Insights from DAS VSP converted wave imaging in complex carbonate geological settings

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Summary

Pre-carbonate imaging in complex geological settings is a challenging task. In the example discussed here, imaging of reservoirs beneath a shallow, high impedance carbonate layer has proven difficult, because of significant mode conversions within the carbonate limiting penetration of primary energy beneath. In standard processing and imaging workflows, such mode conversions are usually considered to be noise and are removed.

However, we show that imaging using this mode converted energy has great potential to provide additional insight into the reservoir structures beneath the shallow carbonate.

In a survey with shallow water environment, marine streamer data, Ocean Bottom Node (OBN) data, 3-C Vertical Incidence Vertical Seismic Profiling (VIVSP) data and 3D Distributed Acoustic Sensing (DAS) VSP data were acquired.

The 3D VSP survey utilizing a wireline fiber-optic cable was conducted in a deviated well. Despite the single-component (1-C) limitation of DAS recording, the acquired 3D DAS VSP data captured both P-waves and notable converted waves, resulting from mode conversions within a shallow, high velocity carbonate layer.

This paper highlights key findings from the analysis of the field 3D DAS VSP data and examines the possibility of using converted waves for DAS VSP imaging in a geologically complex setting.

Introduction

Seismic imaging in a complex carbonate geological setting is notably challenging, especially in shallow-water.
These challenges are primarily caused by a complex overburden, dominated by a shallow, high-velocity carbonate layer with significant acoustic impedance.

Surface seismic surveys have yielded suboptimal images with poor continuity of subsurface events beneath this layer, largely due to the impact of the complex overburden.

To address this, surface (marine, OBN) and borehole data (3-C VIVSP and 3D DAS VSP) were acquired (Figure 1). Alai et al. (2024) showcased the values of Shear wave propagation in carbonates identified from DAS VSP Data. Figure 2 shows 3D DAS VSP DATA for source offset of 1500[m].

Note the shallow water multiples, the P-wave interbed multiples bouncing between Water-Bottom (WB) and Top Of Carbonate (TOC), the P-wave interbed multiples bouncing within layers of TOC and Base Of Carbonate (BOC). Interestingly, in pre-carbonate section mode-converted S-waves are dominant (red arrows).

The coloured wave propagation and reflections indicates P- (blue) and S-wave (red) interbed multiples generated at BOC. This is an important finding emphasizing that with P-waves only it is very challenging to obtain high quality and accurate deeper pre-carbonate images.

The DAS VSP data aimed to improve the mapping of geological structures and deliver more accurate insights around the VSP well, especially for characterizing reservoirs beneath the shallow carbonate layer. The analysis of the DAS VSP data revealed essential acoustic-to-elastic mode converted waves at the carbonate layer.

Figure 3a shows a complex overburden, dominated by a shallow, high-velocity carbonate layer with significant acoustic impedance. Figure 3b shows a snapshot of mode conversions, using constant density elastic forward modeling.

Figures 3c and 3d show a comparison of elastic modeled and field data emphasizing their similarities and confirming that downgoing P-waves undergo multiple mode conversions at TOC and BOC, generating prominent P-to-S converted waves.

These converted waves significantly interfere with P-waves, posing challenges for conventional VSP imaging that relies on P-wave data only. Since mode converted waves are dominant over P-waves, they provide additional insight in pre-carbonate imaging.

This paper discusses processing workflows designed to utilize mode converted waves and leverage them to enhance pre-carbonate imaging, revealing structures that are obscured by the carbonate layer above the target area.
Figure 3e outlines a flow diagram emphasizing the findings and achievements.

VSP wavefield separation and S-velocity estimation

The DAS VSP data exposed reasonably good signal-to-noise ratio, despite being acquired using a wireline fiber, which is known for suboptimal coupling.

Additionally, it was observed that shots on the side opposite to the direction of well deviation exhibited fewer fiber directivity issues compared to those along the well deviation direction. Imaging VSP converted waves requires isolating the upgoing converted wavefield from the full wavefield, making wavefield separation a critical step in the processing workflow. In this paper, the separation was performed in two stages: the full wavefield was separated into upgoing and downgoing components using a dip-based approach.

