Introduction

Imaging targets under salt, basalt, and chalk is a challenge because such overburden scatters and attenuates seismic waves and because building accurate velocity models is subject to cycle skipping. Low frequency waves attenuate and scatter less than high frequency waves and mitigate cycle skipping. 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 narrow band data, inversion programs 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 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 (Figure 1; Grobe, 2006). The large 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 including 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.

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, demonstrate the effectiveness of TPS in imaging deep targets under complex salt structures and improved blocky earth model post salt. Processing testing using TPS data show that without the low-frequency signal, FWI failed to image deep targets. Imaging legacy Airgun data with velocity models from TPS data also failed. Figure 4 shows a comparison of the image from a legacy FAZ streamer survey using Airgun 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.

Environmental, safety, and permitting

The environmental impact of very large volume pneumatic sources, commonly known as Airguns, has been a concern. Permitting was granted only after considerable effort using data from very large sources recorded onshore in lakes. The safety of the crew was also a concern. Airgun auto-fires onboard is a big safety risk. An onboard auto-fire of a large-volume pneumatic source would be devastating. The TPS design is different from the design of conventional Airguns. Deliberate differences reduces its environmental impact and prevents auto-fires. If time permits, we will present environmental impact reports from Jasco and from the California Ocean Alliance (COA, 2024). Jasco is an independent company, and COA is an independent organization. These reports show that TPS has a significantly lower environmental impact than Airguns with much smaller volumes.



Figure 1 *2000 cubic inch Airgun being serviced. Two of these Airguns were used in a survey that was designed by Ziolkowski et al and 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 cubic inched compared to 28000 for the TPS. The pressure of this source was 2000 PSI which is double the TPS pressure. (Figure from Wikipedia By Hannes Grobe, 2006.)*

Conclusion

The added value of low frequency signal is proven for sub-basalt and pre-salt imaging. Added value for post and no salt and basalt is anticipated for exploration as well as development and production. Low frequency sources have recently become available. Their practical deployment will add much more than their added cost to the value of information coming from seismic surveys at the equatorial margins and in the general,

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.

COA, 2024. https://gulfspillrestoration.noaa.gov/media/document/2024-05-oo-marine-mammal-noise-project.

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

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.

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

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.

