New insights on the role of low-velocity shales in subsalt Paleogene exploration in the deepwater Gulf of Mexico

Daniel Carruthers, Carl Watkins, Shuo Ji, ZhiPing Yang (Viridien)*

Summary

New long-offset, low-frequency (LOLF) OBN acquired using the innovative TPS low-frequency source provides transformational imaging of the subsalt geology in the complex and inboard, minibasin domain of the central Gulf of Mexico (GOM). The role of low-velocity (LV) shale bodies in the deformation, which fundamentally controls exploration in this domain, has, until now, been under-recognized. The new data, even in the early-out test, is already providing the basis for significantly improved understanding on deepwater Paleogene. Further processing, with the latest elastic FWI, is likely to provide data that will drive renewed exploration activity in this previously challenging part of a prolific basin.

Introduction

The Paleogene 'Wilcox' turbidites is a proven, prolific play in the deepwater GOM yielding major discoveries such as Great White, Kaskida, Julia, and Tiber. To date, the majority of exploration has focused in the subsalt foldbelts, which transect the deepwater protractions of Alaminos Canyon (AC), Keathley Canyon (KC), and Walker Ridge (WR) (Figure 1). Advancements in acquisition and processing technology over the past two decades have facilitated this exploration, imaging the subsalt foldbelts in good detail. Inboard, however, where the subsalt structure is more complex, existing streamer data have struggled to optimally image the subsalt.

Inboard of the Keathley-Walker fold and thrust belt (after Hudec et al., 2013), there is a structural domain of Paleogene-age minibasin separated by Neogene-age minibasins (Figure 2). This domain formed during repeated phases of minibasin subsidence into salt, leaving behind a complex system of vertical to oblique salt feeders and canopies that compartmentalize stratigraphy and encase minibasins (Pilcher et al., 2011 and references therein).

The Wilcox turbidites were deposited in the Paleogene and Early Eocene. Fed from the major rivers active at the time, sand was episodically shed into the deepwater (Snedden and Galloway, 2019). Good reservoir quality has been proven at the major discoveries along the outer foldbelt trend (BSEE Well Database). All indications suggest the KC and WR protractions received sand from the north, so clearly turbidites have made their way through the complex assemblage of Paleogene-age minibasins. Locating these

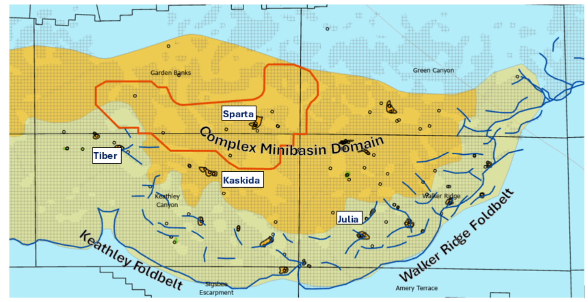

Figure 1: The Laconia Phase I & II (orange polygon) cover the inner part of the deepwater Wilcox trend. The pale buff color represents the outer foldbelt trend and the darker buff color the inner minibasin trend. Highlighted wells and dark outlined fields are those with Wilcox intersections or discoveries. Source of Wells and Fields: WoodMackenzie Lens Upstream

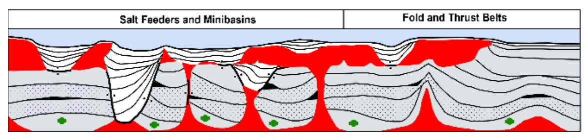

Figure 2: Schematic cross section of the central deepwater GOM illustrating the inboard (left side) minibasin domain and outboard fold and thrust belts (modified from Pilcher et al., 2011). The salt distribution (in red) and the base of salt surface are significantly more complex in the minibasin domain where Neogene (white) minibasins have subsided into the salt canopy and into pre-existing diapirs and salt walls. The resultant stratigraphic and lithological complexity cause severe challenges for deep seismic imaging, including primary minibasins (grey). Source rocks (green symbols), reservoirs (dotted fill), and conceptual hydrocarbon trap/reservoir fill are annotated.

minibasins and imaging their internal architecture is essential in evaluating the evolution of paleobathymetric lows, where seismic facies are consistent with sand deposition, and if there is evidence of hydrocarbon fluids within them. The recently discovered Sparta field (formally North Platte) is one of a few isolated examples that have proven this northward extension of the Wilcox play, but the remaining potential is currently obscured from view.

