Jurassic structures of the eastern Gulf of Mexico: Sakarn, Louann, Norphlet, and Breakup

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Summary

Southwest of the Middle Ground Arch, an expanded Middle Jurassic post-salt section sits basinward of the Norphlet raft trend. Rives et al. (2019) describe the expanded Jurassic section as the Sakarn series comprising Louann Salt, Norphlet, and other unpenetrated stratigraphy. The series rests on a narrow margin (90 km from shelf to oceanic crust) where it is deformed in both extension and compression during the Jurassic. We present 3D seismic data and isochore maps to both describe the deposition of Sakarn subunits and link the deformation of the Sakarn and Norphlet to the breakup and opening of the eastern Gulf of Mexico. Our observations suggest the following first order relationships:

1) The Lower Sakarn is distributed largely inboard of an ocean-continent transition-related Outer Trough; conversely, the Upper Sakarn lies over and adjacent to the trough.
2) Downslope movement of Sakarn minibasins and Norphlet rafts is linked to basinward salt flow during both the widening of the Outer Trough and the subsequent advance of salt over oceanic crust.
3) Post-breakup, the isostatically high oceanic crust in the distal margin acts as a backstop impeding continued downslope movement of Sakarn minibasins. Upslope shortening of the Sakarn follows, distributed across the trough in mid margin minibasins, diapirs, and rafts.
4) The northwest termination of the Sakarn is a salt detached shear zone that juxtaposes thick Sakarn basins against thin rafts or salt.

Introduction

We present detailed regional maps of subunits within the Sakarn series of the Mississippi Canyon, Desoto Canyon, Atwater Valley, and Lloyd Ridge protraction areas (Figure 1). Our maps derive from interpretations of 3D narrow azimuth Kirchhoff depth migrated seismic data. The full expanded Sakarn section has not yet been penetrated. Well control is limited to the Norphlet raft play (e.g., Godo, 2019) and a diapir roof penetration at Cheyenne. Rives et al. (2019) propose the Sakarn to be an evaporite-carbonate-clastic succession inclusive of the Norphlet Formation.

Deposition of the Sakarn, and its Yucatán margin equivalent, preceded the break-up of the Eastern Gulf of Mexico (e.g., Hudec et al., 2013; Hudec and Norton, 2019; Rowan, 2022). Correspondingly, the Sakarn is truncated in the southeast of the study area near the limit of oceanic crust (LOC). To the southwest, the Sakarn was transported farther basinward on the salt nappe that advanced over younger oceanic crust (salt nappe front, pink line in Figure 1). Inboard of the LOC, the Sakarn lies over the Outer Trough, a base of salt low formed by subsalt extension prior to break-up (e.g., Rowan, 2018; Rowan, 2022; Moore et al., 2022). The Sakarn series thins landward and ultimately onlaps the Middle Ground Arch (Godo, 2017). Downslope rafting of the Sakarn occurred during basinward salt flow, gravity gliding, and breakup processes (Pilcher et al., 2014; Godo, 2019; Moore et al., 2022).

Seismic Observations and Interpretations

<u>Sakarn Distribution</u>

The Sakarn varies from thin single reflector rafts flanking the Middle Ground Arch to over 3 km thick turtle structures at the Outer Trough (Figure 1 and 2A). The thick Sakarn truncates abruptly to the northwest along a 110 km northeast-southwest trending boundary that locally juxtaposes thin Sakarn rafts and thick Sakarn minibasins across salt walls, welds, and related faults (blue dashed line in Figure 1 and 2F; Rives et al., 2019). The length, linearity, abrupt thickness change, and coincidence with salt-related structures suggests that this is a structural boundary. There is no subsalt fault that aligns with the boundary, indicating it is detached on salt and unrelated to crustal structure.

<u>Sakarn Correlation and Mapping Units</u>

We define mapping units A through D within the Sakarn series based on seismic facies and structural style. Unit A (Figure 2B-D) is a relatively isopachous lower unit with high contrast seismic character where it is well imaged. Unit B has low seismic contrast and thickens rapidly basinward to over 1.5 km (Figure 2E). Unit C has moderate seismic contrast with growth stratigraphy in turtle structures and in bucket minibasins (Figure 2B-C). Unit D is a low seismic contrast unit with a notably abrupt mid margin pinch-out onto Unit B (Figure 2C-D).

