Challenging preconceptions in complex carbonate imaging: using shear waves and electromagnetic data for improved subsurface understanding

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Summary

Accurate pre-carbonate imaging is a critical necessity in the search for hydrocarbons yet presents substantial geophysical challenges. Preconceptions on what may or may not improve imaging in such settings: can the adoption of innovative imaging techniques delineate and better characterize potential pre-carbonate hydrocarbons in place? Here we challenge two of these preconceptions: The first is the application of converted wave imaging in carbonate environments, an underutilized approach with potential for revealing sub-surface details. Secondly, we advocate for the inclusion of complementary measurements alongside seismic, that can improve the characterization of sub-surface rock and fluid properties. Specifically, we focus on resistivity determined using electromagnetic methods. Traditionally these have been considered challenging in carbonates. Our findings, supported by seismic and well-based modeling, demonstrate the feasibility of controlled source electromagnetic (CSEM) techniques, including both conventional and novel borehole-surface CSEM approaches, to accurately constrain carbonate properties and detect underlying reservoirs. This study underscores the value of converted wave and CSEM interdisciplinary methodologies in overcoming the complexities of pre-carbonate imaging.

Introduction

In shallow water environments with complex carbonates settings, accurate pre-carbonate imaging has been a challenging task. For improved imaging in these particular subsurface regimes, an advanced and latest State-of-the-art acoustic reprocessing and reimaging was performed. However, remaining imaging challenges were observed. In order to address these, we have looked to approaches that have traditionally been considered difficult or impossible in such environments. By challenging these preconceptions on what may or may not work, we have demonstrated that new approaches can add value to carbonate and sub-carbonate imaging and characterization refinement. In our area of interest, an exploration well was drilled and based on dedicated illumination studies of detailed P-wave velocity model, 3C Vertical Incidence VSP (VIVSP) and 3D DAS VSP data were acquired in a deviated well. From the acquired VSP data, strong presence of Shear (S-) waves was identified through conversions from compressional (P-) waves. Some refined separation was performed to emphasize upgoing and downgoing shear data. Alai (1997) introduced a unique display for the VSP data in one-way time (replacing the depth axis), allowing fast and accurate separation of P- and S-waves and retrieving Poisson's Ratio in an alternative way. The interesting observance of significant amount of Shear Data in this specific carbonate setting has opened new opportunities of conducting elastic data reprocessing and reimaging. In addition to the primary and multiple P-wave imaging of VSP data demonstrated by (Zhan et al., 2015), the same primary and multiples reimaging can be obtained from S-waves. The converted waves are providing additional insight in verifying and improving carbonate geometries, subsequently enhancing pre-carbonate imaging targets. In addition to the seismic analysis, a detailed 3D resistivity model was generated utilizing P-wave velocity and calibrated well logs of carbonate and reservoirs beneath. This model was used to investigate the sensitivity of both conventional and innovative borehole-surface EM methods in optimally delineating key features in the model, with encouraging results.