In addition, the upgoing wavefields were further split into upgoing P-waves (Figure 4a) and upgoing S-waves (Figure 4b) based on their moveout differences. Figure 4c presents a color-coded overlay of the upgoing P-waves (blue) and upgoing S-waves (red), highlighting that the upgoing S-wave is more prominent than the upgoing P-wave, particularly in the deeper deviated section of the fiber.

Prior to migrating the upgoing converted waves, a shear velocity model (Vs) was determined utilizing the sonic and shear logs.

A least-squares linear fit was applied to establish a linear relationship between Vp and Vs, ensuring best alignment between estimated Vs and observed Vs. This derived Vp/Vs relationship was then applied to the legacy 3D P-wave velocity model.

Figure 5a shows the P-wave velocity (top) and derived S-wave velocity (bottom).

Converted wave imaging with RTM

The upgoing S-waves were migrated using reciprocity with dual-velocity acoustic reverse-time migration (RTM) (Alai et al., 2022).

In this approach, the forward source propagation is carried out downhole using the constructed S-wave velocity, while the upgoing S-wave field is backward propagated from surface shot locations to the subsurface using either the P-wave velocity or various types of converted wave velocities.

This process is graphically illustrated in the ray diagrams shown in Figure 5b (top).

For comparison, the surface seismic PP image and the conventional DAS VSP image of the upgoing P-wave are shown in Figures 5b (left) and (center).

Figure 5b (right) indicates deeper imaging utilizing upgoing Shear waves (yellow arrow). Note that the VSP images are (gold) overlaid on surface seismic across wellbore direction.

Figure 5c shows a schematic ray diagram illustrating some possible mode-converted PSPP, PPPS and PSPS waves in carbonate settings.

Figure 6 shows the comparison of the migrated surface (KPSDM) and DAS VSP RTM images utilizing mode-converted waves.

Note the depth coincidence of all the images (yellow and cyan arrows), even though dual velocities have been used in the RTM migrations. Orange arrows indicate improved imaging.

The strong alignment between the DAS VSP converted wave images and the surface seismic image demonstrates that this complex carbonate geological setting is well-suited for utilizing converted waves in DAS VSP.

Furthermore, the DAS VSP converted wave images provide subsurface imaging comparable to the conventional P-wave image while also resolving additional features that complement the P-wave image.

Conclusions

Successful 3D DAS VSP data acquisition using a wireline fiber-optic cable was achieved in a shallow water environment.

Rather than following industry standard routinely removing non P-wave energy as noise in DAS VSP Data, this paper emphasizes these being valuable mode-converted waves that can be utilized in deeper pre-carbonate imaging, opening deeper exploration opportunities.

We imaged mode-converted energy to extract valuable information. Our analyses have provided critical insights into acoustic-to-elastic mode converted waves within the carbonate layer end beneath.

The resulting images clearly demonstrate improvement in comparison to surface seismic and conventional DAS VSP upgoing P-wave images in the vicinity of the well.

Our success in imaging mode converted energy in DAS VSP data establishes a novel foundation for advanced elastic wavefield analyses in complex carbonate geological settings.

Acknowledgements

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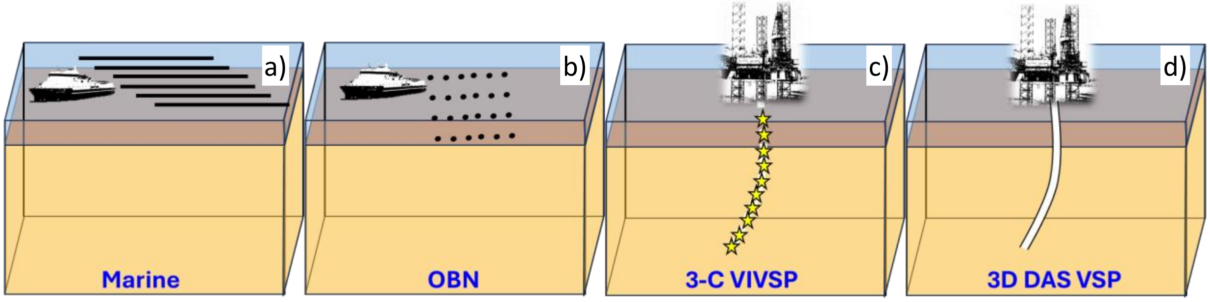

Figure 1: Different acquisition types, a)marine streamer data, b)OBN data; c)3-C VIVSP and d)3D DAS VSP.

