Introduction

Imaging targets under salt, basalt, carbonates, and chalk is a big challenge because such overburden significantly scatters and attenuates seismic waves, and because building accurate velocity models is subject to cycle skipping. Low frequency waves mitigate cycle skipping and overburden attenuation and scattering. Wavelets of broadband data have shallower sidelobes (ten Kroode et al, 2013). Acoustic impedance is inverted by integrating reflectivity. A spike is integrated to a block. With side lobes, the integral is not blocky. With conventional narrow band data, inversion programs must rely on well log data to provide the low frequency signal. Side lobes interference compromise resolution. With neither salt nor basalt nor chalk, low frequency signal is still important for building blocky reservoir models without well log data, and for improving resolution thanks to less interference of side lobes.

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

After a few frustrating attempts to image below basalt between the Shetlands and the Faroes using conventional airguns recorded by long-offset two-vessel streamers with 18 km offset (Bagaini et al, 2000), success came from a low frequency source that included the largest available Airguns of that time. Ziolkowski et al (2003) used 2000 cubic inch (cui) guns shown in Figure 1. The 2000 cui guns produced the low frequency signal that enabled better imaging of the base basalt and pre-basalt structures as shown in Figure 2. A subsequent survey using arrays that included clusters of Airguns whose volume was no larger than 350 cui recorded by Ocean Bottom Nodes (OBN) (Lunnon et al, 2003) produced sub-basalt images that were not as good as what Ziolkowski et al achieved with large guns recorded by a 12 km streamer despite the use of OBN.

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

TPS (Figure 3) were used in several Long Offset Low Frequency (LOLF) OBN surveys (Merritt et al, 2024; Ji et al, 2025; Le Diagon et al, 2025). After the first survey, the technical downtime due to the source was lower than the technical downtime with Airguns on similar surveys. These surveys were done over areas that were already covered by legacy data with Airguns and Full Azimuth (FAZ) streamers that failed to image deep targets under the salt. All surveys, with no exception, demonstrated the effectiveness of TPS for imaging deep targets under complex salt structures and in delivering an improved blocky earth model post salt. Processing tests using TPS data show that without the low-frequency signal, FWI failed to image deep targets. Imaging legacy Airgun data with velocity models derived from TPS data also failed. Figure 4 shows a comparison of the image from a legacy FAZ streamer survey using Airguns to the image from a new OBN survey using TPS. In all case histories, FWI converged much faster than what was experienced with legacy Airgun data, and it was demonstrated that it did not depend on a good starting model to reach a geologically plausible solution.

Safety, Environment, and Permitting

The safety of the crew is always a concern. Airgun auto-fires onboard are a big safety risk. The largest gun in a typical array is 350 cui. The TPS that was used in the above case histories was 28000 cui albeit at half the pressure. Auto-fires of a TPS could be devastating if they happen onboard.

The environmental impact of Airguns is already a concern. Permitting the TPS was granted, reluctantly, not as a 28000 cui gun but as New Untested Technology (NUT) only after considerable effort using TPS data recorded in flooded quarries.

TPS design is different from Airgun design. Deliberate differences reduce its environmental impact and prevent auto-fires. If time permits, we will present environmental impact reports from Jasco (Martin et al, 2023) and from the California Ocean Alliance (Southall et al, 2024). Neither Jasco nor COA are supported by industry. Their reports show that TPS has a significantly lower environmental impact than Airguns with much smaller volumes commonly used in conventional surveys.

Figure 1 *2000 cubic inch Airgun being serviced. These guns were used in a survey that was designed by Ziolkowski et al and was acquired and processed by VeritasDGC in 2001. The head of this Airgun is almost as large as the head of the TPS. The firing chamber, however, is "only" 2000 cui compared to 28000 cui for the TPS. The pressure of this source was 2000 PSI which is double the TPS pressure. So the amount of air discharged per shot of this gun was only factor 7 less than TPS. (Figure from Wikipedia by Grobe, 2006.)*

Conclusion

The added value of low frequency signal is proven for sub-basalt and pre-salt imaging. Its added value for post and no salt nor basalt is anticipated for exploration as well as for development and production. Low frequency sources have recently become available. Their practical deployment adds significant value of information. This was shown in the North Atlantic and is expected also in the equatorial margins.