Identification of Shear waves in carbonates

The acoustic reprocessing and reimaging have pushed the limits of delineating pre-carbonate targets (Figure 2). Based on this dataset, an exploration well was drilled, and borehole seismic data was acquired with 3-C geophones and DAS on retrievable fiber. 3-C Geophone data having the advantage of capturing the full elastic wavefield, expose evidence of mode conversions from P to PS (downgoing & upgoing shear wavefields) at carbonates. Multiple arrivals have also been observed for the shear wavefields. Data from the Geophones is shown in Figures 3a and 3b after rotation using a hodogram analysis to a transverse (HT) and horizontal radial (HR), (in line with source receiver plane). This leaves the vertical component unchanged as it acts as the axis of rotation. For comparison purposes, DAS total wavefield VSP after amplitude recovery is shown in Figure 3c, highlighting interesting similar wave field exposures in both displays. As observed in the data, PS waves are stronger on the geophone because they can capture more of the wave energy compared to the fiber. P- downgoing wavefields were first rejected to improve the interpretation of the shear events, since these amplitudes are lower. Data was then separated into PS down and upgoing wavefields on both the HT and HR components (Figure 4). Formation B (annotated in red) represents the base of carbonate. HT component is the SH shear wavefield, while Shear observed on the HR component can be considered SV. The data shown here has not been deconvolved and therefore will include multiple reflections for the converted wavefield. DAS data also shows P to PS conversions at major interfaces where single component data was processed to get a residual and separated shear. With the limitations of DAS, Mateeva et al. (2012) demonstrated advances of using DAS for VSP acquisition. Willis et al. (2016) compared DAS and geophone amplitudes for P-waves. Wu et al. (2017) demonstrated the reliability of fiber optics to record P-waves and S- waves. This difference in response limits the coverage of DAS compared to geophone. An additional advantage of the geophones is that the data can be rotated using a hodogram analysis to capture the maximum energy of the shear, whereas the DAS response is analogous to a single component along the fiber. Ghazali et al. (2018) outlined the advantages of imaging with multiples using 3D DAS. Figure 5 illustrates the HR and DAS comparison of PS Down and Up at vertical section of well only [DAS filtered to match geophone response]. This data is especially interesting as we observe mode converted shear for source to receiver offsets that would be considered zero offset. We would expect the incident angles of the raypaths to be normal, which would negate any mode conversion. Due to the complexity of the carbonate structure this may cause a scattering affect which will promote mode conversion. Data shows mode conversion in the SV and SH planes. It should be noted that the source positions of the DAS and geophones are not exact. Geophone data was acquired using a walkabove acquisition which places the sources over the well trajectory. DAS data shown for comparison is from a single shot rig source, so the source-receiver offset will be much larger compared to the geophone data, especially for the deeper sections of the well. However, for the area of interest at Formation B they should be similar. For improved definition, geometry and imaging of carbonate bodies, S-waves may be utilized with a similar approach showcased for Salt bodies by (Alai et al. ,2022). Figure 6 shows a schematic diagram illustrating possible mode-converted PPSP, PSPP and PSSP waves in carbonate settings. VSP data can be processed to a single trace representing the well trace seismic response (corridor stack). Negenman et al. (2023) showed how VSP corridor stack data is validated by calculating a correlation coefficient from a zero-phase synthetic seismogram computed for primaries only. Figure 7 illustrates PP and PS Corridor Stacks spliced into surface seismic line. Figure 8 illustrates the comparison of VIVSP shots recorded by geophone and DAS. Note the interesting similarities observed in both displays. Prelimary results of 3D DAS VSP imaging in comparison with the legacy streamer image are shown in Figure 9.

Towards optimal Electromagnetic surveying

Many studies have shown the value of combining seismic and non-seismic data in multiphysics workflows to better understand the sub-surface. As a complement to the seismic approaches, we investigate the value of adding resistivity, derived from controlled source electromagnetic (CSEM) surveys, in multiphysics workflows to characterize both the carbonate and the reservoirs beneath. Carbonates have traditionally been considered challenging for CSEM methods. However, the challenges of imaging and characterizing reservoirs in such settings have driven us to re-evaluate this assumption and look for innovative ways of acquiring and interpreting the data. In the initial sensitivity analysis (Figure 10), a well log calibrated resistivity-velocity transform is used to convert a seismic scale velocity model to resistivity. Synthetic data derived from this model are used to evaluate sensitivity (in a forward sense) and recoverability (in an inverse sense) to both carbonate heterogeneity and reservoir fluid content. Three contrasting approaches to CSEM acquisition are considered: conventional CSEM using seafloor nodes and a towed dipole source, towed streamer CSEM in which both the source and receivers are towed behind a vessel, and borehole-surface CSEM, which has not previously been considered in offshore wells. Results are promising for all three methods, each of which has advantages and disadvantages which must be weighed in deciding on the best acquisition strategy.

Conclusions

This study advances hydrocarbon exploration beneath carbonate layers by validating innovative opportunities of elastic imaging and derisking with electromagnetic techniques. This paper emphasizes presence of DAS converted waves in carbonate environments and using them in imaging, challenging traditional views of removing them as noise. Modeling the practical application of both traditional and novel controlled source electromagnetic (CSEM) techniques have been confirming effective sub-carbonate reservoir detection and characterization. Our analysis underscores the importance of embracing interdisciplinary methods to address the geophysical challenges of pre-carbonate hydrocarbon exploration, offering a pathway to more accurate subsurface imaging and characterization.