The Laconia project

Guided by BP's full-scale 3D synthetic study (Dellinger et al., 2017) and encouraged by Shell's Momentum project (Merritt et al., 2024), Viridien launched the Laconia survey (Figure 1) in July 2024, a massive multi-client survey with more than 8000 node stations covering about 336 OCS

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blocks. With a 20 km shot halo, the source carpet extends to nearly 800 OCS blocks (or over 18,000 sqkm).

Two distinguishable features of the Laconia survey are the long-offset and low-frequency survey design. With a minimum crossline (XL) offset of 30 km and a considerably longer inline (IL) offset, this acquisition geometry allows diving waves to penetrate deep into the target subsalt geological formations. Application of the Tuned Pulse Source (TPS) provided rich, low-frequency signal (coherent signals detected as low as 1 Hz).

The impact of the novel survey design, using raw satellite-transmitted 16 ms hydrophone-only data, is illustrated by an early-out OBN FWI (Figures 3b, e, h). The 15 Hz streamer RTM image, migrated with the 6 Hz streamer FWI velocity in Figure 3(a, d, g), presented a rather chaotic subsalt image with sporadic subsalt events that were difficult to interpret. Figure 3(b, e, h) shows the OBN 5 Hz FWI Image with the OBN FWI velocity overlaid. This display is most effective at revealing the now intact stratigraphy and clearly imaged structure to enable geological interpretation (Figures 3c, f, i).

Image Updates

The early-out OBN FWI provides a significantly improved image of the deep basin architecture in the area of interest (Figure 3). Of most immediate significance are the updates to the imaging of the salt, the recognition of low-velocity shales, and the impact on the imaging of minibasins and salt welds. The imaging of deep structural features, including autochthonous salt and the pre-salt basement, are also significantly enhanced.

Imaging of the allochthonous salt typically shows subtle but important improvements. In contrast, imaging of the deep salt is significantly improved, including unequivocal identification of feeders and the relationship with surrounding stratigraphy (Figures 3d-e, g-h).

One major uplift is the improved recognition and extent of a low-velocity and often chaotic seismic package, typically immediately beneath the allochthonous salt, believed to be an overpressured and remobilized shale. While existing streamer data provided hints of low-velocity zones, their detail, including the structural configuration and stratigraphic contacts with surrounding overburden, were not resolved until using the LOLF OBN (S. Ji et al., personal communication, 2025).

The low-velocity remobilized interval is rarely penetrated by wells, but their position in penetrated stratigraphy suggests that they are likely to range in age from the Oligocene to the lower Miocene. This observation fits with regional models that suggest that sand supply to the area of interest shut off in the Oligocene (Snedden and Galloway, 2019). The low-velocity zones include examples of both in-situ (Figures 3d-i) and highly deformed intervals (Figures 3a-c and g-i), and we have identified cases where these shales occur both stratigraphically on top of allochthonous salt or the Eocene units (see light and dark purple units respectively on Figure 3). The close association in timing between deposition and shallow burial of these shales, and the timing of allochthonous salt tectonics and minibasin formation, creates a complex geological framework that until now has been difficult to resolve.

Remobilization of these shales appears to be localized and is often intimately associated with the base of Neogene 'secondary' minibasins. Although the imaging of the Neogene minibasins themselves is generally good when using the streamer data, the image uplift from the OBN sheds new light on their development, particularly the nature and sequence in which they welded onto the subsalt and pre-salt respectively (Figures 3b-c, h-i). In some cases, low-velocity shales were deposited as precursor basins above salt but have been pushed sideways under the load of rapid Neogene sedimentation (Figures h-i). Additionally, the image uplift allows confident identification of welds (salt, shale, or combined forms). The ability to identify the salt feeder systems and the welds associated with salt (and indeed salt and shale) evacuation has implications both for reconstructing basin evolution and for identifying drilling risks. In other cases, low-velocity shales deposited before allochthonous salt, have been deformed during lateral shortening of the primary minibasins, as shown sub-salt thrusting Figures 3g-i.

The image updates revealed by the OBN FWI also impact the deepest part of the section. Imaging of the top Cretaceous surface is dramatically improved, and there are strong suggestions of fabric in the pre-salt that have not been previously seen, including potential syn-rift structures. The enhancements are sufficient to identify with confidence the key structural features in the subsalt including, for example, thrusted Cretaceous carbonates (Figures 3d-f, g-i).