References

Bagaini, C, Hansen, J.O., Kostov, C., and Ronen, S., 2000. Contributions of wide-angle P and PSP data to sub-basalt imaging. Petex Conference, London.

Ji et al, 2025. Acquisition and early imaging of a long-offset, low-frequency sparse node survey in the Gulf of Mexico. SEG (IMAGE).

Grobe, 2006. https://en.wikipedia.org/wiki/Seismic_source#/media/File:Air_gun_hg.jpg

Le Diagon et al, 2025. Ultralow frequency source for OBN survey design and implementation. SEG.

Lunnon et al, 2003. An evaluation of peak and bubble tuning in sub-basalt seismology: modelling and results from OBS data. First Break **21** 51-56.

Martin S. B., et al. (2023). Tuned Pulse Sound Source Characterization in Gulf of Mexico. https://www.sercel.com/sites/default/files/2025-02/jasco-report_tps_sercel.pdf

Merritt et al, 2024. Revealing subsalt in Garden Banks with a sparsely shot TPS OBN and FWI. SEG.

Southall et al, 2024. Reducing Impacts of Anthropogenic Noise to Cetaceans in the Gulf of Mexico. https://gulfspillrestoration.noaa.gov/media/document/2024-05-oo-marine-mammal-noise-project.

ten Kroode et al, 2013. Broadband seismic data—The importance of low frequencies. Geophysics **78**.

Ziolkowski et al, 2003. Use of low frequencies for sub-basalt imaging. Geophysical Prospecting **51**, 169-182.

