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Extensional Salt Keels Detached on Eocene-Oligocene Sediments in the Deepwater Northern Gulf of Mexico: Insights into Canopy Advancement, Salt-Sediment Interplay, and Evidence for Unrecognized Mass Sediment Displacement

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ABSTRACT

Extension-related salt keels observed in the deepwater northern Gulf of Mexico can be organized into three categories based on the stratigraphic level at which associated extensional movement occurs. The first category of keels have faults which detach within Oligocene-to-Eocene (O–E) strata. The second category of keels have faults which detach into deep salt. The third category appears to be directly associated with basement level deformation. O–E detached keels are the most important economically and the main focus of examination.

The distribution of O–E detached keels can itself be subdivided into two groups. Group 1 keels are well delineated by mapping of the base salt canopy. These keels form a trend parallel to the Sigsbee Escarpment but offset shelfward (updip). The trend extends over 200 km (125 mi) across the Keathley Canyon outer continental shelf (OCS) area and into the Alaminos Canyon OCS area. The canopy over these keels was emplaced in the late Miocene to early Pliocene. Group 2 keels, previously unrecognized as keels, lie updip of the Sigsbee Escarpment but basinward of the ascension zones where salt rises from the primary autochthonous salt basin(s). This group of O–E keels is not easily delineated by mapping of the base salt canopy. The canopy in this area was emplaced in the early to middle Miocene.

The distance between the group 1 O–E keel trend and the Sigsbee Escarpment varies from 10–30 km (6–18 mi). The trend as mapped is not a single discrete continuous structure but a series of linked shorter keel segments with a few gaps. Linkage style between keel segments appears similar to that seen for growth faults (i.e., relays). In eastern Keathley Canyon, the location for detachment initiation is often found in close relationship with deeper salt structures. Some of these deeper salt structures appear to have moved/adjusted at about the time of O–E keel faulting. In western Keathley Canyon, deep salt is absent below the O–E keels. Available well data and mapping constrain the timing for displacement, which must occur after emplacement of the shallow canopy, to late Miocene–early Pliocene but initial movement could be younger. Observations suggest that the canopy needs to reach a thickness of ~1–1.5 km (~0.6–1 mi) before the underlying weak O–E detachment layers near the Sigsbee Escarpment fail. Failure at shallower levels may occur early as frontal thrusts under minimal cover near the sea floor.

Salt loading (gravity) on a weak detachment is the main driver of extension forming O–E keels. Another component believed critical is the absence of deep structures basinward of the detachment. Non-critical but contributing components include the ability to detach towards basement and/or bathymetric lows, the ability to detach onto basinward flanks of deeper structure, and drive from updip sediment loading. One result of strata displacement by keels may be the creation of overpressured or gumbo zones below the canopy.

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INTRODUCTION

The earliest reference found to salt keels comes from Jamieson (1995) who described them as a downward-projecting mass of salt forming a structural low in the base of an allochthonous salt sheet. Another use of the term salt keel refers to any structural low or displacement of salt below the base of a canopy (Holdaway, 2010). Salt keels projecting below the base of shallow allochthonous salt have been observed since modern seismic data in the deep northern Gulf of Mexico could image beneath the canopy (Fiduk, 2012). A large fraction of these early observed keels were the result of incomplete salt models input into typical non-proprietary data processing. By not continuing the base of salt canopy interpretations (and incorporating additional top-salt base-salt pairs) down to their true levels, an artificially shallow base of salt was produced. Restricting the salt models in this way produced keels in the base of salt which extended below the emplacement level of the shallow canopy but did not accurately reflect the true salt geometry (Fiduk, 2012). Many of these keel structures are feeders/diapirs (Jamieson, 1995; Holdaway, 2010).

During the allochthonous emplacement of a canopy, salt rise rate at the feeder(s) greatly exceed the local sedimentation rate (McGuinness and Hossack, 1993). Therefore, the canopy base is often emplaced subparallel to moderately dipping compared to the relatively flat underlying stratigraphy over which it was extruded (Hudec and Jackson, 2011). Deviations from this occur where salt climbs section in a stair-step fashion of ramps and flats during normal forward or lateral advance (Peel et al., 1995; Hearon et al., 2015) or in salt stock canopies (Rowan, 1995). Ramps and flats on the base lead to sutures (where the canopy amalgamates) or to the canopy termination (Hudec and Jackson, 2009), but are always positive deviations above the emplacement surface. An irregular base of canopy, especially where salt deviates below the local emplacement level, has often been looked upon as a salt modelling error contributing to poor subsalt imaging. The presence of salt keels are a notable exception but can cause poor subsalt imaging when they are left out of the salt model.

It was eventually learned that the base of the canopy can, in fact, be dynamic. Rather than being permanently locked in place at the time of canopy emplacement, the canopy base can and has experienced post-depositional positive and/or negative changes in position due to deeper structural deformation. Most commonly this is the result of salt movement/evacuation at a deeper level below the canopy (Holdaway, 2010). This movement can fault or fold the canopy base (Jamieson, 1995). Evidence for this is seen on seismic data where the canopy base is parallel to underlying stratigraphy but where both canopy base and underlying stratigraphy are steeply inclined/folded (i.e. not in their original sub-horizontal depositional position) (e.g., Pilcher, 2011, their figure 4C; Hudec et al., 2009, their figure 24; Rowan and Inman, 2011, their figures 5, 7, and 8). However, extension of the basement could have the same effect on the canopy and its feeders (Vendeville and Jackson, 1992). The formation of bucket welds, collapsed salt stocks now predominantly filled with Plio-Pleistocene strata (Pilcher et al., 2011), may have this mechanism as their origin. So keels may also form by folding the canopy base or from remnant salt on the flanks of encapsulated mini-basins (M. Hudec, 2016, personal communication).

In this study three categories of extensional salt keels were identified based on where associated extensional movement occurred. The first category of keels are associated with comparatively shallow detachments in sediment at the Oligocene-to-Eocene (O–E) level. The second category of keels detach into deep salt. The third category of keels have displacements associated with basement extension. Of basement related keels, only one well imaged example and several candidate features were observed. It is suspected that there are more to be found but sufficiently good imaging on deep seismic data has been challenging. Deep salt detached keels were more common and better imaged but typically did not displace much salt. O–E detached keels were observed to displace and effect the greatest amount of canopy salt volumetrically. They also have an economic potential as trapping mechanisms for petroleum (Jamieson, 1995). The paper will focus on the O–E detached extensional structures. The authors realize that some of the features to be discussed have not previously been recognized as keels and that there may be other types still to be found. To leave the door open for possible new types we refrain from adding any restrictive criteria to the keel definition.

During this investigation it became apparent that extensional salt keels were closely tied to the processes of salt advancement and canopy deformation. Models for salt advancement (e.g., Hudec and Jackson, 2006, 2009; Rowan et al., 2010; Hearon et al., 2015) and related concepts of thrust fault emplacement have been well published (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). Subsequent deformation/modification of the canopy post emplacement has also been intensely studied (e.g., Seni and Jackson, 1992; Diegel et al., 1995; Rowan, 1995, 2002; Schuster, 1995; Prather et al., 1998; Hudec et al., 2009). Yet within this envelope of intense study salt keels have hardly been mentioned. It is the main focus of this paper to describe O–E keel structural styles related to extension, discuss their distribution, and their potential importance to canopy development and hydrocarbon trapping. As a subordinate goal there is an attempt to place keels appropriately within the broader scope of salt tectonic inquiry.

DATA

Wide azimuth and full azimuth dual coil 3D seismic data were used to identify and map the base of salt and regional subsalt marker beds down to and including acoustic basement. In excess of 100,000 sq. km (38,000 sq. mi) of seismic data covering all or parts of Alaminos Canyon, East Breaks, Garden Banks, Keathley Canyon, Sigsbee Escarpment, Amery Terrace, Walker Ridge, Green Canyon, Atwater Valley, and Ewing Bank outer continental shelf (OCS) protraction areas were examined (Fig. 1). All seismic data used in this study come from the Schlumberger multiclient data library and were used with the expressed permission of Schlumberger management.

OBSERVATIONS AND INTERPRETATION

Oligocene-Eocene (O–E) Detached Keels

Salt keels could conceivably detach at any suitable stratigraphic level. However, regional observations indicate there is a strong preference for detachments to form in the Oligocene to Eocene section (Fiduk et al., 2014a). O–E detached keels were first identified in the literature by Holdaway (2010) who described "Keathley Canyon type" salt keels as asymmetrical lows in the base of the salt canopy where subsalt strata terminate against the salt keel on the steep upslope side and are sub-parallel to the base of the salt keel on the more gently-dipping downslope side. He also observed that strata directly beneath the keel were below their regional level and that there was section missing between the keel and deeper Wilcox/Cretaceous strata. These descriptions were found to be consistent with this study but there is some variability which will be described in the following text. Regional observations found two groups of O–E keels with different structural styles and in different locations. Group 1 forms a trend parallel to the Sigsbee Escarpment. Group 2 is found updip of this trend and is more dispersed in distribution.

Figure 2 gives a representative cross section of an O–E detached keel in eastern Keathley Canyon from group 1. As shown in this example, the keel is a simple inverted triangular shape and is a little less than one OCS block, 5 km (~3 mi) in width. A light blue dashed line shows the approximate level of canopy emplacement prior to keel formation (typically the base salt is not perfectly flat). The main listric detachment fault rotates and displaces Oligocene to Pliocene stratal reflections in the hanging-

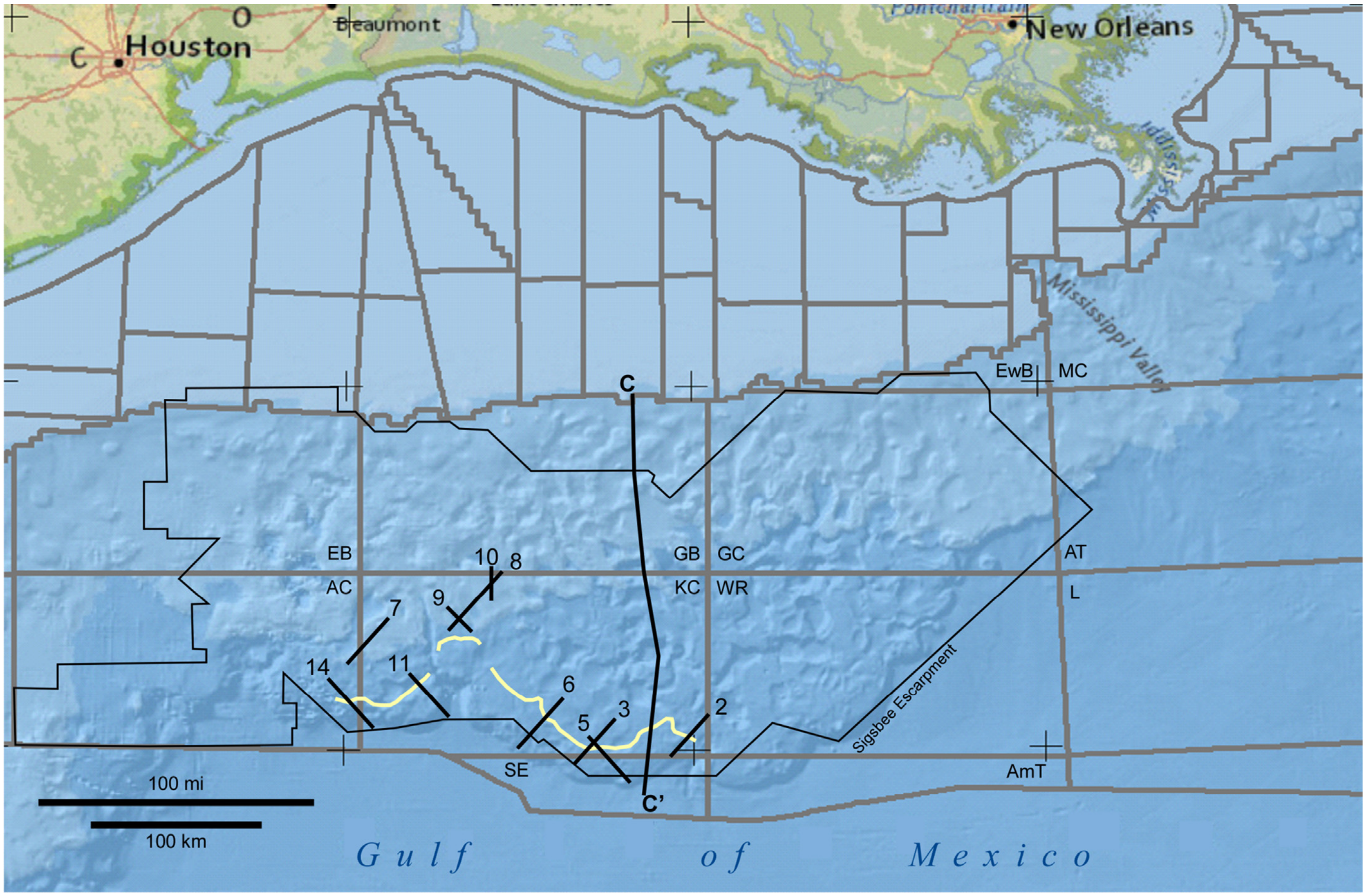

Figure 1. Bathymetry map of the northern Gulf of Mexico showing the composite outline of seismic surveys examined for the study. Yellow lines show the trend of Oligocene-Eocene (O–E) group 1 keels parallel to the Sigsbee Escarpment. Outer continental shelf (OCS) deepwater protraction area abbreviations: AC –Alaminos Canyon, AmT—Amery Terrace, AT—Atwater Valley, EB—East Breaks, EwB—Ewing Bank, GB—Garden Banks, GC—Green Canyon, KC—Keathley Canyon, L—Lund, MC—Mississippi Canyon, SE—Sigsbee Escarpment, and WR—Walker Ridge. Cross-section C–C' is from Pilcher et al. (2011, their figure 4). Black lines and numbers refer to figure locations.

wall block to the southwest. Smaller antithetic and synthetic faults are visible surrounding the main detachment fault. The top and middle Miocene horizons shown in pink and purple, respectively, highlight the sense of displacement. Termination of the main detachment is not resolved because it becomes subparallel to seismic reflections at depth. Due to that ambiguity this group of keels is described as being O–E detached.