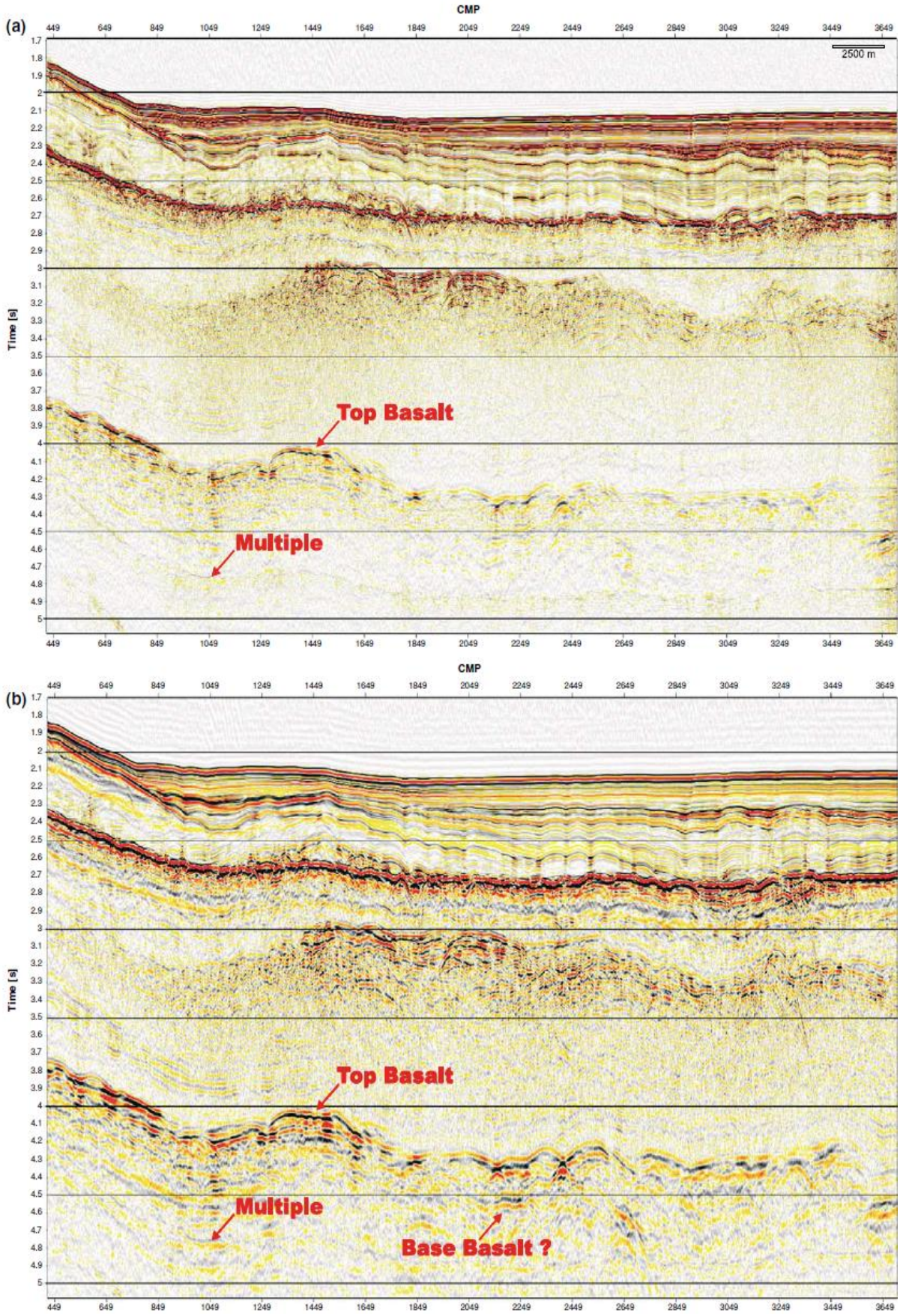


Figure 2 *Sub-basalt imaging. (a) The source was an array of Airguns. The largest guns were 465 cui. (b) the largest guns were 2000 cui. Reproduced from Ziolkowski et al, 2003. Both streamers*

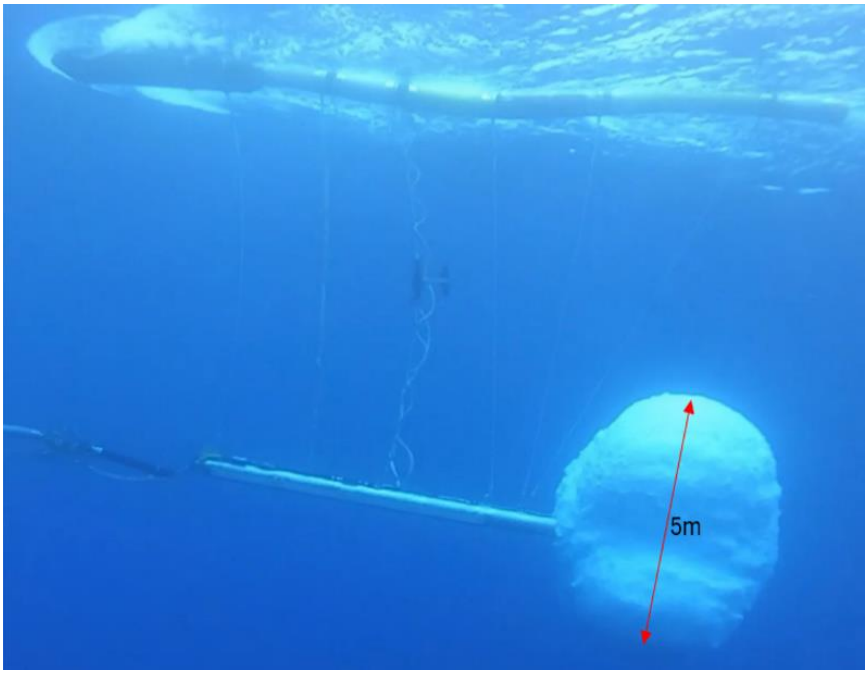


Figure 3 *The Tuned Pulse Source is a pneumatic source. That is, like Airguns, it releases compressed air into the water. Unlike Airguns, it has a different design that reduces its environmental impact and makes it safer for the crew. Unlike Airguns its pressure is 1000 PSI and not 2000 PSI. Like Airguns,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