Discussion and Conclusions

The imaging uplifts outlined will allow key operational tasks to be addressed in future exploration of the subsalt in the newly acquired survey, namely regional understanding, prospect identification/risking, and drilling risks. In all three areas, the newly derived imaging allows for step changes in understanding that materially reduce risk and are considered likely to lead to a new phase of exploration and development.

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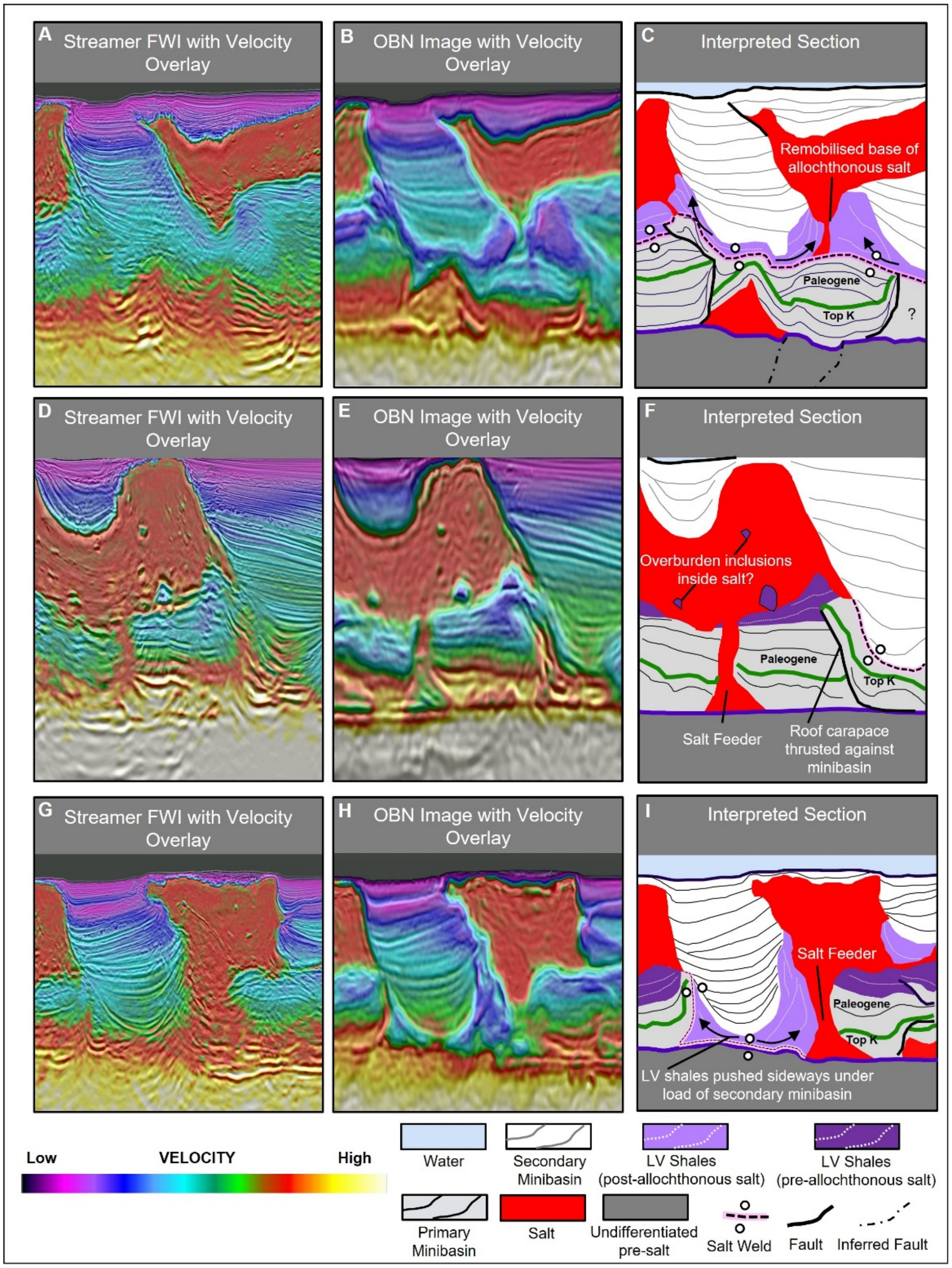

Figure 3: Impact of OBN FWI Image on subsalt understanding. Left column: streamer RTM with color overlay of the streamer-derived velocity field. Central column: OBN FWI Image with a color overlay of the OBN-derived velocity field. In all three cases, coherent subsalt Paleogene stratigraphy, the Cretaceous carbonate sequence, and low-velocity (purple) shales are clearly identified. Right column: Interpreted geological sections of 3 seismic examples. See Legend for more details.