Salt in the keel of Figure 2 truncates seismic reflections in the footwall block but is roughly parallel to reflections in the hanging-wall block. This indicates that the base salt deformed along with fault movement and that the canopy was in place before displacement of the keel (i.e., the canopy did not flow into a preexisting bathymetric low). As displacement on the keel fault occurred, salt moved from the canopy level down into the space created by this movement. The salt acted as growth strata recording movement of the fault just as sediment normally does on a typical growth fault (Rowan and Inman, 2011). A black dashed line marks the regional level of the top Miocene horizon (as the light blue dashed line does for the base canopy). Both the salt keel and the top Miocene horizon are well below their regional levels in the detachment's hanging-wall block. At this location the salt keel is 760 m (2500 ft) below canopy emplacement level (yellow line in Figure 2). Measured from the footwall block there was approximately 3350 m (11,000 ft) of overburden on the detachment prior to canopy emplacement.

Any stratal truncations below the rotated keel would define the exact time of canopy emplacement at this location. Because the canopy was in place prior to keel formation, the age of such truncations would place a maximum age constraint on the keel (assuming that the keel formed immediately after canopy emplacement). Regional mapping brings the top Miocene horizon in below the keel with the reflections that are rotated down in the hanging-wall block. Accepting that there is some potential for mapping/correlation errors and that Pliocene markers were not mapped, this places the oldest age for keel formation in the early Pliocene (Zanclean, 5.33–3.60 Ma) following the time scale of Gradstein et al. (2012). However, the time of initial keel movement could be younger than this.

Deep in the section below the keel is an allochthonous salt body emplaced during the Late Cretaceous (Fiduk et al., 2007). In eastern to central Keathley Canyon there is a close correlation between O–E keels and deep salt structures. Salt in the deep allochthon did not advance any farther to the southwest than shown in Figure 2. Thus strata on the right edge of the section (Fig. 2) were neither deposited above salt nor affected by later salt withdrawal and consequently are at their regional level. Yet the deep salt was loaded by deposition of adjacent strata causing subsequent salt movement that changed the overburden's relationship with the regional level.

Responding to increased deposition in the Miocene, salt movement formed a deep structure lifting some points above the regional level and dropping others points below the regional level (as shown by the red dashed line in Figure 2). Thinning of the yellow shaded middle Miocene interval suggests that the location

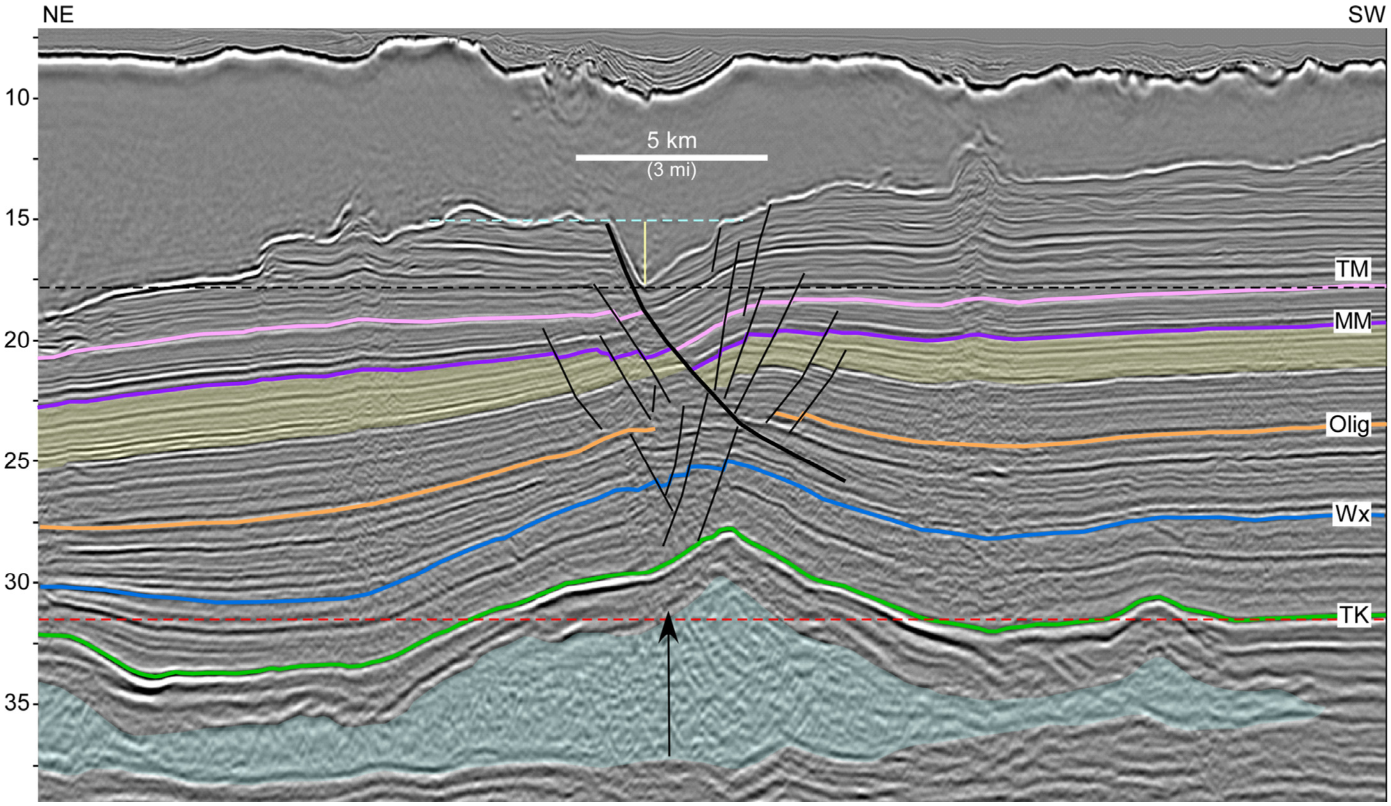

Figure 2. Seismic line showing example of simple group 1 O–E detached keel. The red dashed line shows the top Cretaceous regional level. The light blue dashed line shows the canopy emplacement level at keel. The black dashed line marks the regional level of the top Miocene horizon which is below regional in the keel hanging-wall block. The yellow vertical line shows the keel displacement below canopy. The black arrow points to a graben formed by late salt movement related to keel displacement. The yellow shaded interval shows thinning of middle Miocene over deep salt structure. Horizon abbreviations: Basement—BSMT (red), near top lower Cretaceous—LK (magenta), top Cretaceous—TK (green), top Wilcox Formation—Wx (blue), top Oligocene—Olig (orange), lower Miocene—LM (light green), middle Miocene—MM (violet), and top Miocene—TM (pink). Depth scale in 1000s of feet. Vertical exaggeration ~2:1. Seismic data provided courtesy of Schlumberger Multiclient.

of the deep structural high today is not where it was located in the past (black arrow in Figure 2). Movement of the deep salt resulted in the structural crest migrating basinward and the formation of a small graben over the old crest. There is still work to be done concerning how the deep salt movement and the keel above are related.

All group 1 O–E keel structures are not so simple. The keel shown in Figure 3 has a more complicated shape and developmental history. There are two important faults, one main listric and one antithetic, which connect the base canopy to the detachment level rather than the single listric fault seen in Figure 2. These two faults have displaced a 10+ km (6+ mi) wide section of the canopy base. The keel shape adjacent to the main detachment fault looks similar to that seen in Figure 2. The footwall block strata truncate horizontally into the keel while hanging-wall block strata are roughly parallel to the base salt and rotated down. However, the keel's somewhat triangular shape was modified by displacement on two minor keels and the antithetic fault. Vertical displacement on the main keel is about 1500 m (5000 ft) (long yellow line in Figure 3). There is only 750 m (2500 ft) (short yellow line) of vertical displacement on the smaller keel. The deep salt below this keel shows no obvious late movement and may be too small in volume to respond. Measured from the footwall block there was approximately 2450 m (8000 ft) of overburden on the detachment prior to canopy emplacement.

In the rotated strata below the keel only the middle Miocene and Oligocene horizons could be correlated. Correlation of the top Miocene horizon into the keel is obscured by smaller-scale salt displacement and vertical velocity disruptions in the seismic data. But the presence of the top Miocene horizon below the unaltered canopy to the northeast indicates that it should also be present below the keel. The possibility that strata thin into the keel or that section is missing in the hanging-wall block will be discussed later. Stratal relationships suggest the oldest age for keel formation is in the early Pliocene (Zanclean, 5.33–3.60 Ma). Within the canopy above the keel is the strong trough (white) reflection of an internal suture (black arrow). The suture appears to have been rotated by the downward displacement of the keel. If it was present and subhorizontal prior to keel displacement, then the canopy was at least 1600 m (~5300 ft) thick when movement occurred. An alternative possibility is that allochthonous salt forming the suture experienced downward displacement as it flowed over the already existing keel. This type of displacement has been created in physical models (Dooley et al., 2012).

Mapped Distribution of O–E Keels

Perhaps the most insightful way to look at the distribution of group 1 salt keels is to map the base of the allochthonous salt. The surface shown in Figure 4 is a composite depth to base salt canopy map interpreted on multiple individual seismic surveys acquired by Schlumberger. The different vintages of data have varying velocity models and degrees of overlap. Consequently, there are visible straight line edges, gaps, and interpretation discordances which have not been edited out. There are also local distortions caused by thin salt tongues moving back over mini-

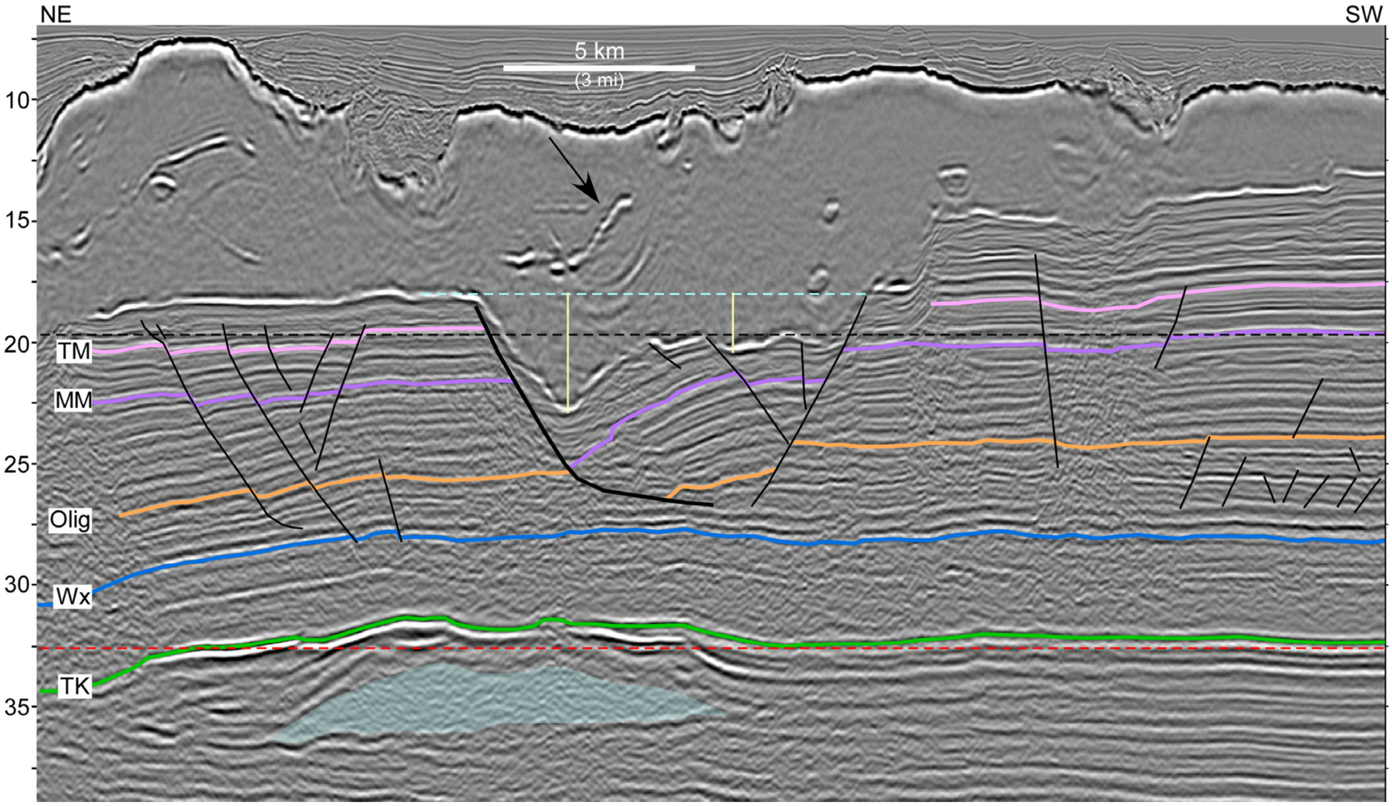

Figure 3. Seismic line showing a large group 1 keel with a more complex displacement. The red dashed line show the top Cretaceous regional level. The light blue dashed line shows the canopy emplacement level at keel. The black dashed line marks the regional level of the middle Miocene horizon which is below regional in the keel hanging-wall block. Black arrow points to folded/rotated suture in canopy. The long yellow vertical line shows the keel displacement below canopy. The short yellow vertical line shows the smaller keel's displacement below canopy. Horizon abbreviations and colors as in Figure 2. Depth scale in 1000s of feet. Vertical exaggeration ~2:1. Seismic data provided courtesy of Schlumberger Multiclient.

basins subsiding into the canopy. The color spectrum ranges from shallow depth warm colors to deep cool colors (red = -3 km [-10,000 ft], purple = -12 km [-40,000 ft]). Areas in black are salt feeders, collapsed feeders, gaps in the interpretation, or locations where the base salt is unresolved. A thick pink dashed line shows the interpreted boundary between salt ascension zones (where salt rises from autochthonous salt basins) and the allochthonous salt canopy.

