Journal of Structural Geology 31 (2009) 1114–1129

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Interaction between spreading salt canopies and their peripheral thrust systems

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ARTICLE INFO

Article history:
Received 29 August 2008
Received in revised form
26 May 2009
Accepted 4 June 2009
Available online 13 June 2009

Keywords:
Salt tectonics
Salt canopy
Gulf of Mexico
Thrust fault
Gravity spreading

ABSTRACT

Gravity spreading of a buried salt canopy produces thrust faults around the canopy rim. These thrusts may form by shear along the base of the salt, by frontal rolling of the canopy, by expulsion of underlying sediments, or by submarine landsliding off the canopy's frontal escarpment. Each mechanism has a characteristic structural style, providing clues to processes of shortening in canopy-margin thrust systems.

Canopy-margin thrust systems along the Sigsbee Escarpment in the deepwater Gulf of Mexico may have three parts. First, nearly all canopy-margin systems include a roof-edge thrust, which cuts upsection from the tip of the salt canopy and separates condensed strata in the canopy roof from thicker sections on the adjoining peripheral plain. Second, roughly one-third of roof-edge thrusts overlie an imbricate wedge, which telescopes sediments on the peripheral plain above a bedding-plane décollement. Third, in a few areas, salt-roof thrusts shorten the roof of the salt sheet.

Because roof-edge thrusts and imbricate wedges both form by shear along the base of the salt allochthon, their abundance along the Sigsbee Escarpment implies that basal shear is the primary mode of advance there. Despite the dominance of basal shear, however, the Sigsbee Escarpment exhibits a wide range of structural styles. We speculate that this range reflects variations in relief on the canopy margin, thickness of the roof above the canopy toe, strength of the base-salt zone, and strength of sediments on the peripheral plain.

1. Introduction

Allochthonous salt sheets are abundant in the deep water of most salt basins on passive margins (Hudec and Jackson, 2006). Most salt sheets on passive margins initially extrude, spreading from a bathymetric bulge above the feeder (Fig. 1A). Adjacent salt sheets commonly merge, forming a salt canopy. The dynamic bulge above feeders decays once the source layer is exhausted and salt supply ebbs, allowing the sheet or canopy to be buried (Fig. 1B–C).

Many studies have examined geometries produced by sedimentary loading of buried, or partly buried, salt canopies (e.g., Seni and Jackson, 1992; Diegel et al., 1995; Rowan, 1995, 2002; Schuster, 1995; Prather et al., 1998; Beaubouef and Friedmann, 2000; Hudec and Jackson, 2006; Hudec et al., 2009). Loading expels salt from beneath subsiding minibasins to inflate intervening diapirs or downdip parts of the canopy. Inflation of distal parts of the canopy maintains relief between the canopy and the peripheral plain, allowing the canopy to continue spreading even though its feeders may no longer be active.

Despite widespread interest in other parts of salt canopies, structures around the periphery of buried salt canopies have been little studied. It is widely accepted that a buried canopy advances as thrusting carries salt and its sedimentary roof in the hanging walls of marginal thrusts (e.g., Huber, 1989; Wu et al., 1990; Hudec et al., 1993; Fletcher et al., 1995; Harrison and Patton, 1995; Baud and Haglund, 1996; Jackson and Hudec, 2004; Hudec and Jackson, 2006). However, these thrust systems have never been described in detail, nor have controls on their formation been systematically discussed. Our goals are to describe canopy-margin thrust systems and to explore their dynamics.

We first describe how thrust faults can form around the periphery of a salt canopy and how to recognize each mechanism. We then focus on the Sigsbee salt canopy in the deepwater Gulf of Mexico and assess which mechanisms are active there. Finally, we discuss factors that may influence development of canopy-margin thrust systems and produce their variable structural styles.

The study area is the downdip edge of the Sigsbee salt canopy, the largest known salt structure on Earth (Fig. 2). This canopy

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doi:10.1016/j.jsg.2009.06.005

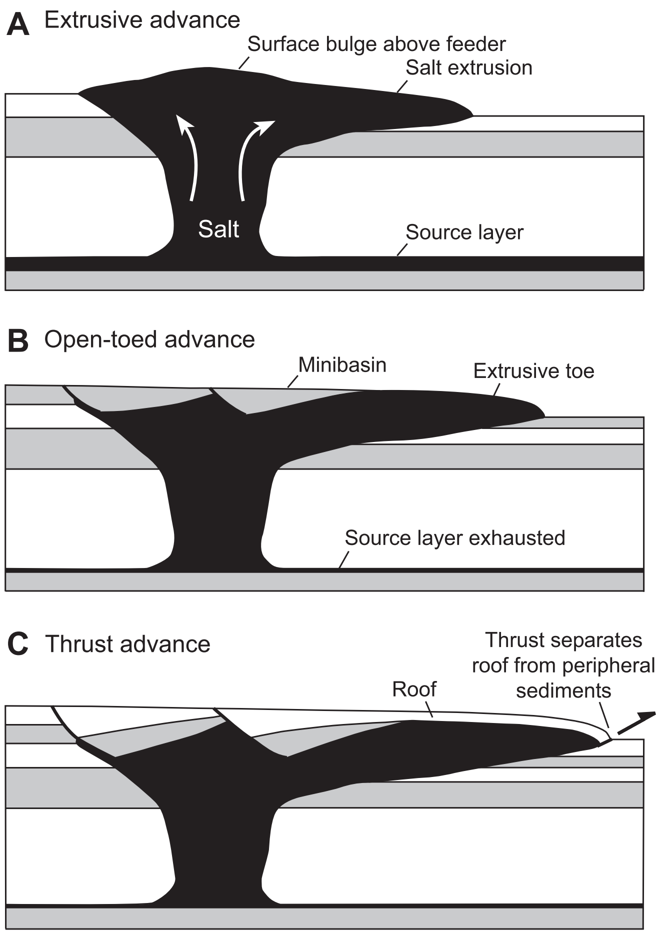

Fig. 1. Schematic diagram showing three main phases of salt-sheet emplacement: (A) extrusive advance fed by salt stock, (B) open-toed advance driven mostly by minibasin subsidence, and (C) thrust advance driven by minibasin subsidence. Modified from Hudec and Jackson (2006).

comprises more than 100 salt sheets and stocks that coalesced to cover more than 137,000 km^2 on the lower continental slope of the northern Gulf of Mexico. The south edge of the canopy extends for more than 1000 km in sinuous length. About 60% of the canopy is advancing along two major thrust systems, each about 300 km in strike length (Fig. 2B). Most of the rest of the canopy stopped advancing during the Quaternary. Our dataset consists of 3D pre-stack-depth-migrated seismic data along almost the entire length of the canopy margin.

Overlying the seaward edge of the Sigsbee salt canopy is the Sigsbee Escarpment, a bathymetric step as high as 1250 m. The leading edge of the canopy-margin thrust system typically follows the base of the escarpment, which is eroded in many areas to depths of up to 700 m.

2. Formation of thrusts along canopy margins

2.1. Spreading detached near the base of the canopy

In the basal-shear model for canopy-margin thrusting, the salt and its roof advance on a detachment near the salt base (Humphris, 1978; Fletcher et al., 1995; Harrison and Patton, 1995; Baud and Haglund, 1996; Jackson and Hudec, 2004; Hudec and Jackson, 2006; Fig. 3A). Slip along the base of salt produces a thrust fault cutting upsection from the canopy front to the sediment surface. In basal shear, the peripheral thrust system is simply the leading edge of a regional detachment at the toe of the spreading allochthon. This type of thrust is analogous to compressional structures at the downdip ends of salt- or shale-based detachments on many of the world's passive margins (e.g., Doust and Omatsola, 1990; Wu et al., 1990; Duval et al., 1992; Lundin, 1992; Weimer and Buffler, 1992; Demercian et al., 1993; Cobbold et al., 1995; Heaton et al., 1995; Letouzey et al., 1995; Mauffret et al., 1995; Peel et al., 1995; Morley and Guerin, 1996; Trudgill et al., 1999; Dailly, 2000; Gaullier et al., 2000; Marton et al., 2000; Wu and Bally, 2000; Tari et al., 2003; Rowan et al., 2004; Bilotti and Shaw, 2005; Camerlo and Benson, 2006; Mount et al., 2007; Jackson et al., 2008). Many of these examples are on autochthonous salt or shale. In this model, shortening at a canopy toe is a measure of allochthon advance, and it is compensated by extension farther updip.

A thrust fault cutting upsection from the salt tip is diagnostic of basal shear if no hanging-wall flat connects to the top of salt (Fig. 3A). Such a flat would indicate a top-salt detachment formed by either frontal rolling or landsliding (Sections 2.2 and 2.4, respectively). More complicated geometries are possible if this thrust is imbricated or if the advancing canopy bulldozes relatively unconsolidated material on the peripheral plain (Sections 3.1 and 3.2).

2.2. Spreading distributed within the canopy

In the absence of a base-salt detachment, a canopy may nevertheless advance if higher parts of the canopy are moving faster than its lower parts because of penetrative shear within the salt (Couette flow; Fig. 3B). This laminar flow causes the top and front of the salt to roll over as the canopy moves forward, similar to an advancing tank tread; the mechanism has therefore been referred to as *frontal rolling* or *tank-tread advance* (e.g., Ramberg, 1981; Brun and Merle, 1985; Merle, 1986; Ings et al., 2004; Hudec and Jackson, 2006). The sedimentary roof of the canopy must either roll over with the salt (which is rare in our experience) or shorten near the edge of the sheet. As in basal shear, extension farther updip compensates shortening and is a measure of allochthon advance.

Diagnostic features of frontal rolling are thrust faults soling into the top of salt near the front of the canopy (Fig. 3B). In contrast to basal shear, thrusts formed by frontal rolling should exhibit hanging-wall flats indicative of a detachment level near the top of salt. Furthermore, thrusts formed by frontal rolling need not connect directly to the salt tip, but may instead root into the top of salt farther updip.

2.3. Substrate expulsion

Substrate expulsion is a form of gravity spreading. Shear stresses generated by the bathymetric slope of a tapering salt sheet expel sediments from beneath the canopy (Fig. 3C). An analogous process occurs beneath the leading edge of ice glaciers, where substrate expulsion is referred to as *the gravity spreading model* (e.g., Rotnicki, 1976; Aber et al., 1989; Benn and Evans, 1998). We prefer *substrate expulsion* to the more general term *gravity spreading* but argue that the same type of structure may form in salt tectonics.

Part of the vertical compressive stress generated by the load of a salt canopy is transferred to a horizontal compressive stress by lateral expansion of the substrate (in accordance with Poisson's ratio). The gradient in vertical load (σ_z) near the edge of the canopy thus produces a corresponding gradient in horizontal stress (σ_x, Fig. 3C). These horizontal stresses are cumulative, leading to a net horizontal compressive stress below the salt-canopy toe (Rotnicki, 1976; Aber et al., 1989). A sufficiently weak substrate may fail and escape laterally from beneath the sheet, forming a bulge of shortening around the sheet's margin. Because substrate-expulsion

