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MODELING THE MESOZOIC-CENOZOIC STRUCTURAL EVOLUTION OF EAST TEXAS

Ofori N. Pearson[1], Elisabeth L. Rowan[2], and John J. Miller[1]

[1]*U.S. Geological Survey, Denver Federal Center, Box 25046, MS 939, Denver, Colorado 80225–0046, U.S.A.*

[2]*U.S. Geological Survey, 12201 Sunrise Valley Dr., 956 National Center, Reston, Virginia 20192, U.S.A.*

ABSTRACT

The U.S. Geological Survey (USGS) recently assessed the undiscovered technically recoverable oil and gas resources within Jurassic and Cretaceous strata of the onshore coastal plain and State waters of the U.S. Gulf Coast. Regional 2D seismic lines for key parts of the Gulf Coast basin were interpreted in order to examine the evolution of structural traps and the burial history of petroleum source rocks. Interpretation and structural modeling of seismic lines from eastern Texas provide insights into the structural evolution of this part of the Gulf of Mexico basin. Since completing the assessment, the USGS has acquired additional regional seismic lines in East Texas; interpretation of these new lines, which extend from the Texas-Oklahoma state line to the Gulf Coast shoreline, show how some of the region's prominent structural elements (e.g., the Talco and Mount Enterprise fault zones, the East Texas salt basin, and the Houston diapir province) vary along strike. The interpretations also indicate that unexplored structures may lie beneath the current drilling floor. Structural restorations based upon interpretation of these lines illustrate the evolution of key structures and show the genetic relation between structural growth and movement of the Jurassic Louann Salt. 1D thermal models that integrate kinetics and burial histories were also created for the region's two primary petroleum source rocks, the Oxfordian Smackover Formation and the Cenomanian-Turonian Eagle Ford Shale. Integrating results from the thermal models with the structural restorations provides insights into the distribution and timing of petroleum expulsion from the Smackover Formation and Eagle Ford Shale in eastern Texas.

INTRODUCTION

In 2007 and 2010, the USGS completed assessments of undiscovered, technically recoverable oil and gas resources within Tertiary, Cretaceous, and Jurassic strata of the onshore coastal plain and State waters of the U.S. Gulf Coast (Dubiel et al., 2007, 2011). The assessments integrated sequence stratigraphic analysis, source-rock burial history and thermal modeling, structural analyses of the evolution of hydrocarbon traps and their distribution, and an examination of past production history and current trends. The structural studies relied in part upon interpretation of a sparse network of 2D reflection seismic lines licensed by the USGS over the past 15 years. The USGS has licensed seismic lines that are regional in nature in order to image as much of the thick stratigraphic section as possible and thereby aid in the understanding of the Gulf Coast basin's stratigraphic and structural evolution.

The two longest composite seismic lines licensed by the USGS extend in a NNW–SSE direction from close to the Texas-Oklahoma state line in Lamar and Delta Counties to the coastline in Galveston and Chambers counties (Fig. 1A). These two lines cross five of the region's major structural elements – from north to south, the Talco fault zone, the East Texas salt basin, the Mount Enterprise fault zone, the Angelina-Caldwell flexure, and the Houston diapir province (Fig. 1A). The Talco fault zone is part of the peripheral graben system that rims the north margin of the onshore Gulf Coast basin. Talco normal faults are rooted in the Jurassic Louann Salt (Fig. 1B) or its weld, and accommodated extension driven by sedimentary loading and the subsequent southward flow of salt (Ewing, 1991). The East Texas salt basin, a major focus for oil and gas production, contains numerous salt-related structural features in the central part of the basin (Jackson, 1982). The Mount Enterprise fault zone is a system of en-echelon normal faults that dip dominantly toward the north, root in the autochthonous Louann Salt, and became active as salt flowed northward into the East Texas salt basin (Ewing, 1991;

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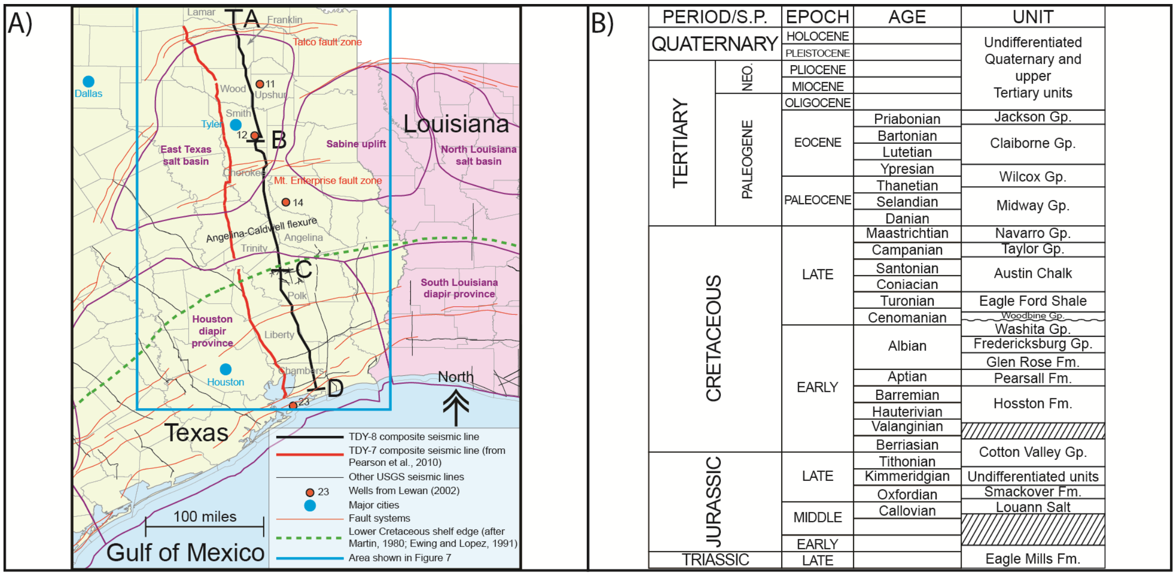

PERIOD/S.P.		EPOCH	AGE	UNIT
QUATERNARY		HOLOCENE		Undifferentiated Quaternary and upper Tertiary units
		PLEISTOCENE		
TERTIARY	NEO.	PLIOCENE		
		MIOCENE		
	PALEOGENE	OLIGOCENE		
		EOCENE	Priabonian	Jackson Gp.
			Bartonian	Claiborne Gp.
			Lutetian	
			Ypresian	Wilcox Gp.
		PALEOCENE	Thanetian	
			Selandian	Midway Gp.
			Danian	
CRETACEOUS		LATE	Maastrichtian	Navarro Gp.
			Campanian	Taylor Gp.
			Santonian	Austin Chalk
			Coniacian	
			Turonian	Eagle Ford Shale
			Cenomanian	Woodbine Gp.
		EARLY	Albian	Washita Gp.
				Fredericksburg Gp.
				Glen Rose Fm.
			Aptian	Pearsall Fm.
			Barremian	Hosston Fm.
			Hauterivian	
			Valanginian	▨
			Berriasian	Cotton Valley Gp.
JURASSIC		LATE	Tithonian	
			Kimmeridgian	Undifferentiated units
			Oxfordian	Smackover Fm.
		MIDDLE	Callovian	Louann Salt
				▨
		EARLY		▨
TRIASSIC		LATE		Eagle Mills Fm.

Figure 1. (A) Location of U.S. Geological Survey 2D reflection seismic lines in east Texas and western Louisiana. Wells shown are from Lewan (2002), and were used for the thermal models discussed in Pearson et al. (2010). TDY–8 segments A–B, B–C, and C–D refer to sections shown in Figures 2 and 3. Onshore fault systems are shown; labeled fault zones are described in the text. Counties through which the TDY–8 composite seismic line pass are labeled in gray. (B) Simplified stratigraphic section for east Texas (modified from Jackson, 1982). The stratigraphic scheme is identical to that used by Pearson et al. (2010). S.P. = Subperiod, Neo. = Neogene, Gp. = Group, and Fm. = Formation.