Despite the noted limitations the base salt canopy map has many interesting features. Of particular interest is a series of slightly arcuate depressions which together form a trend that runs roughly parallel to the Sigsbee Escarpment (just basinward of black dashed line on Figure 4). The trend extends for over 200 km (125 mi) across southern Keathley Canyon and into southern Alaminos Canyon with only a few gaps (Fig. 1). The trend is deflected north as it wraps around the physiographic feature of Keathley Canyon but maintains a relatively consistent distance of 15–30 km (9–18 km) from the canopy's southern termination at the Sigsbee Escarpment. This part of the escarpment has experienced recent active advancement and has been called the Western Sigsbee Thrust System (Hudec and Jackson, 2009). Equally interesting is that the keel trend crosses at least four separate major salt lobes that coalesced to form the shallow canopy. Keathley Canyon itself is a product of the salt lobe/canopy amalgamation process.

Contraction Balancing Extension

The extension forming group 1 O–E keels requires some type of contraction to accommodate it. Yet examination of regional seismic data basinward of the keel front shows no major fold structures or other obvious large-scale contractional features. This begs the question: in what way(s) is/are the extension documented being accommodated?

Figure 5 shows another example of a group 1 O–E keel set back about 30 km (18 mi) landward of the Sigsbee Escarpment. The main keel fault detaches at a level just above the top Wilcox Formation at about 8200 m (27,000 ft), probably within the upper Eocene. Measured from the footwall block there was approximately 2750 m (9000 ft) of overburden on the detachment prior to canopy emplacement. Vertical displacement of the keel is approximately 1370 m (4500 ft) (long yellow line). Vertical displacement on a minor keel fault is less than 300 m (1000 ft) (short yellow line). Below the keel at this location the basinward termination of the deep allochthonous salt is just visible (Fig. 5).

Although there are no large-scale contractional structures present, the interval highlighted in yellow (which sits on the detachment) has a high degree of internal deformation. A lesser amount of deformation at this level is visible in Figure 3. In comparison, the underlying Wilcox and overlying Miocene and younger sections are generally undeformed or display an occasional fault (Fig. 5). Small-scale intra-formational deformation with associated bed thickening is one way to accommodate keel extension. However, qualitatively it is unclear that the intra-formational deformation and bed thickening balance the extension.

The timing of movement for this keel example is more difficult to constrain. Neither the top nor middle Miocene horizon can be correlated under the keel. However, both horizons project below the canopy emplacement level as defined by the top of the

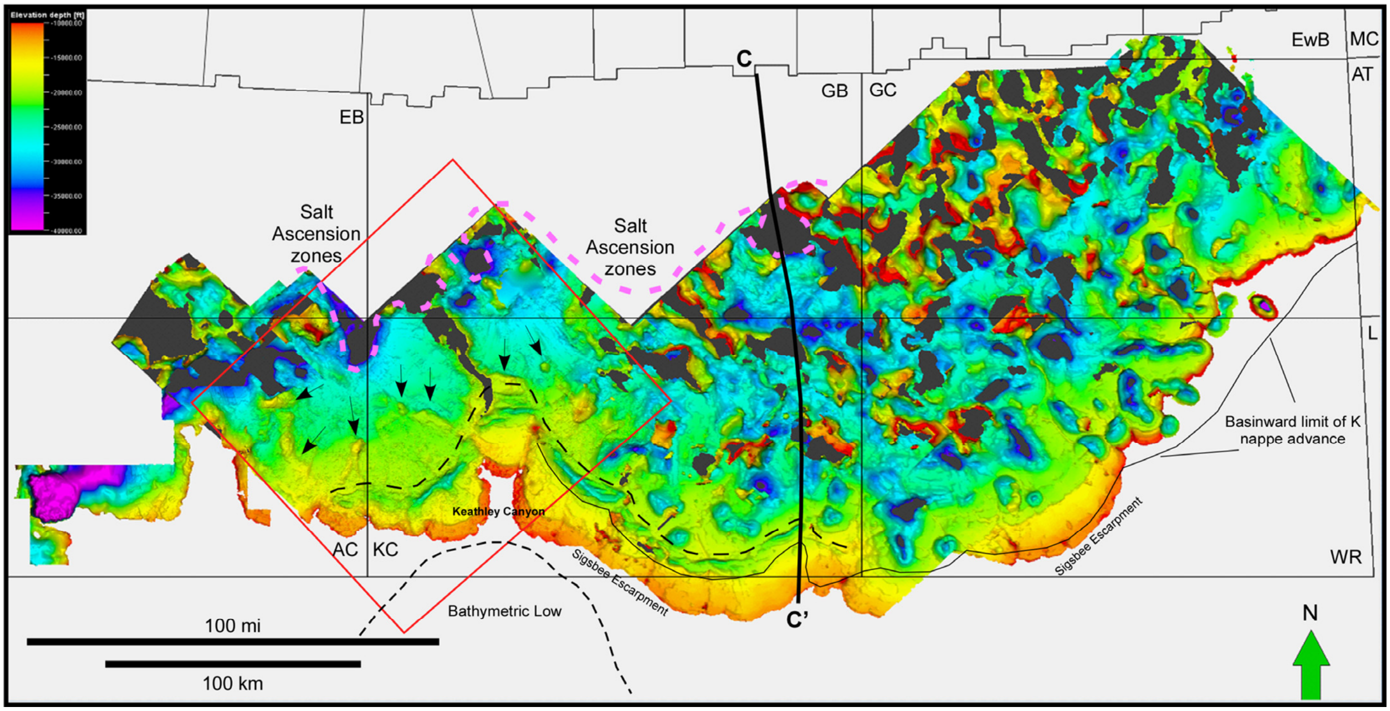

Figure 4. Regional base salt canopy map. Thick pink dashed line shows interpreted boundary between salt ascension zones (where salt rises from autochthonous salt basins) and allochthonous salt canopy. Red square shows location of 3D volume in Figure 13. Unlabeled thin black dashed line shows trend of group 1 O–E detached keels (slightly offset so as not to hide map details). Thin solid black line shows approximate limit of Cretaceous nappe advancement. Small black arrows point to base salt canopy highs. OCS deepwater protraction area abbreviations as in Figure 1. Depth scale, red = -3 km (-10,000 ft), purple = -12 km (-40,000 ft). Areas in black are salt feeders, collapsed feeders, gaps in the interpretation, or locations where the base salt is unresolved.

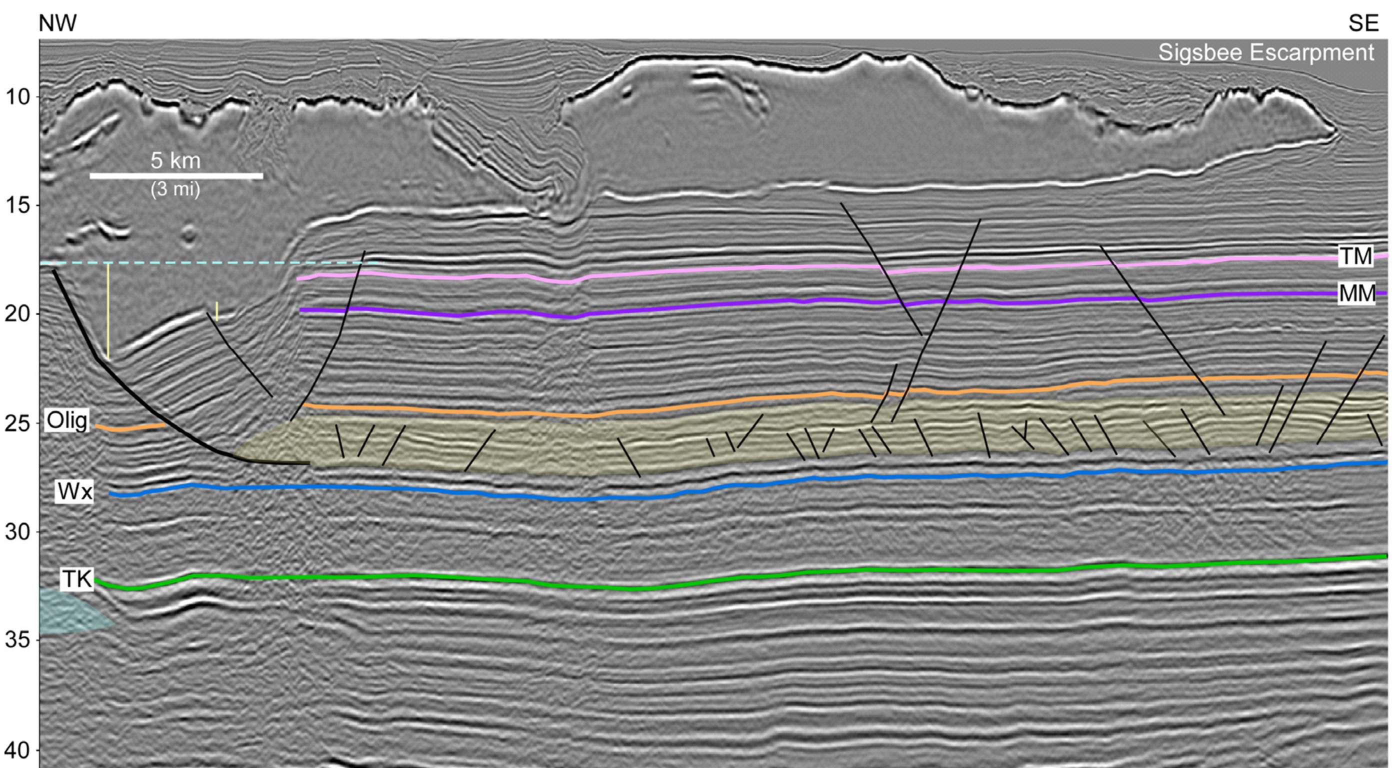

Figure 5. Seismic line showing group 1 O–E keel slightly basinward of deep allochthonous salt limit. Keel extension is partially accommodated by intra-formational deformation (faulting and bed thickening). The light blue dashed line shows the canopy emplacement level at keel. The long yellow vertical line shows the keel displacement below canopy. The short yellow vertical line shows the smaller keel's displacement below canopy. Horizon abbreviations and colors as in Figure 2. Depth scale in 1000s of feet. Vertical exaggeration ~2:1. Seismic data provided courtesy of Schlumberger Multiclient.

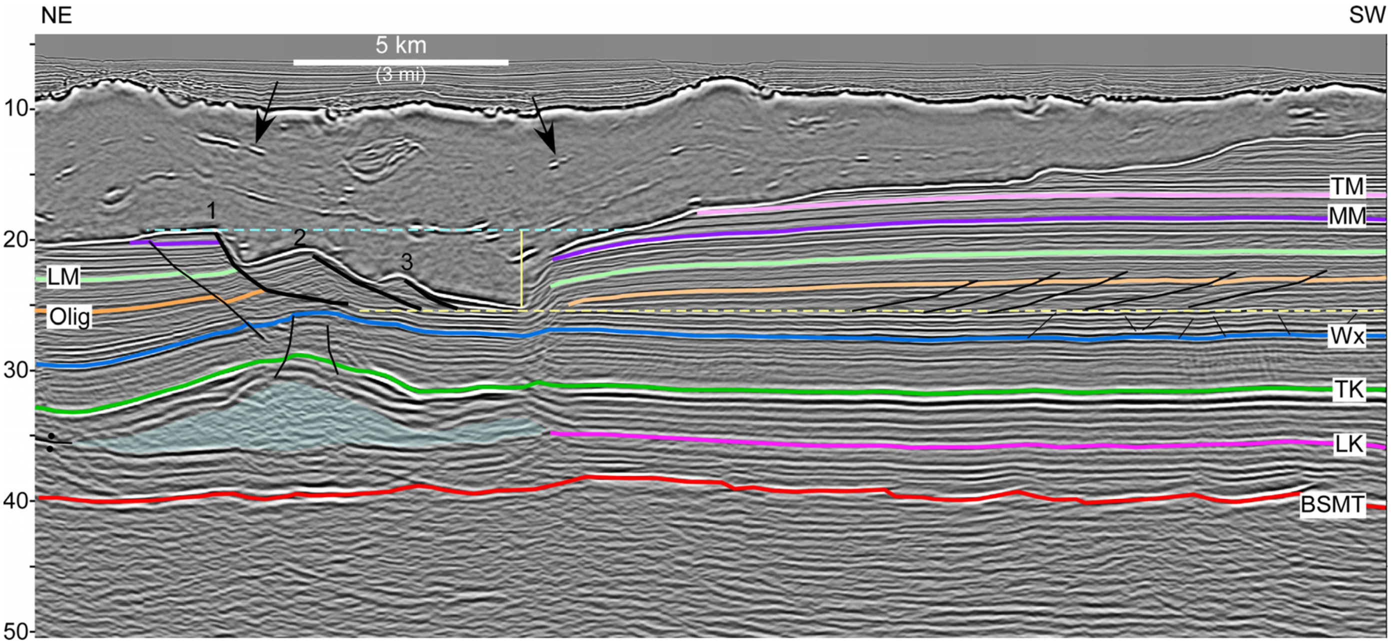

Figure 6. Seismic line showing group 1 O–E keel above deep salt with three individual keels contributing to displacement. The light blue dashed line shows the canopy emplacement level at keel. The yellow dashed line shows keel detachment level. The long yellow vertical line shows the keel displacement below canopy. The black arrow point to sutures in canopy that appear to have been rotated downward by displacement of salt into the keel. Horizon abbreviations and colors as in Figure 2. Depth scale in 1000s of feet. Vertical exaggeration is 1:1. Seismic data provided courtesy of Schlumberger Multiclient.

keel's footwall block (light blue dashed line). This suggests that the time of keel formation is no older than the previous examples (i.e. early Pliocene).

Another way to accommodate keel extension is by thrusting. In central Keathley Canyon there are subtle but visible signs of thrusting basinward of the O–E keels (Fig. 6). A group of low angle thrusts (<15 degrees) with heaves less than 150 m (500 ft) lie 10–15 km (6–9 mi) southwest of the keels. A few of the thrusts offset the top Oligocene horizon and all appear to sole out at the same depth (~7800 m [~25,500 ft]). This is the same level as which the keel detachment projects basinward (yellow dashed line in Figure 6). A few small offset normal and reverse faults lie below the detachment and intersect the top Wilcox horizon. This is the first location where we can infer keel related deformation (albeit minor) possibly continuing down to the top Wilcox level. In all likelihood it may occur in many other locations but is below seismic resolution. Below the keel is a deep allochthonous salt structure and the keel's detachment begins on the basinward side of the deep structure. Although the thrusts are present, they do not qualitatively appear to balance the amount of extension represented by the keels.

