Deep Imaging of the Paleogene, Miocene Structure and Stratigraphy of the Western Gulf of Mexico using 2D Pre-Stack Depth Migration of Mega-Regional Onshore to Deep Water, Long-Offset Seismic Data

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Abstract

The northwestern Gulf of Mexico basin has emerged as an archetype example of a robust, progradational passive margin system that induces substantial translation over underlying detachments due to gravitational loading. Despite this recognition, the difficulties in deep imaging of seismic data have continued to obscure key features of this deformation. Mega-regional, 2D, long-offset **PSDM** data help advance the interpretation of the Paleogene and Miocene of the Gulf of Mexico. We present results from new seismic line composites made up of reprocessed **PSDM** legacy onshore data (sourced from **SEI** and **GPI**), and newly acquired ocean bottom cable data and marine streamer data acquired and processed by GX Technology. Key lines from this dataset link robust, onshore shelf lowstand wedges to deep-water sediments and more clearly image deep structural styles and salt remobilization events. The lines span approximately 300 miles (500 km) from onshore Texas to the ultra-deep water and finally show the full size of geologic features, including a regional salt weld that starts onshore at the top Eocene and extends for over 100 km, ramping up to Oligocene. The interpretation highlights the effects of gravitational forces on the stratigraphic section and delineates prominent extensional faults that sole-out at major detachment levels and are linked to a newly recognized Paleogene thrust belt, as well as to previously documented Oligo-Miocene contractional belts. Significant lateral translation occurs along these detachments. The data image a key fault connection from Oligo-Miocene extensional faults down to the Louann detachment surface, and the interpretations provide viable scenarios for Oligo-Miocene expansion to drive the Perdido fold belt along the Louann detachment.

Introduction

As regional 2D and 3D data became more available in the northern Gulf of Mexico, a basin-scale interpretation approach is needed to understand the key stratigraphic and structural features through geologic time (Diegel *et al.*, 1995; Peel *et al.*, 1995). Modern investigations have recognized a whole-basin system driven by gravity spreading and gliding and enhanced by sediment loading and expanded lowstand sediment wedges; this has resulted in a series of complex salt mobilization events (Schuster, 1995) coinciding with large-scale deformation in the form of proximal, extensional structures linked to distal, contractional belts (Diegel *et al.*, 1995; Peel *et al.*, 1995; Rowan *et al.*, 2004**).** Despite this, the difficulties in deep imaging of seismic data have continued to obscure key features of this deformation, and the size of the basin limits the ability to see the whole linked system in one consistent dataset.

Long-offset data serve the growing industry need for regional data-sets that overcome imaging limitations of legacy seismic and provide a more complete framework for future exploration. Modern, long-offset, long-recording-time, **PSDM** data can help in the development of new criteria and play ideas for the interpretation of the northern Gulf of Mexico. We present an interpretation of selected mega-regional seismic lines in the northwestern Gulf of Mexico that span from onshore to ultra-deep water and are part of a new dataset composed of **PSDM**, widely-spaced, 2D seismic lines that are composites of several surveys. This dataset is part of the GX Technology GulfSPAN™ project. The land component is existing onshore data from two contributors, Seismic Exchange, Inc. (**SEI**) and Geophysical Pursuit, Inc (**GPI**). These data have been reprocessed and depth imaged by GX Technology (**GXT**). The near shore component is from GX Technology ocean bottom cable (**OBC**) long offset, long recording time data, and the deeper water component is GX Technology's long-offset, marine streamer data that was collected and processed in 2004 for the original GulfSPAN project. On this mega-scale, the deepwater stratigraphy and structures can be seen on the same section as landward shelf edges, and the depth-imaged data more properly displays geometric relationships for more accurate stratigraphic and structural interpretation and timings.

Mega-regional seismic line interpretations

The position of the seismic lines is shown on Figure 1, and Figure 2 compares the interpreted horizons shown on the seismic lines to a chart of sea level rises and falls (Haq *et al.*, 1987 and Hardenbol *et al.*, 1998). A stratigraphic and structural interpretation of regional Line **A** (Fig. 1) is shown in Figure 3 at a squeezed 1:6 vertical exaggeration as it spans over 310 miles (500 km) from onshore Texas to the ultra-deep water of the northwestern Gulf of Mexico. A detailed view of part of Line **A** is shown in Figure 4 and a detailed view of Line **B** is shown in Figure 5 (locations on Fig. 1). These larger scale images are shown with and without interpretations and at a slight vertical exaggeration (1:1.5).