Jackson, 1982). The Angelina-Caldwell flexure is a broad feature that marks the hingeline between flexural subsidence in the south due to Cenozoic loading, and flexural uplift and erosion in the north due to the same Cenozoic loading (Glawe, 1989; Ewing, 2009). The southernmost structural feature is the Houston diapir province, which also contains numerous salt-related structures.

The purpose of this paper is to present an interpretation of the eastern regional composite seismic line TDY–8 (Fig. 1A), and to describe a 2D structural restoration that was based upon this interpretation. The western line (TDY–7) was discussed in detail by Pearson et al. (2010). We begin by discussing the 2D seismic reflection lines and by providing a brief summary of the major stratigraphic units that are incorporated into the seismic interpretation and structural restoration. We also discuss key features of a structural restoration based upon the seismic interpretation. Finally, we develop a simple model that shows locations along the regional seismic lines that may have undergone petroleum expulsion at various times from the region's two primary source rocks: the Cenomanian-Turonian Eagle Ford Shale, and the Oxfordian Smackover Formation (Fig. 1B).

LOCATION AND PROCESSING OF 2D SEISMIC REFLECTION LINES

The USGS has licensed numerous 2D reflection seismic line segments that span the onshore U.S. Gulf Coast. Seismic lines covering East Texas and western Louisiana that were interpreted for the 2007 and 2010 assessments of Gulf Coast strata (Dubiel et al., 2007, 2011) are shown in Figure 1A. Since completing the 2010 assessment, the USGS licensed additional lines measuring approximately 275 mi, from Seitel Data, Ltd. that were combined to produce the composite line referred to as the 'TDY–8' line in Figure 1A.

The TDY–8 composite line extends from the Texas coast in Chambers County in the south to Lamar County in the north, near the Texas-Oklahoma state line (Fig. 1A). Teledyne Exploration recorded the data for the southernmost segment of the TDY–8 line in 1968, the two northernmost segments in 1977, and three central segments in 1978. Recording parameters for the segment recorded in 1968 were significantly different from those of the 1977–78 segments. The 1968 versus 1977–78 parameters are separated by a forward slash (/) in the following list of recording parameters: 1) the energy source was a single hole containing 10/20 pounds of dynamite at 65/108 ft depth, 2) there were 24/48 recording channels per shot spaced at 300 ft intervals, 3) the near and far offsets were 1350/450 ft and 8250/7350 ft, respectively, 4) the spread configuration was end-on/split-spread, and 5) the average shot spacing was 600/1200 ft, yielding a nominal subsurface fold of six.

The data were reprocessed post-migration by the USGS using Halliburton's ProMax® seismic data processing software. We combined the industry-processed migrated sections into a single composite line, taking into account physical gaps where data could not be recorded, and joining at the appropriate tie points those segments that either crossed or overlapped one another. We then performed post-stack amplitude scaling (500 milliseconds [ms] automatic gain control), predictive deconvolution (48 ms predictive distance/200 ms filter length) and band-pass filter (6–48 Hz bandpass). We converted the data to depth using industry-determined root mean square velocities, smoothed over 201 common depth points horizontally and 100 ms vertically.

The quality of the data varies greatly along the line; continuous reflectors are present to depths of about 20,000 ft in the southern part of the study area, and to depths of about 15,000 ft in the north. Image quality is generally poor in locations where the Jurassic Louann Salt is present.

STRATIGRAPHIC SUMMARY

The onshore portion of the U.S. Gulf Coast contains an almost continuous succession of middle Mesozoic-Cenozoic strata

(Fig. 1B). Deposition of this sequence of rocks began in response to the Triassic onset of Pangean rifting (Salvador, 1987; Salvador, 1991b; Pindell and Dewey, 1982). In places, more than 60,000 ft of post-Callovian rocks were deposited in a broad, progradational wedge upon extended Paleozoic basement (Galloway, 2008). Along the TDY–8 composite seismic section (Fig. 1A), post-Callovian thicknesses range from about 7000 ft in the north to 40,000 ft in the south. In order to facilitate comparison between the TDY–8 and TDY–7 composite seismic lines, the stratigraphic scheme shown in Figure 1B is identical to that used by Pearson et al. (2010). The stratigraphy of the U.S. Gulf Coast is complex, and numerous member, formation, and group names are described in the literature. A regional study such as this requires a significantly simplified stratigraphic subdivision. The following paragraphs summarize the primary lithologies and depositional environments of the stratigraphic units are shown in Figure 1B. The units shown in Figure 1B and discussed below, however, do not represent the entire onshore Gulf Coast stratigraphic column; only those units for which picks were made on the regional composite seismic line and incorporated into the structural model are discussed.

Upper Triassic and Jurassic Strata

The Upper Triassic–Lower Jurassic Eagle Mills Formation consists of terrestrial red beds that were deposited in continental rift basins during initial stages of the opening of the Gulf of Mexico (Goldhammer and Johnson, 2001). Overlying the red beds is the Callovian-Oxfordian Louann Salt. This unit plays a major role in the petroleum system of the Gulf Coast region, as much of the area's structural evolution is related to the flow of salt. Evaporites that may have reached thicknesses of approximately 13,000 ft were deposited in a broad and structurally complex basin that connected with the Pacific Ocean through central Mexico (Salvador, 1987). Rocks of the Upper Jurassic (Oxfordian) Smackover Formation overlie the evaporites, and were deposited during a continued marine transgression onto the North American margin (Mancini and Puckett, 2005). The Smackover Formation is also one of the most important packages of Gulf Coast rocks for hydrocarbon production. The lower part of the formation is primarily composed of dark carbonate mudstone and argillaceous limestone, and is one of the basin's major source rocks. The Tithonian-Berriasian Cotton Valley Group is a thick sequence of terrigenous clastics that coarsen upward in the updip direction (McGowen and Harris, 1984), and records a major progradational episode. The basin wide Valanginian unconformity separates the Cotton Valley Group from the overlying Coahuilan rocks, and marks the end of sea floor spreading in the Gulf (Galloway, 2008).

Cretaceous Strata

In East Texas, the Lower Cretaceous Coahuilan rocks are primarily fine- to coarse-grained sandstones and platform/reef carbonates of the Hosston and Pettet (Sligo) formations. These strata record a complex depositional episode that was initiated by tectonically forced marine regression and terminated by transgression and the beginning of reef-rimmed carbonate-margin progradation (Galloway, 2008). The Aptian Pearsall Formation consists of shales, thin sandstones, and limestones, and represents a retrogradational stratigraphic systems tract that is bounded at the top by a basin wide maximum flooding surface (Galloway, 2008). The Albian–lower Cenomanian Glen Rose Formation and Fredericksburg and Washita groups were deposited above the Pearsall, and consist primarily of carbonates interbedded with sandstone, shale, marl, and anhydrite layers (McFarlan and Menes, 1991). Deposition of these rocks records a drowning of the shelf during an extended period of sea-level rise, and the subsequent reestablishment of Gulf-wide carbonate platform and barrier reef systems are the most prominent stratigraphic features of the mid-Cretaceous Gulf basin (Galloway, 2008).

Bounding the top of the Washita Group is the mid-Cretaceous unconformity (MCU), which records a major shift (Goldhammer and Johnson, 2001) in Gulf Coast depositional systems. The previously carbonate-dominated shelf was overstepped by clastic progradation that was caused by a combination of continental interior uplift, a drop in global sea level (Buffler, 1991), and initial uplift of the Mississippi embayment region (Cox and Van Arsdale, 2002). Above the MCU are the Cenomanian-Turonian Woodbine Group and Eagle Ford Shale, which record major progradational deltaic systems (Galloway, 2008). The Woodbine Group consists of highly variable fluvio-deltaic to marginal-marine sequences of sandstones, shales, volcanic conglomerates, and carbonaceous shales. The Eagle Ford Shale is composed of sandstone, siltstone, dark organic shale, and calcareous organic mudstone interbedded with limestone and siltstone beds (Sohl et al., 1991), and is one of the major hydrocarbon source rocks for the Gulf Coast petroleum system. In East Texas, the overlying Coniacian-Campanian Austin Chalk consists of chalks, mudstones, marls, and calcareous shales that were deposited during a global sea-level highstand (Galloway, 2008). Deposition of the Upper Cretaceous Taylor and Navarro groups represents a period of continued high sea level and deposition of limited shelfal carbonates, followed by siliciclastic-dominated progradation (Mancini and Puckett, 1995). Taylor Group rocks primarily consist of chalk, marl, clay, limestone, and thin sandstones, whereas the Navarro Group is comprised of sandy clay, sandstone, and chalky marl (Sohl et al., 1991).

