Designing an Exploration Scale OBN: Acquisition design for subsalt imaging and velocity determination

Joakim Blanch, Jon Jarvis, Chris Hurren, (BHP), Yan Liu, Lingli Hu (CGG).

Summary

Direct wave arrivals are the most robust signals to determine velocity and consequently they have been used for almost a century in hydrocarbon exploration. The reason is simple as the arrival time is explicitly available. In order to acquire these direct arrivals in a seismic experimental setting it is necessary that these waves turns back to the surface after having been sent into the Earth. As is well known it is possible to turn waves back up if they encounter faster propagation velocities than have been previously experienced. Using these simple concepts we show how it is possible to design a seismic acquisition to measure subsalt velocities when the salt cover is very thick and potentially not homogeneous.

Until now (in marine seismic surveying) the physical limitations of the Earth have meant that use of direct wave arrivals have been restricted to relatively shallow depths of investigation, linked to streamer length. In this paper we describe how a new and novel application of node technology has been combined with a well established physical phenomena to support the acquisition of a world first exploration-scale Ocean Bottom Node (OBN) survey.

Introduction

Using direct arrivals for velocity estimation is one of the oldest seismic exploration methods, and appears to have been used as early as 1910 (Weatherby, 1940). One early such method is fan shooting where, earlier than expected arrivals (a leading edge) were used to identify areas of higher velocity, in this case indicating the presence of salt domes. Subsequently direct arrivals have been used for refraction tomography with many applications, e.g., Dynes and Lytle (1979), Ivansson (1985), Zelt (1992).

These methods are very labor intensive as individual events need to be identified manually. As the amount of seismic data collected has increased in recent years there has been a growing need for a methodology that automates this process. Full Waveform Inversion (FWI) was originally designed for accurate amplitude inversion of reflected energy (Lailly 1983) but as the kernel mimics a velocity inversion kernel when the method is applied to direct arrivals, it is suitable for velocity inversion as well.

Previous works that applied FWI to determine salt geometry and/or subsalt velocity were using starting models that only took some of velocity properties of the Earth into account. Subsequently the application was somewhat limited to salt sheets that were not too thick and had an edge to sediments such that waves could turn upwards in the sedimentary column.

There are however, areas where the salt is a thick canopy and stretches from essentially sea floor to about 10 km depth and where these models are not functional. The solution is to add basement to the velocity model and use the direct arrivals that are turned upward in the basement for velocity model building. These direct arrivals are key enablers to determine salt geometry and sub salt velocity.

As low frequency data are important in order to handle large velocity errors for FWI, it is necessary to be able to acquire such data. However, conventional source technology generate very little energy at low frequencies and hence it is necessary to understand the behavior of FWI for realistic noise levels at these lower frequencies.

Survey design methodology

We are considering a marine environment where large salt canopies are present. Additionally, in order to be able to acquire long offset data we considered ocean bottom nodes (OBN) with a sea surface source.

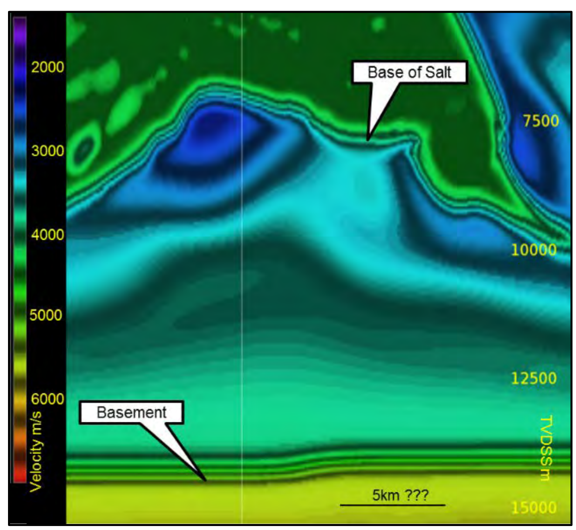

Figure 1. Part of the “complicated” starting velocity model used for the survey design. The color bar shows the velocity in m/s and the axis on the right the depth in meters.

10.1190/segam2019-3216451.1

The first step in the survey design is to build a velocity model that is the best estimate available of the actual subsurface velocity. We used a velocity model derived through standard subsalt imaging and added basement at the basement horizon (Figure 1).

The starting velocity model contains a thick salt canopy consisting of mixed salt and sediment inclusions. The sub-salt succession consists of alternating sand and shale sediments of an unknown velocity. The velocity of and at the top of basement is somewhat uncertain, we decided to work with the range 5 to 6 km/s. (The most likely velocity at the top of basement is 6 km/s but we believed that a slower velocity would put higher demand on an actual survey in terms of offsets. This turned out to be true but does not have a significant impact on survey parameters.) Figures 2 and 3 show ray tracing and finite difference modeling through this velocity model. "Diving waves" are generated below salt at the basement. It is also apparent that at larger incidence angles there is no energy transmitted into the basement, i.e. total reflection, which can be used as diving waves for the purpose of FWI. At a certain smaller incidence angle there will be conventional reflection and transmission at the basement boundary. Rays/wave energy that is refracted in the basement has almost vertical take-off as the shallow salt effectively screens rays/energy with large take-off angles.

