Frontier exploration insights using simultaneous inversion of velocity and reflectivity: a case study, Offshore Canada

C. Reiser[1], N. Chemingui[1], S. Arasanipalai[1], G. Huang[1], S. Crawley[1], J. Ramos-Martinez[1]

[1] PGS

Summary

Quantitative Interpretation (QI) workflows have evolved significantly since the last decade or so. In 2007, the introduction of the broadband marine seismic using multisensor streamer has created a significant step change in the offshore industry. This step change had/has some significant implications on the whole chain from the seismic acquisition to reservoir properties estimation. On the latter, the requirement of a well or model based seismic inversion is significantly reduced allowing a seismic inversion to be more data driven than model driven. With more reliable seismic data being acquired, we have also seen the rapid development of inversion-based techniques such as Full Waveform Inversion, Least-Squares Migration and their integration. The objective of this paper will be to present how in a very frontier exploration setting the simultaneous inversion of velocity and angle dependent reflectivity can have an impact on the quantitative interpretation workflow benefiting for an improved prospectivity assessment and understanding of the area concerned. This will be presented through the mean of a case study in the Offshore Newfoundland and Labrador, Canada and by analyzing the Amplitude versus Angle (AVA) response of this new depth imaging inversion scheme.

Introduction

The offshore basins of the Canadian province of Newfoundland and Labrador are largely unexplored and under-evaluated. These areas offer significant potential for hydrocarbon exploration and development, but also pose many challenges and uncertainties. An assessment of the geological and geophysical (to name just a few) of these basins is needed to reduce the risks and increase the opportunities for successful exploration. Since 2014, OilCo (the state-owned oil and gas company of this region), and partners PGS and TGS, have acquired approximately 50,000 line kilometers of high resolution 2D broadband seismic data throughout the area. In 2019, a 3D multisensor streamer seismic survey of 2,600 km2 was acquired in the South Bank area within the 2022 Licence Round region (Figure 1).

In this setting, estimating the elastic properties distribution of reservoirs can be challenging, even more in exploration or frontier exploration. This is mainly due to the lack of well information, calibration, limited regional geological understanding, and the quality and reliability of seismic data available. Time to assess all of this could be of essence for evaluating the prospectivity of an area.

This case study aims at illustrating how some of the frontier exploration challenges could be addressed through an integrated workflow from broadband seismic acquisition to elastic properties using recently developed depth imaging technologies, in this underexplored deepwater. The focus will be on the comparison between Amplitude versus Angle (AVA) attributes and elastic properties extracted using two distinct imaging workflows: Kirchoff migration (previously available) and the recently performed angle-dependent simultaneous inversion (Chemingui et al., 2023).

