Unravelling the Complex Subsurface Structures of Hydrocarbon Trap by Means of 3D Multi-Component Seismic Data

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Extended abstract

Arabian Gulf has been the home of prolific offshore hydrocarbon producing fields in the world. However, most of the produced hydrocarbon come from the easy-to-read structure or even an overlooked simple structure. These seemingly simple structures usually pose confusion, uncertainties, and enigmas when it comes to the discussion on reservoir rock quality. Prominent uncertainty has been observed in one of the fields in offshore Arabian Gulf, where thickness, porosity and permeability of the same rock formation can be significantly different even from the wells located adjacent to each other. Conventional 3D seismic data which was acquired using OBC method failed to image deep targets with complex fault system and geological structure.

Multicomponent seismology came as a solution to most of the limitations encountered in P-wave imaging. Recording different components of the seismic wave field allows geophysicists to map complex reservoirs and extract information that could not be obtained previously. Initial investigation of 4C-3D seismic data by means of PP Volume only showed simple anticlinal structure with no visible complex fault systems, confirming that 3D seismic with the compressional (P) wave alone was insufficient.

Mode-converted PS volume image has revealed the previously unseen complex faults and structure. Apparently, the former compressional PP volume approach alone could not really reveal the complex geological structure since P-wave is affected not only by matrix but also fluid occurrence. In areas affected by very intensive structures, the faults and fractures are filled with fluids which can attenuate or scatter the P-wave, resulting uncertainties in seismic imagery. Shear waves travel primarily through the rock matrix and are relatively unaffected by the pore fluid, therefore PS volume approach brings tremendous additional information to overcome such an issue.

The result of this approach shows significant improvement of seismic imagery which allows not only better recognition of complex geological structures but also more accurate determination of formation tops, hence the well-to-well correlation. In addition, better recognition of complex faults from this approach leads to satisfactory explanation for variation of petrophysical parameter over the same reservoir in the adjacent wells.

1. General Geological Background

The study field takes place at offshore oil and gas field in Arabian Gulf, in which marginal sea is located next to the southern flank of the Zagros Mountains between Persian Plateau and Arabian Plate (Figure 1). Tectonically this is a basin of the late Pliocene-Pleistocene subdued by Pleistocene limestone which was locally rejuvenated by tectonic activity during the Quaternary. Natural seismic activity around northern part of the Arabian Gulf, which is sometimes associated with great and devastating earthquakes, seems to be mainly under the influence of the convergent movement between Arabia and Eurasian Plate.

It is considered as an elongated anticlinal structure located in a divergent wrench fault zone which runs parallel to the structure with length of approximately 20 km in NNE-SSW direction and width of approximately 5 km in WWN-EES direction. The structural style is associated with basement fault which accommodates wrench- dominated kinematics by means of strike-slip faulting. Flower structure, which is a typical feature associated with wrench fault zones as explained by Huang and Liu (2017), has usually been considered as one of the most important features that can be used to identify strike-slip fault in regional tectonic studies.

Several wells have been drilled to explore the reservoirs of Cretaceous age and various reservoir properties were observed from one well to another. The field is located in the shallow water area (ranging from10 to 50m) over the fast velocity zone. Anhydrite and Karst occurrence on the shallower section above the reservoir (Figure 2), has caused significant seismic energy absorption, hence promoting issue on seismic imaging of the underlying reservoir.

2. Multicomponent Seismic Principles: P-wave and S-wave

Three-dimensional (3D) seismic reflection data has become a powerful tool in reservoir visualization because of its ability to define subtle subsurface structures and stratigraphy. The terminology of seismic refers to the measurement of elastic or acoustic signals at receiver locations from the energy released at source locations. The source generates elastic waves that propagate through the earth, in which it will be eventually reflected, refracted, polarized and absorbed according to well-known physical principles. The receiver measures the seismic signal which was reflected by the subsurface layers or boundaries.