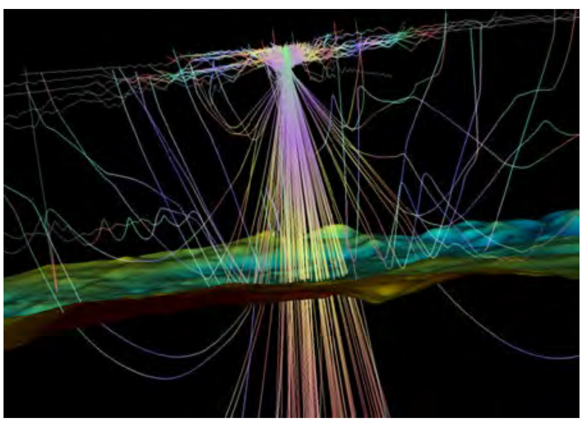

Figure 2. Ray cone with basement horizon. Rays with a high take off angle are either turned at water bottom or top of salt. Rays with a small take off angle are not turned, however a few rays with moderate take off angles are turned within the basement.

In order to evaluate the survey design parameters we used checkerboard velocity model perturbations in addition to a "complicated" velocity model. The correct velocity models were used to generate synthetic data, which were used as input for velocity inversion algorithms (FWI) and imaging.

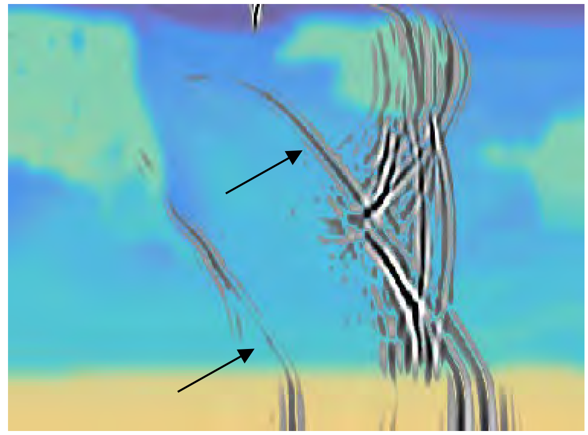

Figure 3. Finite Difference synthetic snapshot, basement refracted waves are indicated by arrows.

To further understand what frequencies could be used in FWI we added as realistic as possible "field-measured" noise levels to the synthetic data.

Results

It is necessary to understand the actual offset required to receive basement refracted events. Using a large model and simple ray tracing it is possible to get an idea at which offset these arrivals start to appear. Figure 4 shows that the events starts to appear at offset of about 25 km.

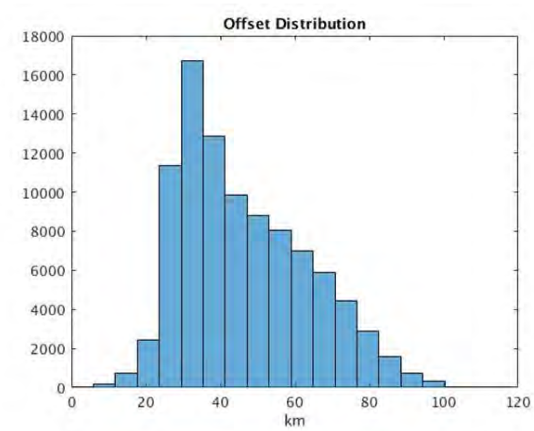

Figure 4. Offset distribution for turning rays. There are essentially no rays with shorter offset than 25 km. The drop-off in the distribution is mostly indicative of model size.

By considering basement refracted events FWI successfully recovered checker board velocity perturbations as well as the "complicated" velocity perturbation, Figures 5 and 6.

10.1190/segam2019-3216451.1

The checkerboard perturbations generally ensures a certain resolution is possible to retrieve whereas the more complex velocity perturbation can be used to investigate imaging effects.