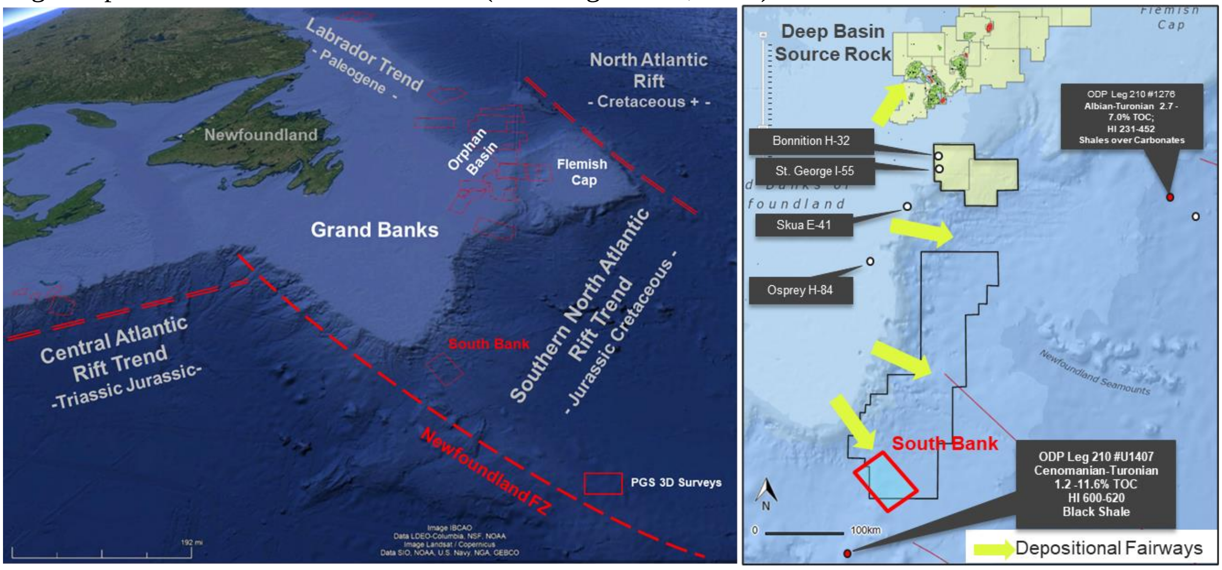

Figure 1: *Illustration of the main structural elements present in the Newfoundland and Labrador, offshore Canada, and the location of the area of interest (the South Bank dataset highlighted in the bottom of the right-hand side image with the red rectangle).*

Geological settings

The Grand Banks platform is located at the intersection of three major plate tectonic systems that are linked with the opening of the Central Atlantic that initiate during Triassic time by crustal extension (Figure 1). The rifting gradually propagated northward during Jurassic time which led to the separation between East Canada called Avalon in plate tectonic terms and Iberia. The opening of the Atlantic continued to migrate northward during Late Cretaceous and branched in Paleogene time in what we know today as the North Atlantic and the South Labrador Sea. The petroleum systems of the Grand Banks area are controlled by the opening, and particularly the migrating rift system associated with the Northern Atlantic. The South Bank survey is located at the deepwater slope of the Grand Banks platform just North of the Newfoundland fracture zone. This area contains some Mesozoic and Cenozoic stratigraphy (Norris D. et al., 2021). It has been defined by Austin et al. (1989), as the southern extent of the Salar Basin. The primary stratigraphic interval under consideration for this case study is the Paleogene interval. Very few wells encountered several potential reservoir intervals throughout the rift phase and in the post-rift passive margin sequence defining a series of stacked hydrocarbon plays. Wells are marked with a small white circle (Figure 1). The most prominent source rock in the section are Tithonian shales with their maturity in the oil window for most of Tertiary time. In the deepwater, the ODP well 210 encountered excellent source rock in the Albian, Cenomanian and Turonian (ACT) marine shales related to the initial opening of the southern North Atlantic. The rock evaluation data yield high TOC readings and promising hydrocarbon indexes. This could therefore indicate a prolific new system for the deep marine slope to basin floor environment off the Grand Banks platform and in our specific area of interest.

Seismic Inversion in the context of Frontier exploration

Reservoir geoscientists and quantitative interpreters gain a better understanding of the subsurface by integrating seismic and well measurements. In exploration, the lack of well information for calibration of the seismic response shifts the emphasis towards optimizing seismic data quality and doing so in a timely fashion to identify and derisk prospects as efficiently as possible. At the same time, more and more accurate imaging is required to resolve the detail of complex reservoir units and trapping configurations as petroleum geoscientists seek to identify and characterize subtle targets. Thus, the development of the broadband acquisition and subsequent processing workflows have some tremendous benefits on the amplitude side of the image and Quantitative Interpretation (QI) analysis (Ozdemir, 2009; Reiser et al., 2012). This has facilitated the development of improved imaging algorithms and more specifically for the velocity model building, as demonstrated over the past decade with Full Waveform Inversion. The frequency gap between the lowest frequency of the reflectivity and the highest frequency of the velocity decreases significantly allowing use of primarily the seismic data for inversion without the need of a derived well-based low frequency model. More recently, new schemes have been developed, allowing the simultaneous inversion of reflectivity and velocity (Yang et al., 2021). This is achieved by jointly performing Full Waveform Inversion (FWI) and non-linear Least-Square Reverse Time Migration (LS-RTM) based on scale separation concepts and the use of inverse scattering theory, and a wave-equation parameterized in vector reflectivity. Additionally, the solution has been extended to the prestack domain for the inversion of angle-dependent reflectivity (Chemingui, et al., 2023). Without entering in extensive details, we are encouraging the reader to refer to the previously cited references for more in-depth readings. This scheme has the advantage of simplifying the overall processing/imaging workflow as the inversion starts from the raw field data with minimal processing. The modeling is done by the generation of the full acoustic wavefield including reflected and refracted energy as well as the multiples. Through an iterative inversion workflow (minimization of the difference between the modelled and the field data), a simultaneous update of both the velocity model and the angle-dependent reflectivity is performed based on scale separation concepts and the use of inverse scattering theory. Thus, the procedure outputs angle-dependent reflectivity (i.e., angle gathers) jointly with a high-resolution velocity model, reducing the imaging workflow of velocity model building and migration into a single process.