The interpretation highlights gravitational effects on the stratigraphic section at different times. The main features of the interpretation include the delineation of prominent, regional extensional faults that sole-out at two major detachment levels and are linked to a newly recognized Paleogene fold-thrust belt as well as to previously documented Oligo-Miocene contractional belts. Significant lateral translation occurs along these detachments. They are labeled on the figures as the Louann Salt detachment surface and the Eocene to Oligocene salt weld detachment, and proposed translation directions are shown with white arrows.

Stratigraphic framework

The horizons interpreted on these lines have been constrained by tops from the Paleo-Data Inc. database of over 250,000 onshore wells and from a selection of offshore wells from the public domain. The major sea level falls and rises are marked on the figures in bold arrows, and the horizons are selected sequence boundaries at major falls while other horizons mark major transgressive intervals. The regional seismic line in Figure 3 shows a Mesozoic stratigraphic section that starts to the northwest at the shelf slope break position of the Cotton Valley on the reprocessed land data. The top Cretaceous, Wilcox, top Eocene, and Miocene horizons are labeled and mark the top of well-developed shelf margins with downlapping reflectors, demonstrating 110 miles of progradation and only 3 miles of aggradation. These shelf margins prograde basinward over thick lowstand wedges and prodelta to upper slope facies and can cause significant sediment loading of the substrate.

Criteria for interpreting disconformable seismic surfaces

The long offset, long recording time, **PSDM** data show seismic reflection geometries and amplitudes of sufficient resolution to apply rigorous criteria for interpretation of various structural and stratigraphic styles. Among the features interpreted on the lines are regionally consistent disconformable seismic surfaces, across which there are changes in the geometry of seismic reflections.

Disconformable surfaces may be created in several ways. First, they may represent salt welds associated with remnant salt bodies or condensed units left behind along the surface. Salt withdrawal or deflation features form above the surface that is not present below. Often the lateral scale of the features above the surface is different than below. Translation along a detachment is a second scenario that can form disconformable seismic surfaces and we often recognize proximal extension linked to distal contraction. Normal growth faults in a proximal position must sole out onto the detachment surface and display sediment expansion into the accommodation space created by the basinward translation. In the distal position, thrust faults step up the same detachment, and contractional detachment folds and folds associated with thrusting form above the surface. The layering below the surface is not affected by the deformation taking place above the detachment. The ages of the growth wedges in the expansion faults matches the ages and growth associated with the contractional features. Again, the lateral scale of features above and below the surface may be very different.

Thirdly, a disconformable surface may be formed by purely stratigraphic processes and represent an erosional truncation, or an onlap or downlap wedge that may have been inverted into a different position by salt movement or other structural event. These features may have a similar lateral scale to features below the disconformable surface, because the sediments above and below the surface are being affected by the same event.

In this study, salt welds and detachment surfaces are interpreted on the data constrained by the criteria above, and these often occupy the same surface; this probably occurs through slip connecting up pre-existing salt weld surfaces into a more laterally continuous detachment surface, and significant basinward translation is interpreted to occur along the detachments.

Paleogene translation and newly-imaged fold-thrust belt

Figure 3 shows the full Line A composite with the land **PSDM** reprocessing, the new ocean bottom cable data, and the streamer *circa* 2004; Figure 4 is a detail from Line **A,** which has much less vertical exaggeration. The interpretation of the Mesozoic and early Paleogene section delineates a new fold-thrust belt in the **OBC** data (Figs. 3 and 4). Associated with clearly imaged Paleogene growth faulting in the land data, these contractional structures represent the oldest linked system seen on these data.

The Cretaceous and early Tertiary shelf edges shown on Figure 3 appear highly deformed by down-to-basin normal faults and probable salt withdrawal features. Paleocene and early Eocene offset and translation takes place along sets of low angle, down-to-basin faults that sole out proximally in lower Paleocene to top Cretaceous but more distally step down onto the Louann detachment surface, and the Wilcox section fills this accommodation space with thick sediments. On most lines in the survey, salt evacuation seems to account for most of the shortening required by this early Paleogene extension (similar to Diegel *et al.*, 1995, their Fig. 31).

We propose that some of this onshore extension results in an outboard contractional fold-and-thrust belt that accommodates a few kilometers of displacement. This belt is present as a series of small but clearly imaged thrusts involving the Mesozoic and Paleogene section. These early Paleogene thrusts are interpreted in only few places, but where present on the **OBC** data they seem compelling, and represent, to our knowledge, a newly recognized contractional response to early Tertiary translation in the northwestern Gulf of Mexico. This belt is called here the Bajo (Spanish for “underneath”) fold-thrust belt. Extension on the younger Corsair fault cuts the Bajo fold-thrust belt in places (Figs. 3 and 4).