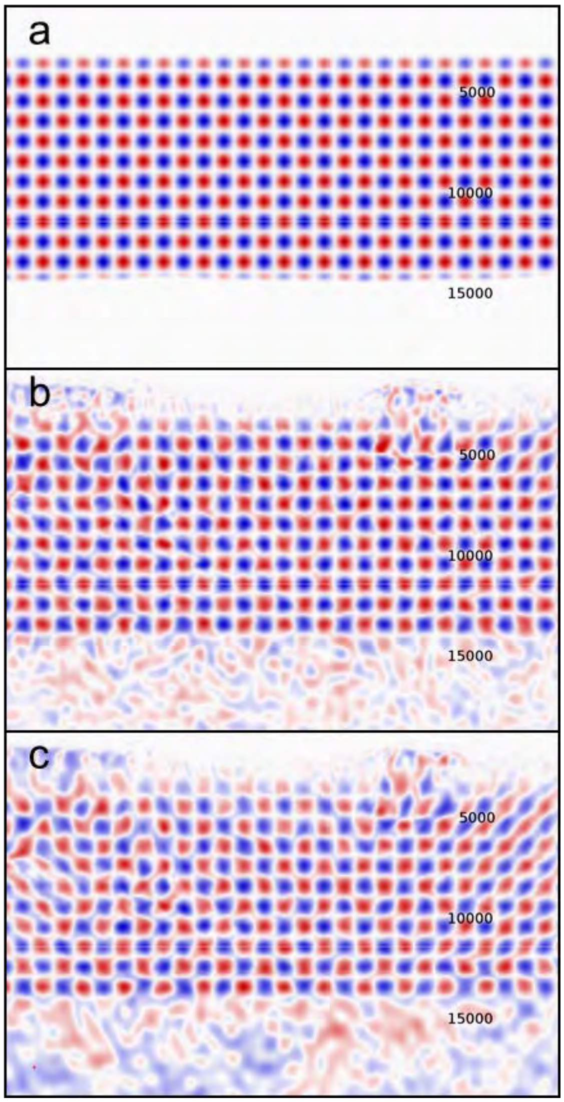

Figure 5. a) True checkerboard velocity perturbation, b) Recovered velocity perturbation, c) Recovered velocity perturbation with noise in data , S/N ~1). The velocity model can only be recovered in volumes with high ray density for the noisy data.

By evaluating the ability to recover a checkerboard pattern we found in this instance that a node spacing of 1.6 km should be sufficient and node patch size should be at least 25 km. For the source effort, 800 m spacing should be sufficient and the source effort should be performed with a 14 km halo around the node patch as described in Figure 7. In reality, it is advisable to use denser spacing in order to allow for instance for failed nodes and general noise.

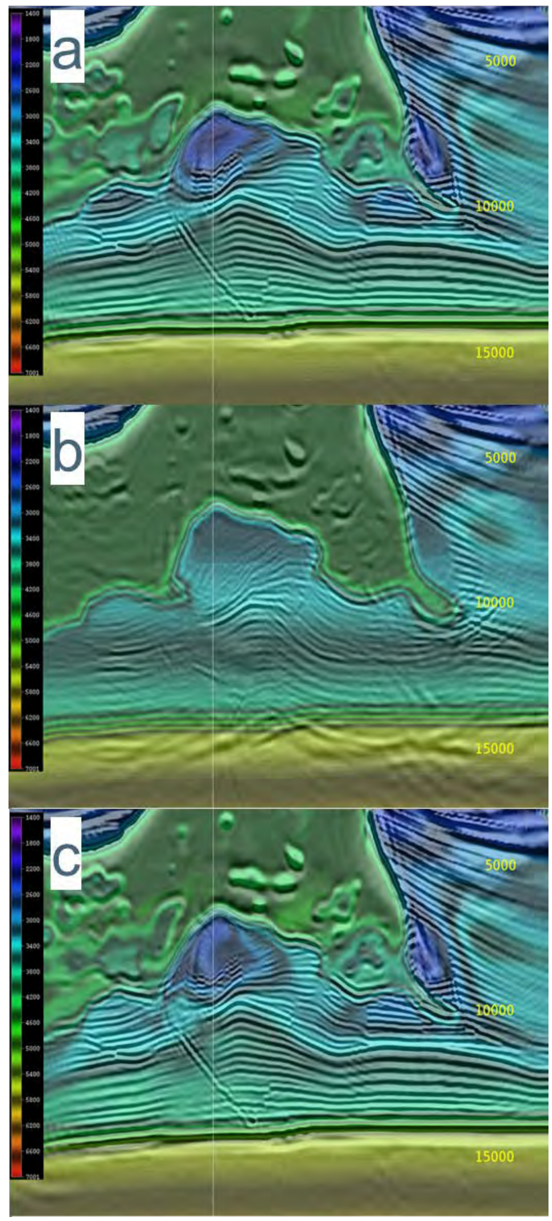

Figure 6. a) is the actual model whereas b) shows the initial model and c) shows the recovered model. The recovered model is accurate enough to enable imaging.