In this case study, we focus mainly on the comparison at the stratigraphic interval of interest: the Oligocene turbiditic fan system and mainly to the "E-lobe" (Figure 2) for the attribute extraction. One of the outputs of the simultaneous inversion is the velocity which can be compared to the existing migration velocity (Figure 2). Several observations can be drawn: the new velocity seems to honour better the geomorphology of the fan system development from the shelf to the deepwater especially at the pre-lobe level (orange arrow) and better describes a normal compaction trend behaviour as opposed to the Kirchoff migration. Additionally, the simultaneous inversion presents significantly less localised rounded shapes (or "blobs") of higher/lower velocity than the Kirchoff migration. In this deepwater environment and with a sand-shale system layer at 1200 m below mudline, we should also expect the sands to be unconsolidated and to have a reasonable link with the velocity. With the simultaneous inversion, velocity variations inside a fan system can be observed at the various lobes from the shelf (left hand-side of each respective image) to the deepwater environment.

On the prestack or angle stack aspect comparison, Figure 3 illustrates the similarities between the two "migration" schemes. There is an overall improvement in the signal-to-noise ratio of the simultaneous inversion results. Regarding the AVA behaviour (on the angle gathers and the product stack) aspect, the amplitude ranges and lateral variations are comparable. Some differences exist between them and could be attributed to the differences in the velocity model (one been mainly based on tomography velocity update compared to FWI), the angle mapping and/or the nature of the migration, scheme itself.

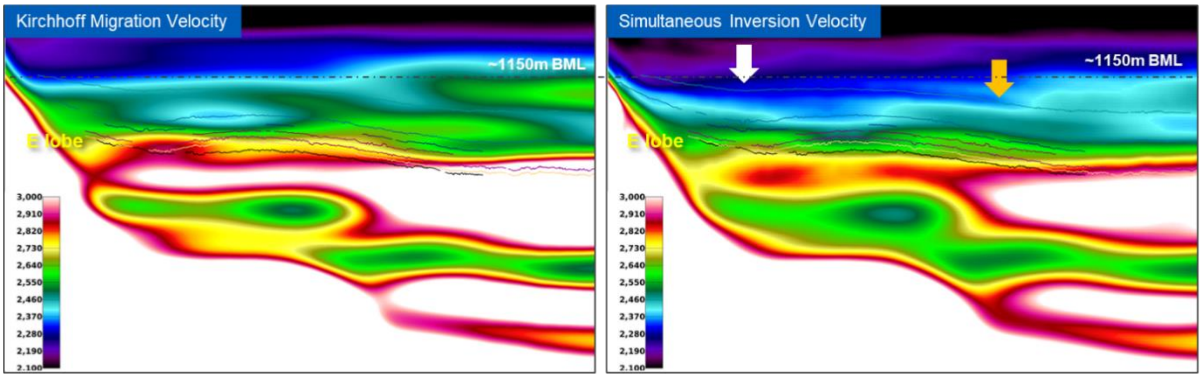

***Figure 2**: Comparison between the Kirchoff migration (left) and the simultaneous inversion velocities (right). Please <u>note the very compressed color bar</u> between 2100 to 3000 m/s to highlight the velocity variation inside the turbiditic lobe from the shelf to the deepwater environment. This illustrates some possible lithology variation: from sandy to more shaly or from proximal to distal environment.*