Conventional seismic source emits compressional waves (P-waves) which penetrate the subsurface, and the resulting images reveal the P-wave properties of the subsurface, comprising both the rock matrix and the fluid contained within the pore space. The reflected P-wave's signal, once appropriately acquired and well-processed, can carry information about structure, lithology, saturating fluids of subsurface formations. However, P-wave alone has encountered numerous difficulties in imaging formation with low acoustic impedance contrast. Therefore, an effort to generate and record more complete vibrations in the earth to complement the P-wave was introduced and demonstrated as a promising solution. Unlike P-wave that can be affected by changes in rock's rigidity, density and compressibility; S-wave is sensitive only to rock rigidity and density. In addition, the P- wave compresses volumes, while S-wave only modifies their shapes.

Nowadays, S-wave provides great assistance to geoscientist to differentiate fluid-saturated formation from the lithological change and simultaneously to image gas cloud zones in which gas trace masks the subsurface formations. Another important aspect of the S-wave is its ability to image fault, fracture densities and its orientation. The knowledge of fracture direction and fracture density can be critical to the success of exploration and reservoir characterization. Since shear waves are sensitive to rock's shear modulus, they respond to changes in rock stiffness and strength. When the changes of stiffness and strength have preferential orientation, shear waves will undergo shear-wave splitting. This can occur also in the presence of fractures in the rock. S-wave passes through faults and fractures, then it splits into two S-waves.

The first one is fast S-wave, which is polarized parallel to the direction of fractures. The second one is slow S-wave, which is perpendicular to the faults and fracture planes. It is a standard practice to measure travel time variation of both waves (SV and SH) recorded at different acquisition azimuths. For SV section, angle at which the wave shows later arrival time is interpreted to be the direction perpendicular to fractures. On the other hand, the angle in which the wave arrives at earlier time is attributed to be the direction of faults and fractures. In the SH section, amplitude drops to zero and phases reversal can be observed at both directions determined on SV section.

In multicomponent seismic, we also seek to utilize shear waves (S-waves) to explore the subsurface. The source (air gun in offshore) emits P-wave and its corresponding reflected P and converted S-waves recorded by the receivers (Figure 3). Shear waves travel primarily through the rock matrix and are relatively unaffected by the pore fluid. This means that the fluid type, saturation, and pressure do not impact the propagation of shear waves, whereas they do affect the compressional waves. This is important when the P-wave image is obscured as a result of gas filled pores as the S-wave image will not be obscured. The combination of both P-wave and S-wave can be used to get better and more reliable reservoir image since they are independent measurement of the same subsurface subject.

Multicomponent sensor packages measure motion in three orthogonal vector directions (Figure 4). The sensors used are either omni directional, which means they will operate correctly at any orientation, or specifically horizontal or vertical, which means that they will only operate at that certain orientation. The vertical sensor yields a measurement similar to the single component measurement of conventional seismic data. Most of the energy on this vertical sensor will be P-wave energy because the shear velocity is very low in the near surface. Conversely, the two horizontal sensors will measure most of the S-wave energy. Shear waves are relatively unaffected by the presence of fluid, hence they can image through gas clouds, while shear-wave splitting and anisotropy simultaneously provide a means of estimating fracture intensity and orientation.

3. Seismic Data History

The legacy 3D seismic data was acquired using Ocean Bottom Cables with dual sensors in 1997. The acquisition bin size is 12.5m x 12.5m with 72 nominal fold coverage. The data quality was poor to fair, and the interpretation was hampered by severe multiple contamination and lacking high frequency content with low signal to noise ratio. High multiples contained inside the data makes the chasing of the events very difficult. Poor fault imaging observed as well inside the data. The field structure was defined as a simple symmetrical anticline cut by a large number of faults that have greater throw in the shallower reservoirs which diminish downwards into the target reservoirs.