Cenozoic Strata

The lower Paleocene Midway Group is primarily comprised of mudrocks and thin marls that record regional flooding of the Gulf Coast margin (Galloway et al., 1991). The Paleocene – Eocene Wilcox Group records a major influx of Laramide-derived clastic sediments, and represents one of the Gulf's major Cenozoic progradational episodes. The high sedimentation rate of Wilcox Group strata caused loading and subsequent mobilization of underlying shales and the Louann Salt, which resulted in extensive growth faulting along the Wilcox fault zone (Ewing, 1991). The Eocene Claiborne Group contains diverse lithologies deposited in wave- and fluvial-dominated deltas and thick barrier and strandplain systems. Deposition of the Eocene Jackson Group occurred during a period of platform aggradation, as terrigenous clastics were deposited on the submerged Wilcox shelf (Galloway et al., 1991). Jackson Group strata consist primarily of sandstones and mudstones that contain layers of volcanic ash. For this study we did not make stratigraphic picks within the Oligocene and younger part of the section; in East Texas this includes the Vicksburg, Frio, and Anahuac formations.

INTERPRETATION OF REGIONAL 2D REFLECTION SEISMIC LINE

An uninterpreted version of the composite TDY–8 seismic line across East Texas is shown in Figure 2, and our interpretation of that line is shown in Figure 3. In order to facilitate com-

Figure 2. Uninterpreted version of the TDY–8 composite seismic section. Locations of segments A–B, B–C, and C–D are shown in Figure 1A. Texas county border locations are shown. Seismic data are shown at 200% vertical exaggeration.

parison with the composite TDY–7 seismic line described in Pearson et al. (2010), horizon picks at the same stratigraphic intervals and identical colors are used. Stratigraphic picks were constrained by tops information (IHS Energy Group, 2012) from more than 4200 wells that reached depths of at least 7500 ft and lie within two mi of the composite seismic line. Because of this large number of wells, the projected locations of individual wells are not shown in Figure 3. In general, the drilling floor along the cross section line is at about 15,000 ft. At the northernmost part of the cross section, in the vicinity of the Talco fault zone, most wells only reach about 7000 ft. In the Houston diapir province at the southern edge of the cross section, a few wells reach depths of about 20,000 ft. At the south edge of the cross section, the seismic data only reach depths of about 30,000 ft; therefore, the interpretation shown at depths below this is hypothetical. We have attempted to portray possible geometries of the deep salt bodies along this portion of the cross section that are similar to well-imaged examples in federal offshore waters. Additionally, the onshore portions of published examples (e.g., Peel et al., 1995) guided the interpretation. Note that the northernmost 10 mi of the seismic line, consisting of parallel subhorizontal reflectors, are not shown in Figures 2 and 3 due to space constraints.

The following list describes key features of the seismic interpretation; numbers correspond to those shown in Figure 3:

1. Navarro Group outcrops.
2. Northernmost extent of autochthonous Louann Salt deposition. Along most of the cross section, the presence of the autochthonous Louann Salt is shown as a weld. Small amounts of autochthonous salt may remain in some locations, such as this possible basement half-graben, which may also contain the Eagle Mills Formation.
3. Talco fault zone. Faults shown in red. Displacements are minor, but growth in the hanging-wall block of all formations suggest that the fault zone may have become active during deposition of the Smackover Formation; displacement continued into the Paleocene with deposition of the Midway Group (Jackson, 1982). A small sliver of autochthonous Louann Salt is shown beneath the Talco fault zone. The main faults root into the autochthonous Louann Salt or its weld.
4. Midway Group outcrops.
5. Wilcox Group outcrops.
6. Claiborne Group outcrops.
7. East Texas salt basin. Rocks overlying the Louann Salt generally thicken in the basin; pronounced intra-basinal thickness variations can be attributed to movement of the Louann Salt. The cross section does not cut any of the basin's numerous salt pillows and diapirs (for a diagram showing these structures, see Jackson and Seni, 1983). The interpretation shows that thicknesses in excess of 2000 ft of autochthonous Louann Salt may still exist in the basin.
8. Basement graben and half-graben containing the Eagle Mills Formation can easily be interpreted in numerous locations along the seismic line.
9. Approximate location of the Smackover Formation shelf edge. All shelf edges locations are from Galloway (2008).
10. Louann Salt weld in the East Texas salt basin.
11. Possible salt pillow in the East Texas salt basin.
12. Louann Salt weld in the East Texas salt basin. This may represent a step-up in the basement due to the proximity of the Sabine uplift.
13. Basement graben filled with the Eagle Mills Formation.
14. This part of the cross section line is characterized by virtually flat-lying strata. Subtle potential traps exist at all stratigraphic levels.
15. Interpreted Smackover Formation pinch-out against the autochthonous Louann Salt weld. Truncated reflectors that we interpret as the top of the Smackover Formation are cut by the autochthonous Louann Salt weld. This implies original onlap against the Louann Salt. The Smackover Formation may not exist between this pinch-out and the Mount Enterprise fault zone; if it is present, it is likely much thinner. The Haynesville Shale, which lies between the Smackover Formation and the Cotton Valley Group (but was not interpreted on the composite seismic line) may not pinch-out in this location.
16. Mount Enterprise fault zone. Several faults with small displacements are present, but only two are shown. Growth in the hanging wall of the primary fault suggests that the fault zone was active between deposition of the Cotton Valley and Wilcox Groups. The largest fault in the Mount Enterprise fault zone is downthrown to the north, which implies that rocks in the hanging wall were displaced northward toward the East Texas salt basin. This motion may have been enabled by northward flow of the Louann Salt from the southern margin of the East Texas salt basin. Although it is possible that this fault extends into strata below the autochthonous Louann Salt weld (e.g., Jackson, 1982), reflectors below the weld on the TDY–8 seismic line do not appear to be offset.
17. Angelina-Caldwell flexure (approximate). Strata are subhorizontal north of the flexure; south of the flexure, dips increase to three degrees towards the south.
18. Autochthonous Louann Salt pillow. The Smackover Formation pinches out onto the crest of the pillow.
19. A small allochthonous Louann Salt sheet at the Cotton Valley Group/Hosston Formation stratigraphic level. The feeder for this small allochthonous body is a weld. Additional welds from the allochthonous body may exist out of the plane of the cross section.
20. Salt pillow (mostly in seismic gap).
21. Jackson Group outcrops.
22. Numerous small-displacement faults, such as this one, exist within Cretaceous strata along this portion of the cross section.
23. Autochthonous Louann Salt pillow with a welded feeder that connects to a small salt sheet within the Cotton Valley Group. An enlarged view of both the uninterpreted and interpreted composite seismic secition is shown in the vicinity of this feature in Figure 4.
24. Surface outcrops of undifferentiated Quaternary and upper Tertiary (Neogene and Oligocene) formations.
25. Approximate location of the Lower Cretaceous (Hosston Formation) shelf edge.
26. Large gap in seismic data coverage. Horizon picks were extended in straight lines across this portion of the cross section.
27. Approximate location of the Washita and Fredericksburg groups' shelf edge.
28. Northern extent of the Houston diapir province.
29. Data resumes; approximate location of the Woodbine Group shelf edge.
30. Autochthonous Louann Salt pillow with a welded feeder that connects to a salt sheet within the Pearsall Formation.
31. Many southward dipping normal faults that cut Wilcox Group and older strata exist along this portion of the cross section; only a couple are shown as it is virtually impossible to correlate across faults due to the lack of deep well control.
32. Approximate location of the lower Wilcox Group shelf edge.
33. Hypothetical Louann Salt pillows with welded feeders.