Allochthonous detachment surface

In Figures 3 to 5, the Mesozoic and early Paleogene section is interpreted as undergoing salt evacuation and shows a systematic, counter-regional, tilted fault block style as described in Schuster (1995) for the eastern Louisiana Gulf coast and also illustrated in Rowan and Inman (2005) in their interpretation of **PSDM** 2004 streamer data from the GulfSPAN project. Inboard, the Mesozoic fault blocks are capped by a pervasive feature of over 100km in length that has been interpreted as an allochthonous salt weld and generally is placed above the top of Eocene in the northwestern shelf Gulf of Mexico area (Rowan *et al.*, 2005). Additional criteria showing that this feature is a true salt weld also are delineated on 3D data by McDonnell *et* *al.* (2007). This weld is labeled as the Eocene to Oligocene Salt Weld Detachment on the seismic lines. The surface, while disrupted by the Corsair, is a throughgoing feature out into the deep water. This has been recognized as a detachment surface in the northwestern Gulf of Mexico (Diegel *et al.*, 1995; Peel *et al.*, 1995) and is generally viewed as detaching in the lower Oligocene (as also interpreted here) ramping up to younger strata basinward and to the east.

The pervasive nature of this time-transgressive weld is shown in Figures 3 to 5 and the supporting criteria are well imaged in these mega-regional lines, where the geometry and scale of the structures above the detachment clearly do not coincide with those in the pre-Oligocene section below. The weld criteria include high amplitude and low frequency seismic reflections, which are interpreted as remnant salt bodies and condensed sections that have been deposited at the top of salt and have been left behind at the weld surface. Thus, the welds could be a regional sealing surface in some areas rather than a window for hydrocarbon migration.

Detachments with Oligo-Miocene translation

The key extensional faults, how they sole out and link to the detachment surfaces, and the age of the expanded sediments into these faults are the key interpretive elements on the data that can demonstrate the link to the contractional Port Isabel and Perdido fold belts. The allochthonous detachment surface described above (Figs. 3 to 5) appears to have been active in late Oligocene to Miocene time (Diegel *et al.*, 1995; Peel *et al.*, 1995). Although much of the up-dip translation has been accommodated by salt evacuation (Diegel *et al.*, 1995) some of the displacement is also recognized (Fig. 4) as being taken up by shortening in the Port Isabel fold belt (Peel *et al.*, 1995)

The similar-aged Perdido fold belt sits more distally than the Port Isabel folds and thrusts but appears to detach at the autochthonous Louann salt level (Fig. 3), suggesting modest amounts of late Oligocene to Miocene translation at the Louann level to account for shortening in the Perdido fold belt (Peel *et al.*, 1995; Trudgill *et al.*, 1999; Rowan *et al.*, 2005; Camerlo and Benson, 2006). The manner in which translation is transferred down to the Louann level to drive the Perdido fold belt remains a challenge but is probably related to the Corsair trend. Peel *et al.* (1995) show a cross section (their Line 5) that has the Corsair fault soling out in a Louann detachment. Rowan *et al.* (2005) discuss the possibility that a widening diaper below the Corsair that could, at least in places, accommodate some of the deeper extension.

These new **PSDM** data, particularly the long-offset long-recording time **OBC** data, shed some light on this interesting problem of deeper displacement at Louann level, as well as on the complexities of the Corsair trend at 10 to 15 km depth. Figure 3 (Line **A** in Fig. 1) and the detail in Figure 4 show a series of seaward-dipping listric normal faults soling out onto the Eocene to Oligocene salt weld detachment.

The Oligocene and lower and middle Miocene sediments expand and fill the accommodation space created by slip along these faults, along with continuing autochthonous salt deflation. The faults merge with the Corsair trend at the position just above an imbricate in the Paleogene-age Bajo fold-thrust belt. At this merge point, translation is interpreted to continue along the allochthonous detachment as well as step down, deforming the older Bajo fold-thrust belt and soling out along the Louann detachment. Proposed translation directions are marked in white arrows. This is the only possible deep down-to-basin fault system that has a growth history (early to middle Miocene) that corresponds to the growth wedges in the Perdido fold belt. The interpretation on the seismic data shown here is similar to the cross sections drawn by Peel *et al.* (1995). We emphasize that the series of expansion faults including the Corsair fault have a link to both the upper level Oligocene salt weld detachment driving the Port Isabel fold-thrust belt, and to the lower Louann detachment driving the Perdido fold belt.

