Low Frequency Sources: mission critical for pre-salt and sub-basalt and added value with neither salt nor basalt

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Introduction

Imaging targets under salt, basalt, carbonates, and chalk is a challenge because such overburdens scatter and attenuate seismic waves, and because building accurate velocity models is subject to cycle skipping. Low frequency waves do not attenuate and scatter as much as high frequency waves. They better penetrate any overburden and they mitigate the cycle skipping problem. We will present a few case histories showing that low frequency signal is mission critical for sub-salt and sub-basalt imaging.

Low frequency signal also adds value in general, with neither salt, basalt, carbonates, nor chalk. Wavelets of broadband data have shallower and wider sidelobes (ten Kroode et al, 2013). In addition to mitigating cycle skipping, low frequency signal is needed for building blocky earth models of thick beds. Acoustic impedance is found by integrating reflectivity. A spike is integrated to a block. With side lobes, the spike is less of a spike, and its integral is less of a block. With narrow band seismic data, inversion programs must rely on well log data to provide the required low frequency signal. Well log data are great near the wells but less so between wells, and in exploration. Yet another added value of low frequency signal is improved resolution. Side lobes interfere with main lobes of other reflectors of thin beds, and compromise resolution. With shallower and wider sidelobes, resolution is improved.

Sub-basalt imaging with large Airguns (2000 cubic inch)

After frustrating attempts to image below basalt between the Shetlands and the Faroes using conventional airguns recorded by long-offset two-vessel streamers with up to 18 km offset (Bagaini et al, 2000), success came from a low frequency source that included the largest available Airguns of the time (Figure 1). Ziolkowski et al (2003) used 2000 cubic inch (cui) guns. The large guns produced low the frequency signal that enabled better imaging of the base basalt and pre-basalt structures as shown in Figure 2. A subsequent survey using large arrays with clusters of Airguns whose volume was no larger than 350 cui recorded by both Ocean Bottom Nodes (OBN) and streamers (Lunnon et al, 2003) produced sub-basalt images that were not as good as what Ziolkowski et al achieved with the large guns recorded by only a streamer.

Pre-salt imaging with Tuned Pulse Sources (28000 cubic inch)

This source (figure 3) has been used in several Long Offset Low Frequency (LOLF) OBN surveys in the Gulf of Mexico (Merritt et al, 2024; Ji et al, 2025; Le Diagon et al, 2025). These surveys were done over areas that were already covered by legacy Full Azimuth (FAZ) streamers data (Airguns sources) that failed to image sub-salt prospects (figure 4a). All surveys, no exception, demonstrate the effectiveness of TPS in imaging sub-salt and improved blocky earth model post salt (figure 4b). Processing tests using the new LOLF data show that if low-frequency signal is taken out by a 1.7Hz lowcut filter, then FWI fails to image the deep targets. Other processing tests show that imaging legacy data with velocity models from new data also failed. In addition to the improved quality of the final image, additional added value came from shorter data processing turn-around-time. In all case histories, FWI always converged much faster than what was experienced with legacy Airgun data—weeks instead of months. It was also demonstrated that it did not depend on a good starting velocity model.

Safety, Environment, and Permitting

The safety of the crew is a top concern. Airgun auto-fires onboard are a big safety risk. The largest gun in a typical array is 350 cui. With a 28000 cui source, albeit at half the pressure, an auto-fire could be devastating if it happened onboard.

The environmental impact of Airguns is also a top a concern. Permitting the large volume sources was granted, reluctantly and on probation, as New Untested Technology (NUT). The probation of the TPS resulted in two independent third party environmental impact reports. One from Jasco (Martin et al, 2023)

and another one from the California Ocean Alliance (Southall et al, 2024). If time permits, we will show how deliberate design features of the TPS reduce its environmental impact and prevent auto-fires.

Conclusion

Low frequency sources have recently become available. Their practical deployment is adding much more value of information than their added cost. The added value of low frequency signal is proven for sub-basalt and pre-salt imaging. Added value in general is blocky earth model with no need for well data and improved resolution.

References

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Figure 1 *2000 cubic inch Airgun being serviced. Two of these Airguns were used in a survey that was designed by Ziolkowski et al (2003). The data were acquired and processed by VeritasDGC. The head of this Airgun is almost as large as the head of the figure 3 (which is inside the bubble). The firing chamber, however, is "only" 2000 cui compared to the 28000 cui chamber of figure 3. (This figure is from Wikipedia.)*

This source was used to acquire the data shown in figure 2b.