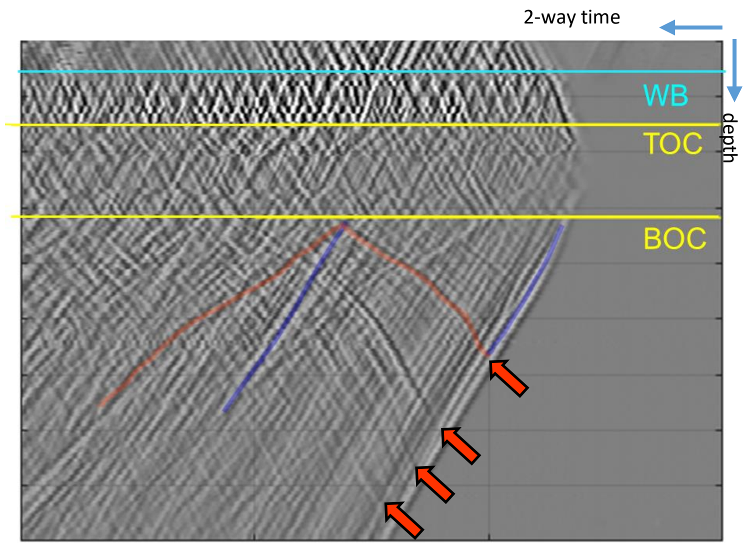

Figure 2: 3D DAS VSP DATA for source offset of 1500[m]. Note the shallow water multiples, the P-wave interbed multiples bouncing between Water-Bottom (WB) and Top Of Carbonate (TOC), the P-wave interbed multiples bouncing within layers of TOC and Base Of Carbonate (BOC). Interestingly, in pre-carbonate section mode-converted S-waves are dominant (red arrows). The coloured wave propagation and reflections indicates P- (blue) and S-wave (red) interbed multiples generated at BOC. This is an important finding emphasizing that with P-waves only it is very challenging to obtain high quality and accurate deeper pre-carbonate images.