The offset of the Cretaceous, Wilcox, and Eocene horizons and transfer of slip down to the Louann level is on the order of a few kilometers. More displacement, though, is interpreted at the allochthonous level to drive the Port Isabel fold-thrust belt. The Oligocene and lower Miocene show much greater offsets on the Corsair fault, on the order of 5-8 km. The Oligocene allochthonous salt weld surface is shown bowing downwards into the accommodation space created by continued, basinward translation of the Mesozoic to Paleogene section at the deeper Louann detachment level. This space is being filled with the lower and middle Miocene sediments above.

The deeper Corsair appears to vary along strike. Figure 5 shows a detail from an adjacent seismic Line **B** (location on Fig. 1). The key down-to-basin extensional fault is clearly imaged to depth and is landward of, and distinctly separated from the younger Corsair fault. Thick, expanded Oligocene section fills the accommodation space, and Oligocene section sits directly on the base Louann. In order to account for this Oligocene expansion, the fault must sole out at two levels. First, the fault most directly soles out along the Louann detachment, and the Mesozoic, Wilcox, and Eocene section translates basinward to the right in the figure, driving the Perdido fold belt. A second fault trace merges with the Corsair fault at the Oligocene salt weld detachment. Lower to middle Miocene expansion occurs across the entire set of faults including the Corsair fault and this extension drives the Port Isabel fold belt. The fault surfaces are drawn convex-up, bowing downwards into the gap interpreted in the Mesozoic and Paleogene section. This effect may be caused by a combination of continuing slip along the Louann detachment and salt withdrawal at the Louann level, as proposed by Rowan *et al.* (2005) in an interpretation of a line along-strike to the northeast. Figures 3 to 5 demonstrate the complexities of the deeper Corsair trend and the nature of slip partitioning between the allochthonous and autochthonous detachment levels. Rigorous analysis of deep depth data at a closer spacing than this regional dataset would be necessary to quantify the magnitudes of slip transferred to the Perdido and Port Isabel fold belts.

Oligocene deposition onto extensive salt canopy

The interpretation of the regional seismic line in Figure 3 clearly shows a thick, prograding Oligocene section depositing onto what was possibly a regional salt canopy that covered 50 km of the shelf and extended onshore almost another 50 km. This detachment surface has been recognized in the past (Diegel *et al.*, 1995), but it is worth reflecting on the effects of Oligocene deposition onto an aerially extensive, deflating salt canopy as sea level is rising and falling. Other investigators have anticipated the effects of salt canopies on sediment accumulation and transport maps. Fillon and Lawless (1999) document complex sediment accumulation patterns from assembling a series of Paleocene through lower Miocene deposystem maps and infer extensive sediment interactions with salt canopies and salt collapse events to explain key elements of the depositional patterns.

The late Oligocene lowstand is one of the more prominent lowstands on the sea level chart shown in Figure 2 (Haq *et al.*, 1987 and Hardenbol *et al.*, 1998) and since the publication of the charts, this sea level drop and the updip success of the equivalent-age Frio play has fueled the expectation of a downdip equivalent basin floor fan play in the deep water Gulf basin. A recent summary of the Oligocene sediments drilled in deep water wells integrated with sequence stratigraphy from seismic data by Zarra (2007) has documented a generally low energy, sand-poor depositional system but with some areas of variable sediment lithologies and depositional patterns. The most consistently sand-prone sequence in deep water reported from this study is the 29.4-32 Ma sequence, exactly at the highest point in sea level (Fig. 2). Salt canopy deflation over the broad area seen here in this regional composite dataset, would have mitigated the effect of the sea level fall in the late Oligocene as accommodation space was being created fast enough to keep up with falling sea level. In addition, contractional toes would form barriers and accumulate thick sediment wedges behind the barriers, and only marginal sediments could be transported through isolated pathways to deep water. As salt deflated, the sea level rises would have created even more inboard accommodation space trapping sediments there. But outboard, the sea level rise could have facilitated sediment transport by flooding barriers and opening up new pathways to deep water.