The keel structure visible in Figure 6 is unusual in several respects. First, strata below the keel are older than in earlier examples. No Pliocene strata are present until 10–12 km (6–7.5 mi) basinward. This indicates an earlier time (late Miocene) for canopy emplacement. Second, there are three keel faults offsetting the base canopy displacing salt downward. Each of the three faults successively displaces the canopy base to deeper depths and preserves less strata in the hanging-wall block. Third, salt in the keel actually touches down on the detachment. At that point salt is 1800 m (6000 ft) below the canopy emplacement level (yellow line in Figure 6). Measured from the footwall block there was approximately 2150 m (7000 ft) of overburden on the detachment prior to canopy emplacement. It has yet to be determined if the keels moved all at once or at different times.

Similar to Figure 3, there are strong trough (white) reflections of internal sutures within the canopy above the keel (black arrows, Fig. 6). Multiple sutures appear to have been rotated by the downward displacement of salt into the keel. If we take the highest suture and again assume it was present and subhorizontal prior to keel displacement, then the canopy could have been 2100 m (7000 ft) thick or more when displacement occurred. An alternative possibility is that allochthonous salt forming the sutures experienced downward displacement as it flowed over the already existing keels as have been observed in physical models (Dooley et al., 2012).

Maximum age for keel movement is constrained by regional mapping to late Miocene. The development of a thick canopy with multiple downturned sutures hint that displacement could have occurred much later. Alternately, the three keels may suggest loading by three separate salt lobes causing three phases of keel movement.

O–E detached salt keels along the Sigsbee Escarpment are not the only ones to be found. Updip from the Sigsbee Escarpment in western Keathley Canyon and eastern Alaminos Canyon is a second group of O–E detached keels with a less well defined structural style. These keels typically do not have the simple growth fault profile with rotated strata in the hanging-wall block. Often they are characterized by thrusted or displaced strata ahead of the keel and extension hidden in the salt (salt is the growth strata). The displaced strata produce high areas in the base salt canopy (small black arrows on Figure 4) and are less obvious or trend forming than group 1 keels. These high areas were created by imbricate thrusting of sub-canopy strata (lower Miocene, Oligocene, and in rare instances Wilcox) that stacked hundreds to thousands of meters thick. These features may be the imbricate wedges of Hudec and Jackson (2009) and their presence would indicate that canopy advance is at least partly accommodated by subsalt basal shear (Harrison et al., 2004; Harrison and Patton, 1995) and/or substrate expulsion (Hudec and Jackson, 2009).

Figure 7 shows one of the more basinward locations where the stack is over 5 km (3 mi) wide and just under 2000 m (6500 ft) thick (dashed yellow line). Just updip of the thick sediment stack is a broad flat group 2 O–E keel (labeled 1) sitting on the

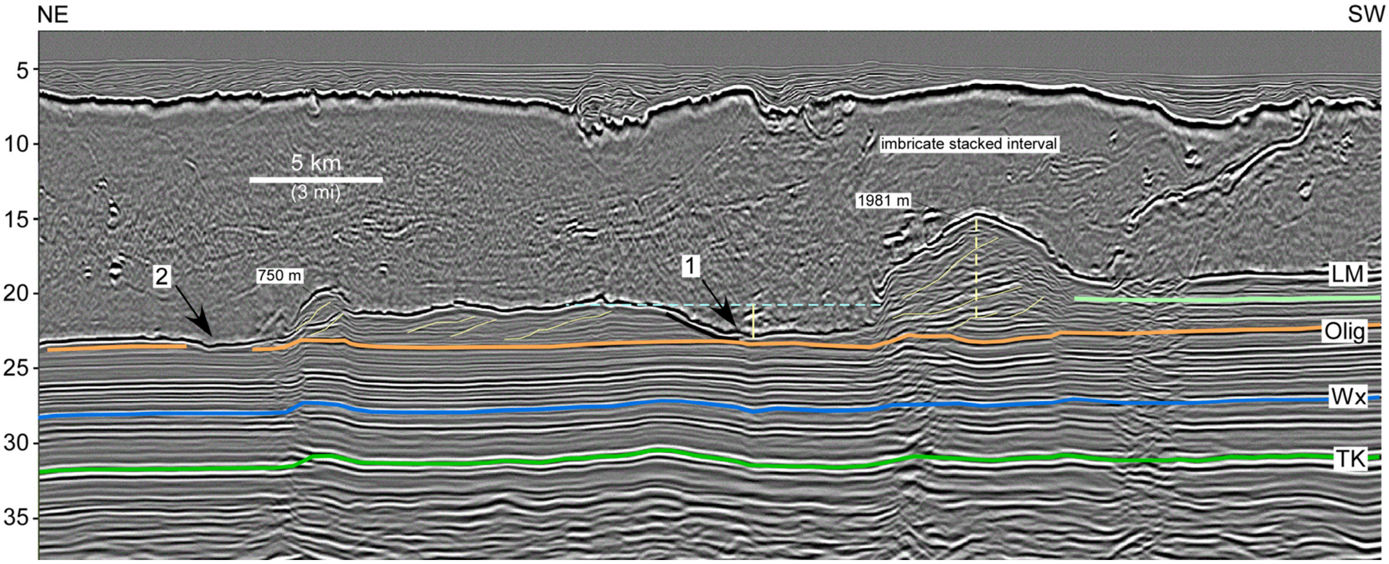

Figure 7. Seismic line in western Keathley Canyon updip from Sigsbee Escarpment showing two group 2 keels. Keels in this area are less obvious and associated keel faults may appear very small. Often the displaced strata are not rotated below the keel but thrusted laterally in front of the advancing canopy. The thrusted strata may form imbricated stacks many 100s to 1000+ m thick. The yellow vertical line shows the keel displacement below canopy. Dashed yellow line shows thick imbricated stack. The black arrows point to keels. The light blue dashed line shows the canopy emplacement level at keel. Horizon abbreviations and colors as in Figure 2. Depth scale in 1000s of feet. Vertical exaggeration ~2:1. Seismic data provided courtesy of Schlumberger Multiclient.

top Oligocene horizon (orange). If the light blue dashed line represents the level of canopy emplacement then this keel has a vertical displacement of 700 m (2300 ft) (yellow line). Updip of keel 1 the lower Miocene section is thickened by low angle thrusts (Fig. 7). The lower Miocene section ends updip at a small stacked interval 750 m (2460 ft) thick. Another group 2 O–E keel (labeled 2) borders the stack and drops below the top Oligocene horizon, but seems to have a negligible vertical offset. The appearance is that the canopy was emplaced just above the top Oligocene horizon. However, we know from regional observations that there is 450–600 m (1500–2000 ft) of missing Miocene section. Thus keel 2 actually extends off Figure 7 to the northeast. It could be argued that these keels are just folded base of canopy features. However, all keels are folded (or faulted) base of canopy features. What is not readily apparent is the nature of the extension (described below).

Both keels in Figure 7 fit the description given by the substrate expulsion hypothesis for canopy margin thrust systems (Hudec and Jackson, 2009, their figure 3C). This occurs when shear stresses created by the advancing canopy become horizontal compressive stresses that drive underlying sediment forward. The keels dropped into holes left behind by the displaced strata. This is the extension seemingly missing in the description above. Although both keels displaced strata ahead of the canopy, canopy advancement may have been temporarily halted by the stacked sediment causing the canopy to inflate before further advancement (i.e., pinned inflation model of Hudec and Jackson, 2006, 2009). Thus it is thought that there are several different processes interacting to achieve basinward advancement of the canopy.

The section shown in Figure 8 is located about 30 km (18 mi) northeast of Figure 7 near the Garden Banks–Keathley Canyon boundary. This is close to where salt rises from the primary autochthonous salt basins to flow south and southeast to form the canopy. There are three group 2 keels identified, labeled 1–3, from downdip to updip respectively. Keel 1 is the highest stratigraphically, sitting on faulted middle Miocene strata. It is 5 km wide (3 mi) with a vertical displacement of 750 m (2500 ft). The footwall block of keel 1 is composed of well imaged, complex, imbricately thrusted lower and middle Miocene strata. This forms a stacked interval similar to that seen in Figure 7 and a corresponding high in the canopy base. The canopy above is over 4100 m (13,500 ft) thick. The Oligocene section below shows thickening caused by low angle thrusts. Keel 2 is over 10 km (6 mi) wide and has a variable detachment level. At its deepest point it detaches into the Oligocene, has a vertical offset of 900 m (3000 ft), and 5 km (3 mi) of canopy overhead. There is no rotated strata beneath it (probably an indicator of substrate expulsion). Most of keel 2 is overlain by a thick minibasin where the canopy is reduced to <2000 m (<7000 ft). Here keel 2 sits on highly thinned lower Miocene strata and thinner than normal Oligocene strata. The missing strata have been displaced to the southwest. Just as in Figure 7 there is evidence for basal shear, substrate expulsion, and pinned inflation as processes involved in canopy advancement (Harrison et al., 2004; Harrison and Patton, 1995; Hudec and Jackson, 2006, 2009).

Keel 3 sits the farthest updip and at the lowest stratigraphic level of any keel yet examined, being virtually on the top Wilcox horizon (blue line, Fig. 8). The maximum vertical displacement is 1800 m (6000 ft) and may have occurred in two steps. The base canopy between keels 2 and 3 is almost a straight line and appears to have been emplaced horizontal but later rotated to its present position. Eocene and Oligocene strata thicken downdip towards keel 2 with the Oligocene exhibiting low angle thrust faults. The top Wilcox and top Cretaceous horizons are folded over a poorly imaged structure at the northeast end of the figure. The original canopy emplacement level is directly above the structure's crest. Based on Figure 8 it appears that the canopy advanced across the deep fold and then developed keel 3 on the fold's basinward limb. Miocene, Oligocene, and any Eocene strata originally on the northeast side of the fold are missing below keel 3. The displaced strata are not seen in this plane of section. Deformation of the underlying fold must have occurred prior to canopy emplacement (since part of the fold crest and flank are missing). It is unclear but the structure may be salt cored. Between keels 2 and 3 strata below the top Cretaceous horizon display minor disharmonic folding indicating multiple detachment surfaces. Again, all three keels fit the description by the substrate expulsion hypothesis for canopy

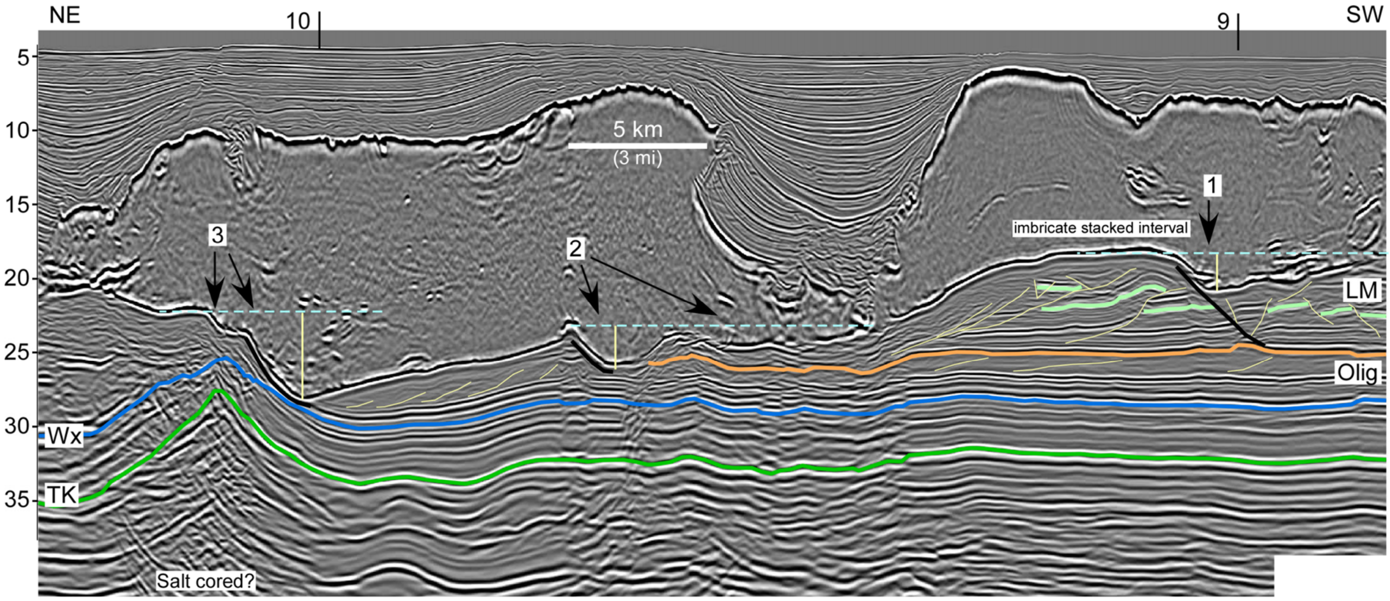

Figure 8. Seismic line in central Keathley Canyon near the border with Garden Banks showing three group 2 keels. The canopy advanced from left to right and arrived above keel 3 in the early Miocene. Once the canopy crossed over the deep fold and reached a critical thickness the keel detached and displaced all strata down to the top Wilcox horizon. The black arrows point to keels. The light blue dashed line shows the canopy emplacement level at keel. The yellow vertical lines show the three keels' displacement below canopy. Tie points for Figures 9 and 10 are identified by numbers at the top of the section. Horizon abbreviations and colors as in Figure 2. Depth scale in 1000s of feet. Vertical exaggeration ~2:1. Seismic data provided courtesy of Schlumberger Multiclient.

margin thrust systems (Hudec and Jackson, 2009, see their figure 3C).

A short seismic line perpendicular to keel 1 in Figure 8 helps reveal the keel's true extensional nature (Fig. 9). The tie point with Figure 8 is 5–6 km (3.1–3.7 mi) to the northwest (updip) of a well formed group 1 O–E keel. Rotated strata in the group 1 keel hanging-wall block downlap onto the detachment at the top of the Oligocene. Keel 1 from Figure 8 can now be seen as one of 4–5 small keels with minor extension and limited rotation on Figure 9. The section also offers a good comparison of the relative simplicity of strata displaced by group 1 keels (right) and the complexity of strata displaced by group 2 keels (left). As would be expected on 3D data, the amount of vertical displacement (750 m [2500 ft]) is the same.