The decision was made in 2012 to reshoot the seismic data with the purposes of enhancing the structure image, determining the reservoir architecture, distribution of rock properties, lithology & fluids to assist in the rejuvenation of the field. The new survey was acquired using Ocean-Bottom Cable (OBC) technology with both hydrophone and 3-component orthogonal accelerometers (MEMS), in which airguns were used as a source (Figure 5). The full acquisition fold of the field is around 225 Km^2 (at target formation). The sub-surface coverage is 225 sq.km full fold migrated with acquisition bin size of 12.5 x 12.5 m and nominal fold of 375. The P-wave (PP) and mode-converted S-wave (PS) seismic volume have been processed using Kirchhoff Pre-stack Time Migration (K-PSTM). The new data has showed remarkable improvement in term of reflector continuity, signal-to-noise ratio horizontal and vertical resolution of the 2012 PSTM volume in comparison to the 1997 3D data (Figure 6). This is attributed to the much higher fold of coverage, more careful attention to velocity analysis and multiple attenuation.

4. Seismic Interpretation

As we can see from Figure 6, the legacy OBC 3D seismic data contained a lot of noises inside, therefore, structural identification was extremely difficult. In other hand, PP data alone from multi-component 4C-3D seismic data showed much better quality in term of events and faults recognition as compared to the legacy data. Conventional seismic structural interpretation was conducted using PP PSTM Seismic Volume. Faults has been interpreted to identify the skeleton of the structure. Based on regional tectonic and the geomechanics study conducted in the field, the field is located in the dextral strike- slip, and negative flower faulting system is expected to be shown in the seismic data. However, PP seismic volume alone failed to identify the image of the flower structure within the area.

5. Benefit of Mode-Converted PS Seismic Data

As P wave travels for all environment, including rock matrix and fluid content inside the rock; PP seismic volume will be contaminated and contain a lot of noise, which affecting its ability to image the fault and fracture. PS volume in the other hand provides good fault and fracture imaging due to its ability to travel only in rock matrix. Meanwhile, shear-wave splitting provides the complete azimuth of fracture and fault detection. Figure 7 and Figure 8 showed the PP and PS seismic section display in two different locations from North to South of the survey. PS seismic data showed very clear image of the event discontinuity, and more important, provide the image of flower structure in the field.

Fault interpretation using PS seismic data has shed more light to explain the reservoir heterogeneity observed in several wells. Figure 9 shows petrophysical evaluation which clearly exhibits very tight reservoir in well A, limiting its hydrocarbon potential. The PS seismic data reveals that well A intersects the fault zone at this reservoir interval, which could not be recognized properly on PP seismic data. In contrary, figure 10 shows well B, which penetrates the same reservoir encountered in well A with better porosity and hydrocarbon potential, in which no fault is intersected over the reservoir interval based on PS seismic data. In this case, the intersection of the reservoir with the fault is interpreted as the controlling factor of the reservoir quality and this phenomenon can only be observed through PS seismic data interpretation.

6. Conclusion

In principle, for the same geological formations, the seismic sections displayed in PP and PS have different seismic reflection display. This is due to the different measurement contrast from P impedance (PP data) and S impedance (PS data). Due to the low contrast impedance between the reservoir and the surrounding rocks, P- wave data failed to image the reservoir reflection and fault system, while the converted wave has showed clearer image of fault system.

Furthermore, the reservoir seismicity response to the converted wave has positive correlation with petrophysical information, in which the presence of fault can significantly reduce the reservoir quality. This unique insight is paramount for further well placement activity in this field, as multicomponent seismic data (both PP and mode- converted PS data) can assist in delineating prolific carbonate reservoirs. The hybrid interpretation of PP and PS images is beneficial both in structural and stratigraphical terms.

