

Revitalizing legacy VSP data using elastic FWI at Mad Dog field, Gulf of America

Introduction

The Mad Dog field is one of the largest producing fields in Gulf of America (GoA). Discovered by bp in 1998, the field commenced production in 2005 and is located approximately 190 miles south of New Orleans, near the edge of the Sigsbee Escarpment. As with many subsalt fields in the GoA, seismic imaging at Mad Dog field is particularly challenging due to the presence of complex salt geometries in the overburden, which strongly distort seismic wave propagation and degrade image quality.

In recent years, elastic full waveform inversion (FWI) has been successfully applied to ocean-bottom node (OBN) data, leading to significant improvements in velocity model building and seismic imaging (Liu et al., 2024). At Mad Dog field, the application of elastic FWI to OBN data resulted in a step-change improvement in subsalt reservoir imaging (Liu et al., 2023). While the rich low-frequency content of OBN data is well suited for recovering long-wavelength background velocity models, the limited high-frequency energy due to two-way propagation and subsurface attenuation, constrains FWI's ability to resolve fine-scale reflectivity. In contrast, legacy 3D vertical seismic profile (VSP) datasets retain substantially higher-frequency content due to shorter propagation paths and receiver placement in close proximity to the reservoir (Rollins et al., 2015). This contrast raises a key question - can legacy VSP data be revitalized through an elastic FWI workflow to deliver the high-resolution imaging that OBN data alone cannot achieve?

To assist the continued development of the Mad Dog field, two large-scale 3D VSP surveys were acquired in 2015 and 2018 (Li et al., 2016, van Gestel et al., 2019). A representative geological cross-section (Figure 1a) highlights subsalt faulting as a primary risk to reservoir deliverability, underscoring the need for higher resolution imaging to guide well placement and evaluate connectivity. However, the existing 25 Hz OBN elastic FWI-derived reflectivity (FDR) image (Figure 1b) does not provide sufficient detail for this purpose. To overcome this limitation, we apply elastic FWI to the legacy 3D VSP datasets to finetune the OBN-derived velocity model and recover additional high-frequency detail in both the velocity model and FDR image.

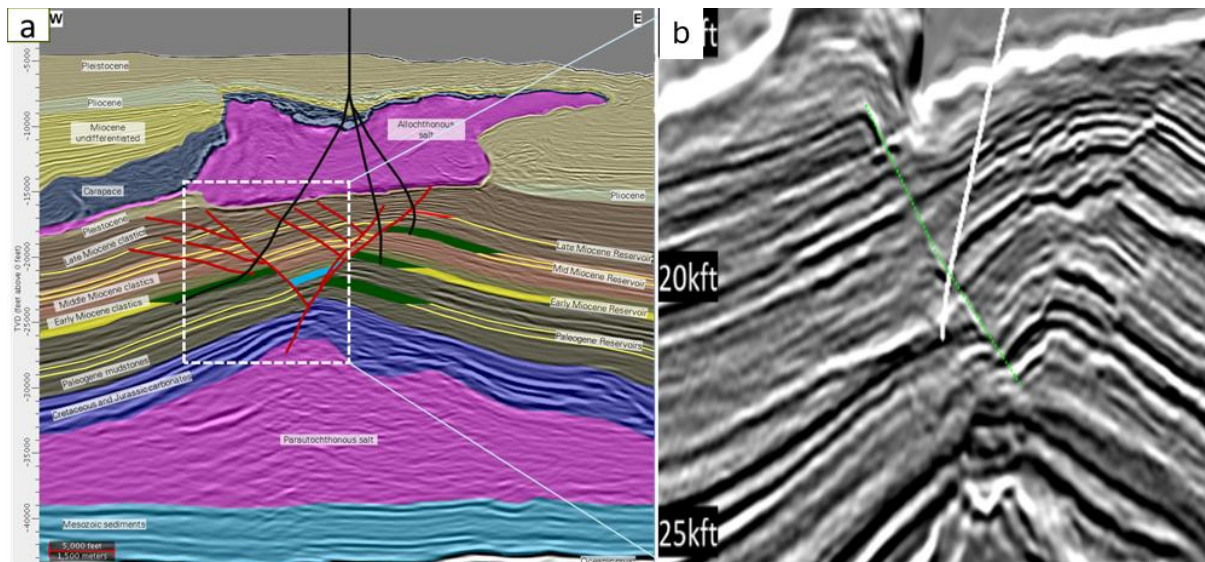


Figure 1 (a) Geological cross-section across the Mad Dog field, and (b) a zoomed subsalt section of the 25 Hz OBN elastic FDR image.