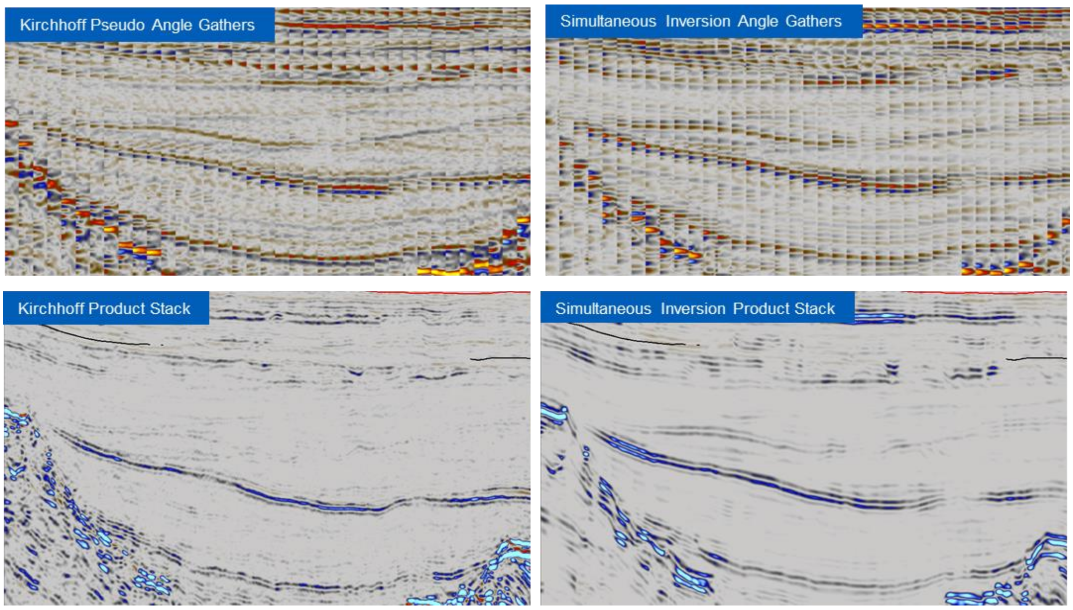

***Figure 3** Example of a comparison between the Kirchoff migration and simultaneous inversion angle gathers (top row) and product stack (multiplication of the estimated Shuey 2 term Intercept and gradient).*

With regards to the elastic property estimation and differences between the two workflows, a prestack inversion of the amplitudes from the two products has been performed using their respective angle stacks (Figure 4). Two main elastic attributes have been estimated: the relative impedance and the Vp/Vs with the same process. Being in this context of the frontier exploration and without any close by wells, any attempt of building a low frequency model without a rock physics understanding would be hazardous, hence we stayed in the relative domain. As previously shown with the amplitude data, the relative attributes of the simultaneous inversion exhibit a higher signal to noise and very comparable anomalies, variation to the one estimated from the Kirchoff migration accepted since years as an AVA friendly migration scheme. Some differences exist in some areas and would need further analysis.

Conclusions

This on-going analysis over the South Bank survey shows some potential sand reservoirs in large-scale clastic fan systems throughout the Paleogene sequence. The new simultaneous inversion scheme estimating simultaneously the angle dependent reflectivity and the seismic velocity does exhibit similar response compared to the legacy Kirchhoff migration. Some differences exist in some locations and can be easily explained by the nature of the different workflows. However, the inversion workflow does offer the possibility in a frontier exploration context, where unfortunately no well calibration is available, to have a different view of the subsurface in a shorter time. While the rock physics analysis is a work in progress, the new inversion workflow for joint estimation of velocity and reflectivity provides a promising approach for accurate and reliable estimation of the elastic properties of the subsurface directly from field records.

