Seismic imaging below the basalt: Lessons learned and ideas for the future

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Sub-basalt imaging is one of the most challenging geologic scenarios for hydrocarbon exploration worldwide, especially offshore India. Using conventional seismic imaging methods, we can usually establish the top basalt accurately, but it is often challenging to image the base of basalt and more importantly the sediments below. Poor seismic imaging below basalt can be attributed to several interrelated causes including:

- Illumination – the required data were never recorded, due to limited acquisition design.
- Kinematics – reflection data have not been focused (poor velocity model)
- Scattering – roughness of surfaces and heterogeneities in the subsurface mean that high frequencies do not image, but low frequencies may
- Transmission – most of the signal was reflected before it reached to the target due to high velocity/density contrasts
- Absorption – Intrinsic attenuation means that the signal was absorbed
- Signal and noise issues – the noise level has not been sufficiently suppressed during acquisition and/or processing to reveal weak underlying signal

These six factors provide a useful analysis methodology for the technical issues and potential methods to overcome a severe 'Geo-Challenge' such as sub-basalt imaging. For sub-basalt, all six of these factors play a part to some degree in limiting our success; therefore, it is likely that there is no single 'magic-bullet' technique or technology that alone will produce a dramatic improvement in the seismic image. Improvements have, and will be, gained incrementally and by combining various techniques. These techniques and technologies include combining reflection seismic with magnetic and gravity measurements, super long offset acquisition, the use of converted and diving waves, low-frequency, wide-azimuth 3D seismic acquisition, and amplitude and signal preservation embedded in processing and depth imaging workflows.

Past work

Some of the older work from the Atlantic margins basalt province include projects to acquire very long-offset data.

Figure 1 illustrates some simple 2D modelling of PP and mode converted rays through a basalt layer approximately 1 km thick and shows the nomenclature for labeling such that each leg through the model is designated a letter P or S. It can be seen that the sub-basalt mode converted events occur at much longer offsets than the P only events. Figure 2 shows the modelled shot gathers with some interpretation of the events on the gather. We can see main direct arrivals and refractions, in red are the sub-basalt, P-wave, wide angle reflections and, in green, are the reflections which have travelled as mode converted energy through the basalt. We can detect some moveout on these events which indicates that they are not pure refractions. The important thing to note is that we predict mode-converted, S-wave events, occurring at offsets from about 4 km all the way out to the full extent of the model. It also shows them occurring before the arrivals and multiples from

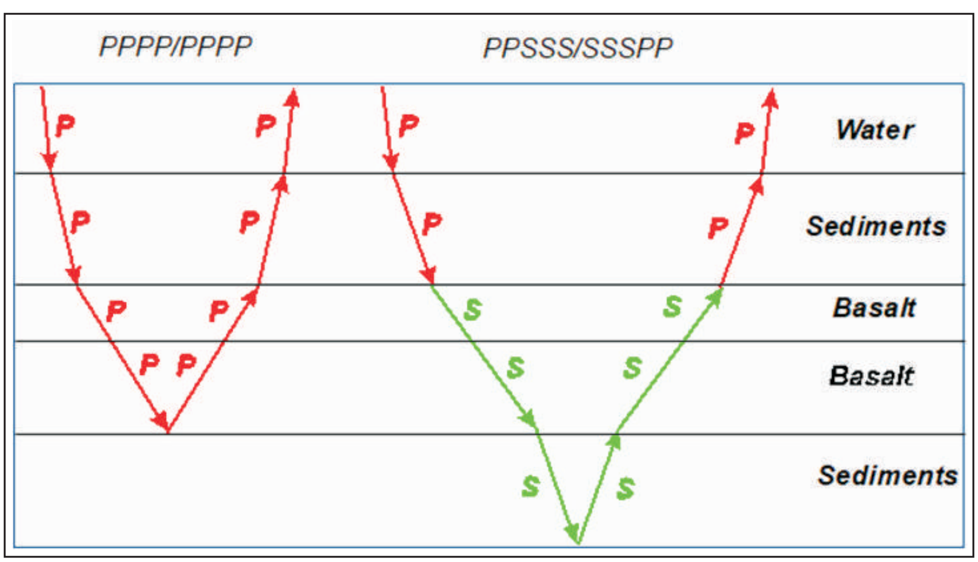

Figure 1: Simple 2D model showing P and converted mode propagation paths through basalt.

shallower horizons at these ultra long offsets which will help us in processing the data.This type of modelling is inexpensive and provides insight of the challenge and what dimensions and sampling a new acquisition would require.