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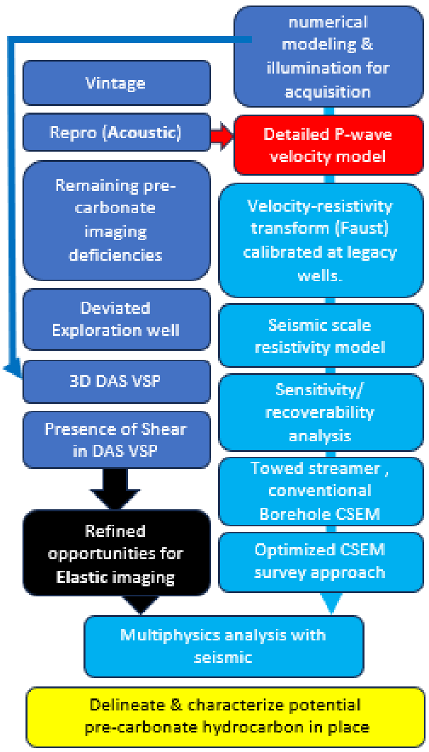

Figure 1: Schematic view of a series of initiatives towards improved insight and pre-carbonate imaging.

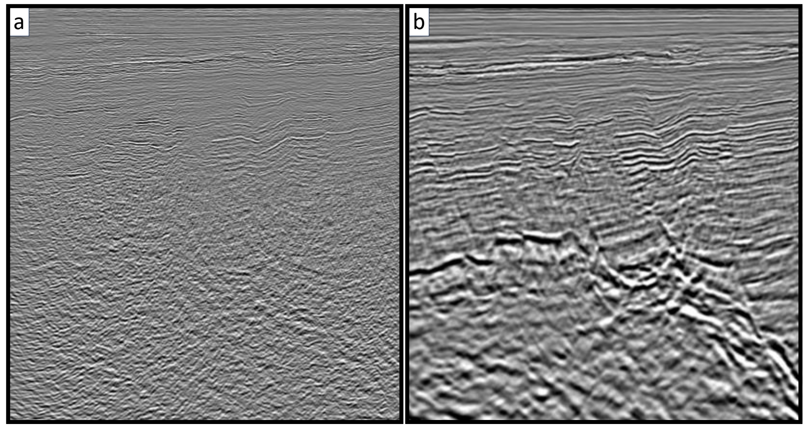

Figure 2: a)Vintage stack, b)stack after acoustic reprocessing.

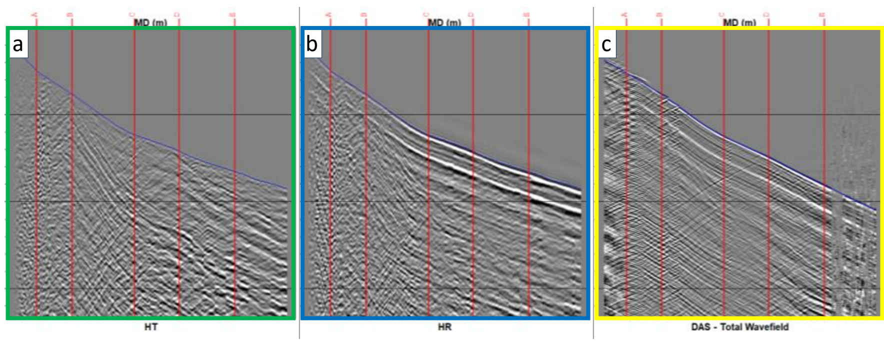

Figure 3: Rotated a)HT & b)HR components of VIVSP. c)DAS total wavefield.