Conclusions

The northern Gulf of Mexico basin has emerged as the archetype example of a robust, progradational passive margin system that induces substantial translation over underlying detachments due to gravitational loading. On **PSDM** composite seismic lines, from land to abyssal plain, the mega-geologic scale displayed at depth enhances our understanding of the interaction of the stratigraphy, extensional faults, salt movement, detachment surfaces, and contractional features and timing of all these events. The Mesozoic and Cenozoic shelf margin development and progradation of 110 miles in the northwestern Gulf of Mexico and the continuation of these sediments into the abyssal plain can finally be seen with the **PSDM** deep imaging. Mesozoic to Paleogene extension occurred at a series of down-to-base Louann faults.

Wilcox sedimentation developed with rapid progradation and high sedimentation rates, and filled the accommodation space created by this extension. Translation along the Louann detachment surface resulted in a Paleogene contractional belt that is clearly imaged in these data and is called here the Bajo fold-thrust belt. Salt evacuation formed characteristic tilted fault block styles that involved the Mesozoic to top Eocene section. Thick Oligocene to middle Miocene sediments prograded onto a regionally extensive salt canopy; the full size and scale of this canopy was clearly recognized on the composite lines. More study is needed to understand the interaction of the Oligo-Miocene deposition with this salt canopy and salt deflation events.

Slip along a series of extensional faults, including the Corsair trend, facilitated the development of a thick Oligocene to middle Miocene section as shelf-slope-break positions moved basinwards. These extensional faults soled out first along a continuous allochthonous salt weld that forms at the top Eocene and became younger basinwards, ramping up to approximately the middle Oligocene level in this area.

This salt weld surface becomes a second major detachment surface in this area of the Gulf, and translation along this surface drives the Port Isabel fold-thrust belt. These data also show that the previously challenging problem of establishing the key fault connection from the series of Oligo-Miocene extension faults down to the Louann detachment surface is reasonably clearly imaged here at depth, and the interpretations presented provide viable scenarios for the Oligo-Miocene expansion to drive the Perdido fold belt along the Louann detachment.

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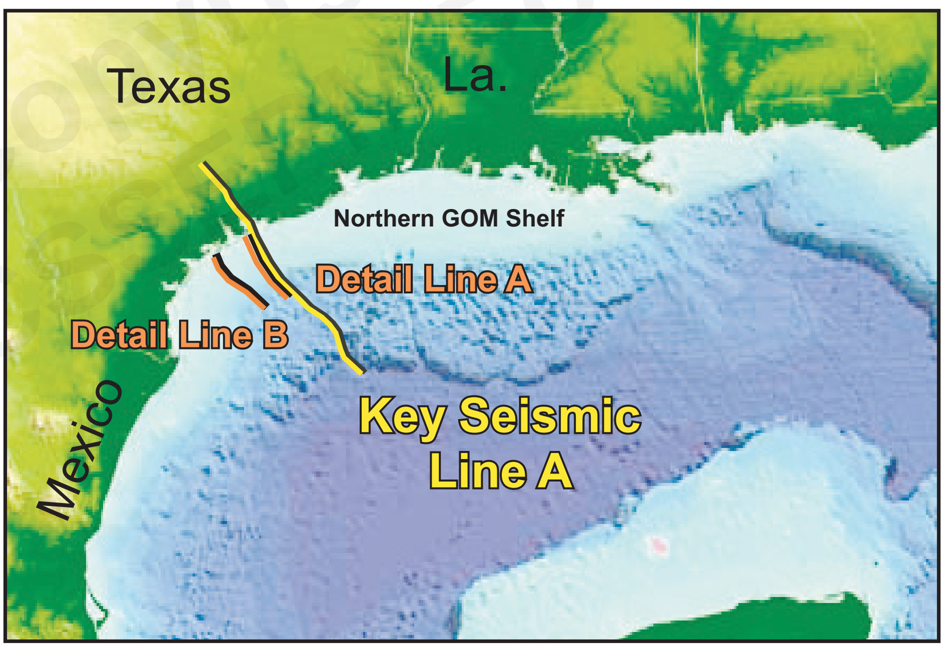

Figure 1. The location of a mega-regional seismic Line A (bold yellow) is shown on a Gulf of Mexico bathymetry map. This regional line is interpreted in Figure 3 and spans over 310 miles (500 km) from onshore to ultra deep water. A detail from Line A (interpreted in Figure 4) and a detail Line B (interpreted in Figure 5) from an adjacent line are located on the map in bold red lines.