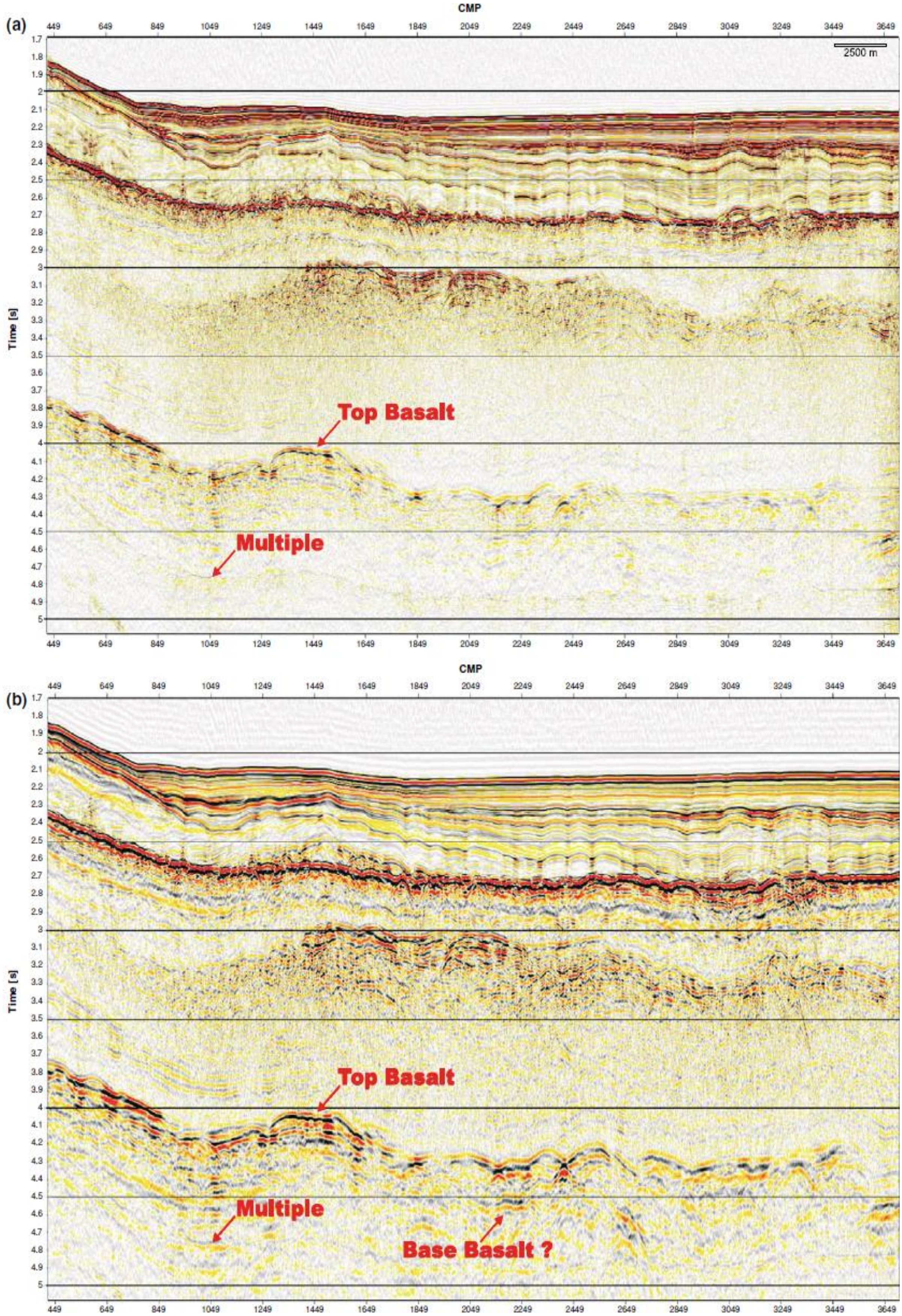

Figure 2 *Sub-basalt imaging. (a) The source was an array of Airguns. The largest guns were 465 cui. (b) the largest guns were 2000 cui. Reproduced from Ziolkowski et al, 2003. Both streamers*

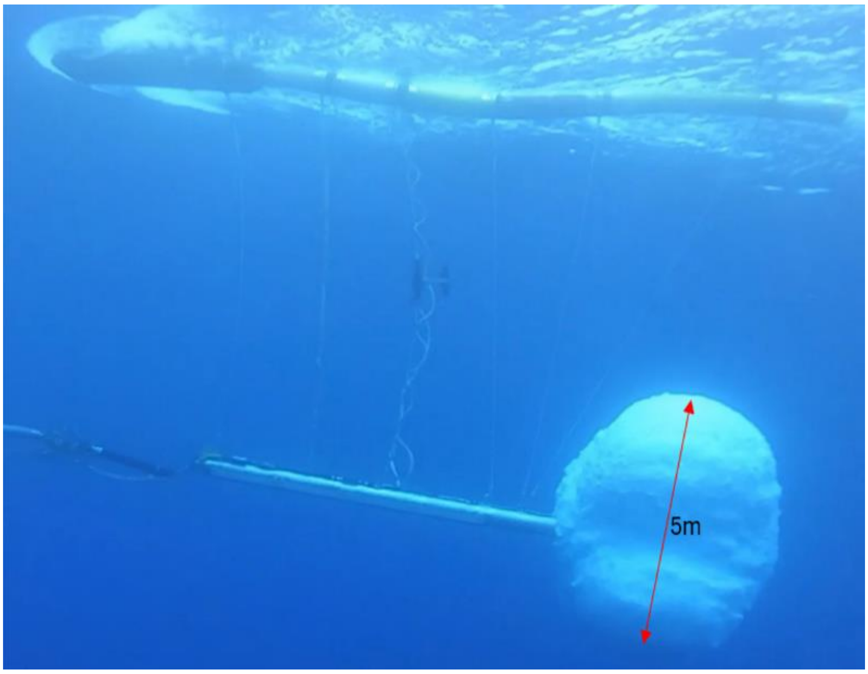

Figure 3 *The Tuned Pulse Source is a pneumatic source. That is, like Airguns, it releases compressed air into the water. Unlike Airguns, it has a different design that reduces its environmental impact and makes it safer for the crew. Unlike Airguns its pressure is 1000 PSI and not 2000 PSI. Like Airguns, 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.*