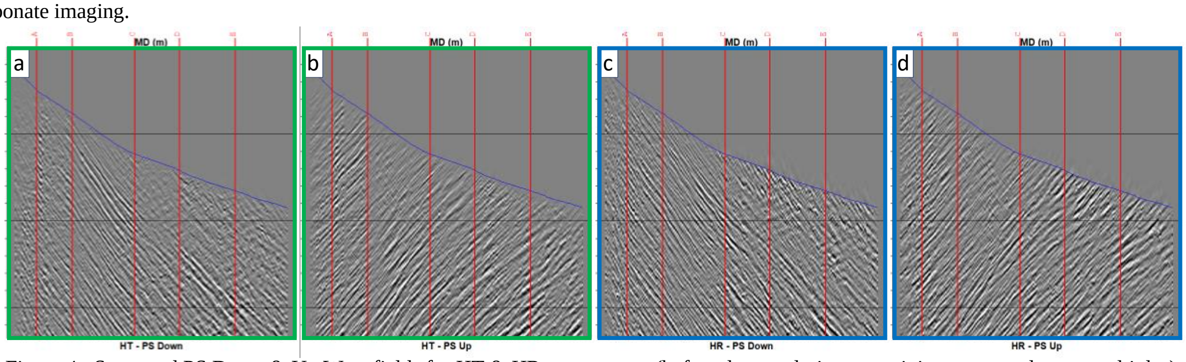

Figure 4: Separated PS Down & Up Wavefields for HT & HR components (before deconvolution, containing converted wave multiples).

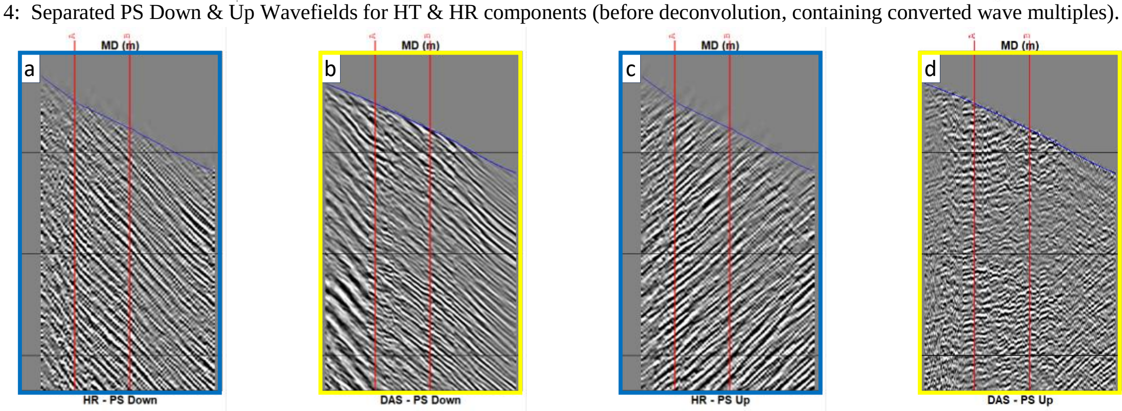

Figure 5: HR & DAS comparison of PS Down & Up at vertical section of well only [DAS filtered to match geophone response].

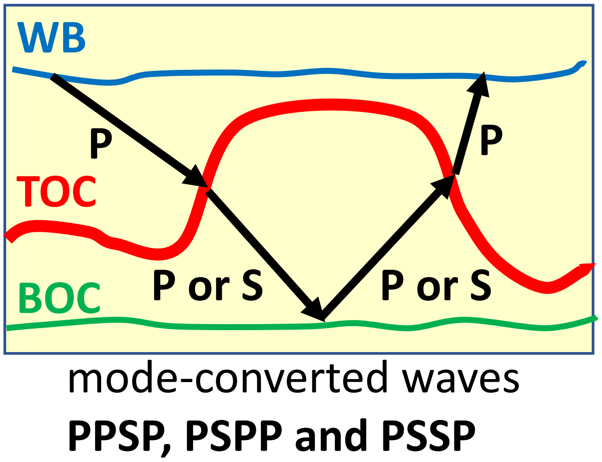

Figure 6: Schematic diagram illustrating possible mode-converted PPSP, PSPP and PSSP waves in carbonate settings.

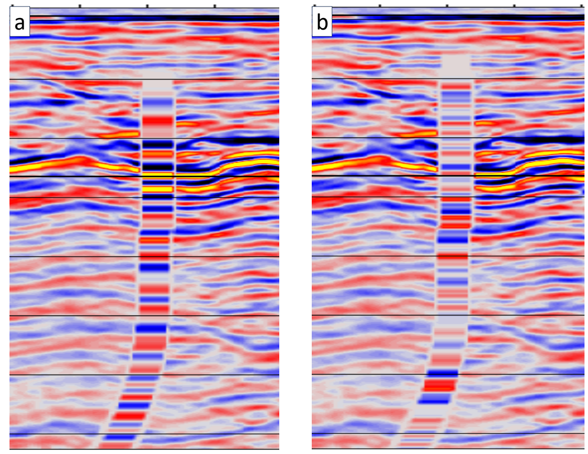

Figure 7: (a) PP & (b) PS Corridor Stacks spliced into surface seismic line. Data has been filtered to 40Hz. See good agreement between PS & PP events in time at base of carbonate.