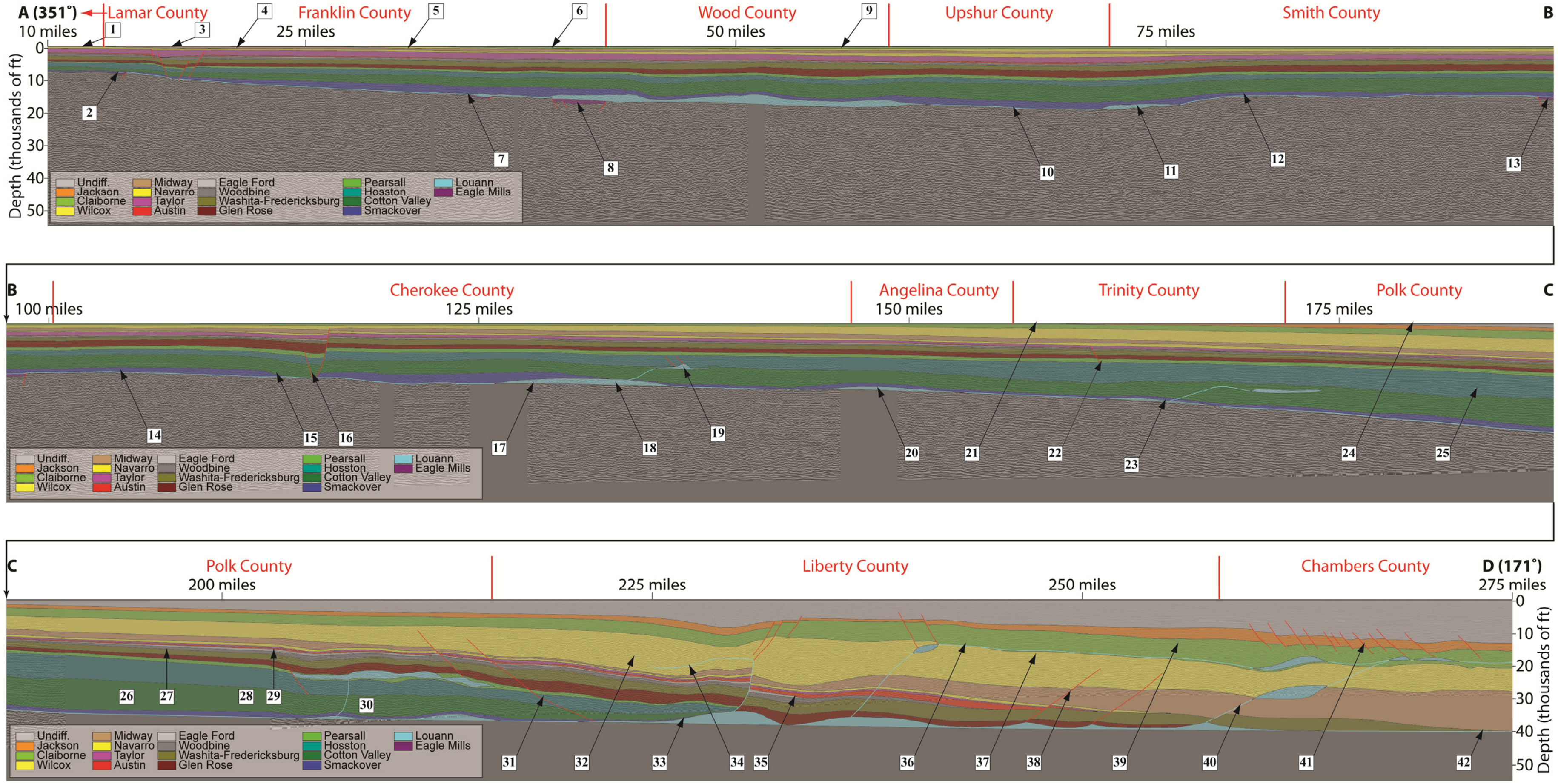

Figure 3. Interpretation of TDY–8 composite seismic section. Numbered features are described in the text. Locations of segments A–B, B–C, and C–D are shown in Figure 1A. Texas county border locations are shown. Interpreted section is shown at 200% vertical exaggeration.

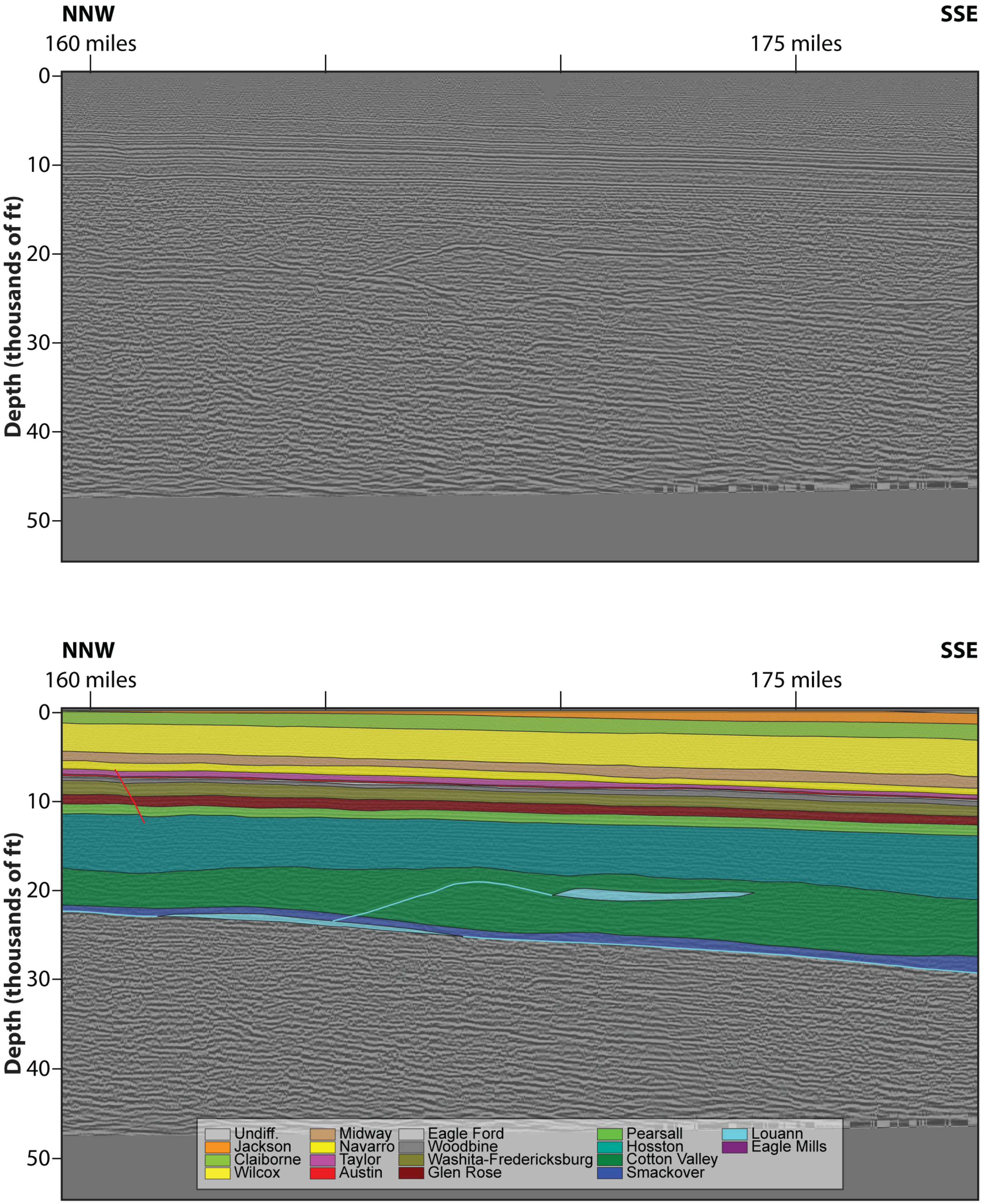

Figure 4. Enlarged section of the composite seismic line. The top panel shows the uninterpreted composite seismic line. The bottom panel shows the interpreted section.