7. Acknowledgement

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8. References

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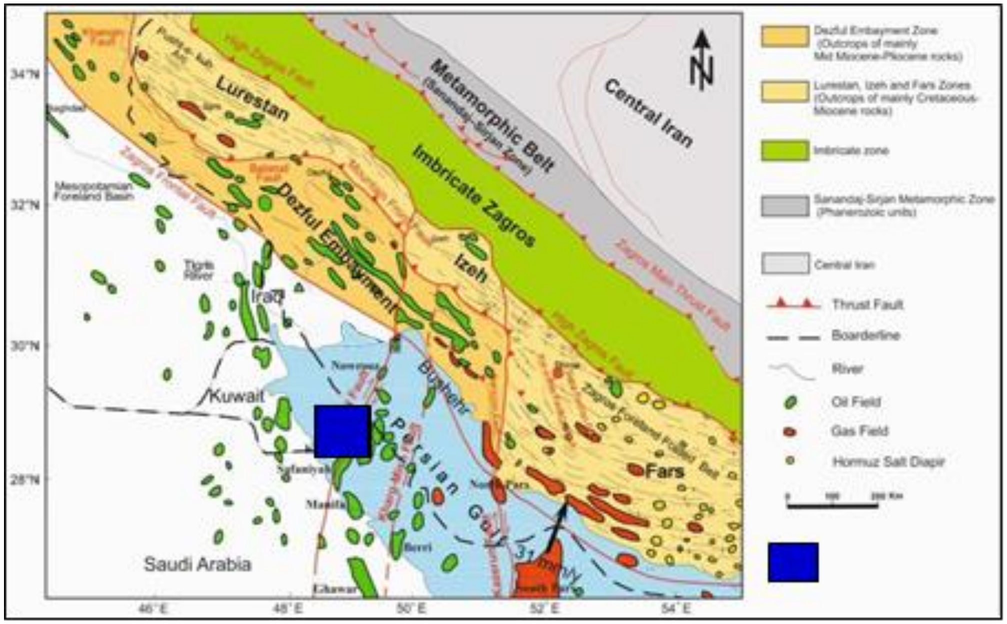
SLB Energy Glossary, [https://glossary.slb.com.](https://glossary.slb.com)

Figure 1: Study Location Area (Mohammadrezaei, H., et al., 2022)



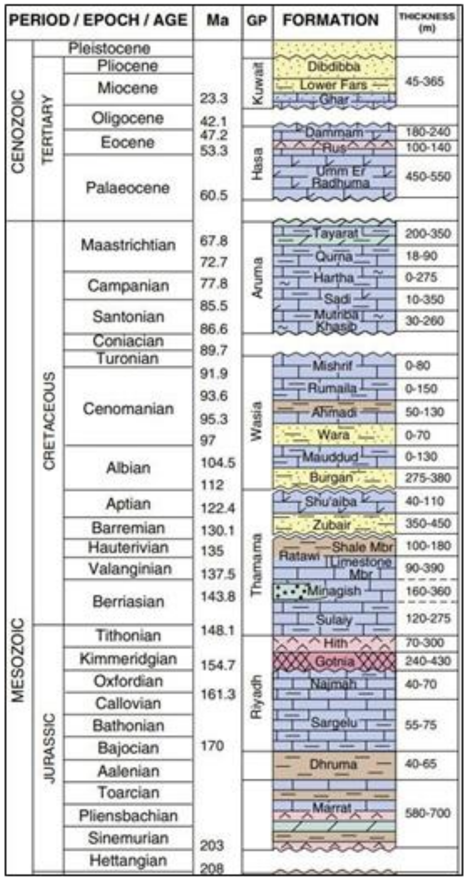


Figure 2: Stratigraphic column of the study area (Abdullah, F. H., et al., 2005)

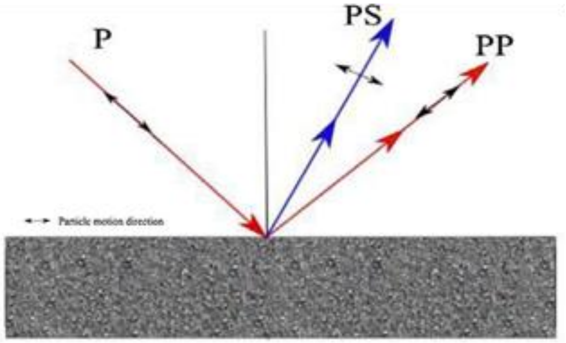


Figure 3: P-wave and its corresponding reflected P and converted S-waves (Farfour, M., et al., 2015)