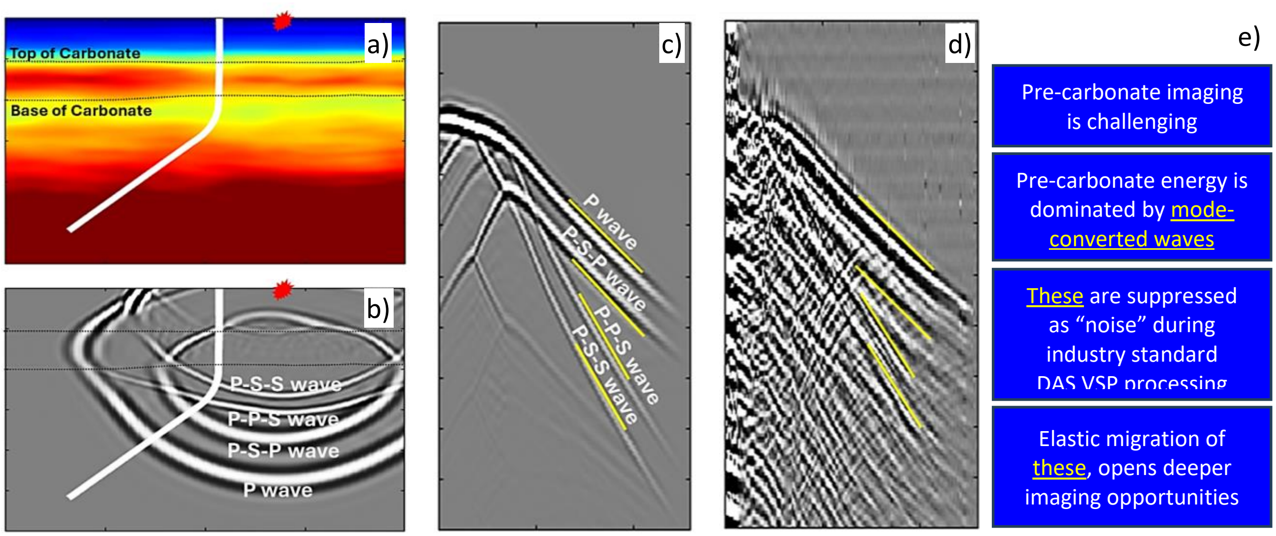

Figure 3: Illustration of wave mode conversions with P-waves propagating through a carbonate layer: a)P-wave velocity model, red dot indicating the surface shot location and white line representing the fiber-optic cable; b)snapshot of the elastic wavefield, highlighting multiple mode conversions at the carbonate layer; c)synthetic VSP; d)DAS VSP and e)flow diagram emphasizing the findings and achievements.

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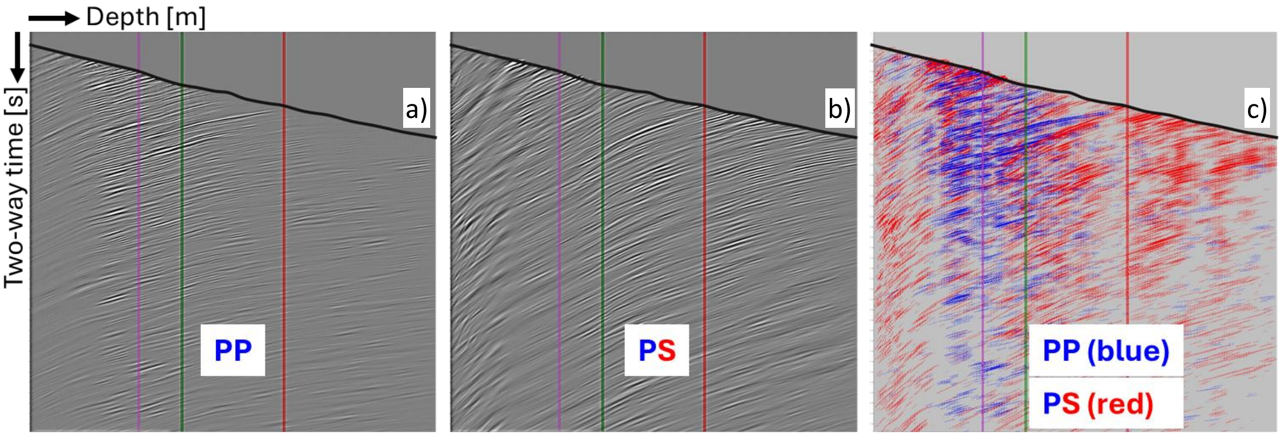

Figure 4: Upgoing waves in DAS VSP Data : a)PP waves , b)PS waves and c)integrated display of PP waves (blue) and d)PS waves (red).