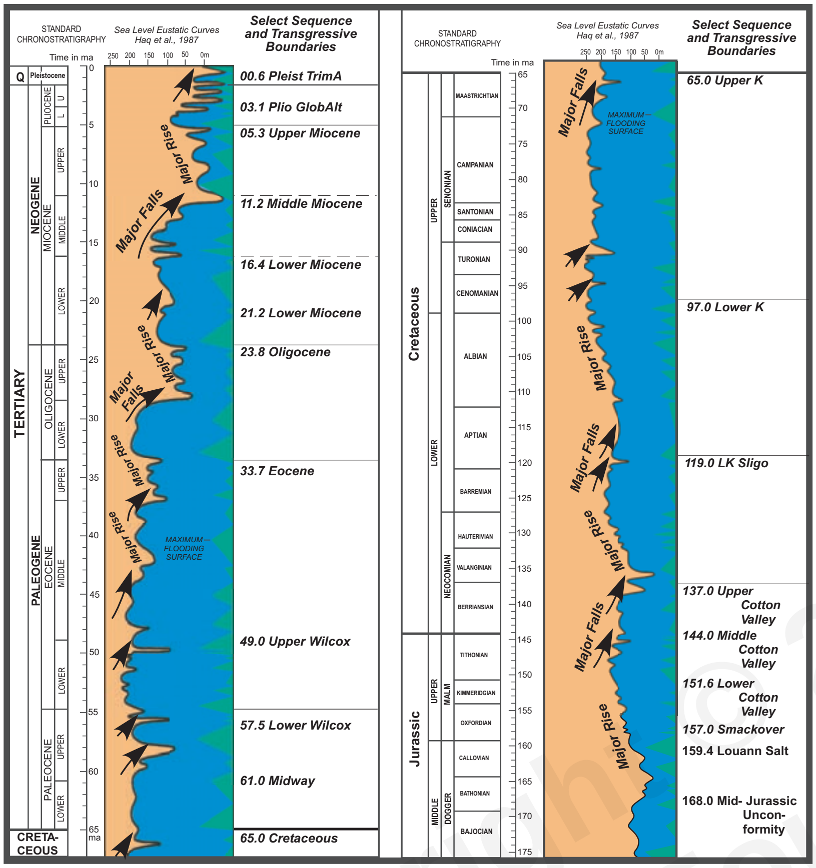

Figure 2. Cenozoic and Mesozoic horizons interpreted on the seismic lines denote selected sequence boundaries and specific transgressive events. The sea level chart is from Haq et al. (1987) and the bold black arrows show the major sea level lowstands and rises. The green inlay shows the position of the transgressions and maximum flooding surfaces.