In addition to longer offsets, some past efforts have been focused on the use of low frequency sources and more recently complete broadband acquisition and processing. An example of broadband acquisition and processing is shown in Figure 3 where these technologies were used to successfully map beneath basalt layers. Low frequencies are particularly important in this case, but the key point is not only having low frequencies but also retaining phase control and establishing a good signal-to-noise ratio in the critical three octaves between 1.5 and 12 Hertz. Control of low frequency noise and the stability of the low frequencies during de-ghosting and further processing are key contributors to successful sub-basalt imaging.

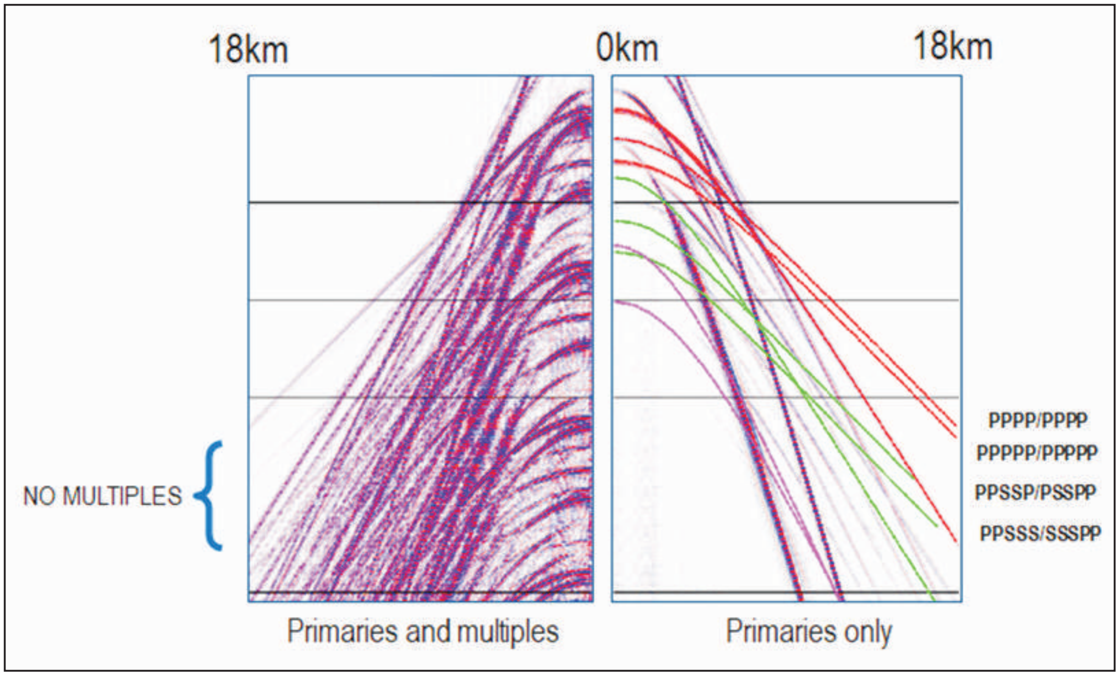

Figure 2: Shot gathers from 2D modelling (note the maximum offset of the records).