Workflow and Results

The elastic FWI workflow (Figure 2) applied to the legacy VSP dataset delivered substantial improvements in both background velocity accuracy and high-resolution reflectivity recovery. Starting from a mildly smoothed OBN-derived model, consecutive 10 Hz and 15 Hz updates focused on correcting long-wavelength velocity errors. Prior to inversion, first-arrival misalignment between field and synthetic data indicated clear deficiencies in the initial model (Figure 3a). After the low-frequency updates, these discrepancies were largely eliminated (Figure 3b), demonstrating that the VSP wavefield provides strong constraints on near-borehole kinematics and effectively refines the subsalt velocity structure.

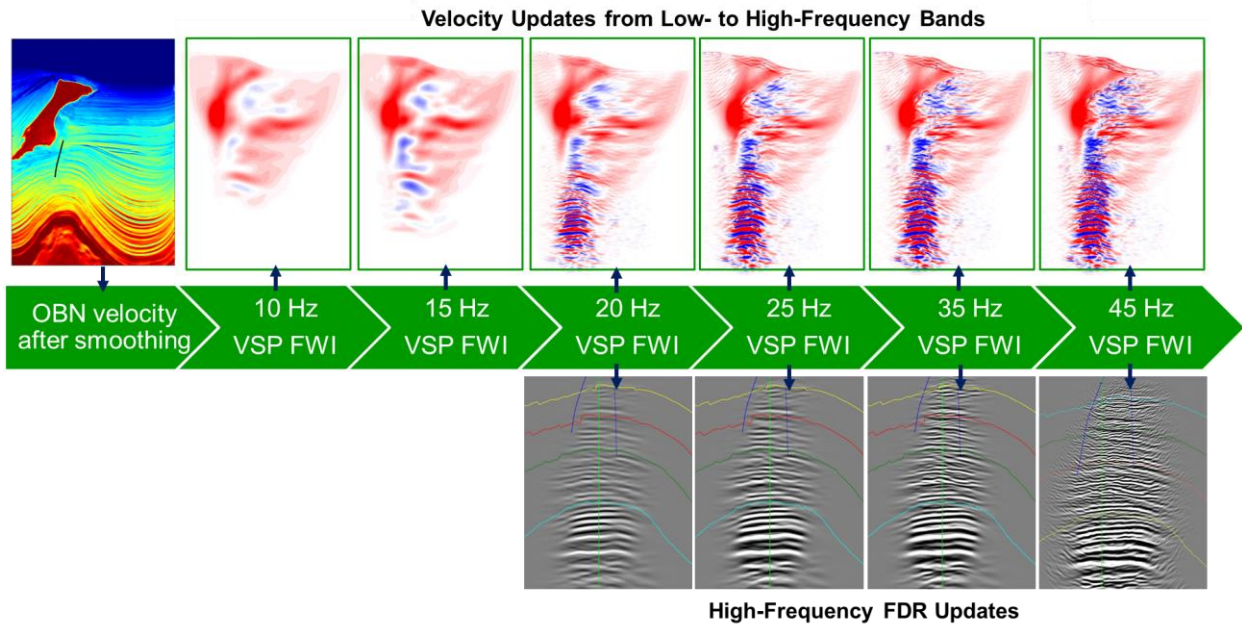


Figure 2 Workflow for applying elastic FWI to VSP dataset and the corresponding results.