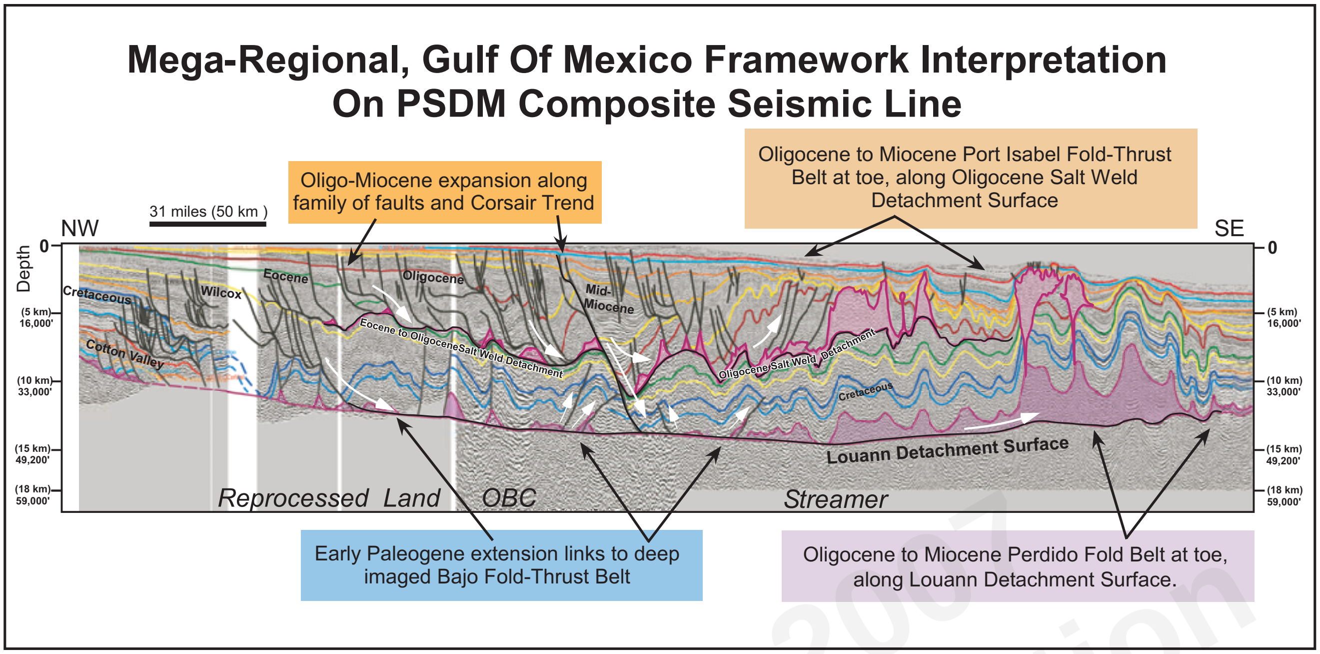

Figure 3. The stratigraphic and structural framework interpretation is shown on a mega-regional PSDM seismic line composite of reprocessed PSDM land, ocean bottom cable, and streamer data. The highlights of this interpretation include robust Paleogene shelf edges and pervasive salt withdrawal features, Paleogene extension linked to a new Paleogene contractional belt called the Bajo Fold-thrust Belt, a regional Eocene to Oligocene allochthonous salt weld, and a major expansion of the Oligo-Miocene sediments linked to the Port Isabel and Perdido compressional belts forming on detachment surfaces at the Louann salt and at the allochthonous salt weld. The land data is reprocessed by GX Technology and licensed through Seismic Exchange Inc (SEI). The OBC and streamer data are acquired and processed by GX Technology. The data is part of the GulfSPAN™ project and shown courtesy of GXT and SEI. The vertical exaggeration is 6:1.