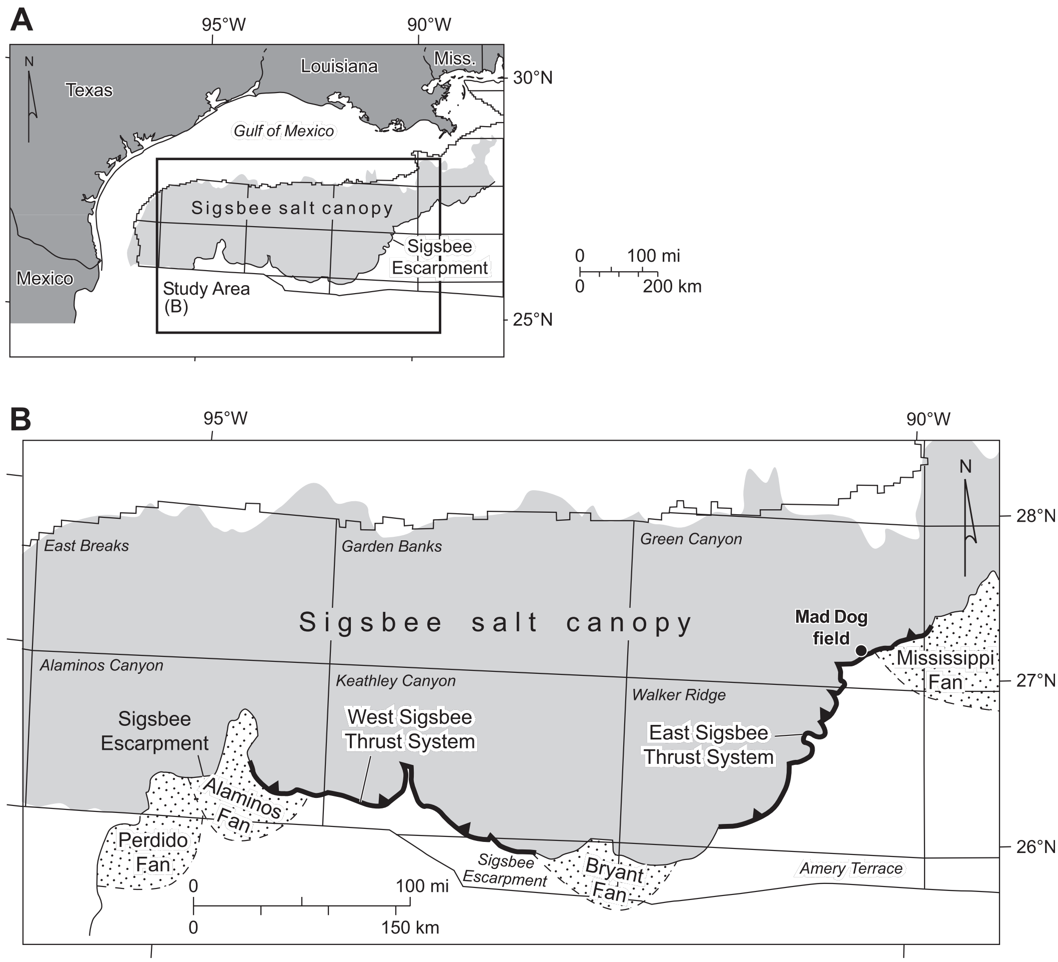

Fig. 2. (A) Map of the northern Gulf of Mexico showing location of the Sigsbee salt canopy. (B) Map of the Sigsbee salt canopy, showing peripheral thrust systems (thick lines with triangles) and approximate extent of submarine fans. Outline of the Sigsbee salt canopy is based on our own mapping and bathymetric data from Bryant and Liu (2000). Fan outlines interpreted from bathymetric contours in Taylor et al. (2002). Named polygonal blocks are Minerals Management Service protraction areas.

structures are produced by subcanopy deformation, the magnitude of shortening is not a measure of canopy advance.

Substrate expulsion around the margins of ice glaciers produces a type of thrust moraine (e.g., Rotnicki, 1976; van der Wateren, 1985; Aber et al., 1989; Benn and Evans, 1998). In thrust moraines, thrust sheets stack to form a ridge around the periphery of the glacier. The volume of material in the ridge (or hill) is balanced by an extensional low (or hole) excavated beneath the ice, forming a *hill-hole pair.*

A hill-hole pair typifies substrate expulsion. Each thrust stack formed by substrate expulsion should lie immediately downslope of the hole from which it was sourced. This hole would have been filled with salt from the overlying canopy and form a structural low in the base of salt (Fig. 3C). Assuming plane strain, the hole should be comparable in cross-sectional area to that of the sediment above regional in the thrust stack.

2.4. Landsliding

Mass wasting degrades bathymetric escarpments at the edge of salt canopies, as evidenced by widespread erosion along the Sigsbee Escarpment. Wasting may involve submarine landslides, producing thrusts at escarpment base (e.g., Orange et al., 2003; Fig. 3D). Because a landslide is a surficial process, magnitude of shortening at the landslide toe is not a measure of canopy advance.

Diagnostic features of landsliding are thrust faults at the escarpment base connected to normal faults near the escarpment crest. Orange et al. (2003) suggested that landsliding is particularly likely if beds dip toward the base of the escarpment, in which case bedding surfaces provide a superior detachment surface. If a bedding-parallel detachment exists, landsliding will produce a hanging-wall flat along the frontal thrust system (Fig. 3D).

3. Geometry and kinematics of thrusting along the Sigsbee Escarpment

Canopy-margin thrust systems along the Sigsbee Escarpment have three parts (Fig. 4, Table 1): (1) a roof-edge thrust separates condensed roof strata from thicker sediments on the peripheral plain, (2) an imbricate wedge shortens sediments on the peripheral plain, and (3) salt-roof thrusts shorten roof strata. These three structural geometries define a shortening zone near the canopy edge that may exist as much as 6 km in front of the salt tip.

3.1. Roof-edge thrusts

Roof-edge thrusts cut upsection from the tip of a salt sheet (Figs. 4–6, Table 1). Most roof-edge thrusts have a single strand, but a few provide the sole to one or more imbricate thrusts. The fault tip can extend to the water bottom, forming an inflection in the

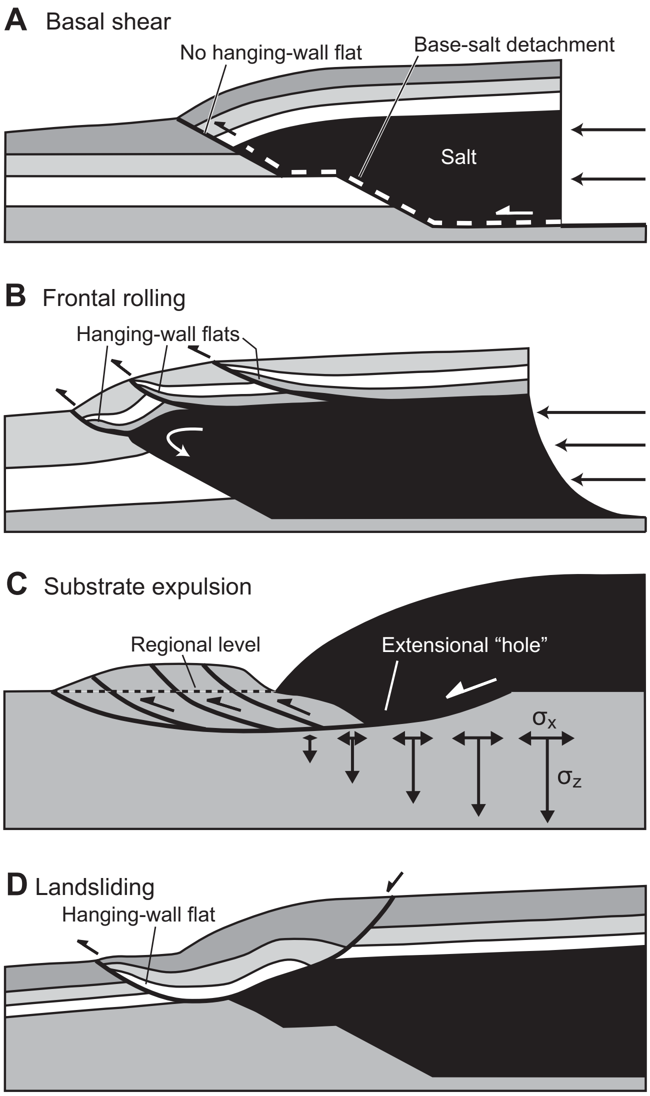

Fig. 3. Cross sections showing possible origins of canopy-margin thrust systems.

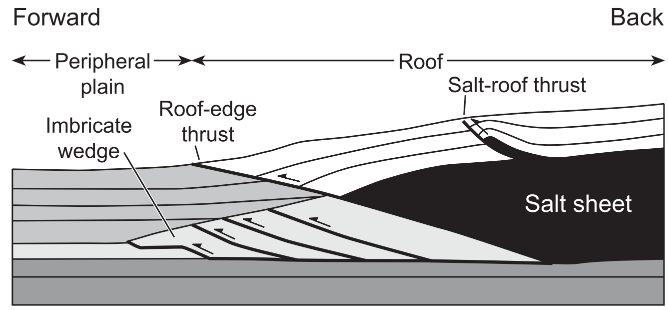

Fig. 4. Schematic cross section illustrating the three types of canopy-margin thrust. The diagram illustrates our reference frame for salt-canopy margins: "forward" refers to the direction of canopy advance, and "back" is toward the interior of the canopy.

bathymetry (e.g., Fig. 5B–C). Elsewhere, undeformed peripheral sediments bury the fault tip (e.g., Fig. 5A, D). Burial of a fault tip is most common where the roof above the salt tip is thicker than 1000 m.

Hanging-wall flats are rare in roof-edge thrusts (<10% of strike length along the Sigsbee thrust systems). Moreover, their displacements (equal to the length of the flat) are typically less than 1.5 km.

Because roof-edge thrusts separate roof and peripheral-plain sediments, strata on either side of the thrust typically have very different thicknesses. For example, the Quaternary section along the Sigsbee Escarpment near Mad Dog oil field is 2700 m thick on the peripheral plain and 1200 m thick above the salt canopy, a thickness ratio of 2.25:1 (Fig. 6). This difference arises because roof strata are typically condensed as a result of their accumulating hemipelagically on a salt-cored topographic high.

At Mad Dog field, the roof-edge thrust accumulated 8500 m of slip from the beginning of the Pleistocene, for an average slip rate of approximately 4.7 mm a^{-1} (Fig. 6). We cannot calculate roof-edge displacements away from paleontologic control. However, if we assume that the footwall to hanging-wall thickness ratio of 2.25:1 across the Mad Dog thrust is typical of the Sigsbee Escarpment, then displacements of 5–10 km are widespread.

3.2. Imbricate wedges

Along roughly 65% of their strike length, Sigsbee thrust systems consist only of a roof-edge thrust. Along the other 35%, the roof-edge thrust is underlain by imbricated peripheral sediments (Fig. 7). Because this imbricated zone is typically wedge shaped, we refer to it loosely as an *imbricate wedge*.

Most imbricate wedges detach along a bedding-plane décollement that merges into a bedding-parallel segment of the base of salt (a salt flat). The branch point between the décollement and the base of salt may be at the salt tip (a salt-tip imbricate wedge; Fig. 7B) or at the bottom of a base-salt ramp behind the salt tip (a salt-floor imbricate wedge; Fig. 7A, C–F). Salt-tip and salt-floor imbricate wedges have similar internal geometries and can transition along strike (Fig. 8).

Imbricate wedges are locally exposed at the seafloor along the Sigsbee Escarpment (Fig. 7D), but mostly they are buried beneath unfaulted peripheral-plain sediments (Figs. 7A–C, E–F, 8). Wedges and suprawedge sediments may be related in two ways (Fig. 9). Some smaller wedges are onlapped by flat-lying strata that maintain uniform thickness until they pinch out against the wedge top (Figs. 7B, 9A). Mostly, however, suprawedge strata thin and steepen toward the wedge top (Figs. 7A, C–F, 9B). The suprawedge package is typically unfaulted near the wedge toe. An imbricate thrust can cut through the top of the wedge farther back, however (Fig. 7E).

Fanning, onlapping, and truncated strata above some imbricate wedges imply that the wedges were shortening and steepening during burial (Figs. 7E–F, 9B). That thrusts within the wedge did not propagate into the suprawedge strata suggests that shortening was instead transferred to a backthrust at the top of the wedge. Where such backthrusts exist, these wedges were passive-roof duplexes (also known as *delta structures* or *triangle zones*; e.g., Gordy et al., 1977; Banks and Warburton, 1986; Jones, 1996) during their later stages.

Most examples presented here lie at the leading edge of the modern Sigsbee canopy. However, in at least one area, a second, more deeply buried, imbricate wedge projects farther updip beneath the canopy (Fig. 7F). Given that subsalt image quality is poor in many areas, such wedges may exist next to many deeper ramps at the base of the Sigsbee salt canopy (e.g., Alexander et al., 2005).

Shortening in imbricate wedges can be calculated by line-length balancing in well-imaged structures (Fig. 7A–C) or, more commonly, by area balancing in poorly imaged wedges (Figs. 7D–F). Area balancing assumes (1) no erosion of emergent thrusts, (2) no tectonic compaction, and that (3) all shortened sediments are prekinematic. Because all these assumptions are debatable, our estimates of shortening are approximate.

Table 1
Geometry of canopy-margin thrust systems along the Sigsbee Escarpment.