Identification and risking of all the key components of the deepwater Paleogene Wilcox petroleum system are impacted by the new OBN FWI. Basin architecture and evolution controls the fundamentals of source rock presence and maturity, and the distribution and quality of the deepwater Wilcox reservoir. Trap and seal risk are also critical and, in common with source rock maturation and charge access, need to be considered in the light of timing. The new data allows the top Cretaceous to be clearly and confidently identified, but early results further suggest that key elements of the architecture of both the late Cretaceous sediments and the deeper stratigraphy, including syn-rift structures, can be seen (Figure 3). These raise the possibility of building an enhanced understanding of the source rock distribution and the regional controls on subsequent structuration.

The reservoir in the deepwater Wilcox play consists of gravity flow deposits (deepwater channel and fan systems), the distribution of which was fundamentally controlled by paleobathymetry, i.e., the water depth at the time of deposition. Water depths during the Paleogene were controlled by a combination of regional slope and the presence and distribution of salt diapirs, a distribution that was fundamentally different from that seen today. In the inboard minibasin domain, early diapiric structures have been locally replaced by secondary (Neogene) minibasins, the fill of which clearly defines the timing of periods of salt movement. From our new data, it is also clear that the low-velocity shales, of likely Oligocene age, were intimately involved in this deformation and need to be carefully considered in any reconstruction. While the new data provides improved imaging to identify the presence of coherent Paleogene stratigraphy (Figure 3), mapping the distribution and connectivity pathways of these primary minibasins is a key tool in predicting Wilcox reservoir presence and quality, a task that was simply impossible on the original streamer data. Reconstructing the distribution and connectivity of depositional basins and transport pathways clearly requires the development of an understanding of the deformation history. It is this deformation that ultimately controls the location and scale of structural closures and the timing that can impact charge and seal integrity. Understanding of both of these key components of the petroleum system is materially enhanced as a result of the new data.

The most consequential impact of the imaging uplift is in the identification and risking of leads and prospects. This relies on an accurate interpretation of the prospective and sealing stratigraphy, and the trap geometry. The clear definition of the Paleogene minibasins, overlying salt and low-velocity shales, and in particular, salt/shale welds, allow different interpretations to be discussed, validated, and quantitatively risked with enough precision to justify drilling.

Finally, the enhanced imaging provides key information to support well planning and operations. While the enhancement in confidence of well prognoses facilitated by improved imaging is obvious, the ability to consider the risks associated with encountering salt welds and pressure kicks is equally important. Pressure kicks across salt welds and feeders are a known risk in the deepwater GOM (Pilcher et al., 2011; Edwards et al., 2014; Shumaker et al., 2014; Jackon and Hudec, 2017) and are a particular risk in situations where streamer data may suggest that the salt is fully evacuated or where the potential presence of a weld cannot be confidently identified. Mobile shale, especially where overpressured, presents an additional and related drilling hazard (Jackson and Hudec, 2016; Soto et al., 2021), both in terms of its presence, the potential for pressure kicks at shale welds, and the likely bedding dip and geometry changes that impact drilling operations and well integrity. The enhanced imaging of the subsalt allows for confident pre-drill identification of potentially overpressured mobile shales, an improved prediction of fault distribution and bedding dips and recognition of the presence of salt welds or salt/shale welds, allowing mitigation of geohazards.

In conclusion, new LOLF OBN data acquired using the innovative TPS low-frequency source is providing transformational imaging of the subsalt geology in the complex region of the central GOM. The new data, even in this early-out test, is already providing the basis for significantly improved understanding of the Wilcox play and the structural evolution basin involving salt and shale tectonics. Further processing, ultimately with the latest elastic FWI workflows, is likely to provide data that will drive renewed exploration activity in this previously challenging part of a prolific basin.

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