10.1190/segam2019-3216451.1

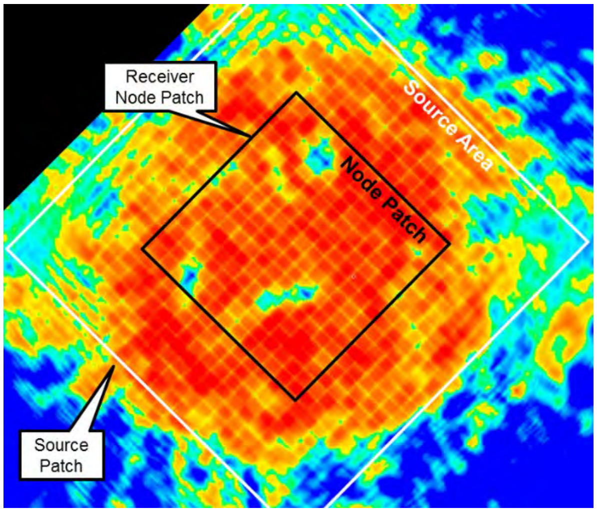

Figure 7. Evaluation of velocity perturbation recovery. The node patch is indicated by the black polygon and the source area is indicated by the white polygon. Warmer colors indicate more successful velocity recovery. The fully red area under the node patch indicates the source halo is sufficient to recover the velocity below the node patch.

Figure 8 shows imaging with the more complex model. Imaging using the incorrect velocity model clearly distorts the subsalt image, but by using FWI derived velocities it is possible to image the subsalt strata reasonably accurate.

Conclusions

Through forward modelling we have shown that using basement refracted events in conjunction with FWI it is possible to retrieve sub-salt velocities below thick salt canopies. Combining these modelling efforts with modern OBN technology we have successfully designed and optimized a seismic acquisition program whereby these velocity updates are expected to provide a step change in subsalt imaging for use in regional exploration.

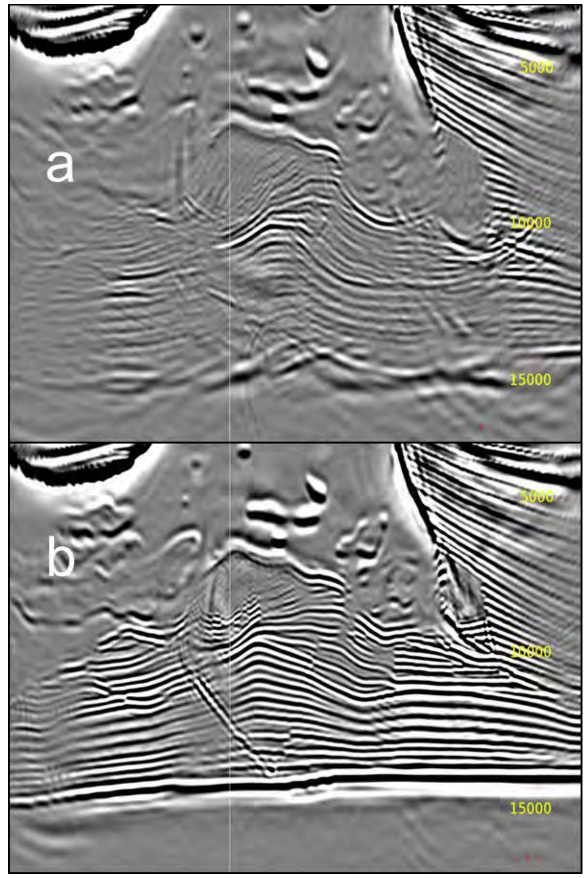

Figure 8. The image using the initial velocity model is shown in a), and the image using the recovered velocity model (Figure 6c) is shown in b). The initial model is clearly not accurate enough to properly focused the imaging data, whereas using FWI to recover the sub-salt velocity model enables focusing of the seismic data.

Acknowledgments

The authors wish to thank BHP for permission to publish the results.

REFERENCES

Dines, K., and J. Lytle, 1979, Computerized geophysical tomography: Proceedings of the IEEE, **67**, 1065–1073, 10.1109/proc.1979.11390.

Ivansson, S., 1985, A study of methods for tomographic velocity estimation in the presence of low velocity zones: Geophysics, **50**, 969–988, 10.1190/1.1441975.

Lailly, P., 1983, Seismic inverse problem as a sequence of before stack migrations, *in* J. Bednar, R. Redner, E. Robinson, and A. Weglein, eds., Conference on Inverse Scattering: Theory and Applications: SIAM, 206–220.

Weatherby, B. B., 1940, The history and development of seismic prospecting: Geophysics, **5**, 215–230, 10.1190/1.1441805.

Zelt, C. A., and R. B. Smith, 1992, Seismic traveltime inversion for 2-D crustal velocity structure: Geophysical Journal International, **108**, 16–34, 10.1111/j.1365-246x.1992.tb00836.x.