	Roof-edge thrusts	Imbricate wedges	Salt-roof thrusts
Thrust dip (°)	0–20	10–30	
Dominant vergence	Forward	Forward	Forward
Dip length (m)	0–3500	2000–6000	
Shortening (m)	0–10,000	0–10,000	0–2500
Thickness of synkinematic section (m)	0–2000	0–500	0–3000
Occurrence along Sigsbee thrust systems (%)	>99	35	<1

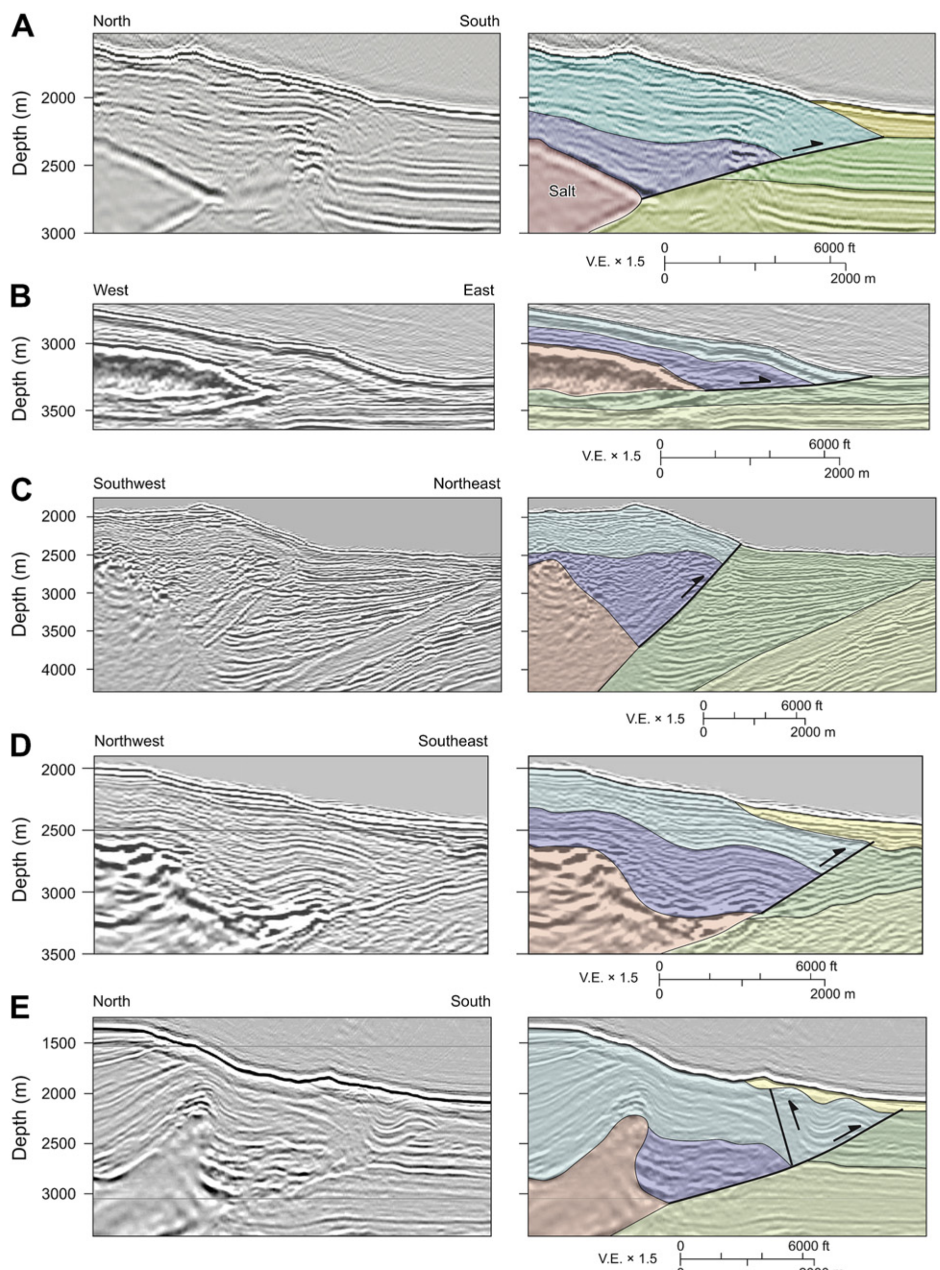

Fig. 5. Uninterpreted and interpreted 3D prestack-depth-migrated seismic sections of roof-edge thrusts. Salt is pink, canopy roof is in shades of blue, peripheral plain is in shades of green, and strata that bury the fault tip are yellow. Colors do not correlate stratigraphically from section to section. Protraction areas shown in Fig. 2. (A) Recently buried part of the East Sigsbee thrust system, Green Canyon area. (B) East Sigsbee thrust system, Walker Ridge area. (C) West Sigsbee thrust system, Alaminos Canyon area. (D) Recently buried part of the West Sigsbee thrust system, Alaminos Canyon area. (E) Recently buried part of the East Sigsbee thrust system, Green Canyon area. Seismic image A, courtesy of BP, Unocal, and BHP; seismic images B–D, courtesy of CGGVeritas; and seismic image E, courtesy of WesternGeco.

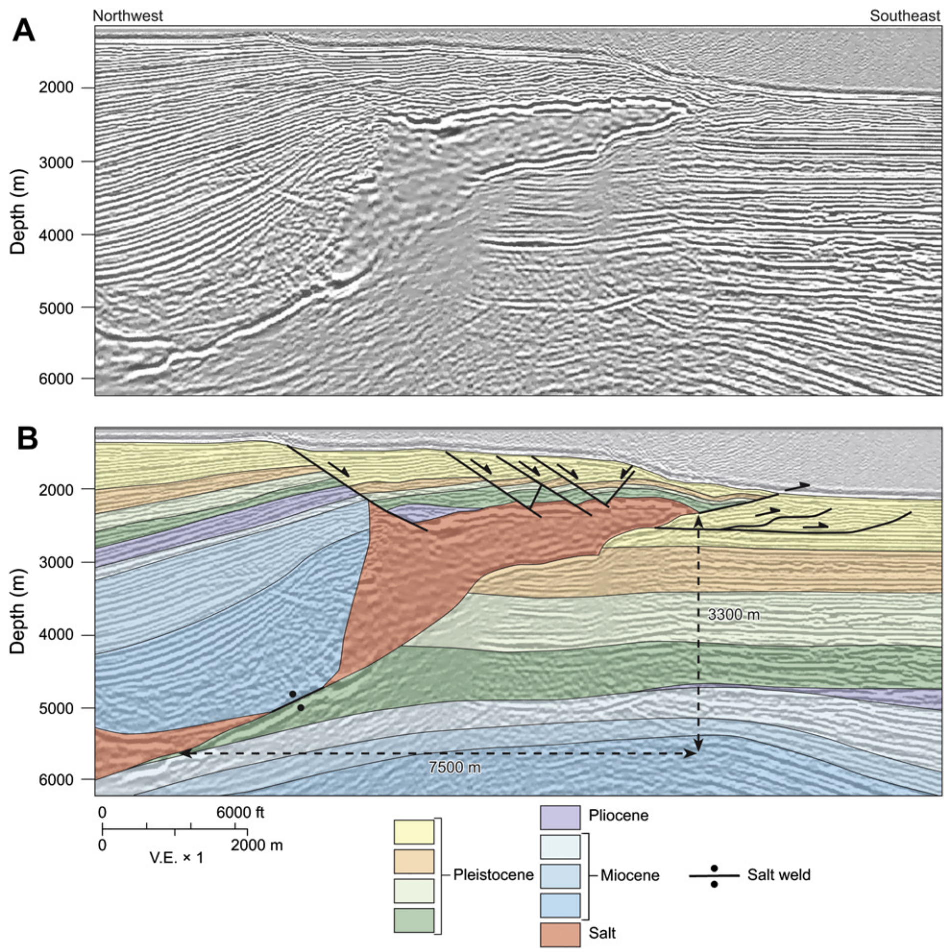

Fig. 6. (A) Uninterpreted and (B) interpreted versions of a 3D prestack-depth-migrated seismic section near Mad Dog field, Green Canyon area (see Fig. 2 for location). Correlations above and below the salt are based on proprietary borehole data. Pleistocene units are condensed above the canopy, suggesting that the roof-edge thrust has been active since the end of the Pliocene. Seismic section courtesy of BP, Unocal, and BHP.

Shortening estimates from 23 seismic sections across imbricate wedges range from near zero to almost 10 km (Table 1). Wedges that imbricate thin stratigraphic sections may accumulate more shortening than those involving thick sections, as illustrated by plots of wedge shortening versus height of the frontal ramp (Fig. 10). Data points in Fig. 10 are bounded by a curve having negative slope, with greater shortening possible for short frontal ramps. The relation between shortening and frontal ramp height is reasonable because thicker stratigraphic sections should be stronger and more resistant to shortening. Stratigraphic sections of any thickness may shorten by modest amounts, but only the thinnest sections can be telescoped enough to reach large strains. Because paleontologic resolution is poor, we have not been able to estimate shortening rates in imbricate wedges.

3.3. Salt-roof thrusts

Salt-roof thrusts that root into the top of salt (Figs. 4, 11) are rare, observed along less than 1% of the strike length of the Sigsbee Escarpment. Salt-roof thrusts are planar to gently listric. They can carry in their hanging walls a salt sliver as much as several hundred meters thick (Fig. 11A, C). Beds immediately above the salt in the hanging wall are typically subparallel to the top of salt and so form a hanging-wall flat. This flat continues until the end of the salt sliver, where beds fold and truncate against the thrust. Beds higher in the hanging wall thin toward the crest of the thrust anticline. Groups of salt-roof thrusts are known (e.g., Fig. 11B, D), but complex multifault arrays forming imbricate fans or duplexes are not.

Some salt-roof thrusts die out laterally at a fault tip with little secondary deformation. Other salt-roof thrusts merge laterally into an asymmetric fold or into extrusive salt (Fig. 12).

4. Thrusting mechanisms along the Sigsbee Escarpment

We evaluate the three observed thrust geometries in the light of the four possible formation processes (Table 2).

4.1. Roof-edge thrusts

Four key properties of roof-edge thrusts are: (1) they are typically composed of a single thrust, (2) they connect to the salt tip, (3) hanging-wall flats are rare, and (4) many hanging-wall units have footwall equivalents that intersect the base of salt.

The only mechanism common to all four properties is basal shear (Table 2). In particular, the existence of footwall cutoffs against the base of salt indicates that the salt canopy has advanced up the hanging wall of the thrust. This pattern of footwall cutoffs fits a detachment at or near the base of salt, as well as an intrasalt detachment passing from the middle of a canopy to the salt tip. A discrete detachment, however, seems much more likely along a mechanical discontinuity such as the base of salt, rather than in the more homogeneous middle of a salt canopy.