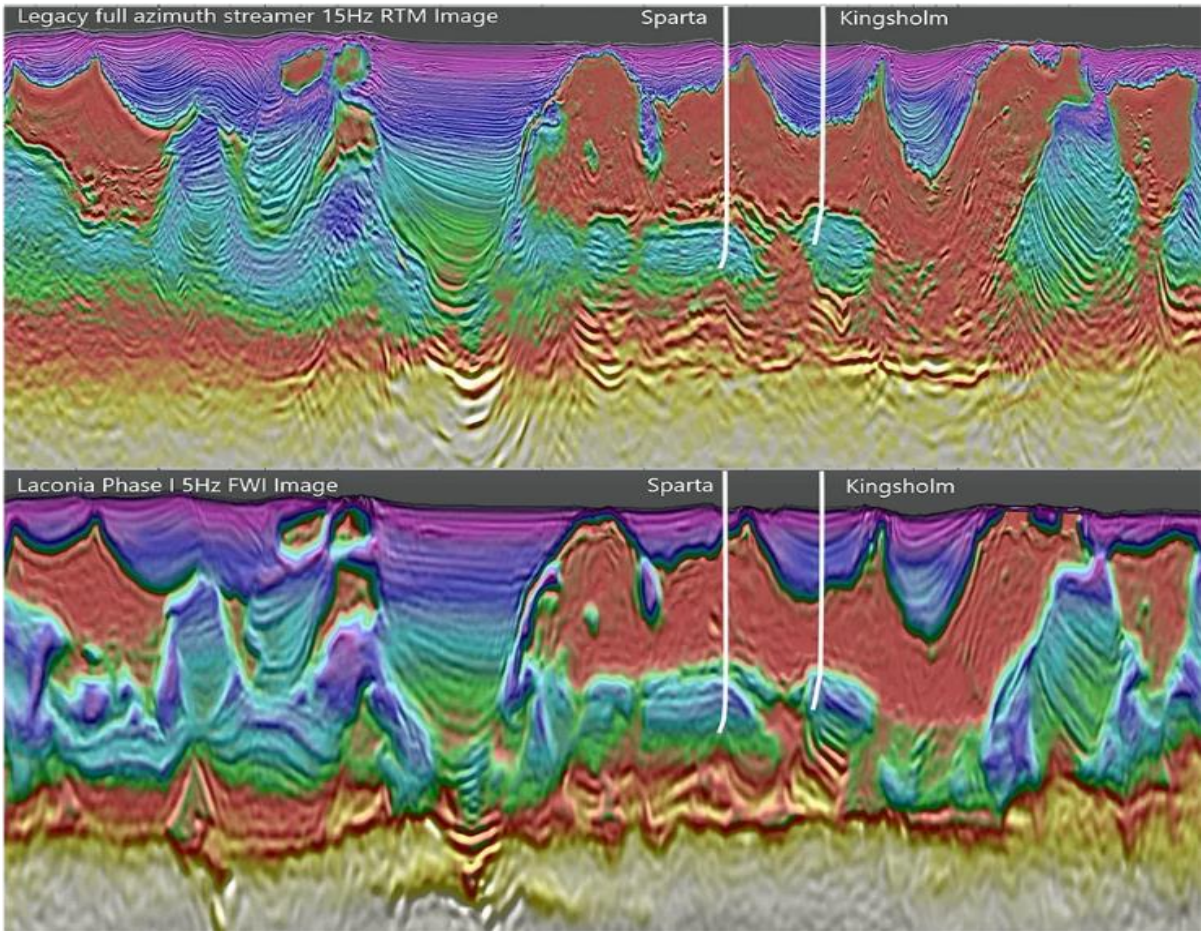


Figure 4 *Legacy full azimuth streamer 15 Hz RTM image overlaid with 6 Hz streamer FWI velocity (top) and Laconia Phase I long-offset low-frequency sparse OBN "early-out" 5 Hz FWI Image overlaid with corresponding velocity (bottom). The early-out demonstrates significantly improved imaging of the salt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