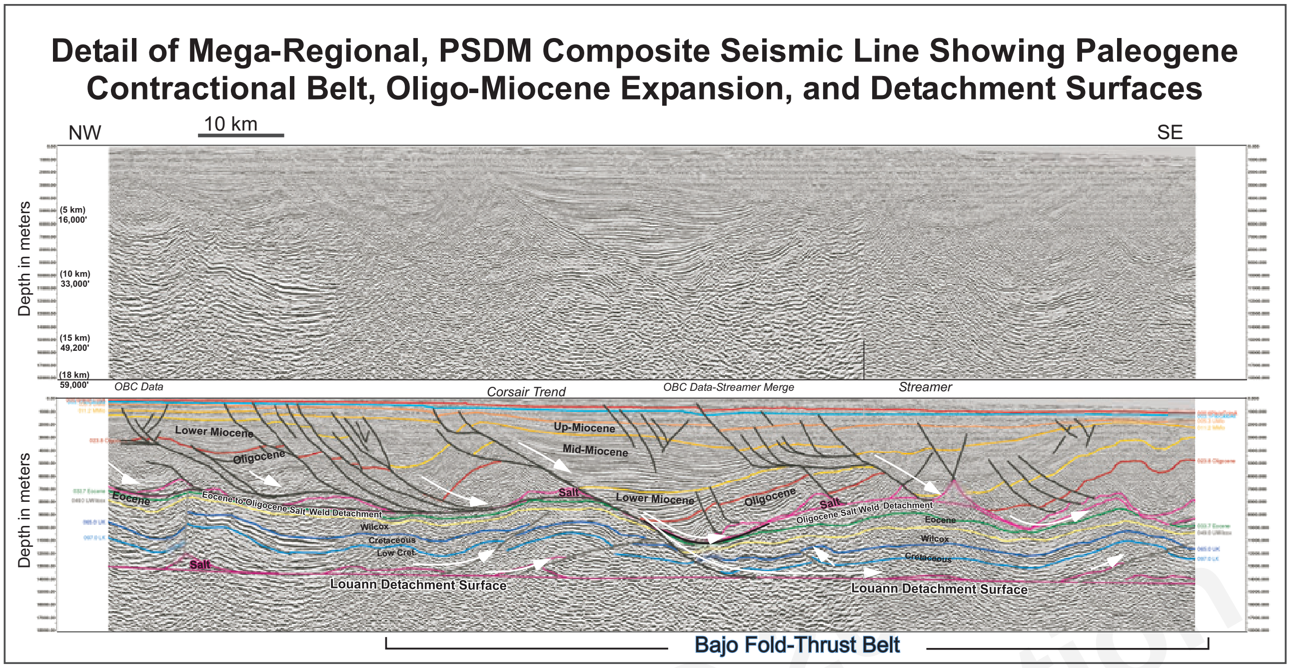

Figure 4. This is a detail of Line A from Figure 3. It shows an uninterpreted and interpreted PSDM seismic line at a 1:1.5 vertical exaggeration to more clearly demonstrate the listric normal faults and their linkage to both the Louann detachment surface and the allochthonous salt weld. White arrows show interpreted translation directions. A new, deep imaged thrust belt involving the Mesozoic to Wilcox section is called here the Bajo Fold-thrust Belt. The updip expansion of the Wilcox section (Fig. 3) links to these thrusts. The belt is cut by younger Oligo-Miocene extension faults that sole onto the Louann detachment surface. The OBC and streamer data is part of the GulfSPAN™ project and shown courtesy of GXT.

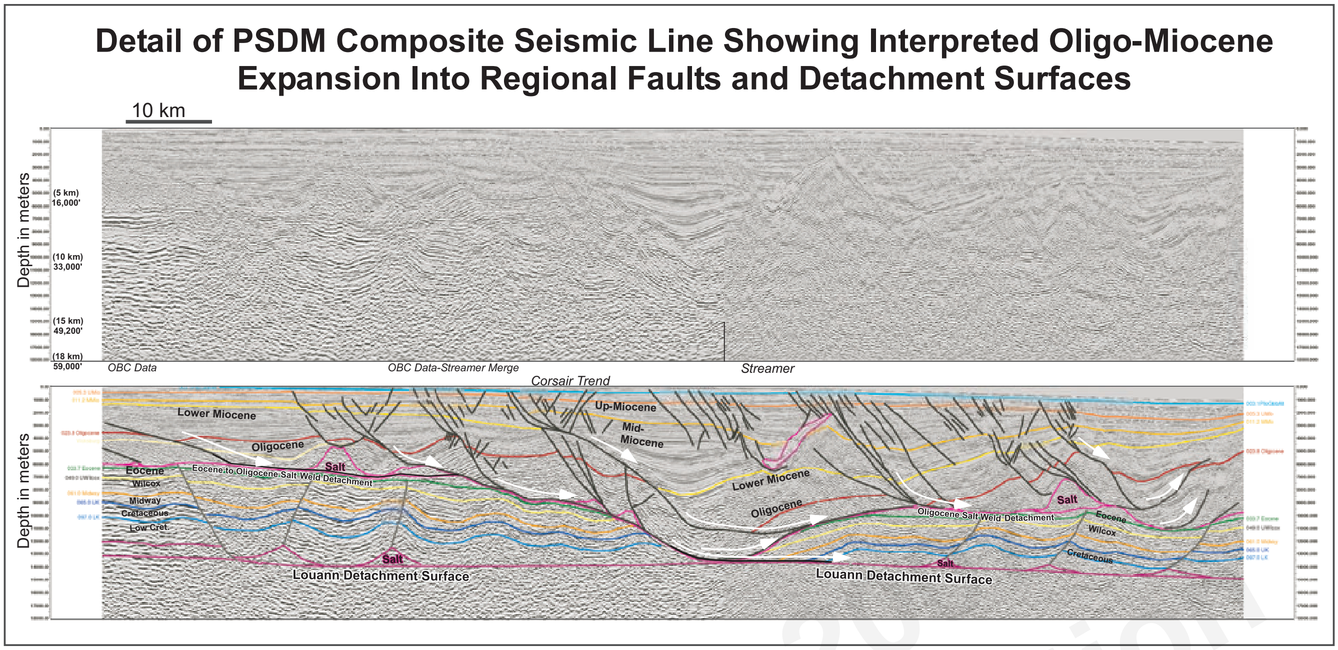

Figure 5. This is a detail of Line B and shows an uninterpreted and interpreted PSDM seismic line at a 1:1.5 vertical exaggeration to more clearly demonstrate another viable scenario for how the series of expansion faults sole out at the Louann and allochthonous salt detachment surfaces. The Oligocene expanded sediments fill the accommodation space created by translation of the Paleogene and Mesozoic section basinwards to the right in the figure. The Oligocene section sits directly on the base Louann and thus two soling faults are drawn with white arrows showing the translation directions. The fault slip and translation along the Louann detachment is concurrent with the other shown expansion faults; thus deforming the faults that sole onto the allochthonous weld detachment in the shallower section. The OBC and streamer data is part of the GulfSPAN™ project and shown courtesy of GXT.