34. Welded allochthonous salt body within the Wilcox Group. The normal faults above the allochthonous weld that cut the Wilcox, Claiborne, and Jackson groups provide evidence that the body may have been inflated with salt during these time periods. This allochthonous salt feature may be associated with the Batson salt diapir, which is just east of the cross section.

35. Stratigraphic pinch-outs of Eagle Ford Shale and older units begin. These pinch-outs are hypothetical, due to a complete lack of well control. Furthermore, the pinch-outs lie below the seismic record, and are thus completely unconstrained. The primary rationale for interpreting pinch-outs was the consistent southward thinning of the units. It is important to note, however, that it is equally plausible that the units may be continuous further to the south. If this were the case, the structural restoration (discussed in the next section) would need to be modified to account for this continuation. Although the Smackover through Pearsall formations are shown to pinch out, strata of this age are known to extend as far south as the Sigsbee escarpment in Federal offshore waters. The interpretation shows pinch-out of these units primarily to emphasize the point that the geometry of these units is completely unconstrained by both seismic and well data along this line of section.

36. Allochthonous salt body with a long, nearly horizontal weld that was likely inflated into a canopy during deposition of the latest Wilcox Group and earliest Claiborne Group sediments. This salt feature may be associated with the Hull diapir, which lies a few miles west of the cross section. The horizontal weld was recognized by changes in the character of otherwise continuous reflectors that are interpreted as small amounts of remnant salt along the weld. Additionally, just north of the allochthonous body at the southern end of the weld (at approximately mile 260), reflectors within what is interpreted as the Claiborne Group appear to be truncated by the weld.

37. Approximate location of the upper Wilcox Group shelf edge.

38. Counter-regional normal faults. These likely root in the autochthonous Louann Salt, and could also be interpreted as welds.

39. Approximate location of the Claiborne shelf edge.

40. Welded feeder connecting to an allochthonous salt body located between the Midway and Wilcox groups. The interpretation shows that this body had a secondary feeder that connected to the overlying canopy system within the Claiborne Group. These allochthonous features may connect to the Anahuac salt diapir, which lies west of the cross section.

41. The numerous normal faults that cut the Jackson and Claiborne Groups are likely related to deflation of the underlying canopy system. It is possible that these faults could be roller faults and the underlying weld could be a roho weld (e.g., Rowan et al., 1999).

42. The depth of the allochthonous Louann Salt weld is shown to be about 40,000 ft below sea level. This depth is slightly deeper than the interpreted depths for the weld on TDY–7 (Pearson et al., 2010), where the seismic data are deep enough to image the autochthonous Louann Salt.

STRUCTURAL RESTORATION

A structural restoration of the interpreted seismic line was built using Midland Valley's 2D Move^{TM} software. The restoration shown in Figure 5 details 16 stages corresponding to each of the major stratigraphic units described above and shown in Figure 1B. The restoration was pinned at the north end of the section, and all stratigraphic horizons were restored to a surface that approximates the present slope (a 500-ft elevation gain over approximately 275 mi). Due to the highly mobile nature of the Louann Salt, it is not possible or wise to balance the salt area in the restoration; we assume that a large amount of salt has flowed basinward past the south end of the cross section. Furthermore, we assume that salt flowed both into and out of the plane of the cross section, particularly in the East Texas salt basin and the Houston diapir province. The primary restoration algorithm used was vertical simple shear strain, as we assume that most of the deformation apparent in the seismic interpretation is genetically related to the movement of the Louann Salt.

In the vicinity of the Talco and Mount Enterprise fault zones, and for restoration stages that included the normal faults within the Houston diapir province, a fault-parallel flow algorithm was used to restore hanging-wall and footwall cutoffs. The small amount of shortening shown in the restoration (Figs. 5G–5I) is completely unconstrained, and is meant to symbolically show regional extension associated with flowage of sediment toward the Gulf of Mexico. Inflation of salt features, both at the allochthonous and autochthonous levels, was accomplished by restoring the upper surface of the salt bodies using vertical simple shear strain, and manually creating a lower surface. This manual creation of a lower surface was required in order to account for the inflation and deflation of salt bodies. In the case of allochthonous salt bodies, the geometries of the lower surfaces generally mimic the structure of underlying units. The lower surfaces of autochthonous salt bodies are generally subhorizontal. The main constraint in judging the amount of salt inflation was achieving primary Louann Salt thicknesses of less than 4000 ft in the East Texas salt basin and between 5000 and 10,000 ft at the south end of the cross section in the final stage of the restoration (Fig. 5P). These constraints are based upon estimates for original Louann Salt thicknesses from Salvador (1991a) and references therein. As mentioned previously, these estimates are highly speculative, but nevertheless provide an important constraint.

The structural restoration shown in Figure 5 covers a cross section line that is approximately 275 mi long; therefore, each restored panel has been vertically exaggerated by 300% in order to show individual structural features and stratigraphic units. In a similar manner to the seismic interpretation shown in Figure 3, the northernmost 10 mi of the structural restoration is also not shown due to space constraints. The following descriptions detail key features from each stage of the structural restoration in chronological order.

Smackover time (Fig. 5P): The Jurassic Louann Salt was continuous at the autochthonous level for more than 250 mi. Thicknesses of the salt range from about 200 ft in the north to about 7000 ft in the south. Salt thicknesses are greatest in the East Texas salt basin and the Houston diapir province. Thicknesses of the Smackover Formation vary along the length of section, and reflect the mobile nature of the underlying salt, even at this early structural stage. In some locations along the section line, the Smackover Formation was not deposited, as is evident from the existence of salt at the surface; these surficial features would later become salt walls and vertical feeders. The long (approximately 50 mi) section at the south edge of the restoration where the Louann Salt is exposed at the surface is directly related to the interpreted pinch-out of the Smackover through Pearsall formations further to the north. If this interpreted pinch-out is incorrect, the wide expanse of Louann Salt exposed at the surface in Figure 5P–5L would be buried beneath thin layers of Smackover through Pearsall strata.