A second short, north-south arbitrary seismic line, rotated 45° to keel 3 on Figure 8 provides a similar perspective on its true extensional nature (Fig. 10). Beneath the canopy more of the contractional deformation of the Cretaceous and Paleogene section is visible as thrust faults, reverse faults, and folding. In contrast to Figure 8 there is less missing section below the canopy. However, directly below the keel it can be seen that the middle Miocene, lower Miocene, and Oligocene are completely missing (Fig. 10). There is a clear updip cutoff of the Oligocene reflection in the keel footwall block above the fold. There is thrusting and bed thickening of the Oligocene and lower Miocene section in the keel hanging-wall block. Downdip offset of the Oligocene reflection is over 5 km. The amount of vertical displacement cannot be confirmed as equal (but it is close) because the canopy emplacement level lies off the section just to the north.

Figures 7–10 have shown that group 2 O–E keels do not require the presence of deeper salt structures to assist their formation. The same is true of group 1 O–E keels even though Figures 2, 3, 5, and 6 all showed salt below the keels. The group 1 O–E keel shown in Figure 11 is in western Keathley Canyon 17–18 km (10.6–11.2 mi) updip of the Sigsbee Escarpment. The keel drops nearly 1800 m (6000 ft) (vertical yellow line) below the canopy emplacement level. The top Oligocene, lower Miocene, and middle Miocene horizons plus upper Miocene strata are rotated down in the hanging-wall block of the main keel fault. Strata at these levels are thickened basinward by intraformational deformation and visible thrust faults. A second smaller displacement keel detaches in the upper Miocene and has the top Miocene horizon rotated in its hanging-wall block (black arrow in Figure 11). There may be several faults within the canopy associated with this keel. Measured from the footwall block there was approximately 1850 m (6000 ft) of overburden on the detachment prior to canopy emplacement.

There are two observations to be made from Figure 11. First, there is no deep salt layer present beneath the keel. The Cretaceous age nappe did not advance across the area west or north of the Keathley Canyon reentrant (Fig. 4). Therefore, the presence of deep salt is not a controlling factor in O–E keel development. Second, there is a significant basement low coincident with the deepest Gulf of Mexico bathymetry basinward of the shallow canopy (Fig. 4). All the horizons older than Oligocene are at greater depth in the basement low than under the keel footwall block, suggesting that gravity has been directing sedimentation towards this area since the creation of the underlying crust. Although the main detachment appears to be flat (yellow dashed line, Fig. 11), it may not have always been so. Updip sediment loading during the Neogene has significantly changed the dip on basement and the location and thickness of the shallow canopy (Peel et al., 1995). This observation will not be discussed here. But basement may have a yet-to-be determined role to play in where and which direction keels develop.

For all the keel examples shown so far, it appears that salt and sediment have reversed their normal roles. In most published field examples and physical models salt forms the detachment and sediment creates the load (Hudec and Jackson, 2011; Rowan et al., 2004; Diegel et al., 1995; and many others). In the examples shown here the canopy is emplaced and inflates until the underlying weak detachment(s) fail. Salt loading (gravity) on a weak detachment is the main driver in keel formation. A simi-

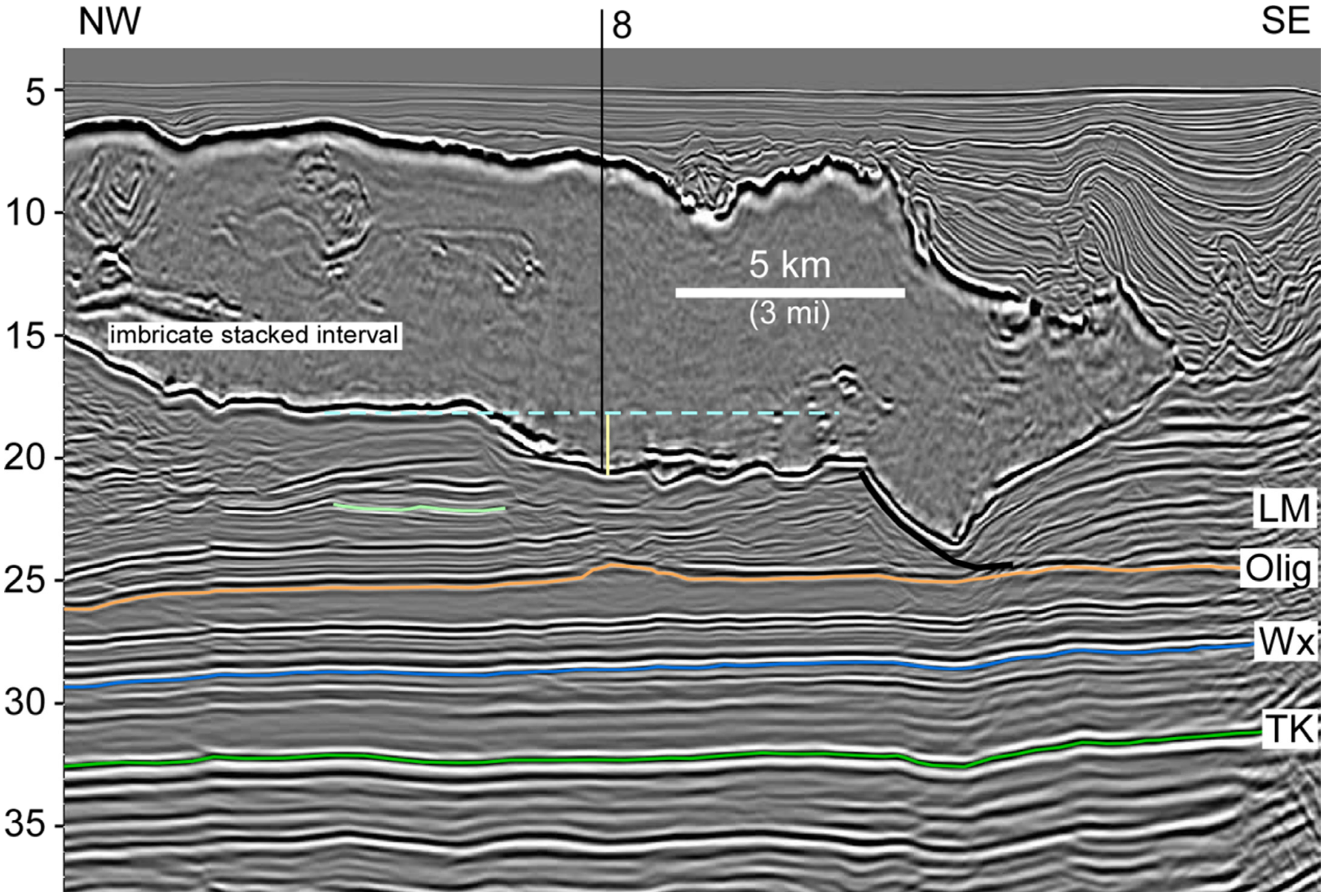

Figure 9. Seismic line in central Keathley Canyon that ties Figure 8 at keel 1. The northwest-southeast line orientation shows more clearly the true extensional nature of keel 1. The section offers a good comparison of the relative simplicity of strata displaced by group 1 keels (right) and the complexity of strata displaced by group 2 keels (left). Horizon abbreviations and colors as in Figure 2. Depth scale in 1000s of feet. Vertical exaggeration ~2:1. Seismic data provided courtesy of Schlumberger Multiclient.

lar process is observed beneath ice glaciers and is known as the gravity spreading model (e.g., Rotnicki, 1976; Aber et al., 1989; Benn and Evans, 1998; Hudec and Jackson, 2009). A question still to be answered is how much loading is necessary to cause failure of the weak detachment layers.

Exploration Prospectivity

Jamieson (1995) first described the trapping potential of salt keels and the economic value of keel structures has since been established. The Enchilada area along the Flex Trend in Garden Banks, including discoveries at Enchilada (block 128), Salsa (block 172), and Chimichanga (block 127), is associated with a down-faulted salt keel that provides part of the updip trap (Robison et al., 1997). The Lucius Field along the group 1 O–E keel trend (Fig. 4) was discovered in December of 2009 in Keathley Canyon block 875. The field now covers Keathley Canyon blocks 874, 875, 918, and 919. Anadarko is the operator with partners Freeport McMoRan, ExxonMobil, Petrobras, INPEX, and Eni. The discovery well was drilled in 2200 m (7100 ft) of water to a depth of 6100 m (20,000 ft). It encountered 60 m (200 ft) of net pay sand in the lower Pliocene and upper Miocene. An appraisal well found 180 m (600 ft) of net pay containing the same high quality 29 degree API (American Petroleum Institute) gravity oil. Initial oil production began in January 2015. The trap is a three-way closure against a salt barrier (refer to the keel fault footwall block in Figures 2, 3, or 6). Total reserves are estimated at 300+ million barrels of oil equivalent. The above field data come from the Anadarko Petroleum Corporation (2016) website and OffshoreTechnology.com (2016).

The structural and geologic settings are very similar to what is shown in Figure 2 (this seismic line is only 6–8 km (3.7–5 mi) southeast of the Lucius discovery well). A group 1 O–E detached keel drops from the canopy above a deep salt structure. One difference is that the keel at Lucius is located just basinward of the deep structural crest. It is also possible that the deep structure is actually a small diapir (the data are inconclusive). If the Wilcox Formation had become a charged reservoir and was subsequently breached, either by diapirism or late salt movement, then the deep structure would focus hydrocarbon migration to shallower potential reservoir intervals like those in the Lucius keel's footwall block. This is the likely charge scenario for the Lucius Field pay sands.

The nearby Hadrian North and South fields operated by ExxonMobil are other examples of petroleum production associated with keel structures. The reservoir there consists of lower Pliocene sand, as seen at Lucius, which produce some oil but mostly gas. The charge scenario is also likely to be the same as at Lucius. Unfortunately, aside from these three examples successful analogs have been hard to find along the group 1 O–E keel trend. A better understanding of how and why the petroleum system at Lucius and Hadrian works would be of great benefit to the industry.

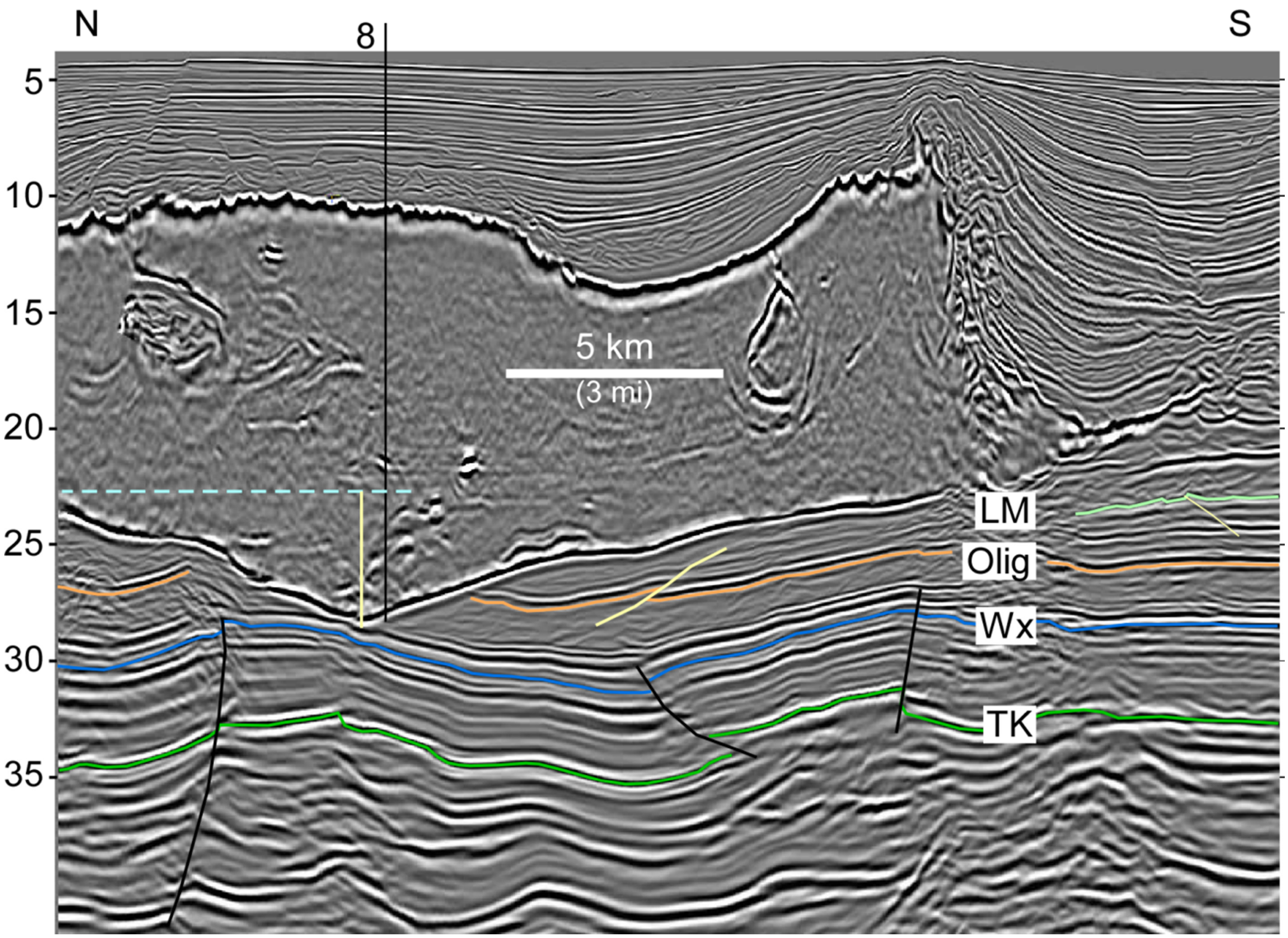

Figure 10. Seismic line in central Keathley Canyon that ties Figure 8 at keel 3. The north-south line orientation shows more clearly the true extensional nature of keel 3. There is a clear updip cutoff of the Oligocene reflection in the keel footwall block above the fold. Downdip offset of the Oligocene reflection is over 5 km. Horizon abbreviations and colors as in Figure 2. Depth scale in 1000s of feet. Vertical exaggeration ~2:1. Seismic data provided courtesy of Schlumberger Multiclient.