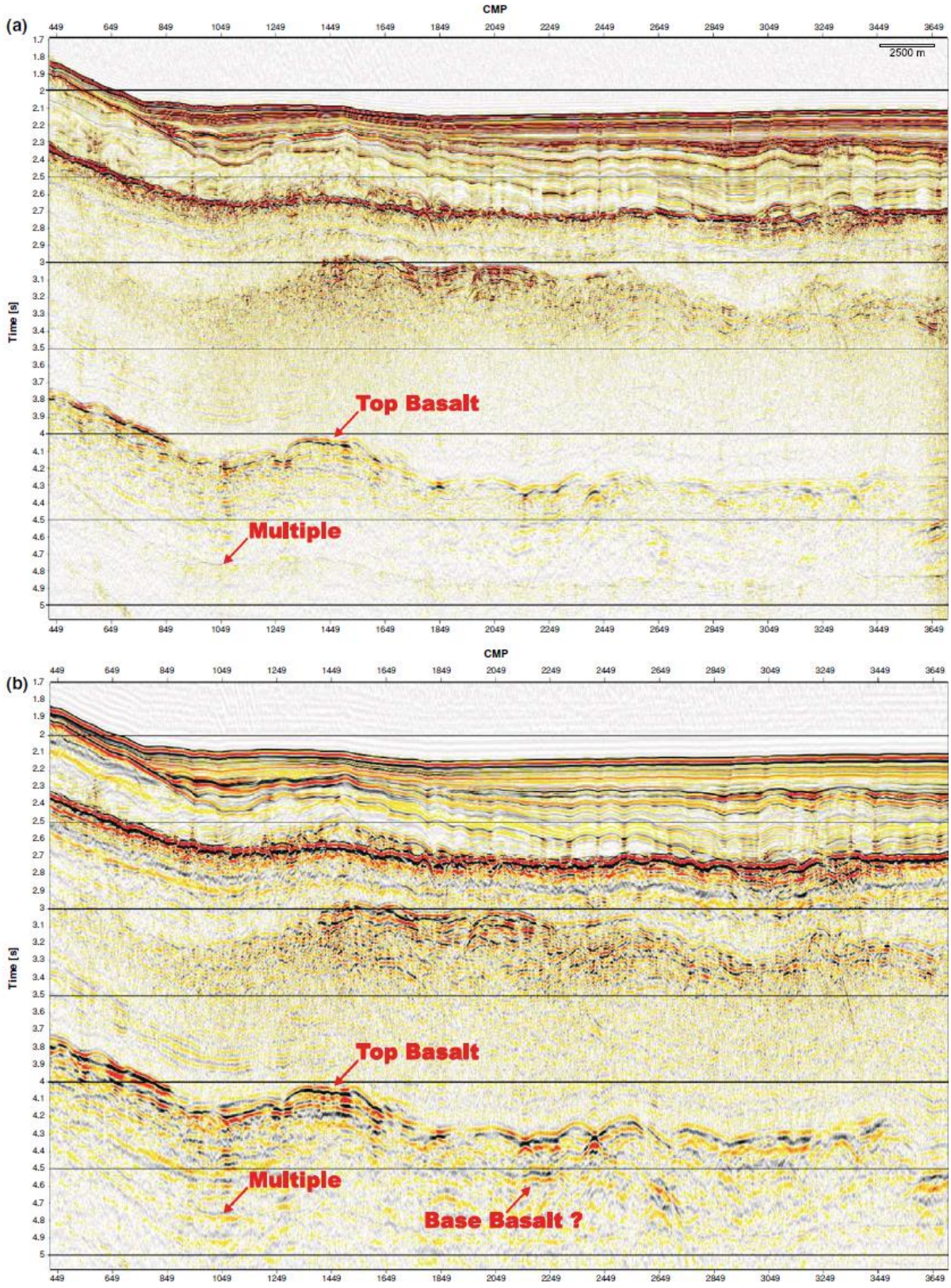
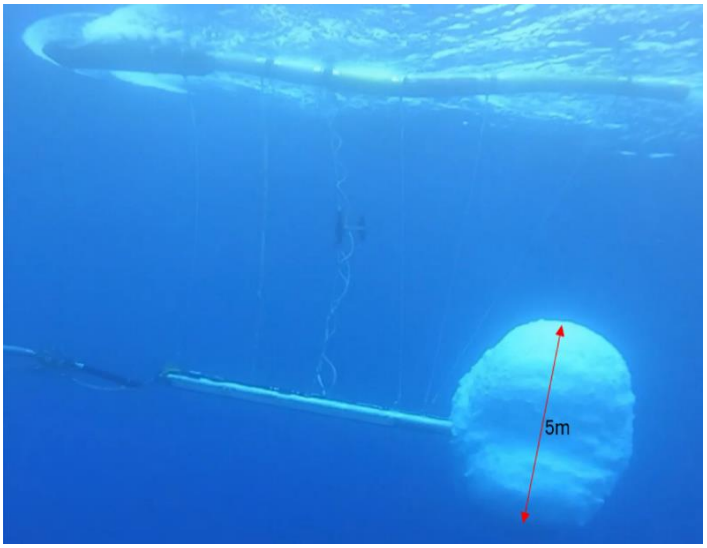


Figure 2 *Sub-basalt imaging. (a) The source was an array of Airguns. The largest guns were 465 cui. (b) the largest guns were 2000 cui. Reproduced from Ziolkowski et al, 2003. Both streamer surveys.*

Figure 3 *The Tuned Pulse Source is a pneumatic source. That is, like Airguns, it releases compressed air into the water. Unlike Airguns, it has a different design that reduces its environmental impact and makes it safer for the crew. Unlike Airguns its pressure is 1000 PSI and not 2000 PSI. Like Airguns, a TPS head can be mounted on firing chambers of various volumes. In this paper, we present surveys in which the volume of the firing chamber was 28 thousand cubic inches.*

This source was used to acquire the data shown in figure 4b.