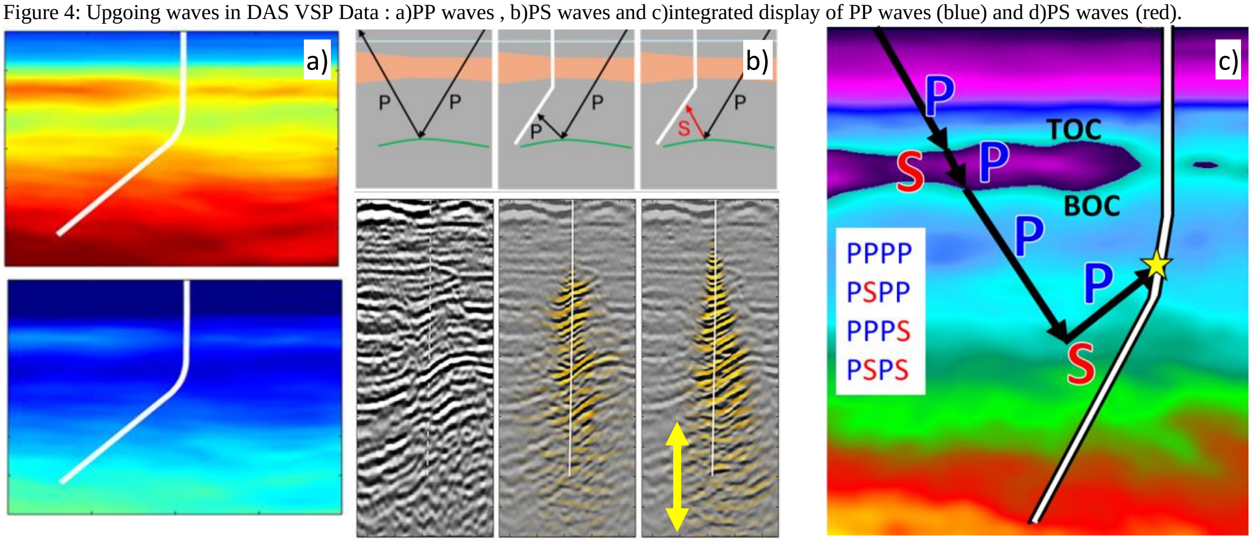

Figure 5: a)P-wave velocity (top) and derived S-wave velocity (bottom); b)composite plot with ray diagrams, surface seismic (grayscale), and DAS VSP PPPP and PPPS images (gold) overlaid on surface seismic across wellbore direction; c)schematic diagram illustrating possible mode-converted PSPP, PPPS and PSPS waves in carbonate settings : Top of Carbonate body (TOC) and Base Of Carbonate body (BOC).

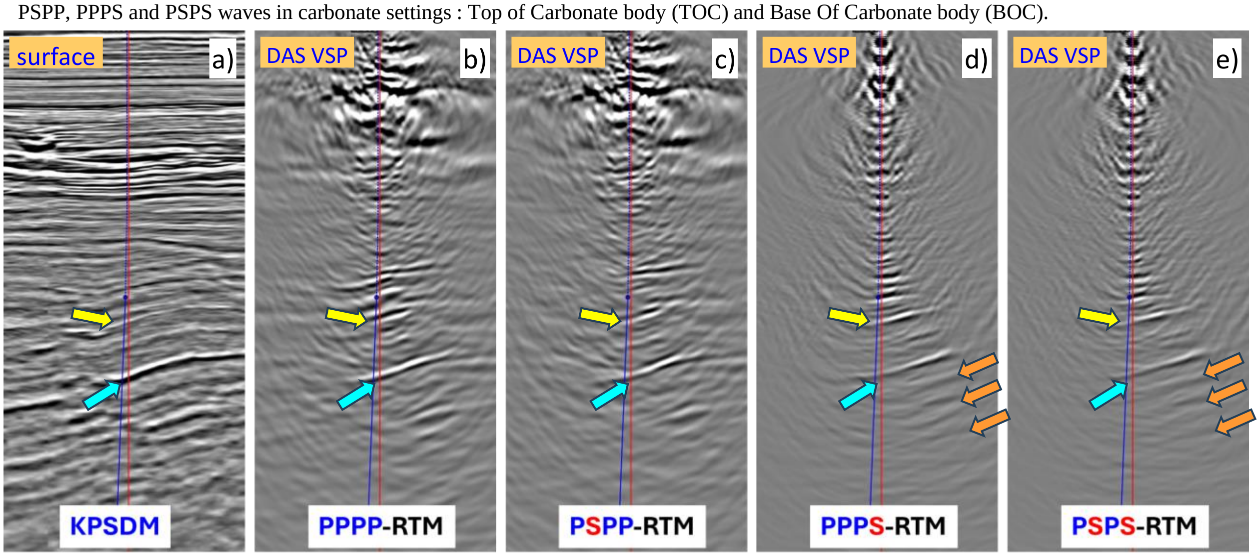

Figure 6: Comparisons of migrated images: a)KPSDM, b)PPPP RTM, c)PSPP RTM, d)PPPS RTM, e)PSPS RTM. Note depth coincidence of all images (yellow and cyan arrows), even through dual velocities have been used in the RTM migrations. Orange arrows indicate improved imaging.

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