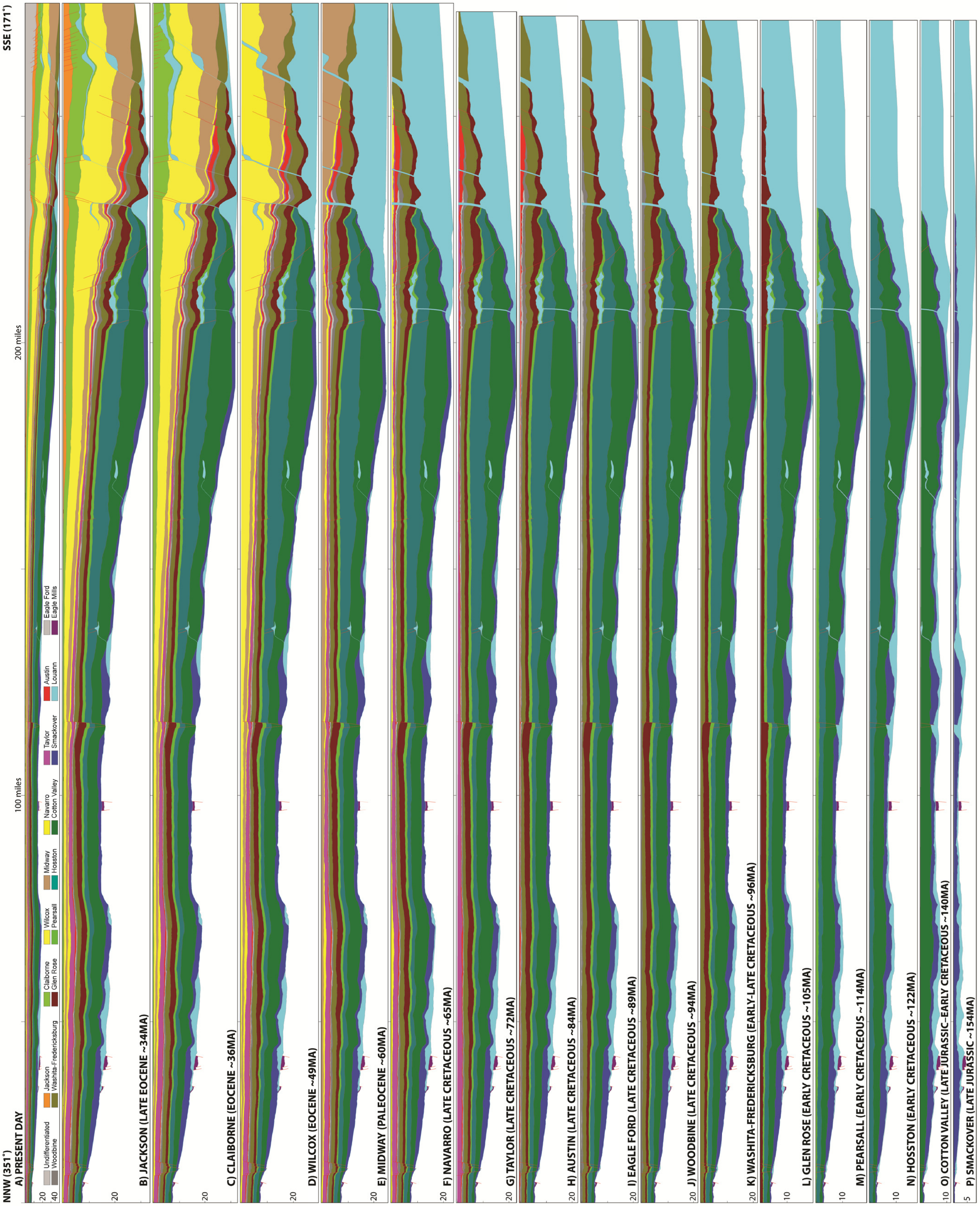

Figure 5. Structural restoration panels of the seismic interpretation shown in Figure 3. Vertical exaggeration for each panel is 300%, with the exception of the present day, which is shown at 100%. Depths are in thousands of feet. The same horizontal and vertical scales apply for each panel. Faults are shown as thin red lines and Louann Salt welds are thin light blue lines.

Cotton Valley time (Fig. 5O): Thickness variations in Cotton Valley Group rocks near both the Talco and Mount Enterprise fault zones imply that either the faults may have been active at this time, or salt may have been flowing before the commencement of faulting. The faults root in the Louann Salt, and displacement is likely linked to the commencement of southward flow of autochthonous salt due to sedimentary loading. The Louann Salt that had been present at the surface in the vicinity of the Mount Enterprise fault zone was buried by Cotton Valley Group sediments, which suggests that autochthonous salt was welded to the north and south, preventing the continued inflation of the salt pillow. Thickness variations in the Cotton Valley Group are likely related to movement of the Louann Salt. South of the Mount Enterprise fault zone, two small allochthonous salt bodies formed, with feeders that are connected to autochthonous salt pillows.

Hosston time (Fig. 5N): During deposition of the Hosston Formation, the autochthonous Louann Salt was still continuous across the section. In the East Texas salt basin, salt began to thin as it rose through the section into the basin's numerous diapirs that are out of the plane of the cross section. See Jackson (1982) for a map of salt diapirs and pillows in the East Texas salt basin. Faulting continued within both the Talco and Mount Enterprise fault zones. Movement of salt into the two small allochthonous bodies south of the Mount Enterprise fault zone continued as salt was not welded at the autochthonous level, but growth of these bodies occurred out of the plane of the cross section. Broad folds may be present in Cotton Valley Group rocks in the southern portion of the cross section.

Pearsall time (Fig. 5M): The autochthonous Louann Salt was welded both to the north and south of the East Texas salt basin. This means that subsequent thinning of the autochthonous salt within the basin would be accomplished through the flow of salt into diapirs, rather than regional southward flow toward the Gulf of Mexico. This observation only applies for this cross section; further east, towards the basin's axis, southward flow of salt may still have occurred. The vertical salt feature at the north margin of the Houston diapir province grew into an approximately 10-mi wide salt sheet; the Pearsall Formation was not deposited over parts of this salt body, as flow of salt to the surface was rapid enough to prevent deposition. The thickness of salt within the Houston diapir province continued to increase.

Glen Rose time (Fig. 5L): Displacement continued in both the Talco and Mount Enterprise fault zones, as did deflation of the autochthonous Louann Salt in the East Texas salt basin. The wide allochthonous salt body on the northern edge of the Houston diapir province was buried by deposition of the Glen Rose Formation. As salt was still present at the autochthonous level below this feature, growth must have occurred out of the plane of the cross section. Deposition of the Glen Rose Formation also began to bury the autochthonous Louann Salt in the southern portion of the Houston diapir province.

Washita and Fredericksburg time (Fig. 5K): Slip along faults in the Talco and Mount Enterprise fault zones continued. The remaining autochthonous salt below the Talco fault zone was separated by welds into discrete bodies. The Louann Salt in the East Texas salt basin continued to deflate, and the length of welds bordering the basin continued to increase, particularly in the south. Welds separated the small salt pillows south of the Mount Enterprise fault zone. In the Houston diapir province, the autochthonous salt was completely buried by sediments, except in a couple of locations where salt feeders and walls persisted. By this time, the autochthonous salt in the south of the cross section had reached its maximum thickness, and had begun to deflate as salt flowed upsection into allochthons and southward beyond the cross section.

Woodbine through Navarro time (Figs. 5J–5F): Only minor structural changes characterize this period of time. Autochthonous Louann Salt continued to deflate in both the East Texas salt basin and the Houston diapir province, and the length of welds bounding these regions continued to increase. Faulting continued in both the Talco and Mount Enterprise fault zones. Differences in thickness of the Austin Chalk and Navarro Group in the southernmost portion of the cross section imply that slip on the counter-regional normal faults may have begun.

Midway time (Fig. 5E): Intrabasinal welds of the autochthonous Louann Salt formed within the East Texas salt basin. The remaining salt reached its final interpreted thickness, and the development of salt-related structures in the basin ended. A wide expanse of allochthonous salt (that later become part of the Anahuac salt diapir) spread out over the surface in the southern portion of the Houston diapir province.

Wilcox time (Fig. 5D): Virtually all structural growth was now centered in the Houston diapir province. In mid-Wilcox time, the northernmost vertical salt feature in the province fed a small horizontal allochthonous body. By the end of Wilcox deposition, the middle vertical salt feature also fed a horizontal allochthonous body. The small allochthonous salt body fed by the southernmost vertical salt feature began to deflate as salt moved into a secondary feeder. The majority of displacement on the large normal faults on the northern edge of the Houston diapir province occurred during deposition of the Wilcox Group.

Claiborne time (Fig. 5C): During early deposition of the Claiborne Group, allochthonous Louann Salt bodies coalesced into a large canopy system. As salt moved upsection into this canopy, a large amount of deflation occurred at the autochthonous level. Salt pillows became separated into discrete features bounded by intrabasinal welds, and the feeders that connected the pillows to the canopy system closed.

Jackson time (Fig. 5B): The allochthonous salt bodies in the Houston diapir province began to deflate. The normal faults that cut the Jackson and Claiborne Groups developed as a response to deflation of the canopy system. It is also possible that the faults may be roller faults that detach into the underlying allochthonous salt weld—a roho model.

Present time (Fig. 5A): Deflation of the allochthonous salt bodies in the Houston diapir province continued after Jackson time, leaving an extensive salt weld interspersed with isolated remnant salt bodies. This deflation process likely occurred during the Oligocene (as the normal faults that cut the Jackson Group only extend into the lowermost of the undifferentiated rocks), at which point deformation along the cross section ended, except for continued subsidence.

DEPTH OF HYDROCARBON GENERATION

Several authors have modeled the thermal history of the Oxfordian Smackover Formation and the Cenomanian-Turonian Eagle Ford Shale in East Texas (e.g., Lewan, 2002; Mello and Karner, 1996). Pearson et al. (2010) discussed how four 1D wells modeled by Lewan (2002) in East Texas (Fig. 1A) provide estimates for the timing and burial depths of hydrocarbon generation for these two important source rock units. Pearson et al. (2010) developed a simple model which showed when and where along the TDY–7 composite seismic line the Smackover and Eagle Ford units were buried deeply enough to generate hydrocarbons. This simple model was based upon the 1D well models (Lewan, 2002), which show that hydrocarbon generation for the Smackover Formation begins at burial depths of 5790 ft (a transformation ratio of 0.01) and ends at a depth of 9430 ft (a transformation ratio of 0.99). Hydrocarbon generation for the Eagle Ford Shale begins at depths of 10,000 ft, and ends at depths of 14,500 ft.