The mapping units are grouped into an Upper Sakarn and a Lower Sakarn, based on stacking relationships and position relative to the Outer Trough. Lower Sakarn units A and B are primarily inboard of the Outer Trough and are locally folded over the faulted trough edge (Figure 2B). Units A and B must predate the subsalt extension that formed the Outer Trough. Upper Sakarn Units C and D pinch-out onto the Lower Sakarn, locally expand across growth faults, and exist in bucket minibasins between Lower Sakarn rafts and minibasins (Figure 2B-D). The basinward position of the Upper Sakarn suggests its distribution is related to the formation of the Outer Trough. We tentatively correlate the non-eolian Norphlet of the Swordfish and Madagascar wells

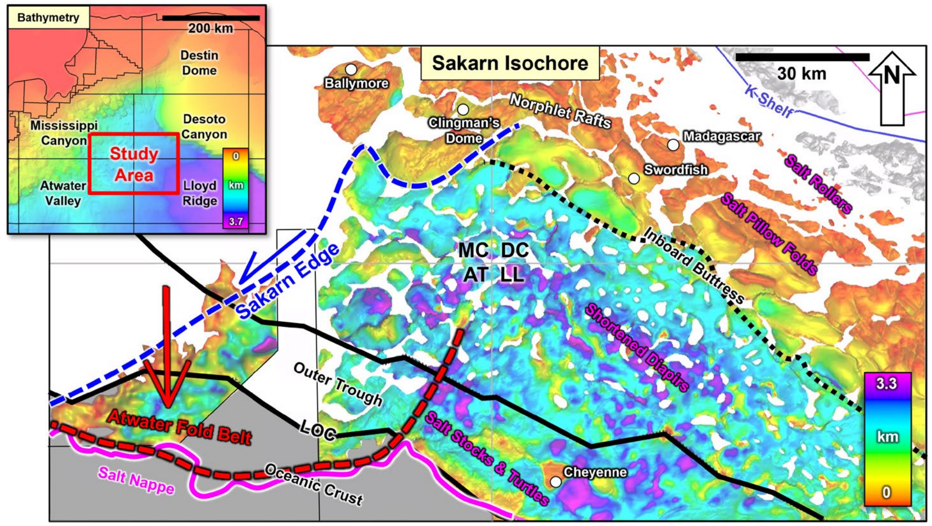

Figure 1: Key well control and total Sakarn isochore map. Norphlet rafts and Sakarn minibasins extend across the margin and Outer Trough to the oceanic crust with an abrupt lateral edge to the northwest (blue dashed line and arrow). Miocene Atwater Fold Belt shortening reactivated the western portion of the study area (red dashed line and arrows). Gray = Oceanic crust. White = salt and fault gaps.

