, with a large aperture and dip limits to image the steep events that might be expected to exhibit low frequencies.

The better the estimate of the source signatures from nearfield hydrophone measurements, the better one can successfully convert the output to an ideal spectrum with a full bandwidth and without residual bubble. Because the standard source strings are not rigidly separated, a shot-by-shot approach is required. Low-frequency source signatures are more repeatable, coming from a simpler array, but still benefit from individual measurements.

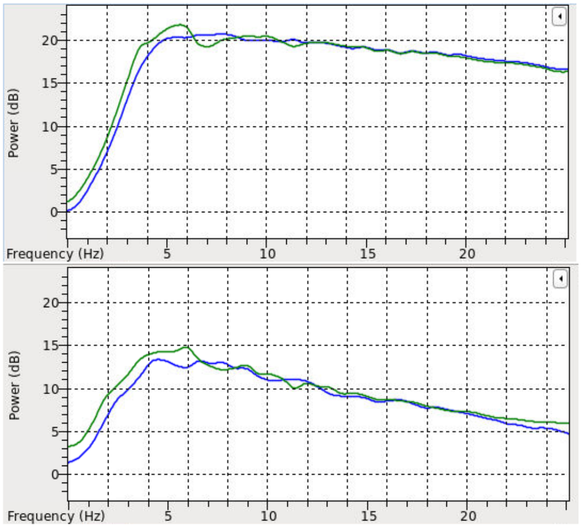

Figure 3: Spectra from the post-basalt (above) and pre-basalt (below). The baseline is blue, and low-frequency source green.

Whereas it's possible to match an input spectrum to any desired output, signal-to-noise ratios are not so amenable: when the signal is boosted, so is the noise, and the difference in decibels remains constant. We can compare the raw source signature in Figure 1 to the spectra from the PSTM image, with standard designature applied, in Figure 3, where the spectra are smooth. However, it's better to assess the quality of the low frequencies using signal-to-noise ratios. The SNR was estimated using cross-correlations of adjacent traces from the stacks, and this is shown in Figure 4, where the low-frequency source shows higher SNR at low frequencies, except a small notch at around 7 Hz, which is much smaller than the notch in the signature.

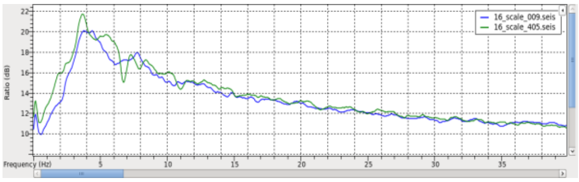

Figure 4: Baseline SNR in blue and low-frequency source in green. The low-frequency source shows higher values at low frequencies.

For another example of improved coherency, we can look at octave panels from raw shots in Figures 5 and 6. These are taken from corresponding shots: the low-frequency source shows more energy in the 2-4Hz range. This is important for full waveform inversion.

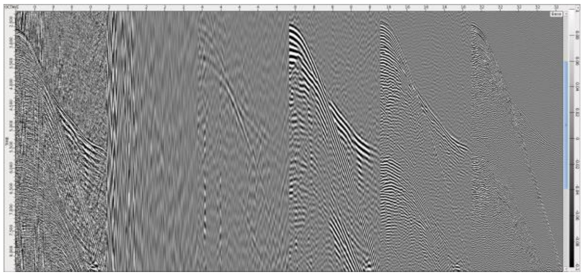

Figure 5: Octave panels from baseline acquisition. Full bandwidth, 0-2Hz, 2-4Hz, 4-8Hz, 8-16Hz and 16-32Hz.

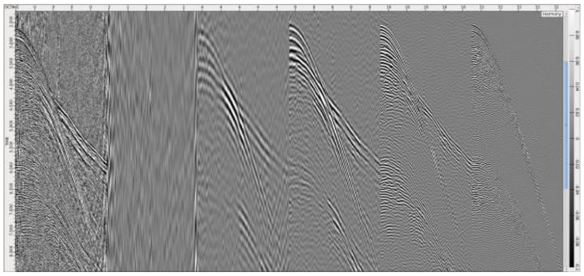

Figure 6: Octave panels from the low-frequency source acquisition. Full bandwidth, 0-2Hz, 2-4Hz, 4-8Hz, 8-16Hz and 16-32H

Results and conclusion

In Figure 7, we can an example of an incremental improvement over the baseline source. The complexities of the geology coupled with the 2D acquisition do not lend themselves to casual interpretation, especially the base of the basalt, and a complete analysis will be carried out. Still, the deeper section shows enhanced coherency in the pre-basalt coming from the additional low-frequencies indicating the value to the source in this area. Other concerns were for the pre-basalt, where the spectral content of the low-frequency source might reduce the expected S/N of higher frequencies, but this is not seen in the spectra and images (Figures 3 and 7, respectively).

The results are promising, and the next step could be taking advantage of the source's deployment flexibility. One example would be to flip-flop the source with a conventional one -thus getting the best response from both source types with no risk to the final image, only potential upside.