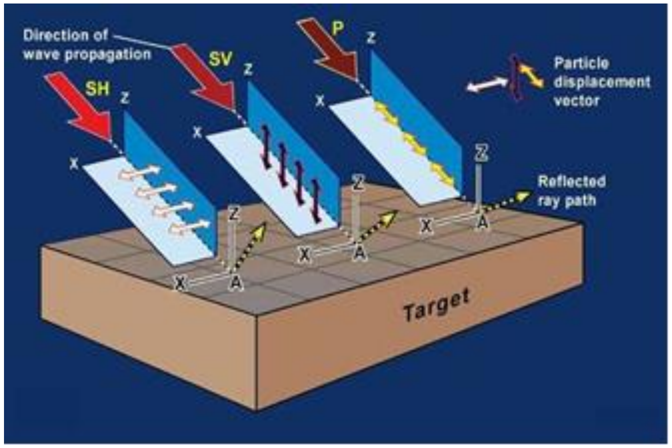


Figure 4: P wave, SV and SH wave particle displacement (modify after Hardage, B., 2003. https://www.beg.utexas.edu/resprog/geophysics/shearwaveseismicstudy.htm)

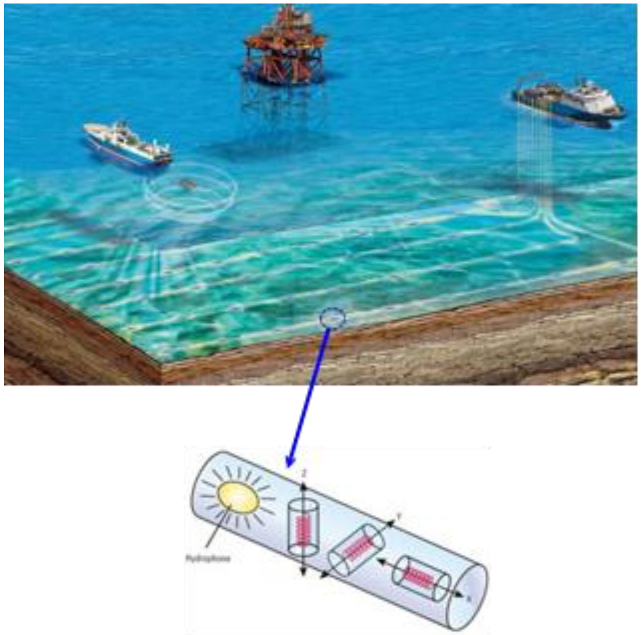


Figure 5: Multicomponent 4C 3D Seismic survey over the study area; each receiver contains 1 hydrophone and 3 accelerometers to measure full azimuth data (SLB Energy Glossary, https://glossary.slb.com)

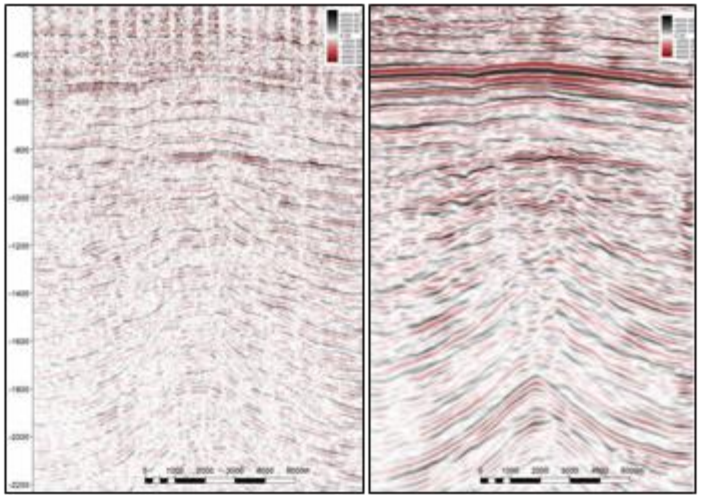


Figure 6: Seismic section showed the data quality difference between the 1997 3D OBS data (left) and multicomponent 4C 3D PP PSTM seismic volume (right)