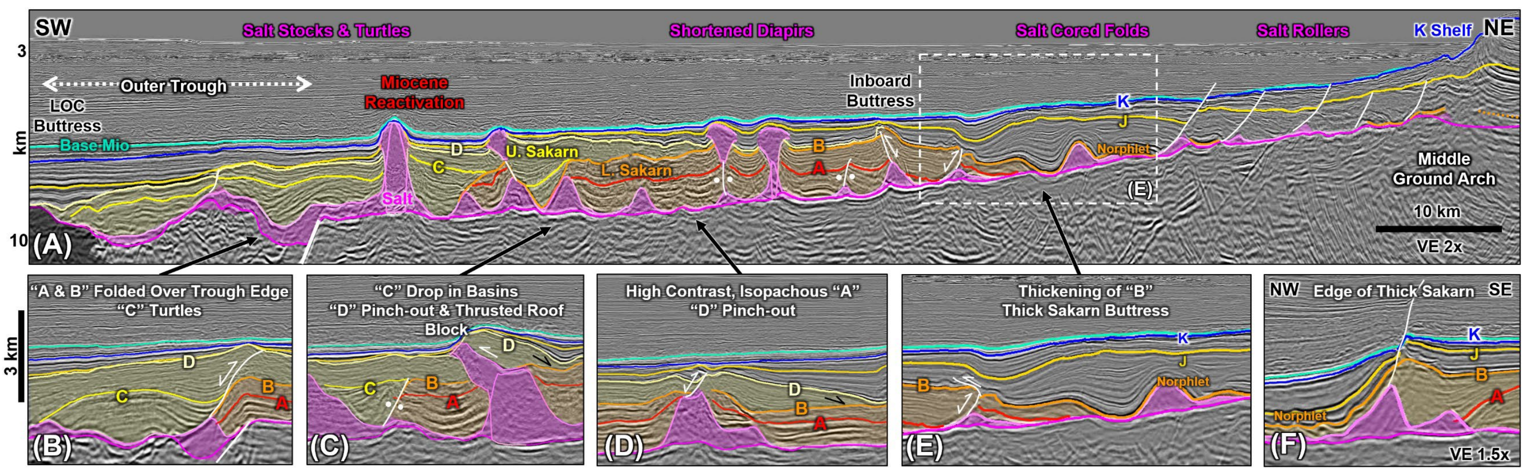

Figure 2: Regional seismic line across the study area on 3D NAZ Kirchhoff depth seismic data. (A) Structural styles vary from proximal rafts and salt rollers, to salt cored folds, shortened diapirs, and distal turtle structures. Lower Sakarn "A" and "B" subunits are observed inboard of the Outer Trough. Upper Sakarn "C" and "D" are over and adjacent to the trough. (B through E) Seismic facies and structural relationships of the Sakarn subunits. Subunit "A" is relatively isopachous with high contrast seismic character. "B" is low contrast and thickens rapidly basinward. "C" is moderate contrast with growth stratigraphy in turtle structures and minibasins. "D" is low contrast with an abrupt updip pinch-out mid margin. (F) Abrupt thickness change across a NE-SW trending structural boundary forming the northwestern edge of the thick Sakarn within the study area (see Figure 1). J = Top Jurassic. K = Top Cretaceous.

(Figure 1) to, or within, the Lower Sakarn B (Figure 2E). The resulting stratigraphic contact varies from a proximal Smackover on Sakarn B (Norphlet) contact to a basinward Smackover on Sakarn D contact.

Structural Styles

Jurassic salt-detached deformation on the margin varies from proximal extension to mid margin shortening with only minor deformation in the distal part of the margin (Figure 1 and 2A). From proximal to distal, we observe:

1) Post-Sakarn Jurassic growth faults, salt rollers, and thin rafts.
2) Thrusted thin rafts of Norphlet equivalent, inverted growth faults, steep flaps, and salt cored folds immediately landward of an abrupt thickening of the Lower Sakarn.
3) A region with early Sakarn minibasins and numerous small diapirs that shortened in the Late Jurassic. Many diapirs are partly closed by steep welds and have roofs that are shortened by folds or thrusts (Figure 2C).
4) Turtle structures, few large open salt stocks, and occasional inverted growth faults in the vicinity of the Outer Trough.

Discussion and Conclusions

The ages of Sakarn subunits are uncertain with existing well control, as are correlations from thin Norphlet rafts to the thick expanded Sakarn (Godo, 2019). Inboard of the Outer Trough, our Lower Sakarn mapping units A and B are generally comparable with the I and II correlation scheme proposed by Rives et al. (2019). The two schemes differ with respect to the distribution of Upper and Lower Sakarn in the vicinity of the Outer Trough and with our tentative correlation of the Norphlet to the Lower Sakarn B mapping unit. Our Norphlet correlation suggests Bajocian-to-Bathonian deposition of the Louann and Lower Sakarn (including Norphlet) based on age dating by Pulham et al. (2019) and Erlich et al. (2022). The Upper Sakarn is then younger than the Norphlet and may represent a Callovian unit not recognized on Gulf of Mexico stratigraphic charts.