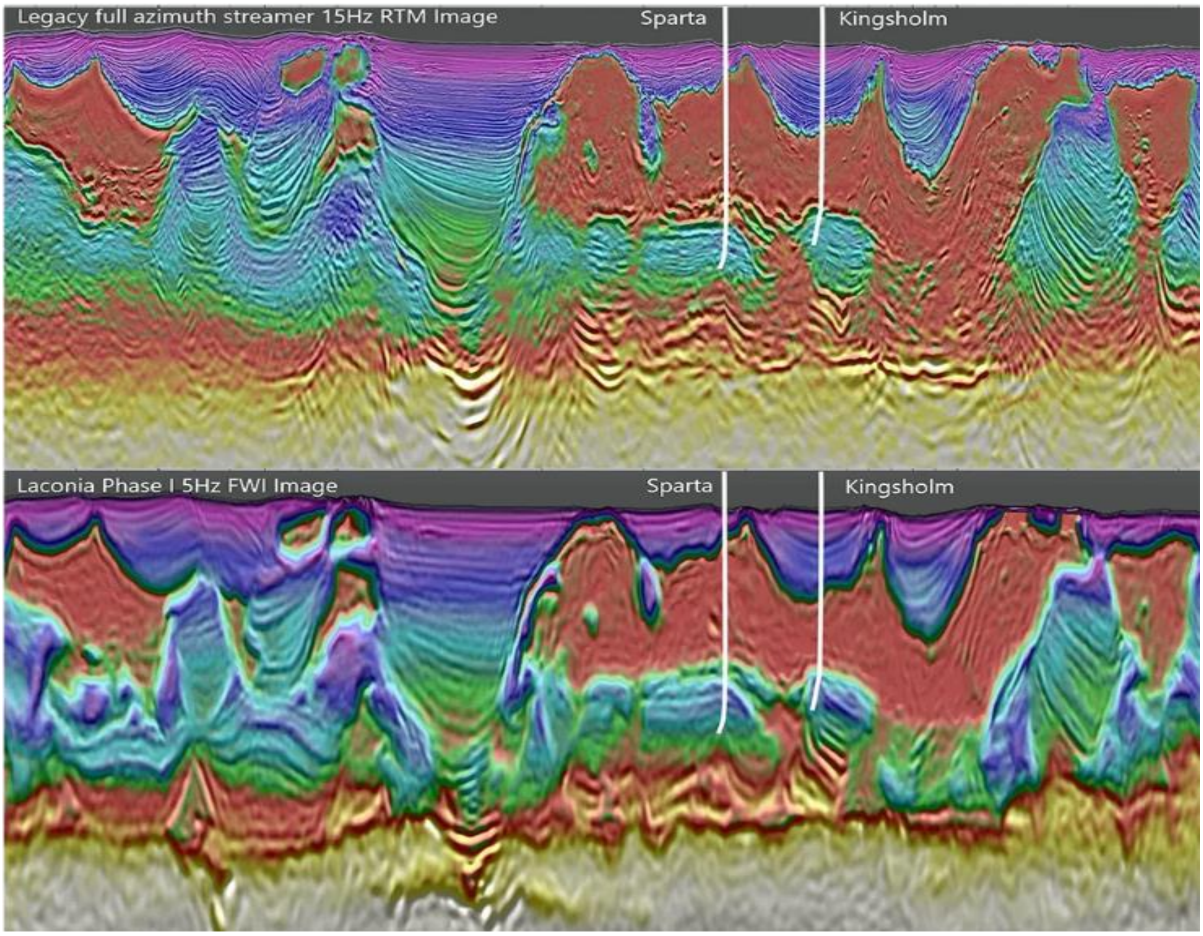

Figure 4 *Legacy full azimuth streamer 15 Hz RTM image overlaid with 6 Hz streamer FWI velocity (top) and Laconia Phase I long-offset low-frequency sparse OBN "early-out" 5 Hz FWI Image overlaid with corresponding velocity (bottom). The early-out demonstrates significantly improved imaging of the salt 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).*