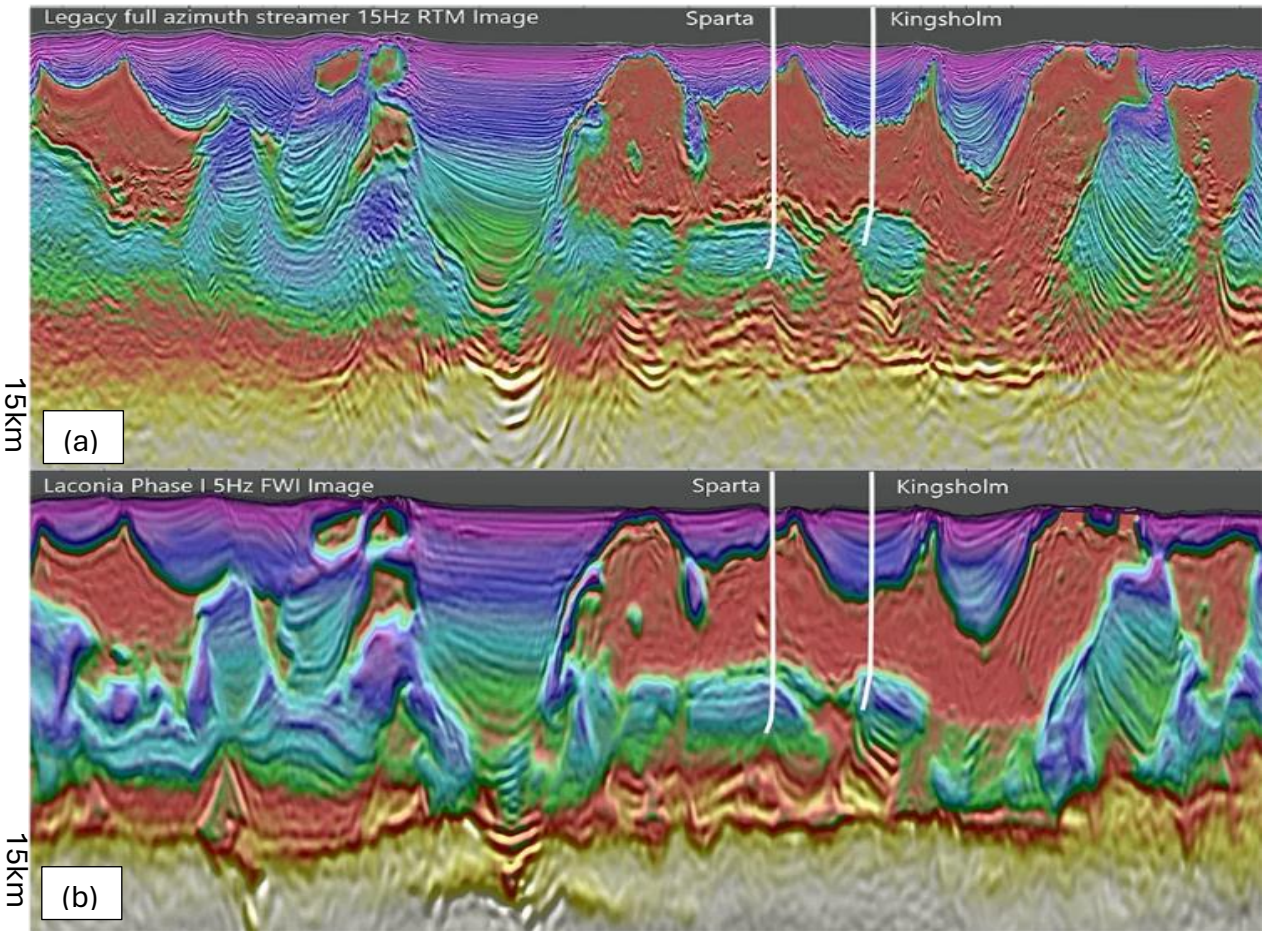


Figure 4 *Legacy full azimuth streamer 15 Hz RTM image overlaid with 6 Hz streamer FWI velocity (top) and Laconia Phase I long-offset low-frequency sparse OBN "early-out" 5 Hz FWI Image overlaid with corresponding velocity (bottom). The early-out demonstrates significantly improved imaging of the salt and the deep basin architecture, including potential subsalt reservoir targets in the Paleogene trend. The seismic sections intersect the Sparta discovery and the Kingsholm prospect (a dry well with oil shows). From Ji et al (2025).*