Using these oil-window depths and thicknesses, it is possible to examine the TDY–8 structural restoration at all time periods (Fig. 5) to determine where each of the source rocks existed within their respective oil windows. These data are plotted in Figure 6; each panel corresponds to a stage of the structural restoration. The results for this simple model along the TDY–7 seismic line (Pearson et al., 2010) are also shown. Expulsion of oil from the Smackover Formation may have begun during deposition of the Cotton Valley Group (Fig. 6O). During deposition of the Hosston and Pearsall formations (Figs. 6N and 6M), the Smackover Formation may have been expelling oil along much of the length of both TDY–8 and TDY–7 cross sections. By the onset of Glen Rose Formation deposition (Fig. 6L), most of the Smackover Formation in the southern part of the cross sections had passed through the oil window, and oil expulsion mainly occurred along northern parts of the cross sections. During deposition of the Upper Cretaceous units (Figs. 6K–6F), expulsion of oil from the Smackover Formation only occurred in the north along TDY–8. Narrow stretches of the Smackover Formation remained within the oil window along TDY–7 in the Houston diapir province. The Eagle Ford Shale may have begun expelling oil during deposition of the Midway (along TDY–7) and Wilcox (along TDY–8) groups (Figs. 6E and 6D). Since the early Eocene, expulsion of oil from both the Smackover Formation and Eagle Ford Shale has been restricted to areas in the vicinity of the Talco fault zone and the northern edge of the Houston diapir province (Figs. 6C–6A).

SUMMARY

1. The USGS acquired and reprocessed regional 2D seismic lines that cover parts of East Texas. These seismic lines were interpreted using formation top information from IHS databases (IHS Energy Group, 2012). Based upon these interpretations, structural restorations were constructed that show the post-Oxfordian structural evolution of East Texas.

2. Broad folds can be seen at all stratigraphic levels along almost the entire length of the TDY–8 composite seismic line. Many of these folds are at depths below the current drilling floor, and may represent targets for future exploration.

3. Due to the highly mobile nature of the Louann Salt, structures began to develop at all stratigraphic levels during deposition of each unit. For example, broad folds already existed in the Cotton Valley Group by the time deposition of the Hosston Formation had ended (Fig. 5N). These early structures could have been traps for early expulsion and migration of Smackover Formation oil.

4. The growth of structures along the TDY–8 composite seismic line is genetically related to movement of the Jurassic Louann Salt. Of the six main structural elements in East Texas, only the developments of the Angelina-Caldwell flexure and the Sabine uplift are not tied directly to movement of the Louann Salt.

5. Thickness variations in all post-Louann Salt rocks attest to the highly mobile nature of the salt. The southward flow of salt was due to a combination of differential loading and general basinward tilting of the entire section. Along updip portions of the cross section (the East Texas salt basin), tilting may have been the dominant driver of the seaward flow of salt. Along downdip portions of the cross section (the Houston diapir province), differential loading drove the basinward flow of salt. As the flow of salt progressed, salt escaped into diapirs within the East Texas salt basin and into diapirs, salt sheets, and canopies within the Houston diapir province. Some of these allochthonous bodies deflated as the salt supply from the autochthonous level was cut off. In the Houston diapir province, a salt sheet developed that may have looked similar to the modern day Sigsbee canopy in Federal offshore waters of the Gulf of Mexico.

6. The structural restoration coupled with the simple thermal models show that at various points in time, expulsion of oil from the Smackover Formation occurred along almost the entire length of the TDY–8 seismic line. Therefore, early structural traps all along the seismic line (in Cotton Valley, Hosston, and lower Cretaceous rocks) could have received charge from the Smackover Formation. Charge of Tertiary units with Smackover oil may be a result of secondary migration from primary traps. On the other hand, expulsion of oil from the Eagle Ford Shale occurred in only a limited geographic area centered on the northern limit of the Houston diapir province. This means that any Eagle Ford oil encountered in wells north of this region is likely a result of lateral migration.

7. Despite the numerous similarities in structural styles and burial depths seen on both the TDY–8 and TDY–7 seismic lines, there is variability especially in the East Texas salt basin and in the Houston diapir province. This variability in structural style, burial depths, and the frequency and size of salt-related features occurs over distances of less than 50 mi. The variability also means that petroleum exploration strategies that depend upon along-strike analogs also need to be grounded in data from a prospect's immediate vicinity.

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REFERENCES CITED

Buffler, R. T., 1991, Seismic stratigraphy of the deep Gulf of Mexico basin and adjacent margins, *in* A. Salvador, ed., The geology of North America, v. J: The Gulf of Mexico basin: Geological Society of America, Boulder, Colorado, p. 353–387.

Cox, R. T., and R. B. Van Arsdale, 2002, The Mississippi embayment, North America: A first order continental structure generated by the Cretaceous superplume mantle event: Journal of Geodynamics, v. 34, p. 163–176.

Dubiel, R. F., J. K. Pitman, O. N. Pearson, P. D. Warwick, A. W. Karlsen, J. L. Coleman, P. C. Hackley, D. O. Hayba, S. M. Swanson, R. R. Charpentier, T. A. Cook, T. R. Klett, R. M. Pollastro, and C. J. Schenk, 2007, Assessment of undiscovered oil and gas resources in tertiary strata of the Gulf Coast, 2007: U.S. Geological Survey Fact Sheet FS 2007–3066, 4 p., 2 figures, and 1 table.

Dubiel, R. F., P. D. Warwick, S. M. Swanson, L. Burke, L. R. H. Biewick, R. R. Charpentier, J. L. Coleman, T. A. Cook, K. Den-