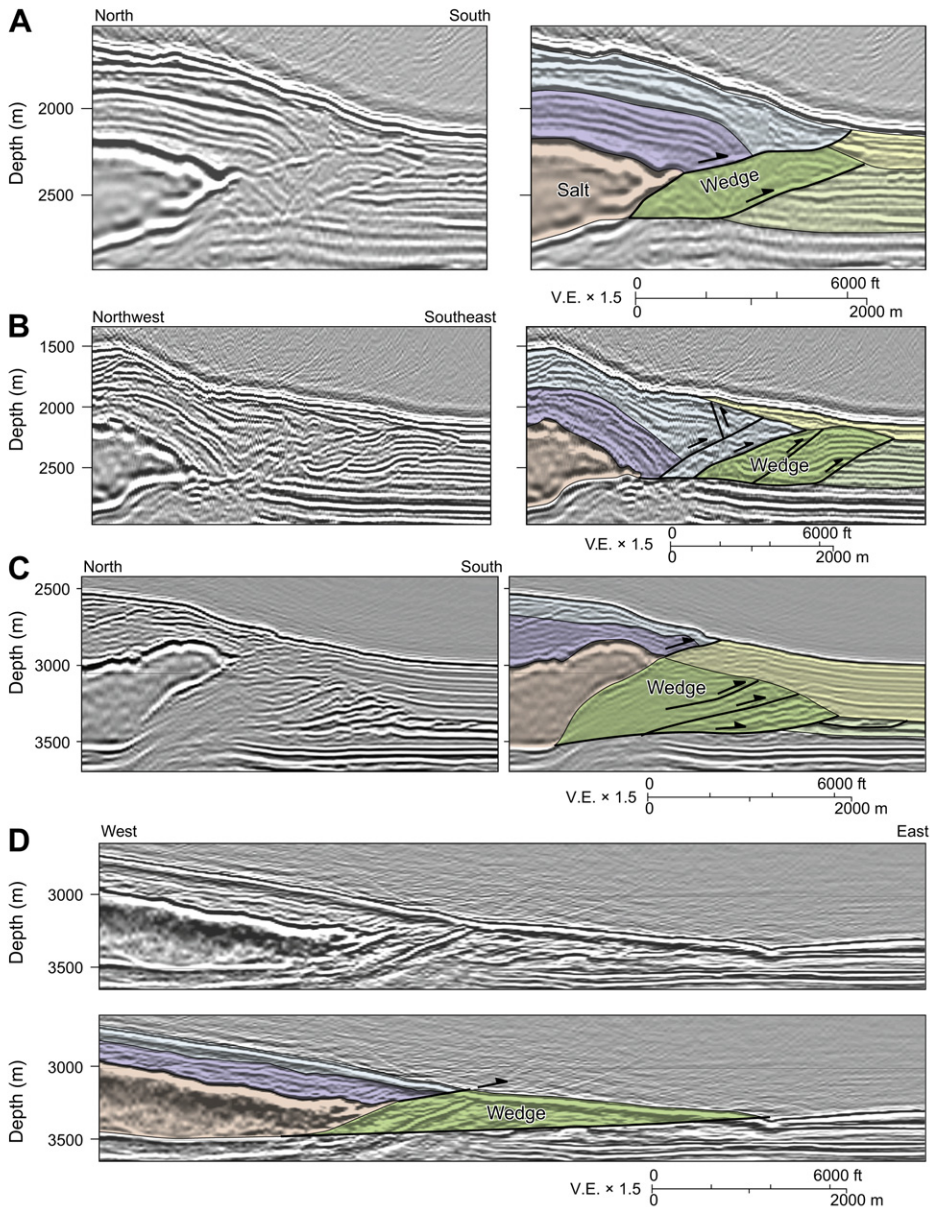

Fig. 7. Uninterpreted and interpreted 3D prestack-depth-migrated seismic sections of imbricate wedges. Salt is pink, canopy roof is in shades of blue, peripheral plain is in shades of green, and strata that onlap the wedge are yellow. Colors do not correlate stratigraphically from section to section. Protraction areas are shown in Fig. 2. (A) Buried salt-floor wedge composed of a single thrust sheet, East Sigsbee thrust system, Green Canyon area. (B) Buried salt-tip wedge composed of two thrust sheets, East Sigsbee thrust system, Green Canyon area. (C) Buried, intensely imbricated salt-floor wedge, West Sigsbee thrust system, Alaminos Canyon area. (D) Active, intensely imbricated salt-floor wedge, East Sigsbee thrust system, Walker Ridge area. (E) Buried, intensely imbricated salt-floor wedge, West Sigsbee thrust system, Alaminos Canyon area. (F) Two stacked imbricate wedges, West Sigsbee thrust system, Alaminos Canyon area. Seismic images A–B, courtesy of BP, Unocal, and BHP; and seismic images C–F, courtesy of CGGVeritas.

Two caveats apply to the phrase *base-salt detachment*. First, seismic resolution does not reveal an exact detachment level. The detachment may be on the salt–sediment interface, in salt immediately above the interface, or in sediments below. The distinction is relevant to grain-scale deformation mechanisms along the décollement but does not significantly affect the kinematics of slip at the allochthon base. A second caveat is that canopy-margin structures provide evidence of detachment geometry only near the front of the salt canopy. Finite-element modeling suggests that, although shear at the base of the allochthon may be concentrated on a base-salt detachment near the front of the salt canopy, strain may widen into a ductile shear zone farther updip within the salt (Jozina Dirkzwager, personal communication, 2006). If so, the front of a salt canopy may move along a discrete detachment near the base of salt, whereas salt farther back may move by distributed flow.

4.2. Imbricate wedges

Key properties of imbricate wedges are as follows: (1) basal décollements of salt-floor imbricate wedges connect to the base of salt (Figs. 6, 7A, C–F), (2) salt-tip and salt-floor imbricate wedges are transitional along strike (Fig. 8), (3) all imbricate wedges occur with roof-edge thrusts, and (4) no significant structural lows are in the base of salt immediately updip of most thrust wedges (Table 2, Figs. 6–8).

These observations argue that imbricate wedges form by basal shear. Basal décollements can connect with the base of salt in salt-floor wedges only if basal shear or substrate expulsion occurs. However, absence of base-salt structural lows rules out substrate expulsion. The common lateral continuity between salt-tip wedges and salt-floor wedges suggests that salt-tip wedges also form by basal shear. Finally, we have already concluded that roof-edge

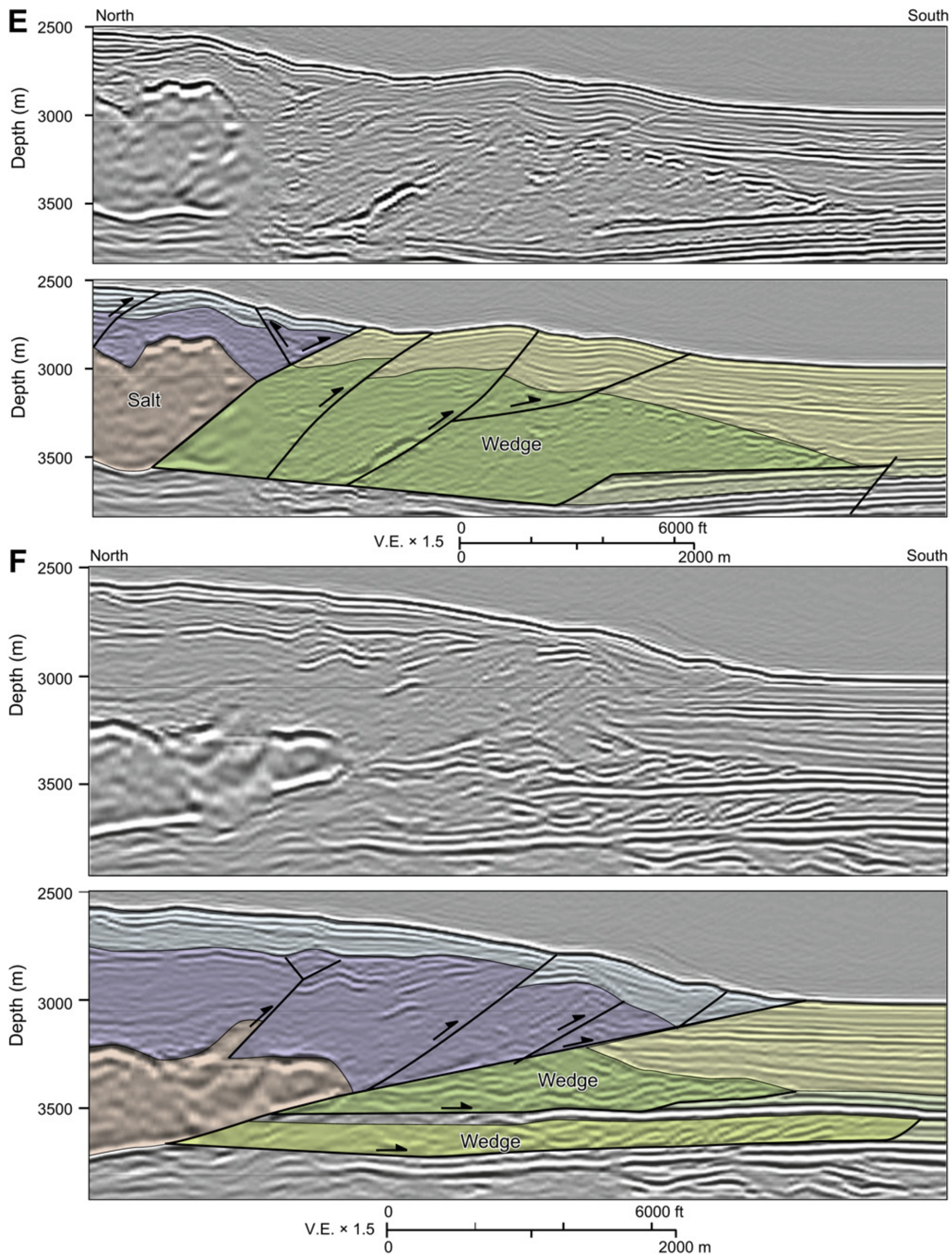

Fig. 7. (*continued*).

thrusts form by basal shear (Section 4.1). Because roof-edge thrusts invariably overlie imbricate wedges, it seems reasonable that the same base-salt detachment links both structures.

4.3. Salt-roof thrusts

Key observations for salt-roof thrusts are as follows: (1) the thrusts are updip of the salt tip and (2) many thrusts have hanging-wall flats, especially above salt in the hanging wall (Figs. 4, 11A–B, D).

Salt-roof thrusts near the canopy toe are unambiguous indicators of frontal rolling because all other thrust mechanisms produce thrusts in front of the salt tip (Table 2, Fig. 3). Hanging-wall flats in a salt-roof thrust indicate a detachment near the top of salt. This detachment is consistent with decoupling between salt and roof, which is inherent in frontal rolling.

The serial sections in Fig. 12 suggest that frontal rolling may accompany reactivation of buried salt sheets. In the northeast, a thick roof pins the salt canopy (Fig. 12A). Southwestward, the frontal escarpment steepens and is cut by a salt-roof thrust, which transitions along strike into a roof-edge thrust. The thrust carries salt in its hanging wall, which eventually reaches the surface (Fig. 12D). These serial sections may represent an evolutionary sequence, showing how a salt canopy breaks out along a salt-roof thrust across the top of an old, buried canopy toe.

5. Control of structural style in canopy-margin thrust systems

We have suggested that the Sigsbee salt canopy advances mostly by basal shear. However, the dominance of basal shear does not explain the wide variety of structural styles observed along the Sigsbee Escarpment (Figs. 5–10, 11), nor does it account for the parts of the canopy that are now stationary (Fig. 2).

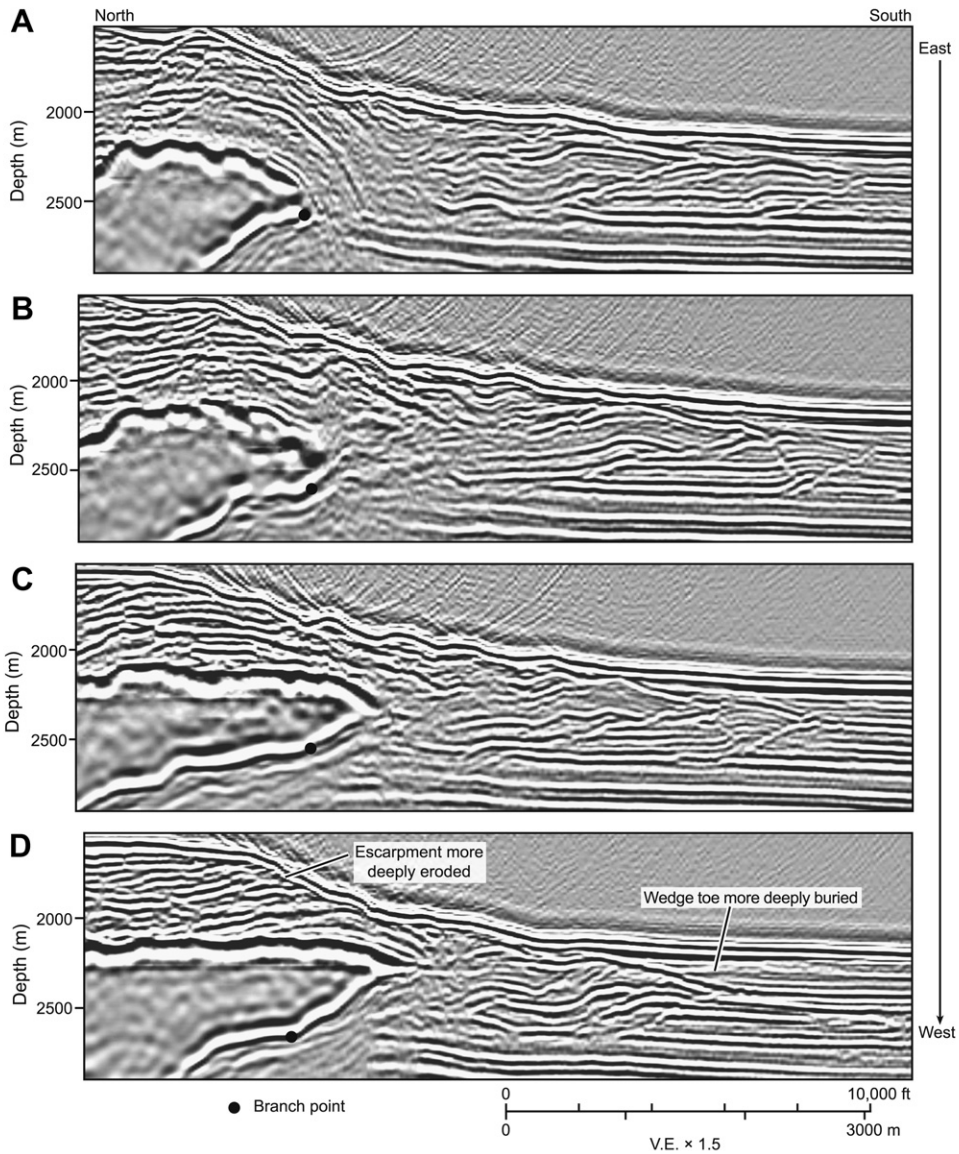

Fig. 8. Serial 3D prestack-depth-migrated seismic sections, showing lateral transition between partly buried imbricate wedges. (A) Salt-tip imbricate-wedge. (B–D) Salt canopy progressively overrides the back of the wedge, which changes into a salt-floor imbricate wedge. The branch point between the base of salt and the décollement shifts backward from the salt tip to a subsalt position. The escarpment becomes more deeply eroded as the salt and its roof rise up the back of the wedge. East Sigsbee thrust system, Green Canyon area. Seismic images courtesy of BP, Unocal, and BHP.