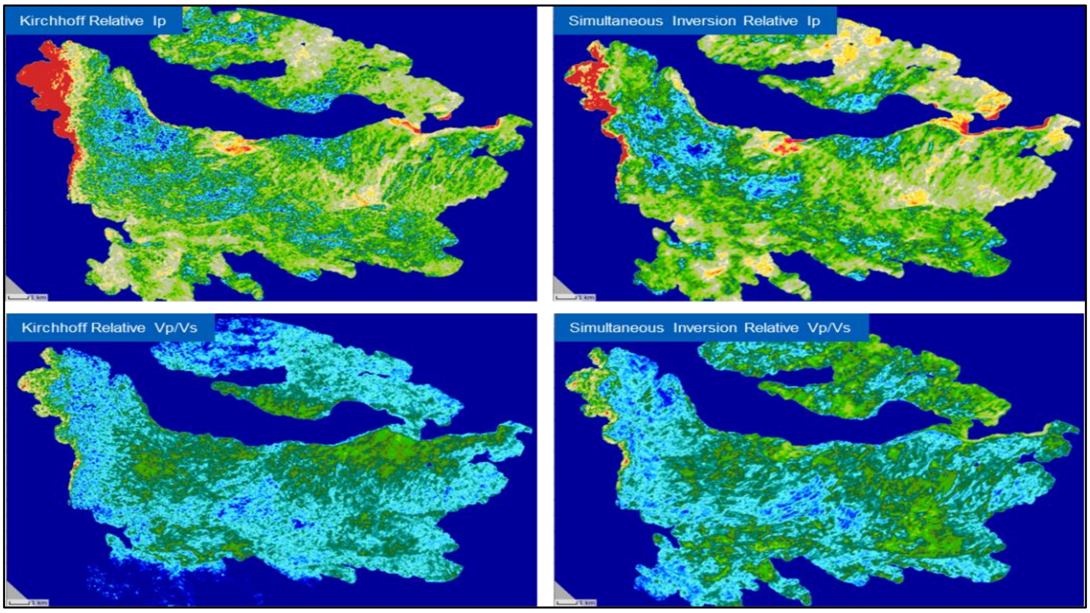

Figure 4 *Example of a comparison of amplitude extraction at one of the Oligocene "E lobe" (0 to 100 m down) between the results of the relative Ip (acoustic impedance) and Vp/Vs between the 2 migrations.*

Acknowledgements

The authors wish to thank PGS MultiClient for permission to show the results, colleagues for all their hard work and very engaged discussions during this project.

References

Austin J.A., Tucholke, B.E. and Uchupi E. [1989] Upper Triassic-Lower Jurassic salt basin southeast of the Grand Banks, Earth and Planetary Science Letters, Volume 92, Issue 3-4, p. 357-370.

Chemingui N., Yang Y., Ramos-Martinez J., Huang G., Whitmore D., Crawley S., Klochikhina E. and Arasanipalai S. [2023] Simultaneous Inversion of velocity and angle-dependent reflectivity. Third International Meeting for Applied Geoscience & Energy, Expanded Abstracts.

Norris D. and Mitchell V. [2021] New Cenozoic Play Trend in the Southern Salar Basin, Offshore Newfoundland and Labrador, First EAGE Workshop on East Canada Offshore Exploration, Nov 2021, Volume 2021, p.1 – 5, https://doi.org/10.3997/2214-4609.202186019

Özdemir, H. [2009] Unbiased deterministic seismic inversion: more seismic, less model. First Break, 27 (11), 43-50.

Reiser, C., Bird, T., Engelmark, F., Anderson, E. and Balabekov, Y. [2012] Value of broadband seismic for interpretation, reservoir characterization and quantitative interpretation workflows. First Break, 30 (9), 67-75.

Yang, Y., Ramos-Martinez, J., Whitmore, D., Guanghui, H. and Chemingui, N. [2021] Simultaneous inversion of velocity and reflectivity. First Break, 39(12), 55-59