There is another potential economic value to understanding keels and the processes of their formation. A joint industry project run from 2005 to 2009 concluded that 64% of the 100+ wells studied had evidence of a subsalt gouge or rubble or gumbo zone (Saleh et al., 2013). The cause of a gumbo zone in the sediment immediately below the canopy has a number of competing theories (beyond the scope of this paper), but it is not well understood. Wells drilling into the subsalt often experience problems including loss of drilling mud, pressure kicks, wellbore instability, cementation issues, and maintaining well control (Saleh et al., 2013). Numerical modeling shows that salt advancing over limited permeability sediments will generate overpressure (Luo et al., 2015). All of these issues are expensive, cause drilling delays, and could lead to well abandonment. Keel detachments and sediment displacement like that seen in Figures 7–10 could be one explanation for how gumbo zones form. Identifying keels, associated detachments, and displaced strata before drilling could lead to better pore pressure and fracture gradient predictions. This would allow better well planning and generate cost savings by avoiding expensive problems. No exploration manager or drilling engineer would willingly plan a well through the large-scale displacement features in Figures 7 and 8. However, most of the overpressured or gumbo zones encountered by drilling are <100 m (<300 ft) thick and are mostly below seismic resolution. Knowing in advance that there are keels present near the well location may allow operations management to plan for the problems before they occur.

DISCUSSION

Distribution of Keels

Any mechanism invoked to explain O–E keel formation must address the mapped distribution shown on the base canopy map (Fig. 4). Group 1 O–E keels form a trend over 200 km (125 mi) long that stretches across Keathley Canyon and parallels the Sigsbee Escarpment. The trend of keels is not straight and deflects northward to curve around the Keathley Canyon reentrant in the Sigsbee Escarpment. In paralleling the Sigsbee Escarpment the trend of keels cross the intersections of at least four major salt lobes merging to form the canopy. The trend of keels is not perfectly continuous either, but has two notable gaps breaking its continuity (Fig. 1). The two gaps formed where major salt lobes merged. Additionally, there must be an explanation for where keels do not exist. There are no O–E detached keels observed east of the Keathley Canyon–Walker Ridge boundary and O–E keels are not found west of easternmost Alaminos Canyon (Fig. 4). Reported observations hope to address why O–E detached keels have a limited distribution in the deep Gulf of Mexico.

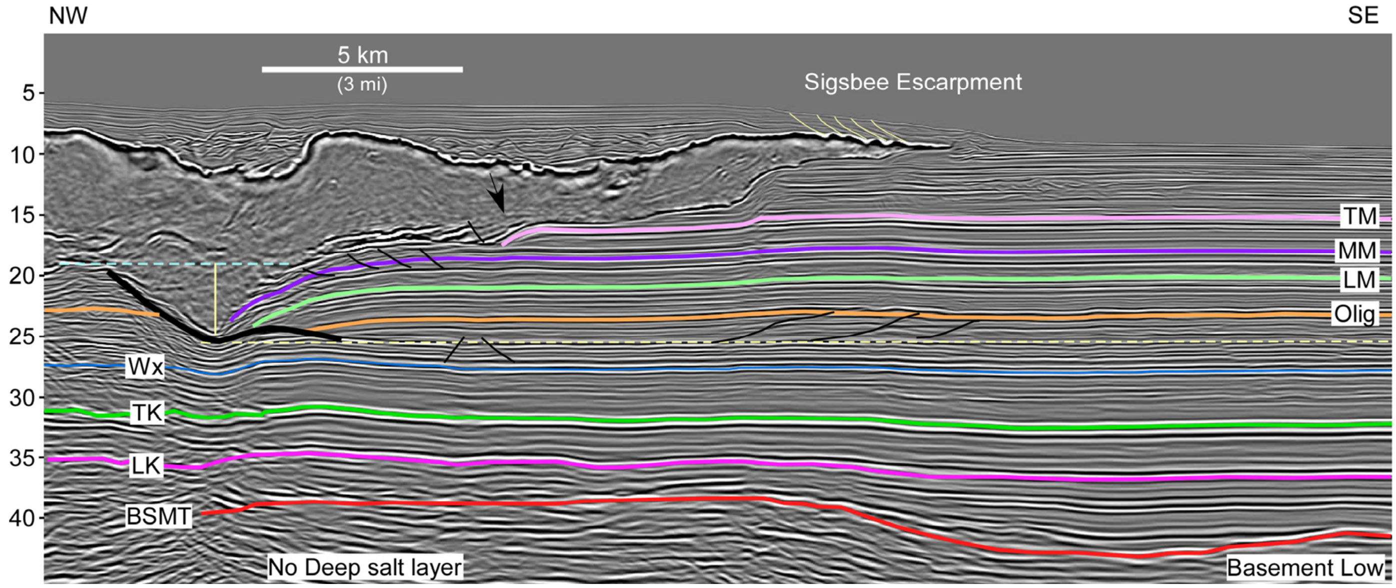

Figure 11. Seismic line showing that group 1 O–E detached keels will still form without a deep salt structures below. The yellow dashed line shows keel detachment level. The light blue dashed line shows the canopy emplacement level at keel. The yellow vertical line show the keel displacement below canopy. The black arrow shows a smaller displacement keel detaching in the upper Miocene with the top Miocene horizon rotating in its hanging-wall block. Horizon abbreviations and colors as in Figure 2. Depth scale in 1000s of feet. Vertical exaggeration is 1:1. Seismic data provided courtesy of Schlumberger Multiclient.

This portion of the discussion will begin by addressing where keels are not found. To the west O–E keels end where they intersect folds of the Perdido Fold Belt. As structural highs, folds in Perdido inhibit the easy basinward translation of strata along the detachments. This disruption happens to both keel groups. Some of the imbricate stacked intervals like those shown on Figures 7 and 8 are piled against the flanks of Perdido folds. To the east the deep Cretaceous salt nappe advanced as far or farther into the basin than the modern canopy (Fig. 4). That nappe has since been dissected by sedimentation forming many diapirs and folds at or near the nappe's termination (e.g., Mississippi Fan fold belt, Green Knoll). These structures may prevent keel formation for the same reason as Perdido folds, by inhibiting the easy basinward translation of strata along the detachments. Additionally, the lower Mississippi Fan presents another structural barrier towards the east. Elevated bathymetry in this direction inhibits faulting as gravity does not typically transport sediment uphill. In the updip areas of eastern Keathley Canyon, western Walker Ridge, and farther north, the structural geology is very complex. Figure 12 shows a north-south regional schematic cross section through eastern Keathley Canyon and Garden Banks, the bucket-weld province of Pilcher et al. (2011). There is discontinuous salt at three separate levels, diapirs connecting the three levels, and both primary and secondary minibasins dissecting the deep salt and canopy. In some places the canopy level has dropped down to the deep salt. The geology is probably too complex and rapidly evolving for large-scale keels to form. However, it is entirely possible that keels or displaced strata below seismic resolution could form in this area. Only at the south end of this section, beyond where there are diapirs, have O–E detached keels been observed.

The locations where O–E detached keels can be found are along the Sigsbee Escarpment in Keathley Canyon and eastern Alaminos Canyon (group 1) and updip of these areas (group 2). The keels detach and move in the same direction as the canopy from which they grow and the canopy has been moving generally to the south. The canopy has moved south because this is the downdip direction and has been so since early in the Gulf's history (Buffler and Sawyer, 1985; Salvador, 1987; Salvador 1991; Sawyer et al., 1991; Hudec et al., 2013). The authors believe that group 1 O–E detached keels are located there because no interfering deep structure exists basinward (otherwise they should also be found to the east). It is speculated that potentially helpful to keel formation is the Gulf of Mexico basin center bathymetric low directly to the south (Figs. 4 and 11). This feature would allow gravity to do the work of moving strata, salt, and keels southward. It helps explain why the deep salt seen in eastern Keathley Canyon isn't a necessary requirement for keels to form along the Escarpment. It also explains why different salt lobes in this area have all converged while moving in this general direction. However, this does not explain why group 2 O–E keels updip from the Escarpment occur where they do and were not observed elsewhere.

Mechanisms for Keel Displacement

A combination of factors that can be observed on or inferred from seismic data control why and how O–E detached keels move. Observations suggest that the primary factors include: (1) salt loading above the detachment (gravity), (2) presence of weak detachment surface(s), and (3) absence of deep structures basinward of the detachment. It is speculated that other lesser factors are: (a) the ability to detach towards bathymetric lows, (b) the ability to detach onto basinward flanks of deeper structures, and (c) drive from updip sediment loading. Each of these lesser factors will contribute to keel formation but are not critical if the primary controls are present. Anything that works against gravity, such as stratal dips in the wrong direction or intervening structural highs, will work to prevent any detachments from forming.

The first O–E detached keels (group 2) developed in the most updip locations as a result of salt rising out of the primary autochthonous salt basins and spreading laterally over sediments deposited outboard of those deep basins. Figures 8 and 10 show a location in southern Garden Banks basinward of several primary salt ascension zones (reference Fig. 4). At this location the canopy reached the crest above a deep fold and keel 3 detached down the basinward flank of the structure (substrate expulsion of Hudec and Jackson, 2009). Keel 3 is now sitting on the Wilcox horizon. If the keel 3 thickness is a representative proxy, then about 1800 m (6000 ft) of section is missing. Using the same proxy and comparing it to undeformed section would suggest an early to middle Miocene time for canopy emplacement. The authors believe that all of the keel related deformation and strata displacement occurred due to the weight of the canopy loading a weak detachment. The main detachment levels are within the Oligocene-Eocene interval and at the base of the lower Miocene–top Oligocene. Deeper deformation may be due to earlier canopy advance updip causing displacement on sub-top Cretaceous detachments. More important is the fact there are no significant deep structures basinward of this fold. All three of the primary controlling factors for keel displacement listed above are present. The setting for keel 3 is essentially the same as seen in Figures 2, 3, 5, and 6. The main difference is in how extension is accommodated below the keel. For group1 keels it is by simple rotation of strata along the keel fault. For group 2 keels it is some combination of this plus sediment expulsion. The point to reemphasize is that a deep structure is not critical to keel formation, just that canopy loading (gravity) overcame the resistance of the detachment.

A three dimensional view of the canopy base in western Keathley Canyon and eastern Alaminos Canyon is shown in Figure 13 (red box in Figure 4). The view shown is looking from northeast to southwest. Linear trends in the canopy base appear to radiate outward from some of the salt ascension zones (black arrows). Similar linear trends in the canopy base can be seen farther downdip in some areas (black arrows). Those linear patterns have been interpreted as flow lines highlighting the direc-

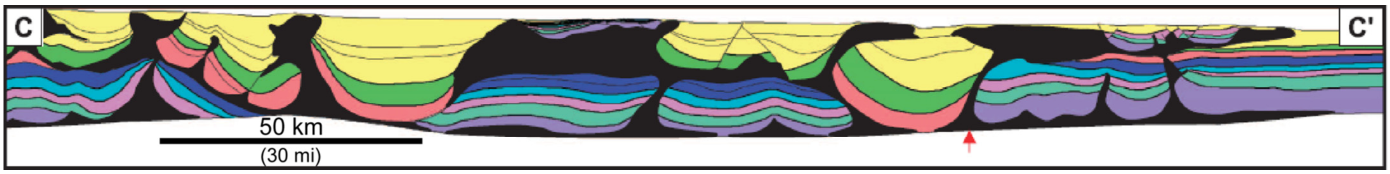

Figure 12. North-south regional schematic cross section through eastern Keathley Canyon and Garden Banks (from Pilcher et al., 2011, reproduced courtesy of the American Association of Petroleum Geologists, whose permission is required for further use). The geology suggests this part of the deep Gulf is probably too complex and rapidly evolving for large keels to form. Section location identified in Figure 1.

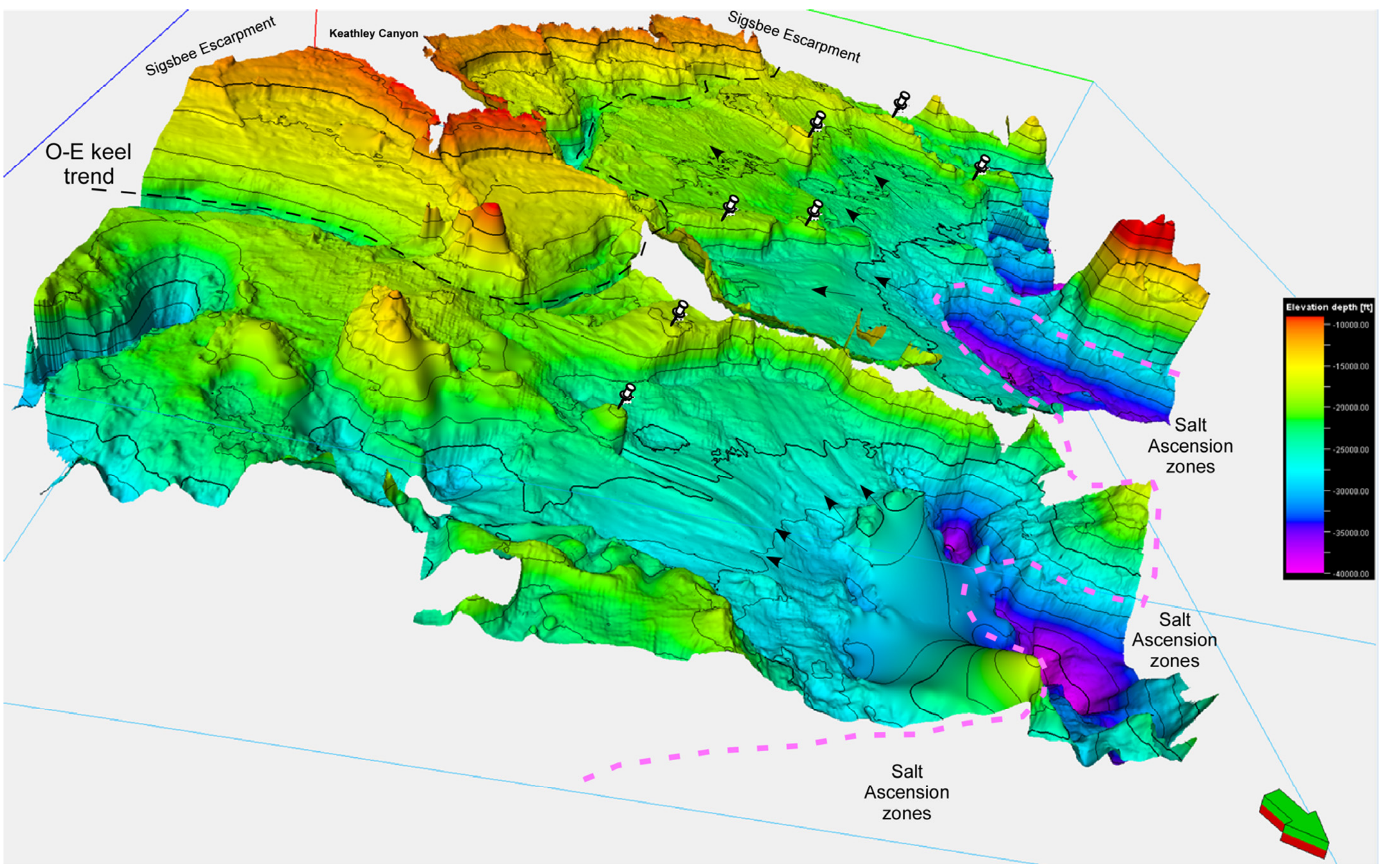

Figure 13. A three dimensional view of the canopy base in western Keathley Canyon and eastern Alaminos Canyon. The view shown is looking from northeast to southwest. The regional view shows the overall ramp-flat-ramp-flat nature of the salt canopy base. Depth scale, red = -3 km (-10,000 ft), purple = -12 km (-40,000 ft). The pink dashed line outlines the salt ascension zones. The black dashed line shows the group 1 O–E keel trend. Black arrows show linear grooves in the canopy base and the direction of allochthonous salt advance into the basin. White pins show concentrations of imbricate thrusted sediment as seen in Figures 8 and 9. Location identified in Figure 4 by red square.