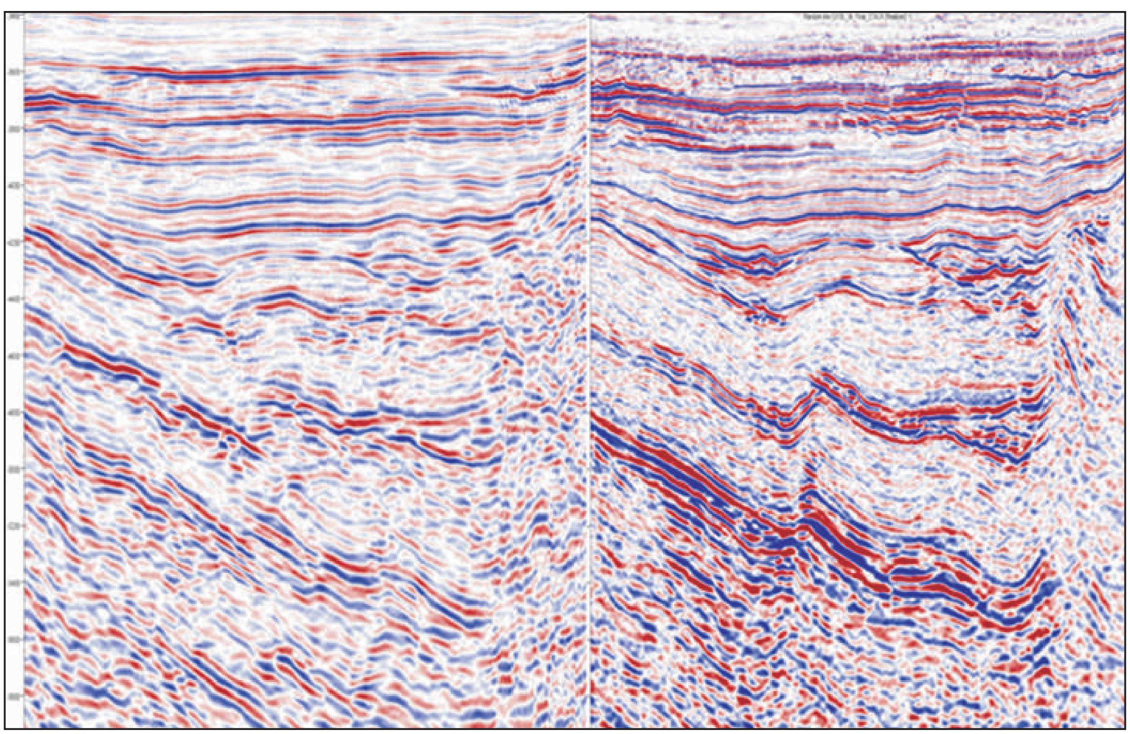

Figure 3: Legacy data (left) versus broadband data (right) acquired offshore India. Data courtesy ONGC.

Future directions

Long offsets have been used in the past for imaging (using both P and mode converted PS waves) however recent developments mean these data can also be effectively used for velocity model building. At the top basalt there is a strong velocity contrast between the sediments and basalt, so the critical angle can be low. Basalts also often have a velocity gradient with depth, with the older laminates having higher velocities. As a result, wave paths with high incident angles at top basalt become diving waves that 'turn' in and below the basalt layer. Diving waves, or their truncation (due to a velocity profile inversion), can be used to determine the basalt thickness, velocity and the nature of the sub-basalt sediments. Today, full waveform inversion (FWI) is rapidly becoming a standard technique to use this ultra long offset information to build a velocity model from surface to target. However, it is necessary that these very long offsets and low frequencies are recorded and legacy data is typically too restricted in these respects. Figure 4 shows the conceptual modelling of diving waves through a basalt layer and illustrates that offsets of upto 20 km are required (in this case). In addition, full azimuth 3D data is also vital to FWI success. Unless the subsurface structure of basalts and sediments are simple planar interfaces of very low dip, attempting FWI with 2D acquisition and processing will fail.

Furthermore, typical wide tow streamer 3D acquisition geometries with limited azimuth coverage, have poor cross-line illumination and source sampling limitations that greatly reduce FWI's effectiveness.

A novel and exciting recent possibility is the use of multi-purpose vessels which can simultaneously deploy seabed and surface streamer technologies to enable the efficient and flexible acquisition of full azimuth, P-wave and PS-wave data. This could also be supplemented with additional ultra-long offset recordings via autonomous marine vessels equipped with 3D seismic sensor arrays. A possible sub-basalt focused recording configuration is shown in Figure 5 where we have a