The transition from Lower to Upper Sakarn involves a shift in deposition to a more distal position relative to the Middle Ground Arch. We interpret the shift to coincide with the onset of Outer Trough extension (Figure 3B). The base of the widening trough dropped during extension, as the overlying salt thinned, to create accommodation for deposition of the Upper Sakarn in the basin axis. It is possible that the last phase of Outer Trough extension exhumed lithospheric mantle (e.g., Moore et al., 2022; Rowan, 2022). Downslope movement of the system generated an updip raft gap to balance the extension from exhumation in the trough (Figure 3C, green arrows in Figure 4B). Later post-breakup raft movement is balanced by shortening of the mid margin diapirs, in addition to thrusting

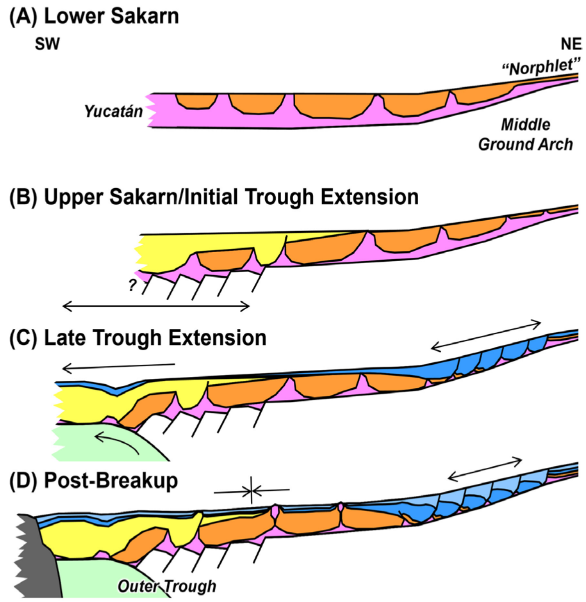

Figure 3: Diagrammatic sequence of events for deposition and salt detached deformation of the Sakarn. (A) Louann and Lower Sakarn deposition are continuous across the basin. (B) Upper Sakarn is deposited in widening Outer Trough. (C) Linked system of updip extension and basinward advance of Sakarn minibasins and rafts during late phase trough extension possibly involving subsalt mantle exhumation. (D) Downslope movements are backstopped by oceanic crust causing shortening of Sakarn diapirs, minibasins, and rafts. Not to scale. Pink = salt. Orange = Lower Sakarn. Yellow = Upper Sakarn. Blue = Late Jurassic. Green = possible exhumed mantle. Gray = oceanic crust.

and folding of the thin rafts inboard of the thick Sakarn buttress (Figure 3D).

Our observations combine in the following conceptual sequence of events for deposition and deformation of the Sakarn in the study area (summarized by Figures 3 and 4).

1) Louann Salt and Lower Sakarn deposition is continuous across the basin from Florida to Yucatán. The thin Sakarn B (Norphlet) facies is deposited adjacent to the Middle Ground Arch and in the Apalachicola Embayment salt basin. Additionally, thick Lower Sakarn minibasins and numerous diapirs develop in the axis of the basin, possibly sourced with sediment from the southeast or from the adjacent Florida and Yucatán crustal terranes (Figures 3A and 4A).
2) Pre-breakup extension of the Sakarn initiates in the basin axis, extending the Lower Sakarn and focusing Upper Sakarn deposition in the vicinity of the widening Outer Trough (Figure 3B).
3) Trough widths of 20-30 km balance rafting of the Sakarn B (Norphlet) away from the southwest flank of the Middle Ground Arch, suggesting a linked system of basinward salt flow and gravity gliding initiated by