What controls the widely variable structural styles along the margins of the Sigsbee canopy? A full answer awaits more complete data on the mechanical properties of sediments along the Sigsbee Escarpment, about which little has been published (e.g., Al-Khafaji et al., 2003; Nadim et al., 2003; Nowacki et al., 2003). However, structural observations and simple mechanical inferences allow us to speculate on what governs thrusting along canopy margins. These speculations generate testable hypotheses for future work along the Sigsbee Escarpment.

We propose that four factors influence the dynamics of canopy advance and, hence, control the thrust systems: (1) relief on the Sigsbee Escarpment, (2) thickness of the roof in front of the salt tip, (3) strength of the base-salt zone, and (4) strength of peripheral-plain strata.

5.1. Relief on the Sigsbee Escarpment

Because salt canopies advance by gravitational spreading, higher relief should produce a greater driving force for canopy advance. If so, escarpment height should correlate with the present canopy-advance rates. Consistent with this hypothesis, a plot of escarpment height versus distance along the Sigsbee Escarpment (Fig. 13) shows that low parts of the escarpment coincide with inactive parts of the canopy. A more thorough test of the hypothesis would be to measure Holocene advance at a series of points along the Sigsbee Escarpment and plot these values against escarpment height.

Relief on the Sigsbee Escarpment is enhanced by flow of salt toward the leading edge of the canopy and is diminished by aggradation of the peripheral plain. Holocene aggradation rates were locally enhanced in front of the Sigsbee Escarpment, where submarine fans formed bathymetric highs in front of the Mississippi, Bryant, Alaminos, and Perdido submarine canyons (Fig. 2B). The Bryant and Perdido/Alaminos fans coincide with pinned parts of the Sigsbee salt canopy (Fig. 13), suggesting that rapid aggradation of the fans partly smothered the escarpment and halted its advance. The relationship is less impressive for the Mississippi fan, although movement on the East Sigsbee thrust system does die out eastward toward the center of the fan (Fig. 2B).

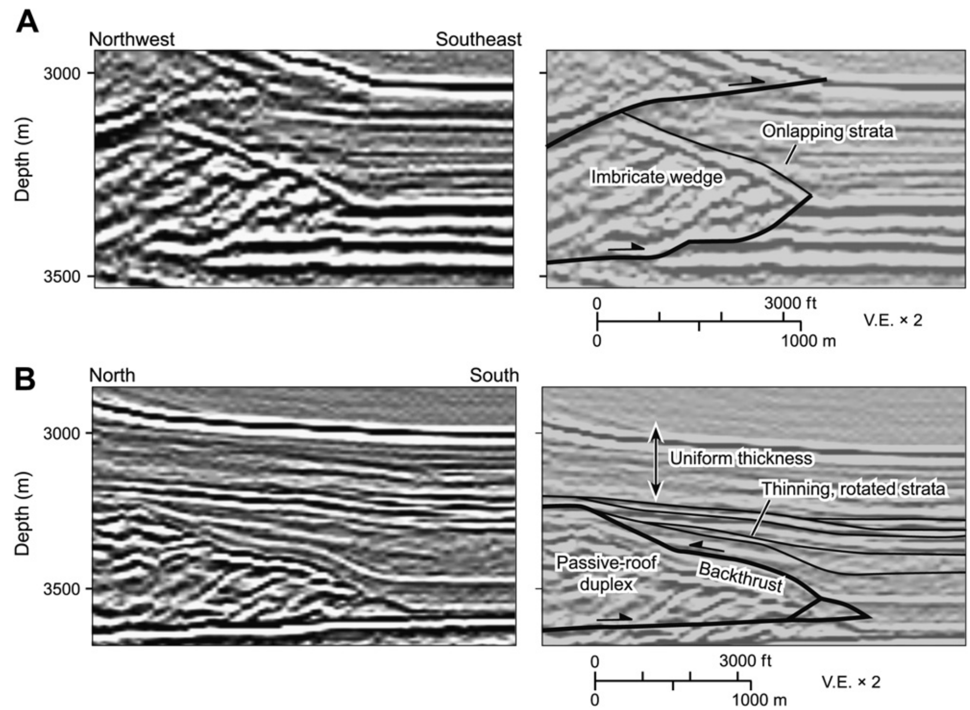

Fig. 9. Uninterpreted and interpreted 3D prestack-depth-migrated seismic sections showing onlap above imbricate wedges. Sections are from the West Sigsbee thrust system, Alaminos Canyon area (location in Fig. 2). (A) Imbricate wedge is onlapped by flat-lying strata, indicating no postburial steepening of the wedge top, merely burial of an imbricate wedge. (B) Units immediately above the wedge are rotated and thin, showing postburial steepening of the wedge top. Without thrust faults breaking through the top of the wedge, this steepening requires a backthrust at the top of the wedge, forming a passive-roof duplex. Shallowest strata have constant thickness across the wedge, suggesting that the wedge is now inactive. Seismic images courtesy of CGGVeritas.

5.2. Thickness of the roof in front of the salt tip

A sedimentary roof in front of the salt tip resists the advance of a canopy because this roof must be pushed along a roof-edge thrust. The force required to push the roof increases with the roof's mass. For a given escarpment height, increasing the thickness of the roof above the salt tip should progressively resist canopy advance, eventually pinning the canopy in place.

This hypothesis could be tested by measuring escarpment height and roof thickness adjacent to roof-edge thrusts whose tips have recently been buried (e.g., Figs. 5A, D–E, 7B). If escarpment height and roof thickness have changed little since the fault tip was buried, then these measurements should represent critical values at which the salt canopy could no longer push its roof forward. If a relationship between driving force (escarpment height) and frictional resistance (related to roof thickness) exists, then these variables should correlate positively. Furthermore, paired values of roof thickness and height of currently advancing escarpments (e.g., Figs. 5B–C, 6, 7A, C–F, 7, 9B–D) should plot on the low-roof-thickness side of the critical values.

Although our hypothesis predicts a positive correlation, the ability of a canopy to advance probably depends also on other factors, especially strength of the base-salt zone (Section 5.3). Therefore, the relationship between roof thickness and escarpment height is unlikely to be perfect.

Frontal roof thickness may also have suppressed substrate-expulsion structures, which are unknown along the Sigsbee Escarpment. This rarity is otherwise difficult to explain, given the large relief on the Sigsbee Escarpment, high lateral density contrast between salt and water, and weakness of subsalt sediments (see Section 5.4). We suggest that the roof above the salt toe forms a buttress against substrate expulsion, preventing the sediments from being expelled from beneath the salt. If so, some substrate may have been expelled earlier when the roof was thin and weak.

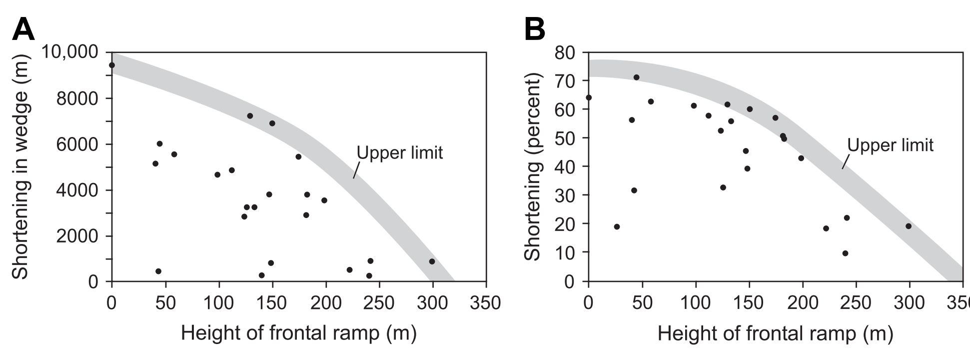

Fig. 10. Graphs of imbricate-wedge shortening versus height of the frontal thrust ramp. Ramp height indicates thickness of strata before thrusting. (A) Total shortening versus height of frontal ramp. (B) Percent shortening versus height of frontal ramp.

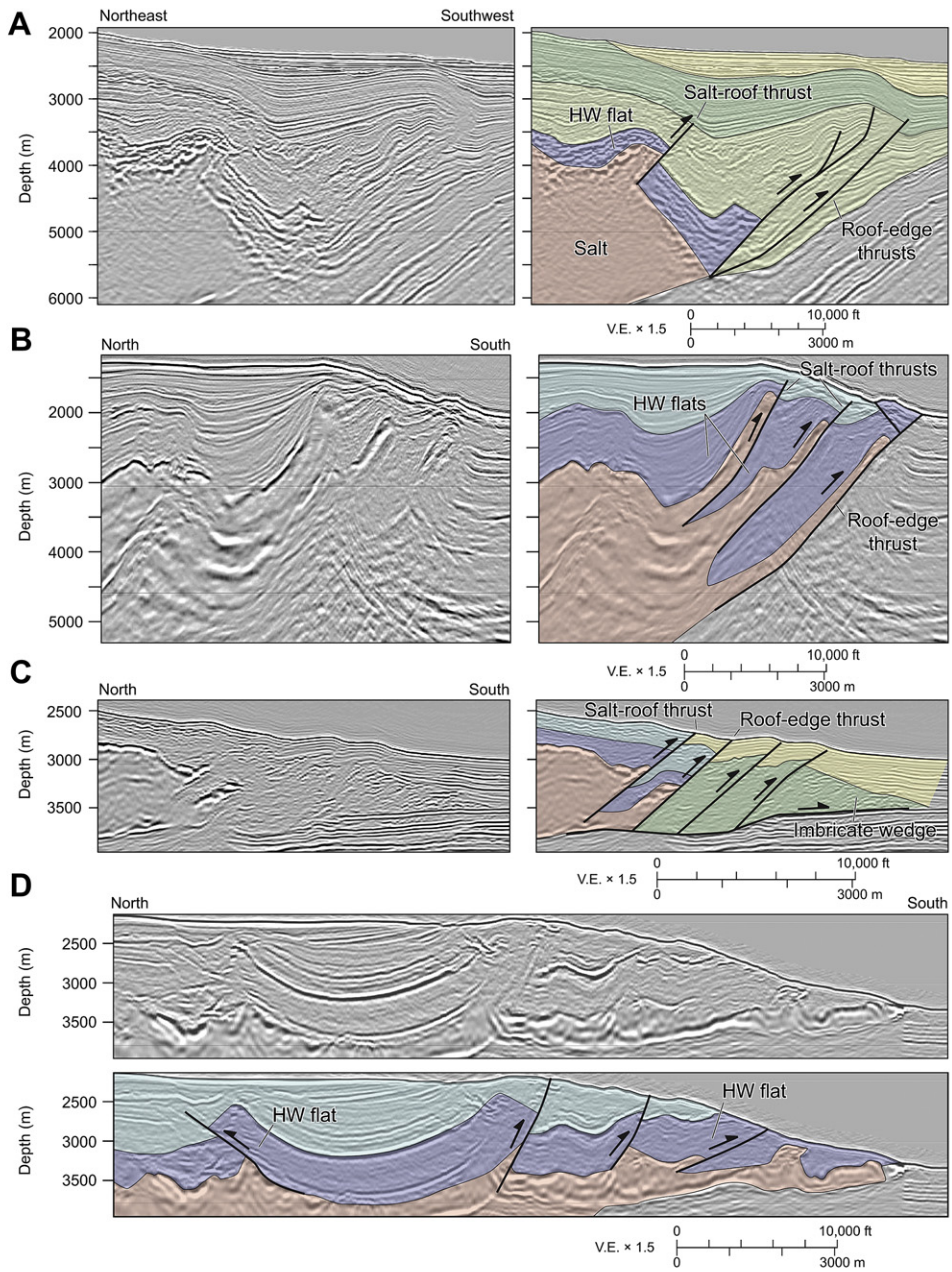

Fig. 11. Uninterpreted and interpreted 3D prestack-depth-migrated seismic sections of salt-roof thrusts. Salt is pink, canopy roof is in shades of blue and purple, and peripheral plain and units correlatable from peripheral plain to roof are in shades of green and yellow. Colors do not correlate stratigraphically from section to section. Protraction areas are shown in Fig. 2. (A) Salt-roof thrust carries short slab of salt in its hanging wall. Inactive part of Sigsbee Escarpment, Alaminos Canyon area. (B) Roof-edge thrust and two salt-roof thrusts, each having a salt sliver in the hanging wall. East Sigsbee thrust system, Green Canyon area. (C) Salt-roof thrust offsetting the top of salt. West Sigsbee thrust system, Alaminos Canyon area. (D) Salt-roof thrusts, including a backthrust. East Sigsbee thrust system, Walker Ridge area. Seismic images A, C, and D, courtesy of CGGVeritas; and seismic image B, courtesy of WesternGeco.