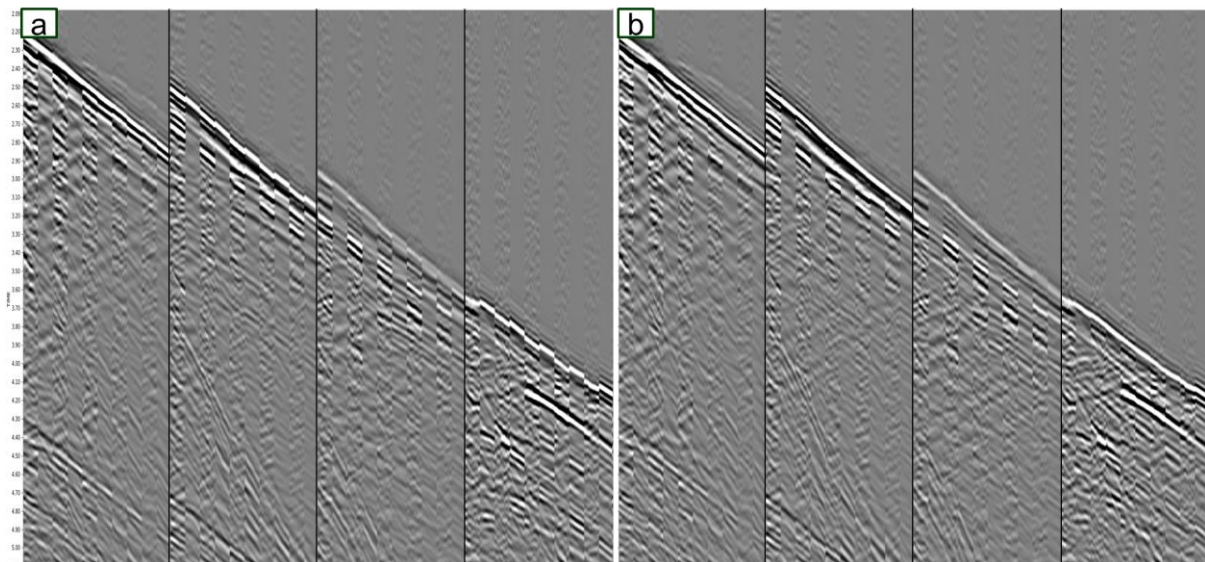


Figure 3 Data-domain QC: (a) interleaved field and synthetic shots before FWI, and (b) the same shots after low-frequency FWI updates.

With a reliable background model in place, the inversion proceeded to incorporate the full elastic VSP wavefield at higher frequencies. An amplitude-Q compensation step was applied prior to the 45 Hz inversion to restore attenuated high-frequency energy and broaden the recoverable spectrum. These high-frequency FWI iterations introduced fine-scale velocity updates and produced a 45 Hz elastic FDR image (Figure 4b) with markedly higher spatial resolution than either the legacy 45 Hz VSP RTM (Figure 4a) or the 25 Hz OBN-derived FDR image (Figure 4c).