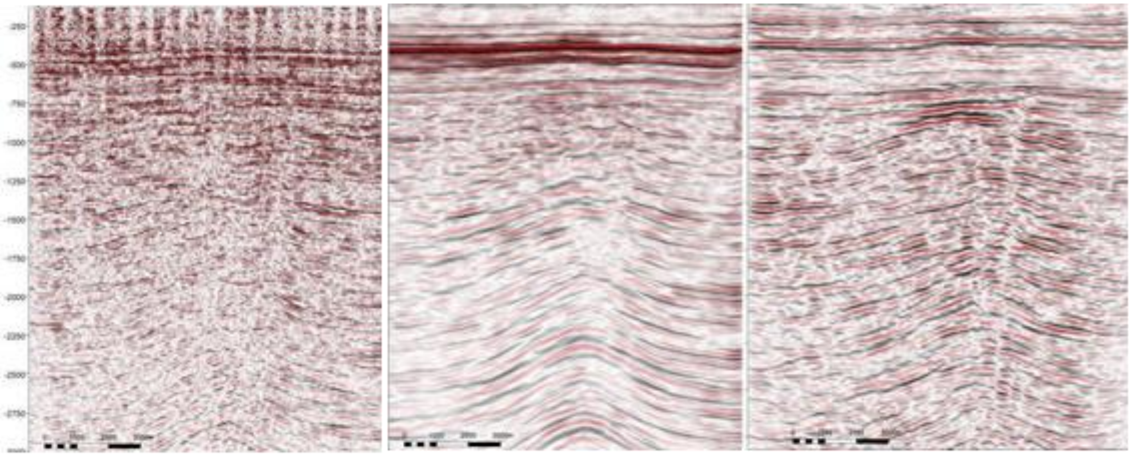


Figure 7: Seismic section in the South of the Survey without fault interpretation; conventional OBS data on the left, multicomponent PP seismic data in the middle and PS seismic data on the right.

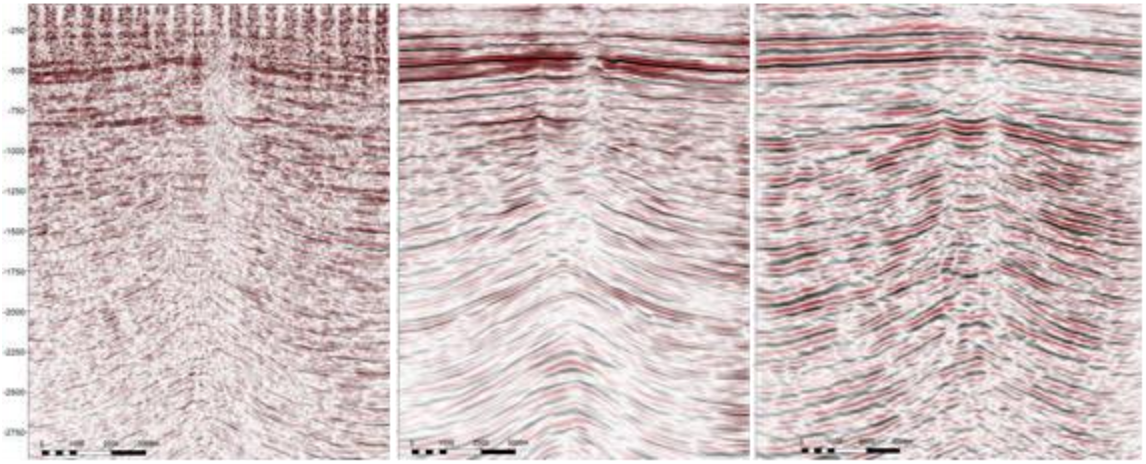


Figure 8: Seismic section display in the North of the Survey without fault interpretation; conventional OBS data on the left, multicomponent PP seismic data in the middle and PS seismic data on the right.