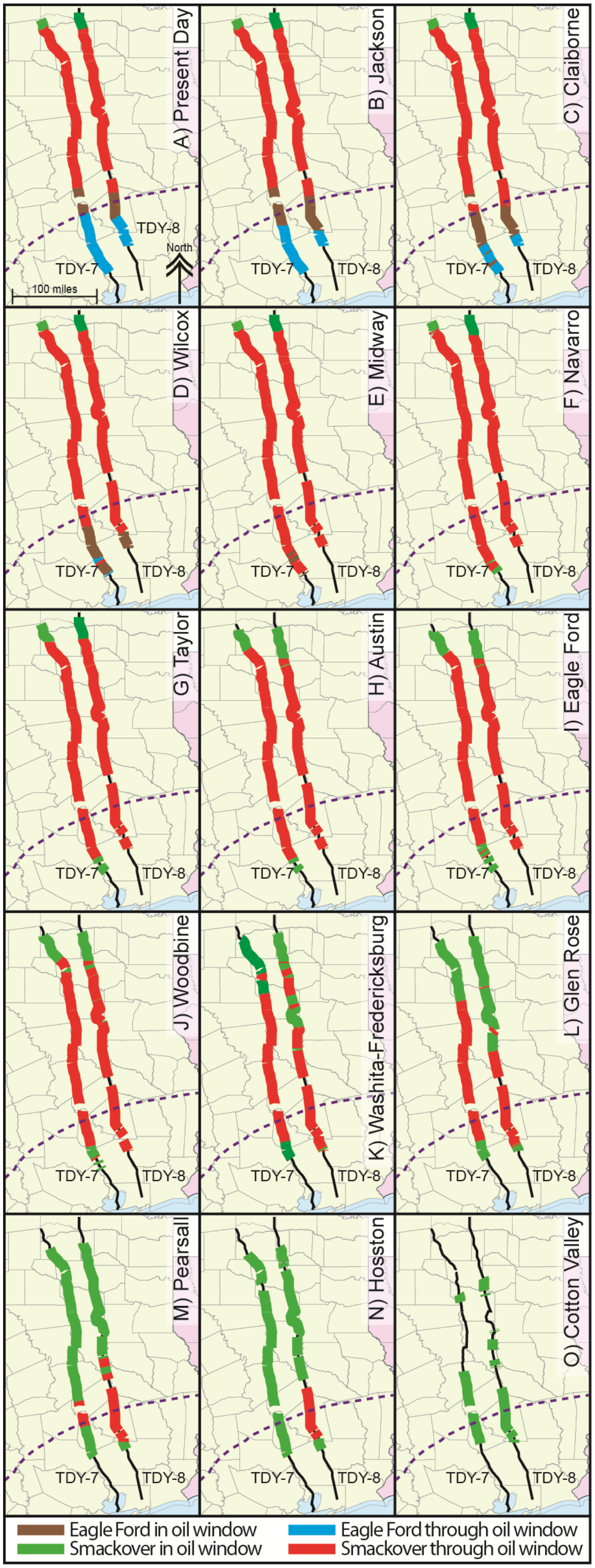

Figure 6. Maps showing where oil and gas may have been generated from the Smackover Formation and Eagle Ford Shale along the lengths of composite seismic lines TDY–8 and TDY–7. Texas is shaded in light green and Louisiana is in pink. The dashed purple line is the Lower Cretaceous shelf edge from Martin (1980) and Ewing and Lopez (1991). Each of the 15 panels corresponds to a stage of the structural restoration shown in Figure 5.

nen, C. Doolan, C. Enomoto, P. C. Hackley, A. W. Karlsen, T. R. Klett, S. A. Kinney, M. D. Lewan, M. Merrill, K. Pearson, O. N. Pearson, J. K. Pitman, R. M. Pollastro, E. L. Rowan, C. J. Schenk, and B. Valentine, 2011, Assessment of undiscovered oil and gas resources in Jurassic and Cretaceous strata of the Gulf Coast, 2010: U.S. Geological Survey Fact Sheet FS 2011–3020, 4 p., 2 figures, and 1 table.

Ewing, T. E., 1991, Structural framework, *in* A. Salvador, ed., The Gulf of Mexico basin, v. J: Geological Society of America, Geology of North America, Boulder, Colorado, p. 31–52.

Ewing, T. E., 2009, The ups and downs of the Sabine uplift and the northern Gulf of Mexico basin: Jurassic basement blocks, Cretaceous thermal uplifts, and Cenozoic flexure: Gulf Coast Association of Geological Societies Transactions, v. 59, p. 253–269.

Ewing, T. E., and R. F. Lopez, 1991, Principal structural features, *in* A. Salvador, ed., The Gulf of Mexico basin, v. J: Geological Society of America, Geology of North America, Boulder, Colorado, Plate 2.

Galloway, W. E., D. B. Bebout, W. L. Fisher, J. B. Dunlap Jr., R. Cabrera-Castro, J. E. Lugo-Rivera, and T. M. Scott, 1991, Cenozoic: *in* A. Salvador, ed., The Gulf of Mexico basin, v. J: Geological Society of America, Geology of North America, Boulder, Colorado, p. 245–324.

Galloway, W. E., 2008, Depositional evolution of the Gulf of Mexico sedimentary basin, *in* A. D. Miall, ed., Sedimentary basins of the world, v. 5: The sedimentary basins of the United States and Canada: Elsevier, Amsterdam, The Netherlands, p. 505–549.

Glawe, L.N., 1989, Stratigraphic relationships between *Odontogryphaea thirsae* beds and the Big Shale of the Wilcox (Paleocene-Eocene) in Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 39, p. 375–383.

Goldhammer, R. K., and C. A. Johnson, 2001, Middle Jurassic–Upper Cretaceous paleogeographic evolution and sequence-stratigraphic framework of the northwest Gulf of Mexico rim, *in* C. Bartolini, R. T. Buffler, and A. Cantú-Chapa, eds., The western Gulf of Mexico basin: Tectonics, sedimentary basins, and petroleum systems: American Association of Petroleum Geologists Memoir 75, p. 45–81.

IHS Energy Group, 2012, PI/Dwights PLUS U.S. well data: Englewood Colo., IHS Energy Group; database available from IHS Energy Group, 15 Inverness Way East, D205, Englewood, Colorado.

Jackson, M. P. A., 1982, Fault tectonics of the East Texas Basin: Texas Bureau of Economic Geology Circular 82–4, Austin, 31 p.

Jackson, M. P. A., and S. J. Seni, 1983, Geometry and evolution of salt structures in a marginal rift basin of the Gulf of Mexico, east Texas: Geology, v. 11, p. 131–135.

Lewan, M. D., 2002, New insights on timing of oil and gas generation in the central Gulf Coast interior zone based on hydrous pyrolysis kinetic parameters: Gulf Coast Association of Geological Societies Transactions, v. 52, p. 607–620.

Mancini, E. A., and T. M. Puckett, 1995, Upper Cretaceous sequence stratigraphy of the Mississippi-Alabama area: Gulf Coast Association of Geological Societies Transactions, v. 45, p. 377–384.

Martin, R. G., 1980, Distribution of salt structures, Gulf of Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MP-1213, 2 sheets, scale 1:2,500,000.

Mancini, E. A., and T. M. Puckett, 2005, Jurassic and Cretaceous transgressive-regressive (T-R) cycles, northern Gulf of Mexico, USA: Stratigraphy, v. 2, p. 31–48.

McFarlan, E., and L. S. Menes, 1991, Lower Cretaceous, *in* A. Salvador, ed., The geology of North America, v. J.: The Gulf of Mexico basin: Geological Society of America, Boulder, Colorado, p. 181–204.

McGowen, M. K., and D. W. Harris, 1984, Cotton Valley (Upper Jurassic) and Hosston (Lower Cretaceous) depositional systems and their influence on salt tectonics in the East Texas basin, *in* P. S. Ventress, and others, eds., The Jurassic of the Gulf rim: Proceedings of the 8th Annual Gulf Coast Section of the Society of Economic Mineralogists and Paleontologists Foundation Conference, Houston, Texas, p. 213–253.

Mello, U. T., and G. D. Karner, 1996, Development of sediment overpressure and its effect on thermal maturation: Application to the Gulf of Mexico basin: American Association of Petroleum Geologists Bulletin, v. 80, p. 1367–1396.

Pearson, O. N., E. L. Rowan, R. F. Dubiel, and J. J. Miller, 2010, Mesozoic-Cenozoic structural evolution of East Texas—Constraints and insights from interpretation of regional 2D seismic lines and structural restoration: Gulf Coast Association of Geological Societies Transactions, v. 60, p. 571–582.

Peel, F. J., C. J. Travis, and J. R. Hossack, 1995, Genetic structural provinces and salt tectonics of the Cenozoic offshore U.S. Gulf of Mexico: A preliminary analysis, *in* M. P. A. Jackson, D. G. Roberts, and S. Snelson, eds., Salt tectonics: A global perspective: American Association of Petroleum Geologists Memoir 65, Tulsa, Oklahoma, p. 153–175.

Pindell, J., and J. F. Dewey, 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, p. 179–211.

Rowan, M. G., M. P. A. Jackson, and B. D. Trudgill, 1999, Salt-related fault families and fault welds in the northern Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 83, p. 1454–1484.

Salvador, A., 1987, Late Triassic–Jurassic paleogeography and origin of the Gulf of Mexico basin: American Association of Petroleum Geologists Bulletin, v. 71, p. 419–451.

Salvador, A., 1991a, Triassic-Jurassic, *in* A. Salvador, ed., The geology of North America, v. J.: The Gulf of Mexico basin: Geological Society of America, Boulder, Colorado, p. 131–180.

Salvador, A., 1991b, Origin and development of the Gulf of Mexico basin, *in* A. Salvador, ed., The geology of North America, v. J.: The Gulf of Mexico basin: Geological Society of America, Boulder, Colorado, p. 389–444.

Sohl, N. F., R. E. Martinez, P. Salmerón-Ureña, and F. Soto-Jaramillo, 1991, Upper Cretaceous, *in* A. Salvador, ed., The geology of North America, v. J.: The Gulf of Mexico basin: Geological Society of America, Boulder, Colorado, p. 205–244.