We therefore predict that small hill-hole pairs could exist along the base of salt farther landward and were overridden during earlier canopy advance.

5.3. Strength of the base-salt zone

Very high overpressures have been measured in many wells penetrating the base of allochthonous salt (e.g., O'Brien et al., 1993a, b; LeBlanc, 1994; O'Brien and Lerche, 1994; Harrison and Patton, 1995; House and Pritchett, 1995; Baud and Haglund, 1996; Niemann, 1997; Whitson and McFadyen, 2001; Rohleder et al., 2003; Willson et al., 2003; Ebrom et al., 2006). This overpressure is a natural consequence of water-rich, shallow sediments rapidly overridden by a thick, dense, impermeable salt sheet.

Overpressure at the base of salt may facilitate basal shear by weakening subsalt sediments (e.g., Harrison and Patton, 1995; Baud and Haglund, 1996). If so, spatial or temporal variations in basal overpressure should affect canopy mechanics and, thus, the structural style of canopy-margin thrust systems.

We therefore propose that the structural style of canopy-margin thrust systems is at least partly a function of overpressure at the base of the canopy. However, we lack a theoretical framework of how canopy-advance mechanics changes with increasing overpressure or how the changing mechanics affects the structural

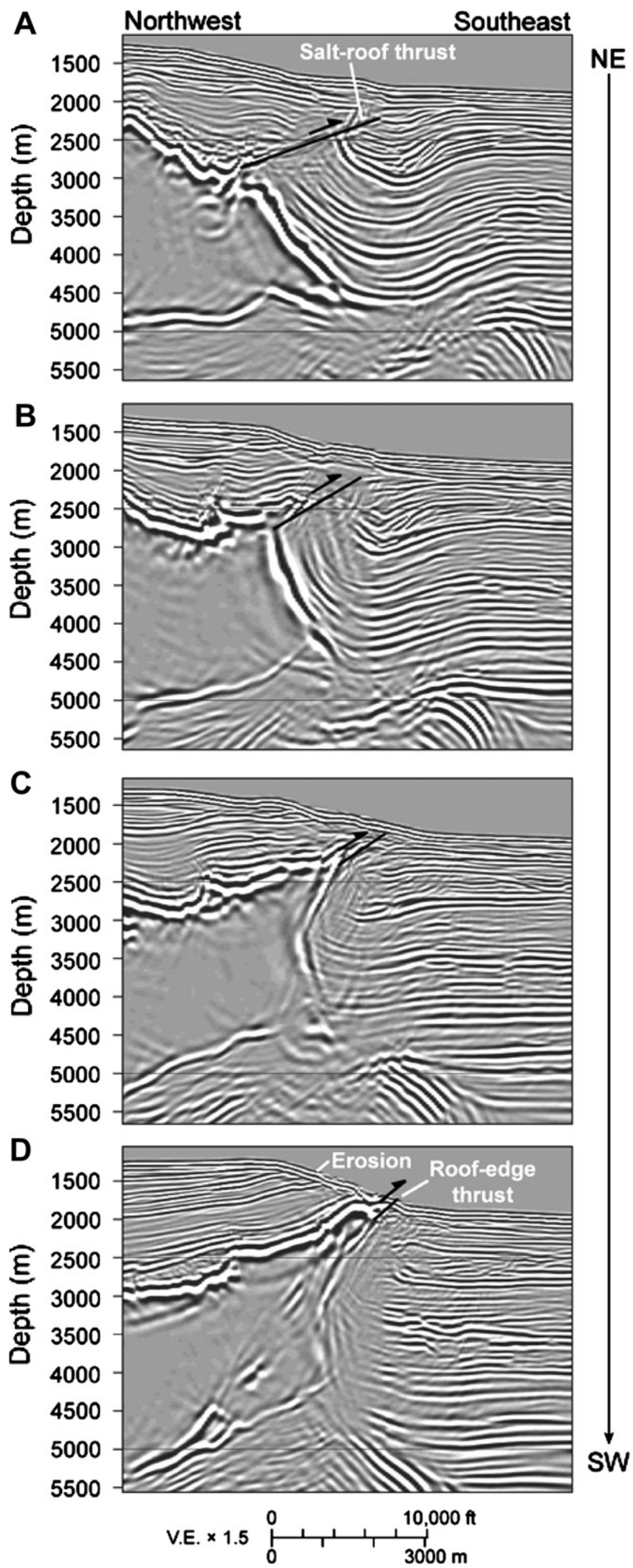

Fig. 12. Serial 3D prestack-depth-migrated seismic sections, showing breakout of a canopy along a salt-roof thrust. (A) Thick, upturned flap of sediments covers the tip of the salt canopy. Folding of parallel-bedded strata indicates that salt inflated after sediment deposition. A small salt-roof thrust cuts through the upturned flap. (B) The salt-roof thrust is larger and carries a wedge of salt in its hanging wall. (C) A larger wedge of salt is carried closer to the seafloor. (D) Salt in the hanging wall of the salt-roof thrust has advanced beyond the deeply buried, inactive salt tip, becoming the new tip of the sheet. Reactivated parts of the escarpment are steeper and more deeply eroded than stationary parts. Seismic images courtesy of CGGVeritas.

style of the frontal thrust system. We need (1) numerical modeling to determine the mechanical linkage between base-salt overpressure and frontal structure and (2) publication of subsalt overpressures in wells drilled near the Sigsbee Escarpment.

5.4. Strength of peripheral-plain strata

We have interpreted Fig. 10 to indicate that imbricate wedges can shorten more where the imbricated section is thin. However, a thin peripheral section cannot be the sole prerequisite for imbricate wedges, because most parts of the Sigsbee Escarpment lack wedges even though their roofs were once thin. Evidently, even thin peripheral sections can resist compression by the advancing salt canopy. We therefore hypothesize that imbricate wedges can form only where abyssal strata or the basal detachment are exceptionally weak.

We have only sparse information on sediment strength along the Sigsbee Escarpment (e.g., Al-Khafaji et al., 2003). However, in an analogous setting, the mechanical properties of deepwater thrust wedges have been extensively studied in accretionary prisms in oceanic trenches. These studies focus on pore pressure because it is critical in modifying basal and internal shear strength. Mechanical properties of accretionary prisms have been estimated by numerical modeling of fluid flow (e.g., Saffer and Bekins, 2002, 2006), observation of fluid-escape structures (e.g., Westbrook and Smith, 1983; Brown and Westbrook, 1988), critical-wedge mechanics (e.g., Davis et al., 1983; Saffer and Bekins, 2002, 2006), interpretation of seismic velocities (e.g., Bray and Karig, 1985; Bangs et al., 1990; Cochrane et al., 1994) and reflectivity (e.g., Bangs et al., 1999, 2004), and direct observation in boreholes (e.g., Bray and Karig, 1985; Bangs et al., 1999).

Along the Sigsbee Escarpment, borehole data are sparse and 3D seismic data are abundant. The most useful techniques for estimating material properties of imbricate wedges are thus seismic velocity, seismic reflectivity, existence of fluid-escape and sapping structures, and critical-wedge morphology. If our hypothesis is correct, active wedges should either be weaker than abyssal-plain strata or have a weaker detachment. A weak wedge should have slow seismic velocities owing to fluid overpressure, possible fluid-escape structures, and a steep wedge taper. A weak detachment should have high seismic reflectivity if overpressured, fluid-escape structures near the fault tip, and a low wedge taper.

Material properties for active (Fig. 7D) and inactive (Fig. 7A–C, E–F) imbricate wedges should be compared. One explanation for the death and burial of imbricate wedges is that they become too strong to be deformed by spreading salt because of structural thickening and loss of pore pressure. If so, inactive wedges should be stronger than active ones, or they should have stronger detachments.

5.5. Hypothetical scenario of structural-style variation

If variations in local conditions do modify canopy mechanics, then canopy-margin thrust systems should evolve as a result of changing base-salt overpressure, roof thickness, escarpment height, and abyssal-plain strength. Assuming for the moment that this is so, Fig. 14 illustrates how changing conditions might produce some of the complex structures observed along the 1000-km length of the Sigsbee Escarpment. It is unlikely that any single section would contain all of these features.

In the earliest stage (Fig. 14A), our schematic canopy is extrusive. In the absence of a buttressing roof, substrate expulsion creates a small imbricate wedge, and salt flow fills the extensional hole from which the substrate escaped. After canopy burial, the sheet

Table 2
Advance mechanisms of salt canopies inferred from canopy-margin thrusts.

Thrust type	Key observations	Compatible advance mechanisms	Inferred advance mechanism[a]
Roof-edge thrust	Single thrust	Basal shear, frontal rolling, landslide	Basal shear
	Thrust connects to salt tip	Basal shear, frontal rolling, substrate expulsion, landslide	
	Hanging-wall flats are rare	Basal shear, substrate expulsion	
	Footwall cutoffs intersect base of salt	Basal shear, frontal rolling	
Imbricate wedge	Basal décollements of salt-floor wedges connect to base of salt	Basal shear, substrate expulsion	Basal shear
	Strike transitions between salt-tip and salt-floor wedges	Basal shear, substrate expulsion	
	Imbricate wedges associated with roof-edge thrusts	Basal shear	
	No significant structural lows in the base of salt updip of wedges	Basal shear, frontal rolling, landslide	
Salt-roof thrust	Thrusts are behind salt tip	Frontal rolling	Frontal rolling
	Significant hanging-wall flats	Frontal rolling, landslide	

[a] Advance mechanism common to all key observations.

continues to advance along a roof-edge thrust, leaving the inactive thrust stack in its footwall (Fig. 14B).

Roof-edge thrusting continues until the canopy encounters a particularly weak section of the abyssal plain, perhaps weakened by overpressured fluids pumped from beneath the salt canopy. The abyssal-plain strata shorten to form an imbricate wedge (Fig. 14C), which is short lived for two reasons. First, shortening thickens and strengthens the wedge, making it progressively more difficult to deform. Second, faults within the wedge provide pathways for fluid escape, reducing overpressure on the basal detachment. The imbricate wedge becomes inactive, buried, and overridden by the roof-edge thrust (Fig. 14D).

Roof-edge thrusting continues until the roof above the salt tip becomes thick enough to inhibit further advance, pinning the toe of the canopy (Fig. 14E). Continued flow of salt toward the pinned escarpment inflates the canopy, steepening the escarpment until it fails as a submarine landslide. Landsliding unroofs the canopy and allows the upper parts of the canopy to break out and advance along a new salt-roof thrust (Fig. 14F).

6. Implications

Canopy-margin thrust systems have been little studied but are well imaged on an unrivalled concentration of 3D seismic data. They are therefore an underutilized natural laboratory for the study of thrust geometry, kinematics, and dynamics. We suggest three settings in which an understanding of canopy-margin thrusts could prove useful.

First, the structural style of canopy-margin thrusts may help predict fluid overpressure beneath salt canopies. Pressure prediction is of great interest in hydrocarbon exploration because subsalt overpressure is a major drilling hazard in subsalt exploration in the Gulf of Mexico (e.g., O'Brien and Lerche, 1994; Harrison and Patton, 1995; Perez et al., 2008). Current predictions of overpressure center on basin modeling (e.g., Petmecky et al., 2009) or seismic-velocity analysis (e.g., Ebrom et al., 2006). Canopy mechanics is an independent approach that may supplement these existing methods.

Second, imbricate wedges are analogous to plate-tectonic accretionary prisms in structural style, shale-dominated lithology, and marine setting. Research on the role of overpressure on the dynamics of imbricate wedges may thus have application to accretionary prisms, and vice versa.

Finally, imbricate wedges are closely analogous to glaciotectonic moraines, in that both are composed of weak substrate at the periphery of a spreading crystalline mass. Determining how imbricate wedges relate to surges in canopy advance, geometry of base salt, or substrate overpressure may clarify our understanding of glacial systems, whose subsurface geology is much less known.