tion of salt movement (Fiduk et al., 2014b). Smaller-scale linear features have been observed where it appears that blocks of strata were dragged along at the canopy base, thereby producing a linear feature. These observations are somewhat inconsistent with the mode by which salt is thought to flow, where grains at the salt-sediment interface are essentially motionless. However, if the canopy is displacing strata forward, then those strata may create linear trends or grooves which the salt then infills. If this is the case, then salt is advancing in the hanging-wall block of the frontal thrust either by basal shear or substrate expulsion (Hudec and Jackson, 2006, 2009).

The linear trends or grooves generally run across flat areas of the canopy base (Fig. 13). They end where the base salt often sharply steepens (ramps). At the top of the ramps are high areas in the base salt canopy map (white pins, Fig. 13). These are the same locations identified by black arrows in Figure 4 and represent concentrations of imbricate thrusted sediment seen in Figures 7 and 8. The map suggests there is a link between the linear trends (representing the area where strata are missing) and concentrations of imbricate thrusted sediment (where there is demonstrable excess section). Again, if this is the case, then salt is advancing in the hanging-wall block of the frontal thrust or via substrate expulsion (Hudec and Jackson, 2006, 2009). It also suggests some of the displaced section could have traveled 10s of km.

Displacement of strata basinward and lowering of the base canopy contact has important ramifications. Many operating companies have done the exercise of mapping the subsalt cutoffs for various stratigraphic horizons, just as done here, to gain a better regional understanding of the timing of canopy emplacement to aide their exploration efforts. Western Keathley Canyon has been particularly important because it lacks deep salt structures allowing relatively good subsalt imaging and easy seismic correlations far updip from the canopy edge when compared to other areas. A lot of the regional mapping work was done with 2D seismic data with kilometer-scale grid spacing. It would be very difficult to see the complex base canopy relationships on 2D data that are still difficult to interpret on modern 3D data. The critical facts being that these early interpreted subsalt cutoffs are incorrect (because section is missing) and so is the interpreted timing of canopy emplacement (which now looks to be younger). Miocene strata extended farther updip than predicted by that mapping and potential exploration opportunities have been overlooked. Regional base canopy cutoffs should be reassessed where keels exist.

Figures 7 and 11 serve to reiterate the point that deep structures are not critical to keel formation. Neither example shows deep structures below the keel. In Figure 7 the detachment level, base lower Miocene–top Oligocene, is flat or very slightly inclined down to the northeast (shelfward). However, the keels formed anyway, dropping down to the top Oligocene, displacing the Miocene section to the southwest. The weight of the canopy overcame the strength of the detachment and displaced the underlying section basinward. Eventually the canopy surrounded the displaced section immobilizing it and then overriding it. With most of the detachments being fairly flat, especially those along the Sigsbee Escarpment, we see gravity spreading being dominant over gravity gliding as the main deformational process.

A section located in eastern Alaminos Canyon serves as a good final example to illustrate and summarize the processes believed contributing to keel formation (Fig. 14). All of the interpreted primary controls for keel formation are present. As in Figures 7 and 11 there are no deep structures basinward of the keel to obstruct movement on the detachment. There is a suitable weak detachment layer present. In fact, it appears to be the same as seen on Figures 6 and 11. There is salt loading above the detachment in abundance. Gravity has been at work. The top Oligocene horizon has 5 km of basinward displacement on the main fault. The Oligocene-Eocene section has been thickened outboard of the canopy and the Miocene horizons have all been slightly elevated. Black arrows in Figure 14 point to a large sediment filled suture between two major salt bodies. It is likely that there are at least four or more amalgamated (or autosutured) salt tongues comprising the canopy on this section. All of the group

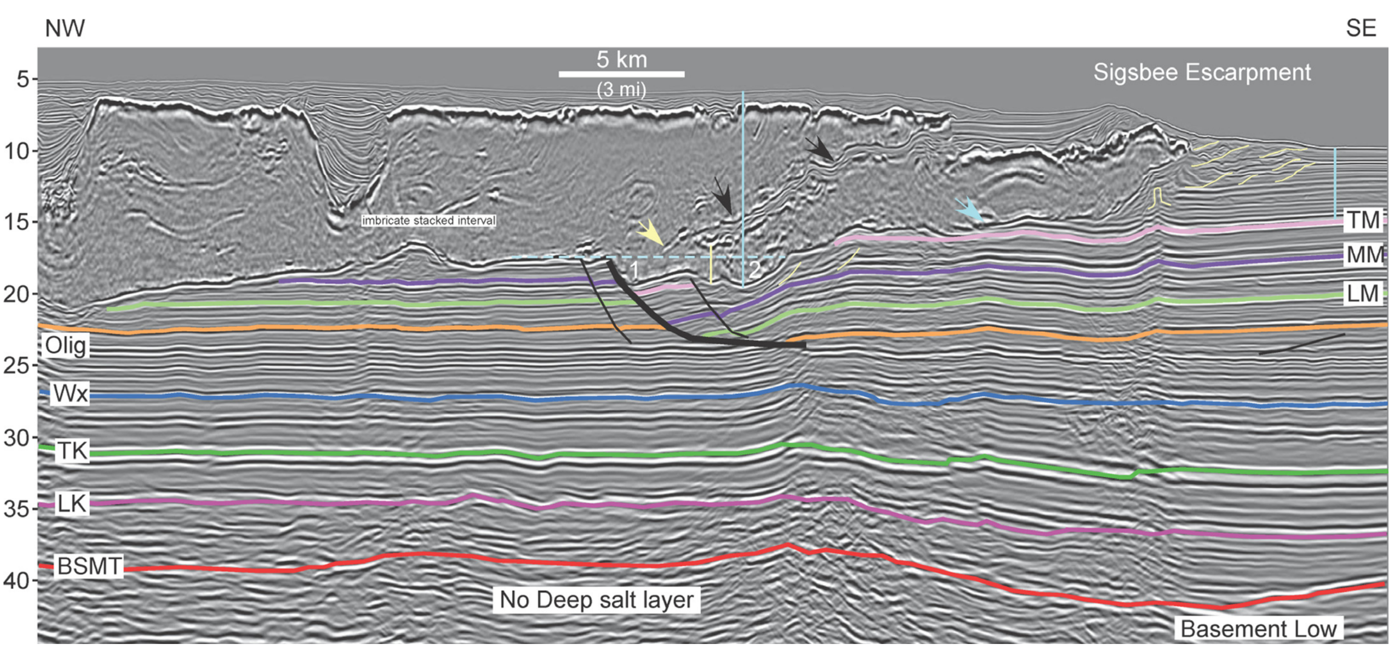

Figure 14. Seismic line located in eastern Alaminos Canyon that illustrates the primary factors contributing to keel formation (gravity, the absence of deeper structures basinward of the detachment, presence of weak detachment surface(s), and salt loading above the detachment). Black arrows point to carapace of initial canopy now within suture. Light blue arrow points to where initial canopy begins climbing section during its advancement. Yellow arrow points to base of second salt lobe dropping into keel 1. Light blue lines show difference in sediment load above keel and outboard of canopy. The yellow vertical line shows the keel displacement below canopy. Horizon abbreviations and colors as in Figure 2. Depth scale in 1000s of feet. Vertical exaggeration ~2:1. Seismic data provided courtesy of Schlumberger Multiclient.

1 O–E keels could be considered limited examples of substrate expulsion (recall in Figures 6 and 11 the keel is down on the detachment).

The initial salt canopy advanced onto this section from the northwest (Fig. 14). The canopy base truncates the lower and middle Miocene horizons. Above the middle Miocene horizon is an imbricate stacked interval like those in Figures 7-8. This one is just 600 m (2000 ft) thick and composed of displaced upper Miocene strata. The salt on either side of the stack has displaced upper Miocene strata (at a minimum) and could be described as Miocene keels. From these features to the main keel fault are some seemingly undisturbed upper Miocene strata under the canopy. However, some strata are probably missing from this area as the top Miocene horizon is present in the rotated strata below the keel (labeled 1, Fig. 14). Measured from the footwall block there was approximately 1850 m (6000 ft) of overburden on the detachment prior to canopy emplacement which should be considered a minimum value. A small amount of lower Pliocene is also present under the keel. Thus the canopy reached the keel by early Pliocene if there is no additional missing section. Below the basinward part of the keel (labeled 2, Fig. 14) the lower Pliocene and some of the upper Miocene are missing (the top Miocene horizon is gone). Beyond the keel the canopy advanced another 7-8 km during the early Pliocene before it started climbing upsection (light blue arrow) over the last 6-7 km of advancement to its present position.

Carapace above the initial canopy is still present as suture material between the amalgamated salt lobes (black arrows, Fig. 14). The carapace is interpreted to have rotated at the time the keel formed. This carapace material shows more rotation than strata in the keel hanging-wall block. That occurs because the initial canopy has deflated some above the keel and inflated some basinward of the keel. This interpretation is supported by examination of other line orientations through the carapace. Thus, it is thought that the carapace was horizontal and undeformed prior to keel displacement and can be deduced that the initial canopy thickness was not great enough to initiate keel displacement. The true thickness of the canopy is unknown but a minimum can be estimated to be slightly over 750 m (2500 ft) based on the distance between the carapace and the keel base (short yellow line, Fig. 14). An alternative interpretation is that this is simply an autosuture in the canopy which is located directly above the keel. If so, it is the only autosuture with any appreciable sediment thickness seen in this part of the canopy.

In this interpretation, at some time after the initial canopy was emplaced a second allochthonous salt body arrived. Loading by this additional salt eventually activated the main keel fault, rotated the carapace, and reinitiated basinward advance/inflation of the initial canopy lobe. Evidence for this loading is visible where the base of the second allochthonous salt body drops into the keel (yellow arrow, Fig. 14). Then, driven by updip loading, the initial canopy lobe both inflated and advanced to the southeast. Forced to climb upsection, the initial canopy lobe itself loaded and displaced strata basinward. An imbricate stacked interval cored by a small isoclinal fold developed in front of the advancing salt. Again forced to climb upsection the initial canopy lobe inflated, crossed over the imbricate stacked interval underneath, and reached its current position at the Sigsbee Escarpment.

Loading and deformation of weak strata in front of the escarpment is beginning anew as evidenced by multiple small thrust faults just below the sea floor and a thickened section. This reveals that where weak layers exist with thin overburden, less loading (thickness) is required by the canopy to cause failure (detachment). Back updip minibasins are forming on the canopy that will drive salt basinward starting the whole process over again. It would seem that cyclicity like this is the natural order for salt-sediment interaction in the deep Gulf of Mexico.

Timing of Keel Displacement

The most updip keels shown in Figures 7–8 displace Oligocene, lower Miocene and middle Miocene strata. This places canopy emplacement and keel movement no earlier than middle Miocene, Langhian to Serravallian (15.97–11.63 Ma). From a regional perspective this seems reasonable albeit loosely constrained. In updip locations close to deep salt feeders canopy amalgamation probably proceeded rapidly with the canopy quickly reaching the critical thickness necessary for gravity to overcome detachment strength and displace strata basinward.

Figures 6 and 11 put canopy emplacement in the late Miocene, Tortonian to Messinian (11.63–5.33 Ma). However in Figure 6 sutures in the canopy that turn down above the keel suggest that the canopy may have been relatively thick prior to keel movement. Finite element modeling does not seem to suggest that canopy inflation is a necessary component of keel initiation (M. Hudec, 2016, personal communication). However, all of the group 1 keels had a substantial overburden on the detachments prior to canopy emplacement, from 1800 to 3350 m (6000–11,000 ft). A few tens of meters of additional salt seems inconsequential to initiating keel movement. Yet a relatively rapidly emplaced (in comparison to an equal sediment volume) thick salt body might have a much greater effect. In view of this potential conflict we believe the topic merits further investigation. Estimates based on the sutures in Figure 6 suggest a canopy thickness of 2100 m (7000 ft). Given the keel's downdip position and close proximity to the canopy termination, it would seem reasonable to suspect it took the canopy some time to reach a critical thickness and hence a younger time for keel displacement. However, the authors will stay with the late Miocene as a maximum age for keel movement.

Figures 2, 3, 5, and 14 all put canopy emplacement in the early Pliocene Zanclean (5.33–3.60 Ma). The seismic line in Figure 3 also has sutures in the canopy that turn down above the keel suggesting a canopy thickness of 1600 m (~5300 ft) when the keel moved. The seismic line in Figure 2 has no sutures in the canopy but it does have a very thick section between the top Miocene and the canopy base. In the footwall block of the main keel fault the interval is 1140 m (3750 ft) thick. One might easily assume a late Pliocene Piacenzian (3.60–2.59 Ma) or even a Pleistocene Gelasian (2.59–1.81 Ma) time for canopy emplacement and keel movement. Again the authors will stay with the early Pliocene as a maximum age for keel movement.