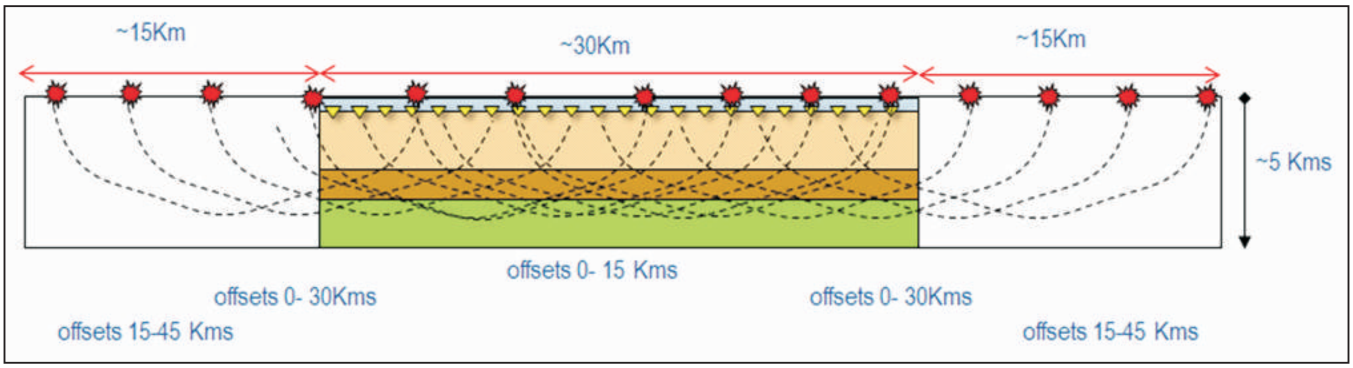

Figure 4: Ultra long offset acquisition model through basalt layer (dark orange) showing diving rays (dashed lines).

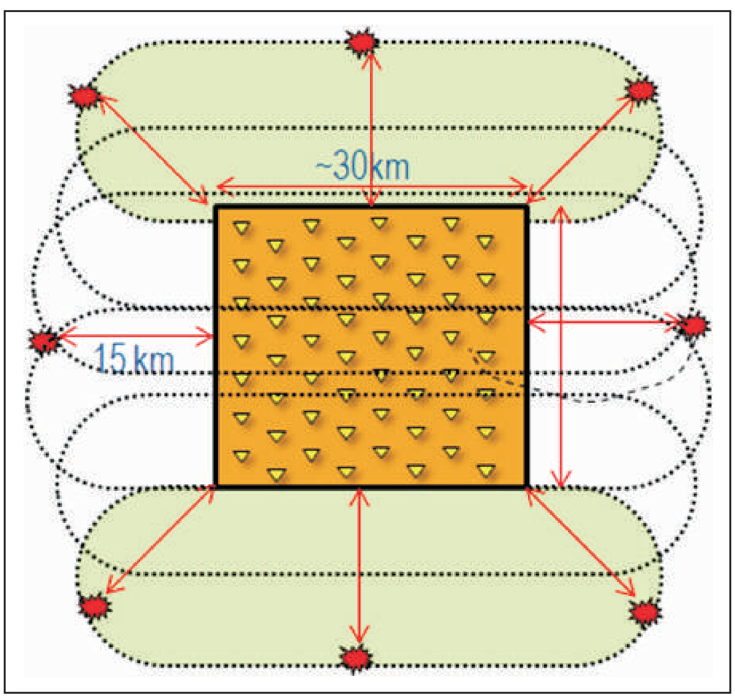

Figure 5: Areal layout of nodes (triangles) and source/streamer lines (red stars on dashed lines).

patch of seabed nodes laid out over a 30 km x 30 km area. After deploying the nodes, the vessel would traverse in a series of larger oval 'racetracks' providing source points. In addition, it would also tow streamers to provide traces outside the node patch and additional densely spaced near offset traces to supplement the node data. This proposed acquisition plan using a single, cost effective, multi-purpose vessel would provide a richly illuminated, ultra long offset, broadband dataset that would be ideal for modern processing and imaging of a sub-basalt 'geo-challenge'.

Source and receiver technologies and survey economics are continually evolving and have developed quickly in recent years. These include multicomponent streamer technology, efficient and cost-effective ocean bottom acquisition, low frequency sources, economic 3D, higher resolution FWI and improved deghosting methods. Careful attention to low frequency noise, combined with significant improvements in source and receiver side deghosting mean that we can expect an improvement in our low frequency content which is vital for our image at depth.

Conclusions

The sub-basalt imaging problem needs to be addressed from many angles and we have shown some modelling results and have proposed some ideas for future acquisition and processing. There is no single technology that will allow us to produce clear seismic images beneath basalt and it is likely that a combination of technologies will be needed. Ideas and concepts can be tested via modelling prior to field acquisition. Acquisition techniques such as multicomponent streamers and multi-azimuth designs, plus the use of ultra long-offset data and nodes can be combined to give us the best raw seismic data. Processing techniques such as prestack depth migration and FWI have already been mentioned and 3D SRME may help in removing any residual multiples. Additional benefits can also be obtained by incorporating non-seismic data such as EM, MT and gravity data to constrain the velocity model.

We believe these new ideas will incrementally improve the subsurface image and will be of great value. The adoption of these techniques for sub-basalt imaging could result in the sort of improvements that have been seen in sub-salt and sub-carbonate imaging in other provinces. This will then provide the impetus to drill and fully test the potential of hydrocarbon systems beneath the basalt and ultimately result in hydrocarbon exploitation in the basalt provinces of India and beyond.