As the source uses one sub-array, unlike the conventional type, which uses three sub-arrays, we

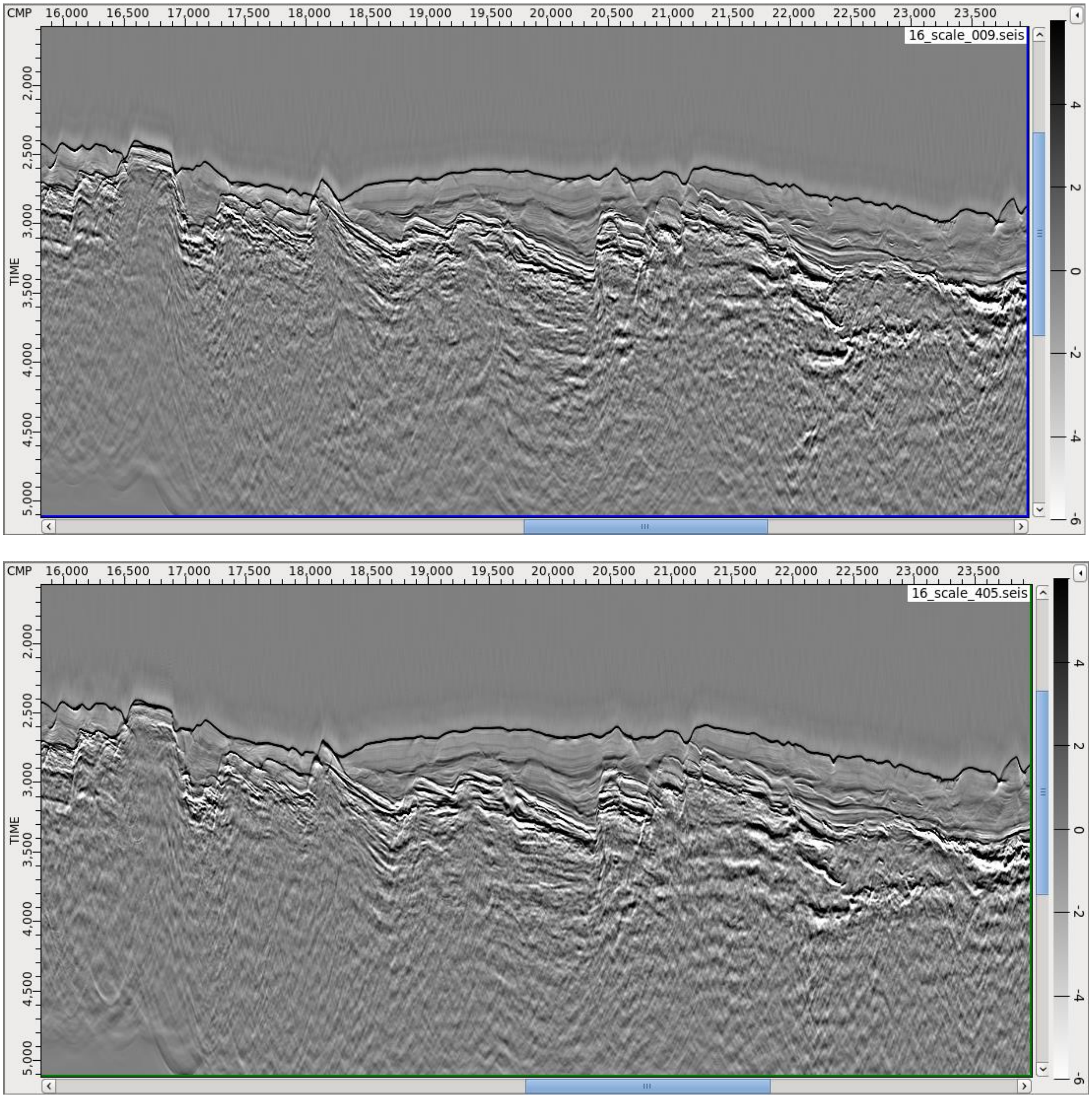

Figure 7: 2D PSTM images, approx. 40km across. Top reference baseline source, bottom the low-frequency source. The feather match between CMPs 16000-18000 was relatively poor so differences may be related to that. To the east of 18000, the feather match was reasonable at a couple of degrees.
The pre-basalt section looks very similar between the sources indicating that the low-frequency bias of the low-frequency source would not affect interpretation in this relatively high-frequency interval.
Between 3.5 and 4 seconds and CMPs 20000-22000, we can see low-frequency events not evident in the baseline. These events appear not to follow the geology above, indicating they are not related to multiples or residual bubble energy.

can increase the power output by using two together - this would double the output -something that would be impossible if using conventional sources. Beyond two sub-arrays would be difficult due to the time it would take to recharge the source to full pressure.

A more complete interpretation of the results will indicate the next steps in developing the optimum strategy for deploying the source in the Kerala Konkan basin.

References

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