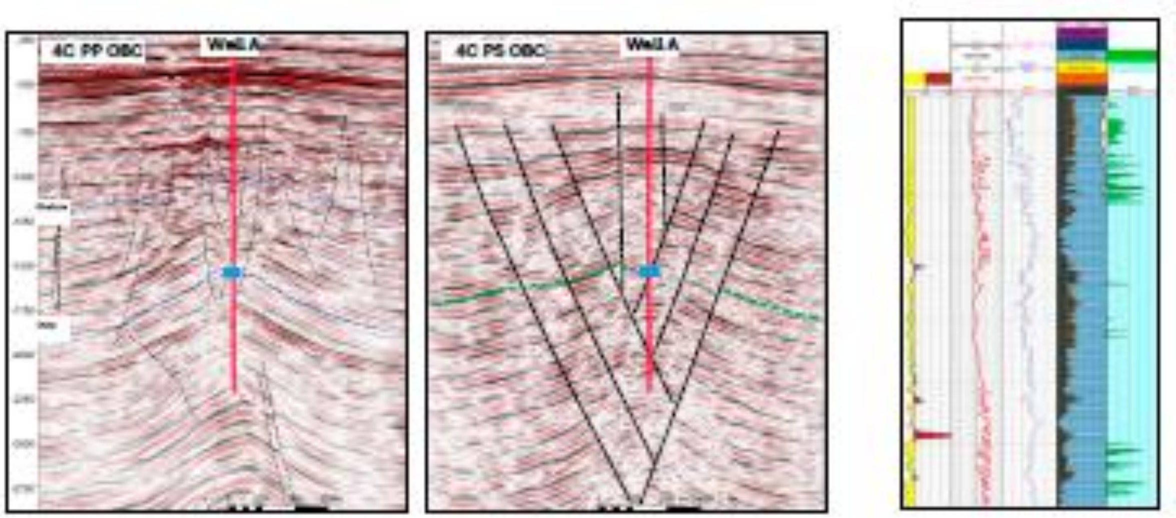


Figure 9: Seismic section display in the vicinity of well A with fault interpretation (black lines); multicomponent PP seismic data on the left and PS seismic data in the middle. Petrophysical analysis of well A on the right side shows a tight reservoir with limited hydrocarbon potential. The blue marker indicates the location of the reservoir on the seismic display.

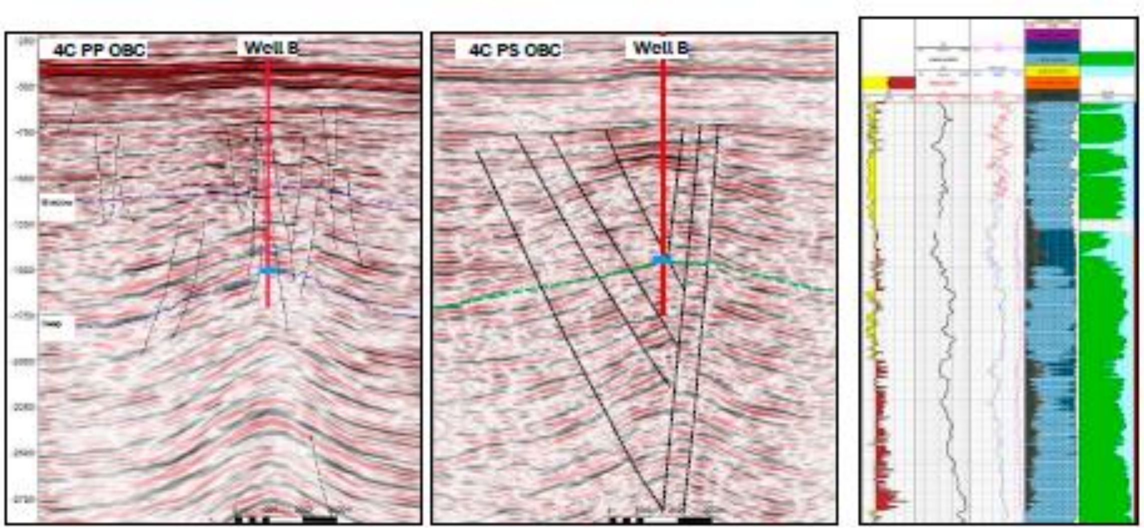


Figure 10: Seismic section display in the vicinity of well B with fault interpretation (Black lines); multicomponent PP seismic data on the left and PS seismic data in the middle. Petrophysical analysis of well B on the right side shows much better reservoir quality compared to Well A. The blue marker indicates the location of the reservoir on the seismic display.