Echoes from the seabed: beginning and evolution of multicomponent seismic data processing and imaging

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Abstract

Over the last 40 years, the processing of ocean-bottom seismic data evolved from ghost attenuation by deconvolution to multicomponent wavefield separation and multidimensional deconvolution, and from single-component P-wave-only to multicomponent PP and PS. It benefited from continuous improvements in imaging applicable to seismic data in general, with the addition of some specific developments associated with peculiarities of ocean bottom data, chiefly for mirror imaging and joint PP-PS tomography with structural constraints. However there are also unresolved challenges. These are associated with the complexity and sampling limitations implicit with this type of data. The rise of full waveform inversion as a velocity model building and imaging tool presents the vision of a new dawn where these challenges may be finally overcome.

Introduction

Zachalardis and Bowden (1986) first introduced ocean-bottom seismic data recording (single component) as a way to acquire data close to clusters of production platforms in the Gulf of Mexico. It was only with Barr (1987) that dual-sensor cables came to the fore, and processing evolved from the attenuation of water layer reverberations by deconvolution to dual-sensor (pressure P and Vertical component of particle velocity Z) summation. The first 4-component (4C) systems introduced the recording of horizontal particle velocity. They were also developed in the late 1980's and used in the North Sea at Tommeliten and Valhall (Granlie et al. 1996). With their advent, the processing of OBC data evolved further, to include converted-waves (PS) as well as P-waves. The first commercial OBC systems, Q-seabed and VectorSeis Ocean, were introduced in 2004. Node systems were developed from the late 1990's and resulted in the CASE system of Seabed Geophysical, with many more to follow up to the present day (see for example Hager et al., 2022).

In parallel with the development of the acquisition systems, processing and imaging methods also evolved, naturally adapting to the increased quality and richness of the recorded data and to the ever-increasing computational power available to practitioners.

The past

Ocean-bottom recording with deep receivers immediately posed the data processing challenge of how to deal with the receiver ghost. The initial deconvolution-based solution for single-component recordings had shortcomings and prompted the introduction of dual-sensor (pressure P and vertical component Z) systems and the advent of the PZ summation method (Barr 1987). P-waves processing remained focused on this technology until the mid-2000s, when two factors introduced a change of perspective and the need to consider both the up-going and down-going parts of the wavefield: an increased awareness and growing successful applications of up-down deconvolution (Amundsen et al. 2001), and the introduction of mirror migration (Grion et al. 2007) to deal with the sparse, deep-water geometries made possible by the advent of OBN nodes. These two factors prompted a significant change in terminology and mindset, with "wavefield separation" gradually replacing "PZ summation", a change necessary to characterize the data processing flows finalized at that time, and exemplified in Figure 1.

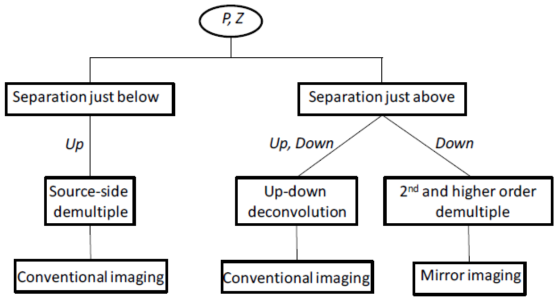

Figure 1: The ocean-bottom P-wave processing sequence established during the years 2005-1010. Mirror imaging of the down-going wavefield provides better illumination in case of sparse receivers. From Grion, (2010).

The goal of seismic exploration is to create 3-D depth images of subsurface properties. S-waves, used jointly with P-waves, aid the characterization of rock structure, type, and its fluid contents. With the introduction of 4C ocean bottom data in the 1990s, converted-wave (PS) processing became possible. PS processing was first proposed for seismic prospecting on land, with processing fundamentals developed in the late 1980s to early 1990s (Garotta et al. (1985)). While a number of successful case histories highlight the potential of converted waves, success is not general and typically associated with the denser receiver sampling possible in shallow water and with simpler near-seabottom geology, as shallow illumination is in general a problem for this type of data.

Unresolved challenges

Making full use of the richness of ocean-bottom 4C data remains a challenge. The nature of the data and the sampling typically available allow a high level of sophistication in terms of P-waves processing, imaging and inversion. Full waveform inversion (FWI) of P-waves is now possible, even with elastic assumptions. However, usage of converted-wave data remains limited, and progress has been slower. This is in part due to the nature of the data: attenuation has a stronger effect on S-waves than on P-waves; velocities are lower, therefore P-wave sampling is often insufficient for PS processing; illumination is poorer in particular for the all-important overburden, where propagation is nearly vertical on the S-leg due to very slow velocities. It is also partly due to the basic flat-layer assumptions of fundamental processing steps, like shear-wave birefringence compensation, as well as due to the basic assumption that conversion occurs purely upon reflection. Converted-wave migration assumes that these effects have been compensated for, no matter how complex the near-surface may be.