Thrust faults form in diverse settings, with a variety of driving forces. Although some aspects of thrust tectonics are unique to a particular environment, others can be applied more widely. Canopy-margin thrusts offer a different perspective of thrust styles,

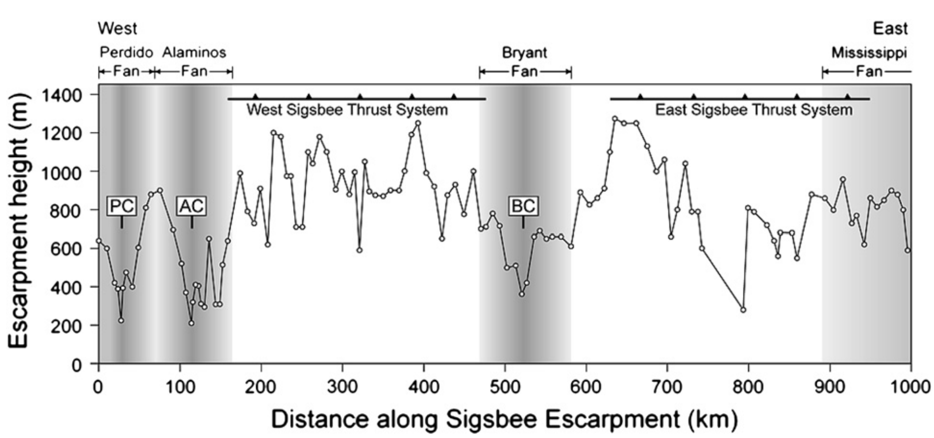

Fig. 13. Plot of escarpment height vs. sinuous distance along the Sigsbee Escarpment, measured eastward from the U.S.–Mexico border. Low-relief parts of the Sigsbee Escarpment correlate with submarine fans, shown as vertical bands with darker gray toward the geographic center of the fan. Active canopy-margin thrust systems occur in the high-escarpment-relief areas between the fans. Vertical black lines annotated by letters in white boxes mark positions of major submarine canyons. PC = Perdido Canyon, AC = Alaminos Canyon, BC = Bryant Canyon.

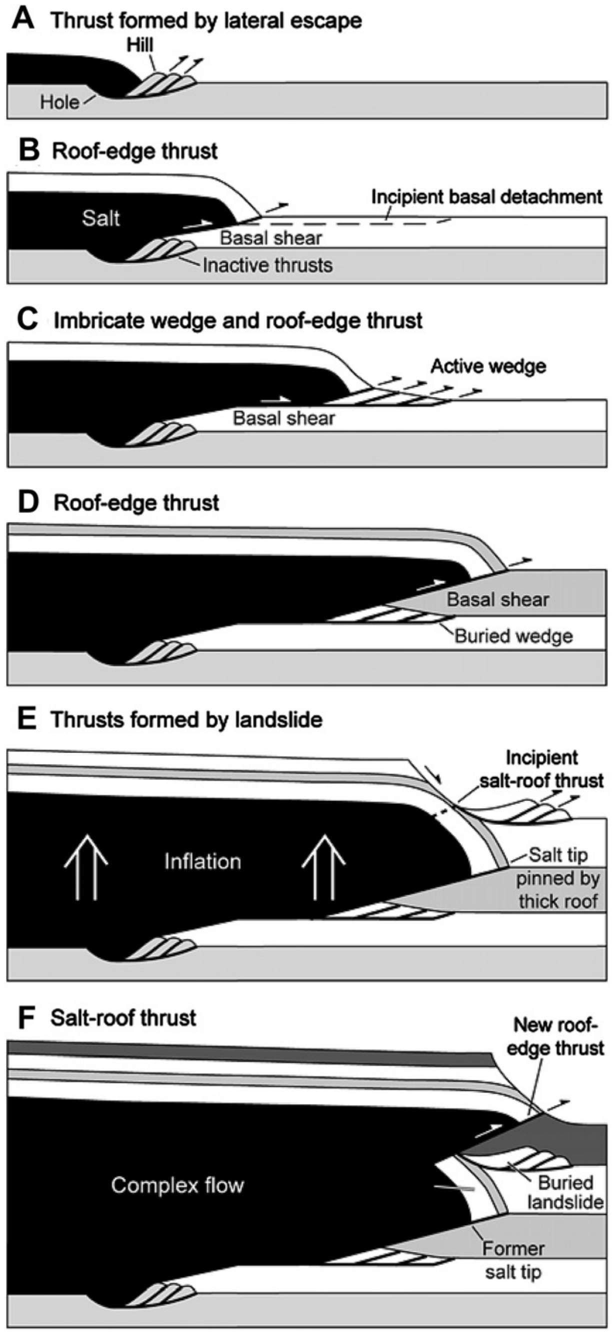

Fig. 14. Schematic cross sections showing how different processes can interact to build a canopy-margin thrust system over time. The sequence of events shown is partly arbitrary, and other evolutionary paths are possible.

and insights from the wealth of exquisite seismic data along the Sigsbee Escarpment may be applicable far beyond the Gulf of Mexico.

Acknowledgments

The authors are grateful to Mark Rowan, William Dunne, and an unnamed reviewer for helpful comments on earlier versions of this manuscript. Diagrams were drafted by Nancy Cottington. The manuscript was edited by Lana Dieterich. The project was funded by the Applied Geodynamics Laboratory consortium, comprising the following companies: Anadarko, BHP Billiton., BP, CGGVeritas, Chevron, Cobalt, ConocoPhillips, Devon, ENI, ExxonMobil, Fugro, GX Technology, Hess, IMP, Maersk, Marathon, Mariner, Maxus, Murphy, Nexen, Noble, Pemex, Petrobras, PGS, Samson, Saudi Aramco, Shell, StatoilHydro, TGS-NOPEC, Total, and Woodside. The authors received additional support from the Jackson School of Geosciences, The University of Texas at Austin. Publication was authorized by the Director, Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin.

References

Aber, J.S., Croot, D.G., Fenton, M.M., 1989. Glaciotectonic Landforms and Structures. Kluwer, Dordrecht.

Alexander, R.J., Bjerstedt, T.W., Moate, S.L., 2005. Edge-Sigsbee folds, Gulf of Mexico, USA. In: Shaw, J.H., Connors, C., Suppe, J. (Eds.), Seismic Interpretation of Contractional Fault-Related Folds: An AAPG Seismic Atlas. American Association of Petroleum Geologists Studies in Geology, 53, pp. 133–134.

Al-Khafaji, Z.A., Young, A.G., DeGroff, W., Humphrey, G.D., 2003. Geotechnical properties of the Sigsbee Escarpment from deep soil borings. Offshore Technology Conference, Houston, Texas, OTC 15158, 26 pp.

Bangs, N.L., Shipley, T.H., Gulick, S.P.S., Moore, G.F., Kuromoto, S., Nakamura, Y., 2004. Evolution of the Nankai Trough décollement from the trench into the seismogenic zone: inferences from three-dimensional seismic reflection imaging. Geology 32, 273–276.

Bangs, N.L., Shipley, T.H., Moore, J.C., Moore, G.F., 1999. Fluid accumulation and channeling along the northern Barbados Ridge décollement thrust. Journal of Geophysical Research 104, 20399–20414.

Bangs, N.L.B., Westbrook, G.K., Ladd, J.W., Buhl, P., 1990. Seismic velocities from the Barbados Ridge complex: indicators of high pore fluid pressures in an accretionary complex. Journal of Geophysical Research 95, 8767–8782.

Banks, C.J., Warburton, J., 1986. 'Passive-roof' duplex geometry in the frontal structure of the Kirthar and Sulaiman mountain belts, Pakistan. Journal of Structural Geology 8, 229–237.

Baud, R.D., Haglund, J.L., 1996. Enhanced subsalt exploration utilizing the basal salt shear model. Gulf Coast Association of Geological Societies Transactions 46, 9–14.

Beaubouef, R.T., Friedmann, S.J., 2000. High resolution seismic/sequence stratigraphic framework for the evolution of Pleistocene intra slope basins, western Gulf of Mexico: depositional models and reservoir analogs. In: Weimer, P., Slatt, R.M., Coleman, J., Rossen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J., Lawrence, D.T. (Eds.), Deep-Water Reservoirs of the World, GCSSEPM Foundation 20th Annual Research Conference, pp. 40–60.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold, London, 734 pp.

Bilotti, F., Shaw, J.H., 2005. Deep-water Niger Delta fold and thrust belt modeled as a critical-taper wedge: the influence of elevated basal fluid pressure on structural styles. AAPG Bulletin 89, 1475–1491.

Bray, C.J., Karig, D.E., 1985. Porosity of sediments in accretionary prisms and some implications for dewatering processes. Journal of Geophysical Research 90, 768–778.

Brown, K., Westbrook, G.K., 1988. Mud diapirism and subcretion in the Barbados Ridge accretionary complex: the role of fluids in accretionary processes. Tectonics 7, 613–640.

Brun, J.P., Merle, O., 1985. Strain patterns in models of spreading-gliding nappes. Tectonics 4, 705–719.

Bryant, W.R., Liu, J.Y., 2000. Bathymetry of the Gulf of Mexico (TAMU-SG-00-606). Texas, Texas Sea Grant, CD-ROM, College Station.

Camerlo, R.H., Benson, E.F., 2006. Geometric and seismic interpretation of the Perdido fold belt: northwestern deep-water Gulf of Mexico. AAPG Bulletin 90, 363–386.

Cobbold, P.R., Szatmari, P., Demercian, L.S., Coelho, D., Rossello, E.A., 1995. Seismic and experimental evidence for thin-skinned horizontal shortening by convergent radial gliding on evaporites, deep-water Santos Basin, Brazil. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.), Salt Tectonics: A Global Perspective, 65. American Association of Petroleum Geologists Memoir, pp. 305–321.

Cochrane, G.R., Moore, J.C., MacKay, M.E., Moore, G.F., 1994. Velocity and inferred porosity model of the Oregon accretionary prism from multichannel seismic reflection data: implications on sediment dewatering and overpressure. Journal of Geophysical Research 99, 7033–7043.

Dailly, P., 2000. Tectonic and stratigraphic development of the Rio Muni Basin, Equatorial Guinea: the role of transform zones in Atlantic Basin evolution. In: Mohriak, W., Talwani, M. (Eds.), Atlantic Rifts and Continental Margins, 115. American Geophysical Union Geophysical Monograph, pp. 105–128.

Davis, D., Suppe, J., Dahlen, F.A., 1983. Mechanics of fold-and-thrust belts and accretionary wedges. Journal of Geophysical Research 88, 1153–1172.

Demercian, S., Szatmari, P., Cobbold, P.R., 1993. Style and pattern of salt diapirs due to thin-skinned gravitational gliding, Campos and Santos basins, offshore Brazil. Tectonophysics 228, 393–433.

Diegel, F.A., Karlo, J.F., Schuster, D.C., Shoup, R.C., Tauvers, P.R., 1995. Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf coast continental margin. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.), Salt Tectonics: A Global Perspective, 65. American Association of Petroleum Geologists Memoir, pp. 109–151.

Doust, H., Omatsola, E.M., 1990. Niger delta. In: Edwards, J.D., Santogrossi, P.A. (Eds.), Divergent/Passive Margins, 48. American Association of Petroleum Geologists Memoir, pp. 201–238.