Overall younging in the age of canopy emplacement and the likely time of keel formation is observed moving downdip towards the Sigsbee Escarpment. A progression from middle Miocene to late Miocene to early Pliocene is well supported by regional mapping and is in agreement with the general trend of what would be expected. These are maximum possible interpreted ages for keel emplacement and movement. Future analysis will probably refine these findings to younger ages. Questions still left unanswered are how strata is lost in the keel hanging-wall blocks and where is the missing contraction to balance keel extension?

CONCLUSIONS

In this study keels at the base of the shallow salt canopy responding to displacement at three different levels have been identified: the basement, the deep salt, and in sediment above the deep salt (mainly the Oligocene-Eocene interval). Volumetrically, the most interesting and potentially of most economic importance are the O–E detached keels.

O–E keels have a bimodal distribution. Group 2 keels lie updip of the Sigsbee Escarpment but basinward of the ascension zones where salt rises from the primary autochthonous salt basins. The canopy in this area was emplaced during the early to middle Miocene and keel movement may have occurred soon afterward. Loading by the canopy caused large-scale sediment displacement under the keels creating numerous stacks of imbricate thrusted sediment, some of which are nearly 2000 m (6500 ft) thick. The salt forming these keels advanced by a combination of basal shear and substrate expulsion. Displacement and deformation of strata at many smaller scales were also observed and likely continue below seismic resolution. The loading and displacement of sub-canopy strata may be one process involved in creating overpressured or gumbo zones. Mapping of the base salt canopy does not easily delineate this group of keels because of their relatively flat bases.

Group 1 keels are well delineated by mapping of the base salt canopy. They form a trend of depressions in the base salt canopy which extends for over 200 km (125 mi) across southern Keathley Canyon and into southern Alaminos Canyon. The trend maintains a relatively consistent distance of 15–30 km (9–18 mi) from the canopy's southern termination at the Sigsbee Escarpment. The canopy over these keels was emplaced in the late Miocene to early Pliocene. Movement on these keels may have occurred shortly after initial canopy emplacement or much later. Observations suggest that the canopy needs to reach a thickness of ~1–1.5 km (~0.6–1 mi) before the underlying weak O–E detachment layers near the Sigsbee Escarpment fail. Failure at shallower levels may occur early as frontal thrusts under minimal cover near the sea floor. All the group 1 O–E keels are relatively young geologic features and could be considered limited examples of substrate expulsion.

Primary factors for keel formation were interpreted to include: (1) salt loading above the detachment (gravity), (2) presence of weak detachment surface(s), and (3) absence of deep structures basinward of the detachment. It is also believed that other lesser factors influencing keel formation are: (a) the ability to detach towards bathymetric lows, (b) the ability to detach onto basinward flanks of deeper structures, and (c) drive from updip sediment loading. Each of these lesser factors will contribute to keel formation but are not critical if the primary controls are present. Anything that works against gravity, such as stratal dips in the wrong direction or intervening structural highs, will work to prevent any detachments from forming.

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REFERENCES CITED

Aber, J. S., D. G. Croot, and M. M. Fenton, 1989, Glaciotectonic landforms and structures: Kluwer, Dordrecht, The Netherlands, 200 p.

Anadarko Petroleum Corporation, 2016, Lucius, 20 p., <https://www.anadarko.com/content/documents/apc/Operations/Gulf_of_Mexico/APC-LuciusMediaBooklet.pdf> Accessed June 2016.

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

Benn, D. I., and D. J. A. Evans, 1998, Glaciers and glaciation: Arnold, London, U.K., 734 p.

Buffler, R. T., and D. S. Sawyer, 1985, Distribution of crust and early history, Gulf of Mexico Basin: Gulf Coast Association of Geological Societies Transactions, v. 35, p. 333–344.

Diegel, F. A., J. F. Karlo, D. C. Schuster, R. C. Shoup, and P. R. Tauvers, 1995, Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf Coast continental margin, *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. 109–151.

Dooley, T. P., M. R. Hudec, and M. P. A. Jackson, 2012, The structure and evolution of sutures in allochthonous salt: American Association of Petroleum Geologists Bulletin, v. 96, p. 1045–1070.

Fiduk, C., 2012, A look at salt keels in the deepwater northern GOM: American Association of Petroleum Geologists Search and Discovery Article 90158, Tulsa, Oklahoma, <http://www.searchanddiscovery.com/abstracts/html/2012/90158gcags/abstracts/fiduk.htm> Last Accessed August 14, 2016.

Fiduk, C., M. Clippard, G. Jamieson, O. Ajose, S. Power, R. C. Martin, Jr., V. Robertson, O. Hassan, L. Rodriguez, L. Jurca, M. Karer, A. Hannan, N. Biles, A. Klebleeva, K. Lyons, D. Kakas, D. Fernandez, and D. Smith, 2014a, Distribution of salt keels in the deepwater northern Gulf of Mexico): American Association of Petroleum Geologists Search and Discovery Article 90189, Tulsa, Oklahoma, <http://www.searchanddiscovery.com/abstracts/html/2014/90189ace/abstracts/1840640.html> Last Accessed August 14, 2016.

Fiduk, J. C., M. Clippard, S. Power, V. Robertson, L. Rodriguez, O. Ajose, D. Fernandez, and D. Smith, 2014b, Origin, transportation, and deformation of Mesozoic carbonate rafts in the northern Gulf of Mexico: Gulf Coast Association of Geological Societies Journal, v. 3, p. 20–32.

Fiduk, J. C., L. E. Anderson, T. R. Schultz, and A. J. Pulham, 2007, Deep-water depositional trends of the Cretaceous and Paleogene in the central northern Gulf of Mexico, *in* L. Kennan, J. Pindell, and N. C. Rosen, eds., The Paleogene of the Gulf of Mexico and Caribbean basins: Processes, events and petroleum systems: Proceedings of the 27th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Research Conference, Houston, Texas, p. 45–53.

Fletcher, R. C., M. R. Hudec, and I. A. Watson, 1995, Salt glacier and composite sediment salt glacier models for the emplacement and early burial of allochthonous salt sheets, *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. 77–108.

Gradstein, F. M., J. G. Ogg, M. D. Schmitz, and G. M. Ogg, eds., 2012, The geologic time scale 2012: Elsevier, Amsterdam, The Netherlands, 1144 p.

Harrison, H., L. Kuhmichel, P. Heppard, A. V. Milkov, J. C. Turner, and D. Greeley, 2004, Base of salt structure and stratigraphy-Data and models from Pompano Field, VK 989/990, Gulf of Mexico, *in* P. J. Post, D. L. Olson, K. T. Lyons, S. L. Palmes, P. F. Harrison, and N. C. Rosen, eds., Salt–sediment interactions and hydrocarbon prospectivity: Concepts, applications, and case studies for the 21st century: Proceedings of the 24th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Research Conference, Houston, Texas, p. 243–270.

Harrison, H. L., and B. Patton, 1995, Translation of salt sheets by basal shear, *in* C. J. Travis, H. Harrison, M. R. Hudec, B. C. Vendeville, F. J. Peel, and B. F. Perkins, eds., Salt, sediment, and hydrocarbons: Proceedings of the 16th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Research Conference, Houston, Texas, p. 99–107.

Hearon, T. E., IV, M. G. Rowan, K. A. Giles, R. A. Kernen, C. E. Gannaway, T. F. Lawton, and J. C. Fiduk, 2015, Allochthonous salt initiation and advance in the northern Flinders and eastern Willouran ranges, South Australia: Using outcrops to test subsurface-based models from the northern Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 99, p. 293–331.

Holdaway, S., 2010, Structural history of Keathley Canyon type salt keels, north-central deepwater Gulf of Mexico: American Association of Petroleum Geologists Search and Discover Article 90104, <http://www.searchanddiscovery.com/pdfz/abstracts/pdf/2010/annual/abstracts/ndx_holdaway.pdf.html> Last Accessed August 14, 2016.

Huber, W. F., 1989, Ewing Bank thrust fault zone, Gulf of Mexico, and its relationship to salt sill emplacement, *in* A. Lowrie, M. B. Edwards, J. F. Fox, J. Watson, D. West, R. Evans, T. H. Nelson, W. F. Wilson, J. Blickwede, L. Fairchild, F. Sauer, and H. Yorston, eds., Gulf of Mexico salt tectonics, associated processes and exploration potential: Proceedings of the 10th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Research Conference, Houston, Texas, p. 60–65.

Hudec, M. R., R. C. Fletcher, and I. A. Watson, 1993, The composite salt glacier: Extension of the salt glacier model to post-burial conditions: American Association of Petroleum Geologists Search and Discover Article 91020, <http://www.searchanddiscovery.com/abstracts/html/1995/annual/abstracts/0045c.htm> Last Accessed August 14, 2016.

Hudec, M. R., and M. P. A. Jackson, 2006, Advance of allochthonous salt sheets in passive margins and orogens: American Association of Petroleum Geologists Bulletin, v. 90, p. 1535–1564.

Hudec, M. R., and M. P. A. Jackson, 2009, The interaction between spreading salt canopies and their peripheral thrust systems: Journal of Structural Geology, v. 31, p. 1114–1129.

Hudec, M. R., M. P. A. Jackson, and D. Schultz-Ela, 2009, The paradox of minibasin subsidence into salt: Clues to the evolution of crustal basins: Geological Society of America Bulletin, v. 121, p. 201–221.

Hudec, M. R., and M. P. A. Jackson, 2011, The salt mine: A digital atlas of salt tectonics: Texas Bureau of Economic Geology Udden Book Series 5, Austin, and American Association of Petroleum Geologists Memoir 99, Tulsa, Oklahoma, 305 p.

Hudec, M. R., I. O. Norton, M. P. A. Jackson, and F. J. Peel, 2013, Jurassic evolution of the Gulf of Mexico salt basin: American Association of Petroleum Geologists Bulletin, v. 97, p. 1683–1710.

Jackson, M. P. A., and M. R. Hudec, 2004, A new mechanism for advance of allochthonous salt sheets, *in* P. J. Post, D. L. Olson, K. T. Lyons, S. L. Palmes, P. F. Harrison, and N. C. Rosen, eds., Salt–sediment interactions and hydrocarbon prospectivity: Concepts, applications, and case studies for the 21st century: Proceedings of the 24th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Research Conference, Houston, Texas, p. 220–242.

Jamieson, G. A., 1995, Subsalt and base-of-salt reflector relationships and hydrocarbon trap implications from a large 3D, depth migrated, seismic volume: Offshore Technology Conference Paper 7638–MS, Houston, Texas, doi:10.4043/7638-MS.

Luo, G., P. B. Flemings, M. R. Hudec, and M. A. Nikolinakou, 2015, The role of pore fluid overpressure in the substrates of advancing salt sheets, ice glaciers, and critical-state wedges: Journal of Geophysical Research: Solid Earth, v. 120, p. 87–105.

McGuinness, D. B., and J. R. Hossack, 1993, The development of allochthonous salt sheets as controlled by the rates of extension, sedimentation, and salt supply, *in* J. M. Armentrout, R. Bloch, H. C. Olson, and B. F. Perkins, eds., Rates of geological processes: Proceedings of the 14th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Research Conference, Houston, Texas, p. 127–139.

OffshoreTechnology.com, 2016, Lucius deepwater oil and gas project, Gulf of Mexico, United States of America, <http://www.offshore-technology.com/projects/lucius-project/> Last Accessed August 14, 2016.

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.

Pilcher, R. S., B. Kilsdonk, and J. Trude, 2011, Primary basins and their boundaries in the deep-water northern Gulf of Mexico: Origin, trap styles, and petroleum system implications: American Association of Petroleum Geologists Bulletin, v. 95, p. 219–240.

Prather, B. E., J. R. Booth, G. S. Steffens, and P. A. Craig, 1998, Classification, lithologic calibration, and stratigraphic succession of seismic facies of intraslope basins, deep-water Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 82, p. 701–728.

Robison, B. A., R. Detomo, Jr., R. D. Garner, A. Spelsnijer, and M. J. Styzen, 1997, Salt geometry and subsalt trapping in the Enchilada area, NE Garden Banks, offshore Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 67, p. 485–491.

Rotnicki, K., 1976, The theoretical basis for and a model of glaciotectonic deformations: *Quaestiones Geographicae*, v. 3, p. 103–139.

Rowan, M. G., 1995, Structural styles and evolution of allochthonous salt, central Louisiana outer shelf and upper slope. *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. 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, v. 52, p. 861–869.

Rowan, M. G., F. J. Peel, and B. C. Vendeville, 2004, Gravity-driven fold belts on passive margins, *in* K. R. McClay, ed., Thrust tectonics and hydrocarbon systems: American Association of Petroleum Geologists Memoir 82, Tulsa, Oklahoma, p. 157–182.

Rowan, M. G., K. A. Giles, T. F. Lawton, T. E. Hearon, IV, and P. T. Hannah, 2010, Salt–sediment interaction during advance of allochthonous salt: American Association of Petroleum Geologists Search and Discovery Article 90104, Tulsa, Oklahoma <http://www.searchanddiscovery.com/pdfz/abstracts/pdf/2010/annual/abstracts/ndx_rowan3.pdf.html> Last Accessed August 14, 2016.

Rowan, M. G., and K. F. Inman, 2011, Salt-related deformation recorded by allochthonous salt rather than growth strata: Gulf Coast Association of Geological Societies Transactions, v. 61, p. 379–390.

Saleh, S. T., K. E. Williams, and A. Rizvi, 2013, Rubble zone below salt: Identification and best drilling practices: Society of Petroleum Engineers Paper SPE–166115, Richardson, Texas, 17 p.

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

Salvador, A., 1991, 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.

Sawyer, D. S., R. T. Buffler, and R. H. Pilger Jr., 1991, The crust under 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. 53–72.

Schuster, D. C., 1995, Deformation of allochthonous salt and evolution of related salt structural systems, eastern Louisiana Gulf Coast, *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. 177–198.

Seni, S. J., and M. P. A. Jackson, 1992, Segmentation of salt allochthons: Geology, v. 20, p. 169–172.

Vendeville, B. C., and M. P. A. Jackson, 1992, The fall of diapirs during thin-skinned extension: Marine and Petroleum Geology, v. 9, p. 354–371.

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