Another remaining challenge is the accurate removal of all multiples, in particular surface multiples in very shallow water and in the presence of complex geology. Despite numerous advances, this remains a challenge, particularly when multiples overlap target reflections and adaptive subtraction methods may affect not only the amplitudes but sometimes also the phase character (kinematics) of these events.

The future

As the marine geophysical investigations of the critical earth and deeper targets continues to increase in terms of quality requirements (improved resolution and quantified uncertainty), multicomponent ocean bottom data is going to play a key role. It is undisputed that this type of data are the richest seismic data available and the ones with the longest shelf life. No other type of seismic data has higher potential in terms of added value to informing subsurface digital twins. Exploiting all the features of these data requires a full waveform inversion approach. There are already remarkable success stories of elastic FWI for the inversion of P-waves, and some examples pf multicomponent FWI. These applications will continue to grow, and technology will further develop in terms of sophistication and precision. One major step forward would be using spectral element modelling engines as a replacement for the current finite difference (FD) engines. This will allow for more precise modelling of boundary effects and any geobody, thanks to the use of unstructured meshes. FWI is by nature less sensitive to sampling than a processing-imaging approach, as the growing number of deep water surveys with 1km node spacings shows. However, this reduced sensitivity has limitations, in particular for the full exploitation of the elastic nature of the data. Smaller, lighter ocean bottom nodes (Hager et al. 2022) are likely to play an increasingly important role in the future, as well as possibly ocean-bottom distributed acoustic sensing (DAS), particularly in monitoring applications.

For the conventional processing route of processing and imaging, the multiple removal challenge can be addressed with emerging developments toward the multidimensional deconvolution method, an extension of up-down deconvolution for complex geology. Its computational cost is high, but 3D applications are becoming possible (See for example Saragoussi et al. 2024, Vasconcelos et al. 2024).

Conclusions

Ocean bottom data offer unparalleled advantages in terms of flexibility around obstacles and full-azimuth coverage. Processing and imaging of P-waves can make full use of these features, and lead to the expansive use of these data types in recent years. Still, ocean-bottom data also have unexploited potential. The full utilization of elastic effects has just begun and in the coming years will expand to the inversion of shear velocities and the usage of all recorded data components. The associated computational complexity and cost is high, and further developments in terms of both novel approaches and compute capacity are necessary in order for industrial applications of 4C elastic FWI to become routine. This time will come. Sampling will remain a fundamental requirement, but the replacement of the processing and imaging approach with inversion may relax the sampling requirements, and will expand the scenarios where full use of shear wave information is possible.

It should be recognized that the traditional PS processing route has reached its potential and will remain applicable to cases with dense receiver sampling and relatively simple shallow subsurface. Full use of the multicomponent nature of ocean bottom data requires the step change to multicomponent elastic FWI.

References

Amundsen L., Ikelle, L., Berg, L. E., 2001, multidimensional signature deconvolution and free-surface multiple elimination of marine multicomponent ocean-bottom seismic data, Geophysics

Barr, F., 1987, Dual sensor OBC technology, The Leading Edge.

Garotta, R., Marechal, P., and Magesan, M., 1985, Two-component acquisition as a routine procedure for recording P-waves and converted waves: Can. J. Expl. Geophys., 21, 40-53.

Grion, S., 2010, From PZ Sum to Wavefield Separation, Mirror Imaging and Up Down Deconvolution: the Evolution of OBS Data Processing, KazGeo -1st EAGE International Geosciences Conference of Kazakhstan

Grion, S., Exley, R., Manin. M., Miao, X., Pica, A.L., Wang, Y., Granger, P., Ronen, S., 2007, Mirror imaging of OBS data, First Break, 25 (11).

Hager, E., Combee, L., Jaavold, V., Husom, V., 2022, The making of a node, First Break, Vol. 40, November.

Kommedal, J.H., & Barkved, O.I. (2004). "Life of Field Seismic: The Permanent 4C Seafloor Installation at Valhall. *First Break*, 22(10), 31-38.

Saragoussi, F., Leake, S., Boiero, D., Miasnikova, G., Ashby, Bagaini, C., 2024, Multidimensional Deconvolution for Processing Non-Dense OBS Data on Rapidly Varying Seabed: A Caspian Sea Case Study, EAGE Annual Meeting

Vasconcelos, I., Vargas, D., Terenghi, P., Ravasi, M., 2024, Deblurring-based, time-domain multidimensional deconvolution – redatuming for target oriented imaging, EAGE Annual Meeting

Zachariadis, R.G., Bowden, E. A., 1986, Ocean Bottom Cable: A fixed sea floor reflection system

Granlie, J.R, Sollid, A., Arntsen ,B., and Hilde, E., 1996 : Improved Imaging of Tommeliten Alpha Using PS-waves, NPF Bi-annual Conference, Kristiansand.