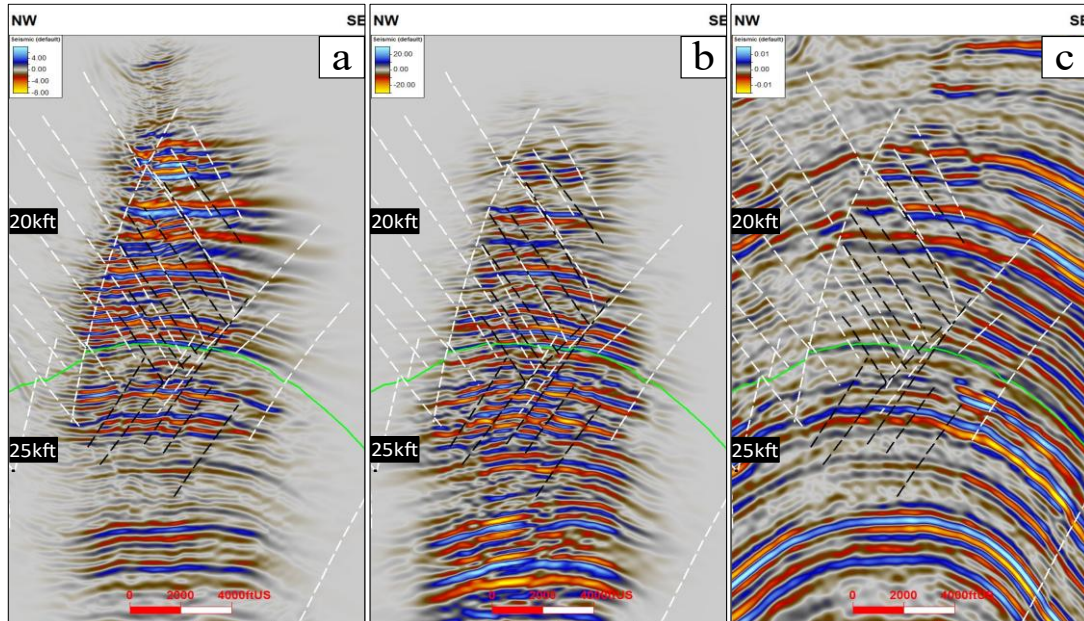


Figure 4 Seismic cross-sections with superimposed fault interpretations (black: latest VSP FDR; white: legacy OBN): (a) legacy 45 Hz VSP RTM, (b) latest 45 Hz VSP FDR, and (c) legacy 25 Hz OBN FDR.

The resulting uplift is most evident in fault imaging. The new VSP FDR exhibits sharper fault terminations, clearer reflector continuity, and improved definition of subtle structural features that were previously poorly illuminated or entirely absent. Fault geometries appear more geologically consistent, with dips and orientations that align better with the regional structural trend. The expanded illumination footprint further increases lateral continuity, enabling a more coherent interpretation.

Interpretation and Discussion

A primary objective of this VSP FWI study was to enhance structural interpretation in an area strongly affected by complex base-of-salt geometry. Previous interpretations based on legacy VSP and OBN data were limited by restricted areal coverage and insufficient image quality, resulting in significant ambiguity. The latest VSP elastic FDR substantially expands the interpretable footprint (Figure 5), enabling more continuous and kinematically consistent fault interpretation. This improvement leads to a clearer understanding of the local structural architecture within the regional context and is directly enabled by the accurate elastic velocity model recovered from the VSP FWI workflow.

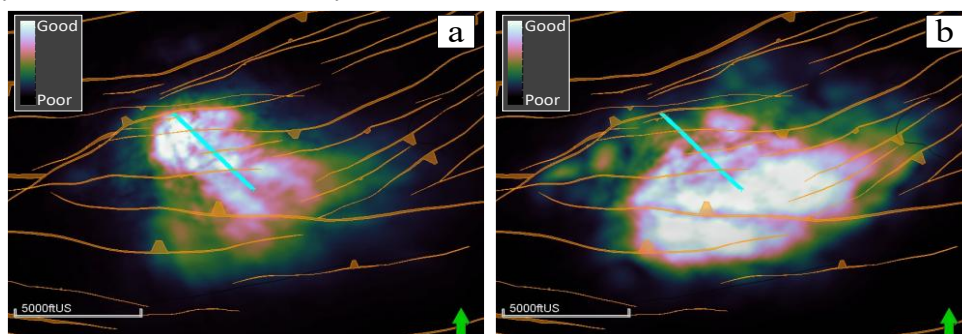


Figure 5 VSP illumination maps comparing (a) the legacy RTM image with (b) the latest elastic FDR image.

Comparison of fault interpretations in Figure 4 from the latest VSP FDR and OBN FDR reveals notable differences in fault position, dip, and strike. The high-resolution VSP data consistently indicate less steeply dipping fault planes, with orientations more closely aligned with the regional structural trend. These differences have important implications for reservoir compartmentalization and potential fluid traps, as fault geometry (particularly dip angle) directly influences seal capacity and migration pathways through the mechanical properties of the fault zone (e.g., shale gouge ratio). Changes in fault strike can also create small compartments capable of trapping perched water, affecting the overall development strategies. Furthermore, the improved subsurface illumination provided by the latest VSP FDR revealed previously unmapped faults, enhancing the structural understanding of the area. Incorporating these refined VSP interpretations into the subsurface model is therefore critical for optimizing drilling strategies and improving reservoir connectivity characterization.

Conclusions

Elastic FWI has been successfully applied to legacy VSP data from the Mad Dog field, yielding a high-fidelity velocity model and FDR image with significantly improved illumination and resolution compared to legacy seismic images. These enhancements facilitate more accurate fault interpretation and reservoir characterization in subsalt intervals, demonstrating that VSP-based elastic FWI is a robust and effective approach for high-resolution imaging and for informing optimized field development strategies. These results also demonstrate that repurposing legacy VSP acquisitions through modern elastic FWI unlocks significant untapped value and offers a robust pathway to high-resolution subsalt imaging in complex Gulf of America settings.

Acknowledgements

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References

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