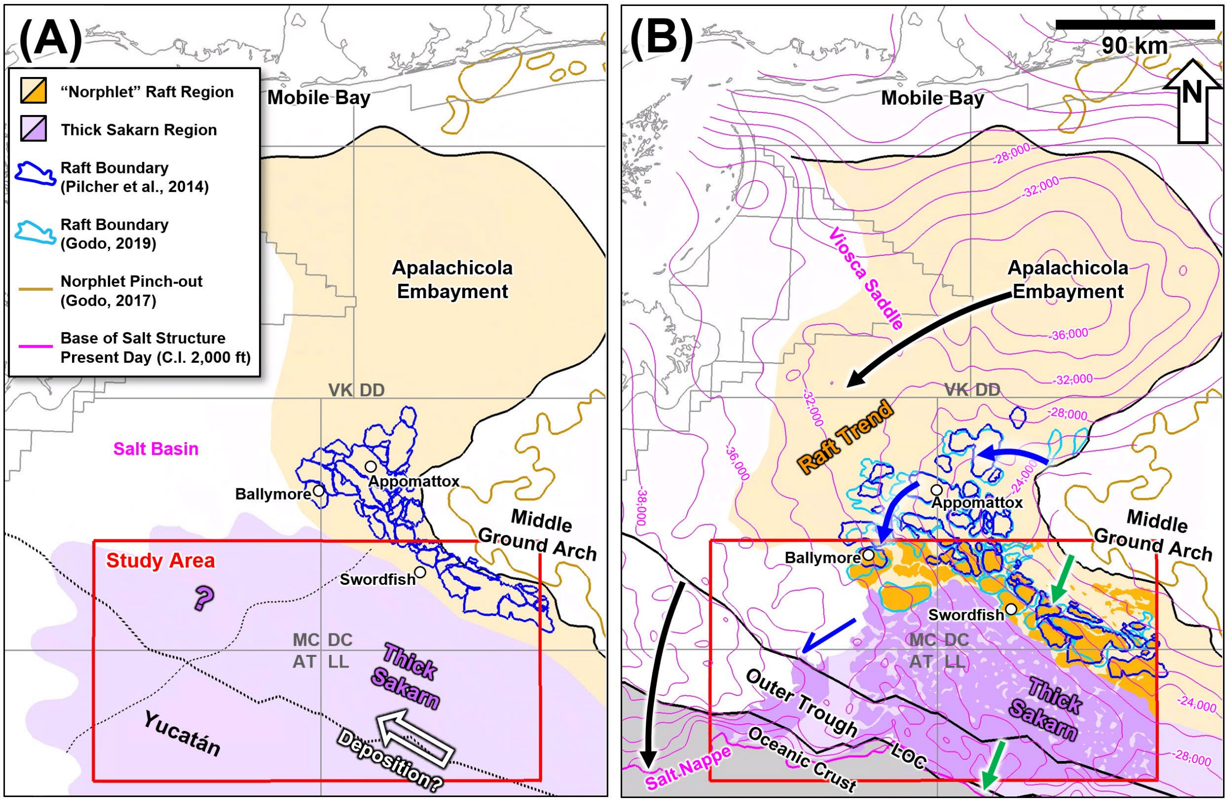

Figure 4: Map view illustration of Sakarn deposition and deformation. (A) Restored distribution of Sakarn and Norphlet facies. (B) Down slope movement of Sakarn rafts and minibasins linked to basinward salt flow and breakup-related extension of the Outer Trough. The northwest edge of the thick Sakarn is a shear zone between farther traveled rafts out of the Apalachicola Embayment (black and blue arrows) and rafts from the southwest flank of the Middle Ground Arch (green arrows).

trough extension (Figure 3C, green arrows in Figure 4B; Moore et al., 2022).

4) Based on regional seismic data, rafts from the Apalachicola Embayment are displaced basinward up to 90 km. The displacement is linked both to widening of the trough and to subsequent salt advance over oceanic crust (black arrows in Figure 4B). The lateral transition from approximately 30 to 90 km of raft displacement is accommodated across a salt detached shear zone resulting in the abrupt northwest edge of the Sakarn. The shear zone locally juxtaposes thick Sakarn basins against thin rafts or salt (Figure 2F and blue arrows in Figure 4B). Sakarn basins deposited west of this shear zone either remain on the Yucatán margin after break-up or have not yet been identified due to thinning of the section (e.g., Rowan, 2023) or seismic imaging limitations.
5) Continental break-up and subsequent seafloor spreading separate the Sakarn on the Florida margin from its Yucatán equivalent. The oceanic crust is isostatically shallower than the base of salt in the Outer Trough and acted as a backstop to downslope movements. Shortening is localized inboard of the LOC, reactivating structures within the trough and shortening the mid margin minibasins and diapirs (Figure 3D).
6) As mid margin shortening ceases, abrupt thickness changes within the Sakarn impede downslope movement of the thinner inboard rafts. Local buttressing leads to shortening inboard, evident in thrusted rafts and salt cored folds (black dashed line in Figure 1, Figure 2A and E, Figure 3D).
7) The northwest structural edge of the thick Sakarn may have restricted the eastern extent of Atwater Fold Belt shortening during the Miocene. Optimally positioned structures were reactivated in the western portion of the study area (red dashed line and arrow in Figure 1).

Acknowledgments

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