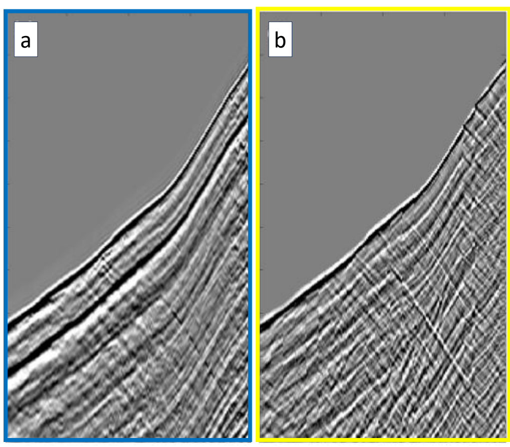

Figure 8: Comparison of VIVSP shots recorded by geophone and DAS. a)Vertical component of geophone VSP data; and b)DAS VSP data.

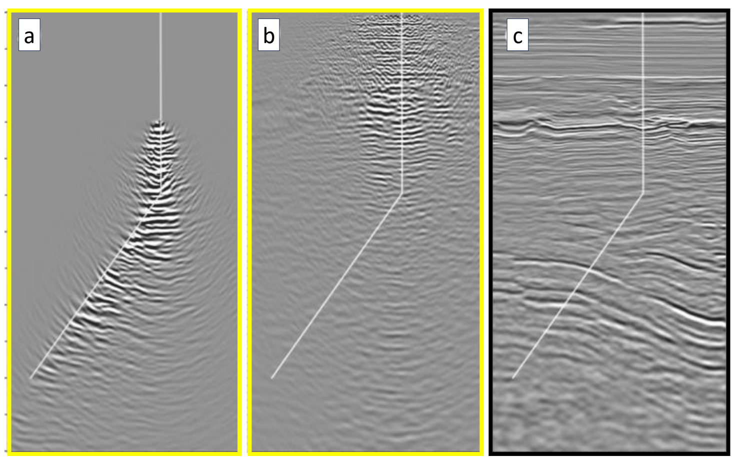

Figure 9: Prelimary results of 3D DAS VSP imaging in comparison with the legacy streamer image: a)DAS VSP upgoing primary image; b)DAS VSP downgoing multiple image; and c)streamer image. The fiber's position is depicted by a white line.

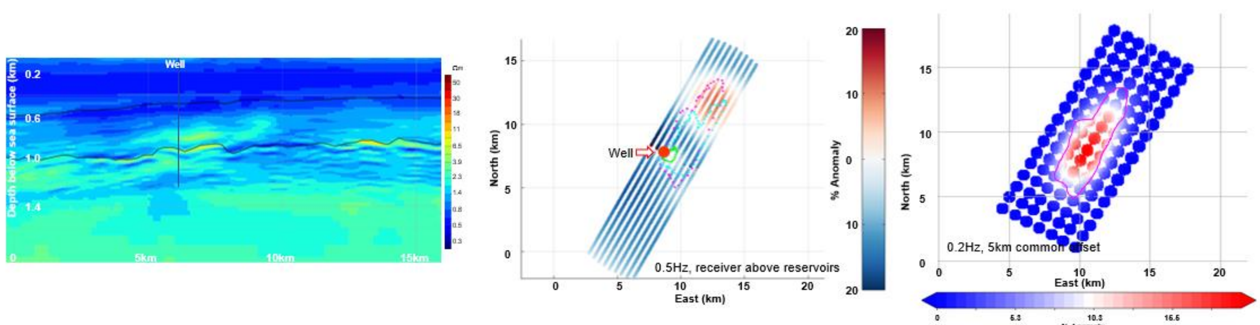

Figure 10: Left- Resistivity model derived from seismic velocity for carbonate and sub-carbonate reservoirs. Top and base carbonate horizon shown. Sensitivity of borehole surface CSEM (middle) and conventional nodal CSEM (Right) for most likely reservoir charge case. Sensitivity is good for both configurations.

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