Duval, B., Cramez, C., Jackson, M.P.A., 1992. Raft tectonics in the Kwanza Basin, Angola. Marine and Petroleum Geology 9, 389–404.
Ebrom, D., Albertin, M., Heppard, P., 2006. Subsalt pressure prediction from multicomponent seismics (and more!). The Leading Edge 25, 1540–1542.
Fletcher, R.C., Hudec, M.R., Watson, I.A., 1995. Salt glacier and composite sediment-salt glacier models for the emplacement and early burial of allochthonous salt sheets. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.), Salt Tectonics: A Global Perspective. American Association of Petroleum Geologists Memoir, 65, pp. 77–108.
Gaullier, V., Mart, Y., Bellaiche, G., Vendeville, B., Mascle, J., Zitter, T., the second leg "PRISMED II" scientific party, 2000. Salt tectonics in and around the Nile deep-sea fan: insights from the "PRISMED II" cruise. In: Vendeville, B.C., Mart, Y., Vigneresse, J.L. (Eds.), Salt, Shale, and Igneous Diapirs In and Around Europe. Geological Society, vol. 174. Special Publications, London, pp. 111–129.
Gordy, P.L., Frey, F.R., Norris, D.K., 1977. Geological Guide for the CSPG 1977 Waterton-Glacier Park Field Conference. Canadian Society of Petroleum Geologists, Calgary, 93 pp.
Harrison, H.L., Patton, B., 1995. Translation of salt sheets by basal shear. In: Travis, C.J., Harrison, H., Hudec, M.R., Vendeville, B.C., Peel, F.J., Perkins, B.E. (Eds.), Salt, Sediment and Hydrocarbons, 16th Annual GCSSEPM Foundation Bob F. Perkins Research Conference Proceedings, pp. 99–107.
Heaton, R.C., Jackson, M.P.A., Bamahmoud, M., Nani, A.S.O., 1995. Superposed Neogene extension, contraction, and salt canopy emplacement in the Yemeni Red Sea. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.), Salt Tectonics: A Global Perspective, 65. American Association of Petroleum Geologists Memoir, pp. 333–351.
House, W.M., Pritchett, J.A., 1995. Fluid migration and formation pressures associated with allochthonous salt sheets in the northern Gulf of Mexico. In: Travis, C.J., Harrison, H., Hudec, M.R., Vendeville, B.C., Peel, F.J., Perkins, B.E. (Eds.), Salt, Sediment and Hydrocarbons, 16th Annual GCSSEPM Foundation Bob F. Perkins Research Conference Proceedings, pp. 121–124.
Huber, W.F., 1989. Ewing Bank thrust fault zone Gulf of Mexico and its relationship to salt sill emplacement, Tenth Annual Research Conference, GCSSEPM Foundation, Houston, Texas, pp. 60–65.
Hudec, M.R., Fletcher, R.C., Watson, I.A., 1993. The composite salt glacier: extension of the salt glacier model to post-burial conditions (abs). Proceedings of the AAPG Hedberg Conference on Salt Tectonics, Bath, England, September 13–17.
Hudec, M.R., Jackson, M.P.A., 2006. Advance of allochthonous salt sheets in passive margins and orogens. AAPG Bulletin 90, 1535–1564.
Hudec, M.R., Jackson, M.P.A., Schultz-Ela, D.D., 2009. The paradox of minibasin subsidence into salt: clues to the evolution of crustal basins. Geological Society of America Bulletin 121, 201–221.
Humphris Jr., C.C., 1978. Salt movement on continental slope, northern Gulf of Mexico. In: Bouma, A.H., Moore, G.T., Coleman, J.M. (Eds.), Framework, Facies, and Oil-Trapping Characteristics of the Upper Continental Margin, 7. AAPG, Studies in Geology, Tulsa, Oklahoma, pp. 69–86.
Ings, S.J., Beaumont, C., Gemmer, L., 2004. Numerical modeling of salt tectonics on passive continental margins: preliminary assessment of the effects of sediment loading, buoyancy, margin tilt, and isostasy. In: Post, P.J., Olson, D.L., Lyons, K.T., Palmes, S.L., Harrison, P.F., Rosen, N.C. (Eds.), Salt-Sediment Interactions and Hydrocarbon Prospectivity, 24th Annual Research Conference, GCSSEPM Foundation, Houston, Texas, pp. 36–68.
Jackson, M.P.A., Hudec, M.R., 2004. A new mechanism for advance of allochthonous salt sheets. In: Post, P.J., Olson, D.L., Lyons, K.T., Palmes, S.L., Harrison, P.F., Rosen, N.C. (Eds.), Salt-Sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century, 24th Annual GCSSEPM Foundation Bob F. Perkins Research Conference, pp. 220–242.
Jackson, M.P.A., Hudec, M.R., Jennette, D.C., Kilby, R.E., 2008. Evolution of the Cretaceous Astrid thrust belt in the ultradeep-water Lower Congo Basin, Gabon. AAPG Bulletin 92, 487–511.
Jones, P.B., 1996. Triangle zone geometry, terminology and kinematics. Bulletin of Canadian Petroleum Geology 44, 139–152.
LeBlanc, L., 1994. Drilling, completion, workover challenges in subsalt formations. Offshore 54 (7), 42–44. 59.
Letouzey, J., Colletta, B., Vially, R., Chermette, J.C., 1995. Evolution of salt-related structures in compressional settings. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.), Salt Tectonics: A Global Perspective, 65. American Association of Petroleum Geologists Memoir, pp. 41–60.
Lundin, E.R., 1992. Thin-skinned extensional tectonics on a salt detachment, northern Kwanza Basin, Angola. Marine and Petroleum Geology 9, 405–411.
Marton, L.G., Tari, G.C., Lehmann, C.T., 2000. Evolution of the Angolan passive margin, west Africa, with emphasis on past-salt structural styles. In: Mohriak, W.U., Talwani, M. (Eds.), Atlantic Rifts and Continental Margins. American Geophysical Union Geophysical Monograph 115, 129–149.
Mauffret, A., Pascal, G., Maillard, A., Gorini, C., 1995. Tectonics and deep structure of the northwestern Mediterranean Basin. Marine and Petroleum Geology 12, 645–666.
Merle, O., 1986. Patterns of stretch trajectories and strain rates within spreading-gliding nappes. Tectonophysics 124, 211–222.
Morley, C.K., Guerin, G., 1996. Comparison of gravity-driven deformation styles and behavior associated with mobile shales and salt. Tectonics 15, 1154–1170.
Mount, V., Dull, K., Mentemeier, S., 2007. Structural style and evolution of traps in the Paleogene play, deepwater Gulf of Mexico. In: Kennan, L., Pindell, J., Rosen, N.C. (Eds.), The Paleogene of the Gulf of Mexico and Caribbean Basins: Processes, Events, and Petroleum Systems, 27th Annual GCSSEPM Foundation Bob F. Perkins Research Conference Proceedings, pp. 54–80.
Nadim, F., Krunic, D., Jeanjean, P., 2003. Probabilistic slope stability analyses of the Sigsbee Escarpment. Offshore Technology Conference, Houston, Texas, OTC 15203, 8 pp.
Niemann, J.C., 1997. Gulf of Mexico subsalt deformation zones; weak formation integrity rather than anomalous high pressure zones. Gulf Coast Association of Geological Societies Transactions 47, 403–411.
Nowacki, F., Solhjell, E., Nadim, F., Liedke, E., Andersen, K.J., Andresen, L., 2003. Deterministic slope stability analyses of the Sigsbee Escarpment. Offshore Technology Conference, Houston, Texas, OTC 15160, 12 pp.
O'Brien, J., Lerche, I., 1994. Understanding subsalt overpressure may reduce drilling risks. Oil and Gas Journal 92 (4), 28–34.
O'Brien, J.J., Lerche, I., Yu, Z., 1993a. Observations and inferences for overpressure development under salt sheets in the Gulf of Mexico. Gulf Coast Association of Geological Societies Transactions 43, 281–289.
O'Brien, J.J., Lerche, I., Yu, Z., 1993b. Measurements and models under salt sheets in the Gulf of Mexico. In: Armentrout, J.M., Bloch, R., Olson, H.C., Perkins B.F. (Eds.), Rates of Geologic Processes; Tectonics, Sedimentation, Eustasy and Climate; Implications for Hydrocarbon Exploration, 14th Annual GCSSEPM Foundation Research Conference Proceedings, pp. 155–163.
Orange, D.L., Angell, M.M., Brand, J.R., Thomson, J., Buddin, T., Williams, M., Hart, W., Berger III, W.J., 2003. Geological and shallow salt tectonic setting of the Mad Dog and Atlantis Fields: relationship between salt, faults, and seafloor geomorphology. Offshore Technology Conference, Houston, Texas, OTC 15157, 16 pp.
Peel, F.J., Travis, C.J., Hossack, J.R., 1995. Genetic structural provinces and salt tectonics of the Cenozoic offshore U.S. Gulf of Mexico: a preliminary analysis. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.), Salt Tectonics: A Global Perspective, 65. American Association of Petroleum Geologists Memoir, pp. 153–175.
Perez, M.A., Clyde, R., D'Ambrosio, P., Israel, R., Leavitt, T., Nutt, L., Johnson, C., Williamson, D., 2008. Meeting the subsalt challenge. Oilfield Review 20, 32–45.
Petmecky, R.S., Albertin, M.L., Burke, N., 2009. Improving sub-salt imaging using 3D basin model derived velocities. Marine and Petroleum Geology 26, 457–463.
Prather, B.E., Booth, J.R., Steffens, G.S., Craig, P.A., 1998. Classification, lithologic calibration, and stratigraphic succession of seismic facies of intraslope basins, deep-water Gulf of Mexico. AAPG Bulletin 82, 701–728.
Ramberg, H., 1981. Gravity, Deformation and the Earth's Crust in Theory, Experiments and Geological Application, second ed. Academic Press, London, 452 pp.
Rohleder, S.A., Sanders, W.W., Williamson, R.N., Faul, G.L., Dooley, L.B., 2003. Challenges of drilling an ultra-deep well in deepwater—Spa Prospect. SPE/IADC Drilling Conference, Amsterdam, The Netherlands, February 19–21, Paper SPE/IADC 79810.
Rotnicki, K., 1976. The theoretical basis for and a model of glaciotectonic deformations. Quaestiones Geographicae 3, 103–139.
Rowan, M.G., 1995. Structural styles and evolution of allochthonous salt, central Louisiana outer shelf and upper slope. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.), Salt Tectonics: A Global Perspective, 65. American Association of Petroleum Geologists Memoir, pp. 199–228.
Rowan, M.G., 2002. Salt-related accommodation in the Gulf of Mexico deepwater: withdrawal or inflation, autochthonous or allochthonous? Gulf Coast Association of Geological Societies Transactions 52, 861–869.
Rowan, M.G., Peel, F.J., Vendeville, B.C., 2004. Gravity-driven fold belts on passive margins. In: McClay, K.R. (Ed.), Thrust Tectonics and Hydrocarbon Systems, 82. American Association of Petroleum Geologists Memoir, pp. 157–182.
Saffer, D.M., Bekins, B.A., 2002. Hydrologic controls on the morphology and mechanics of accretionary wedges. Geology 30, 271–274.
Saffer, D.M., Bekins, B.A., 2006. An evaluation of factors influencing pore pressure in accretionary complexes: implications for taper angle and wedge mechanics. Journal of Geophysical Research 111. doi:10.1016/j.jsg.2009.06.005 B04101.
Schuster, D.C., 1995. Deformation of allochthonous salt and evolution of related salt-structural systems, eastern Louisiana Gulf Coast. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.), Salt Tectonics: A Global Perspective. American Association of Petroleum Geologists Memoir 65, 177–198.
Seni, S.J., Jackson, M.P.A., 1992. Segmentation of salt allochthons. Geology 20, 169–172.
Tari, G., Molnar, J., Ashton, P., 2003. Examples of salt tectonics from West Africa: a comparative approach. In: Arthur, T.J., MacGregor, D.S., Cameron, N.R. (Eds.), Petroleum Geology of Africa: New Themes and Developing Technologies. Geological Society, vol. 207. Special Publications, London, pp. 85–104.
Taylor, L.A., Holcombe, T.L., Bryant, W.R., 2002. Bathymetry of the northern Gulf of Mexico and the Atlantic Ocean east of Florida. NOAA National Geophysical Data Center, Map, Scale 1 2,116,805.
Trudgill, B.D., Rowan, M.G., Fiduk, J.C., Weimer, P., Gale, P.E., Korn, B.E., Phair, R.L., Gafford, W.T., Roberts, G.R., Dobbs, S.W., 1999. The Perdido fold belt, northwestern deep Gulf of Mexico, Part 1: structural geometry, evolution and regional implications. AAPG Bulletin 83, 88–113.
van der Wateren, D.F.M., 1985. A model of glacial tectonics applied to the ice-pushed ridges in the central Netherlands. Bulletin of the Geological Society Denmark 34, 55–74.
Weimer, P., Buffler, R., 1992. Structural geology and evolution of the Mississippi Fan Fold Belt, deep Gulf of Mexico. AAPG Bulletin 76, 225–251.

Westbrook, G.K., Smith, M.J., 1983. Long décollements and mud volcanoes: evidence from the Barbados Ridge Complex for the role of high pore-fluid pressure in the development of an accretionary complex. Geology 11, 279–283.

Whitson, C.D., McFadyen, M.K., 2001. Lessons learned in the planning and drilling of deep, subsalt wells in the deepwater Gulf of Mexico. SPE Annual Technical Conference and Exhibition, New Orleans, LA, September 30–October 3, Paper SPE 71363.

Willson, S.M., Edwards, S., Heppard, Li, X., Coltrin, G., Chester, D.K., Harrison, H.L., Cocales, B.W., 2003. Wellbore stability challenges in the deep water, Gulf of Mexico: case history examples from the Pompano Field. SPE Annual Technical Conferenceand Exhibition, Denver, CO, October 5–8, Paper SPE 84266.

Wu, S., Bally, A.W., 2000. Slope tectonics—comparisons and contrasts of structural styles of salt and shale tectonics of the northern Gulf of Mexico with shale tectonics of offshore Nigeria in Gulf of Guinea. In: Mohriak, W., Talwani, M. (Eds.), Atlantic Rifts and Continental Margins, 115. American Geophysical Union Geophysical Monograph, pp. 151–172.

Wu, S., Bally, A.W., Cramez, C., 1990. Allochthonous salt, structure and stratigraphy of the northeastern Gulf of Mexico, part II: structure. Marine and Petroleum Geology 7, 334–370.