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Origin, Transportation, and Deformation of Mesozoic Carbonate Rafts in the Northern Gulf of Mexico

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ABSTRACT

Seismic correlations and well data confirm that deepwater carbonate beds of Mesozoic age have been found above/in the shallow allochthonous salt canopy in the northern Gulf of Mexico. Publicly available wells in the Garden Banks (GB) (Norton, GB 754; Vienna, GB 840; and Sumatra, GB 941), Keathley Canyon (KC) (Bass, KC 596; Ponza, KC 774; Lucius, KC 875; and Hadrian, KC 919), and Walker Ridge (WR) (Logan, WR 969) Outer Continental Shelf (OCS) protraction areas penetrate Mesozoic carbonates situated above the salt canopy or equivalent salt welds. The seismic character of these rafts strongly resembles that of in situ Mesozoic carbonates and overlying Paleogene strata. Cretaceous and Wilcox seismic facies have been mapped at the salt canopy level on seismic data in Alaminos Canyon, Garden Banks, Green Canyon, Keathley Canyon, and Walker Ridge OCS protraction areas. The presence of displaced Mesozoic carbonate rafts above the canopy raises two important questions: (1) where did these rafts originate and (2) how did blocks of Mesozoic strata get elevated to such shallow levels in the basin stratigraphy?

A geologic mechanism for displacing Mesozoic carbonates from their normal position and transporting them as rafts mirrors the creation of the allochthonous salt canopy. As salt inflates to form large, broad, diapiric structures, overlying strata (i.e., Jurassic and Cretaceous carbonate) are lifted above adjacent subsiding minibasins containing equivalent strata. At later times in the Eocene, Oligocene, and Miocene, salt from the inflated structures broke out to form shallow canopies. As salt flowed laterally it carried the roof material with it. Radial spreading of the salt broke the roof material into multiple smaller units. Seismic mapping suggests some rafts have traveled many tens of kilometers (possibly >100 km [>60 mi]) away from the diapiric structures that lifted them to the shallow salt canopy.

Over 3100 sq. km (1200 sq. mi) of rafted strata has been identified to date. Most of the rafted strata are found near the terminus of the canopy system on the lower slope along the Sigsbee Escarpment. A much smaller amount of rafted strata is found scattered in the middle slope. The total discovered so far almost certainly represents a minimum amount of rafted strata generated. The authors expect to find many additional raft bodies as this investigation continues.

INTRODUCTION

The term "raft" has been used in many connotations by geologists in a variety of disciplines to describe the displacement of strata/rock/material from one location to another. In the discipline of salt tectonics, the term raft has been used in three basic ways (Mark Rowan, 2014, personal communication). First, rafts have been described as blocks of overburden that were displaced basinward by gravity on an autochthonous salt detachment. This process was conceptually discussed by Cobbold and Szatmari (1991) for the Campos Basin and then more fully described in the Kwanza Basin by Duval et al. (1992). Observations of rafted strata were subsequently described in many salt basins worldwide including West Africa (e.g., Duval et al., 1992; Lundin, 1992; Marton et al., 2000; Hudec and Jackson, 2004), offshore Brazil (e.g., Cobbold and Szatmari, 1991; Demercian et al., 1993; Mohriak et al., 2004, 2008; Fiduk et al., 2004a), southern Iran (e.g., Kent, 1970; Talbot and Jackson, 1987) South Australia (e.g., Dalgarno and Johnson, 1968; Preiss, 1987; Hearon et al., in press), and in the northern Gulf of Mexico (e.g., Diegel et al., 1995; Peel et al., 1995; Fiduk et al., 2004b). Modeling of the salt deformation required to produce rafting has been done by numerous researchers (e.g., Vendeville and Jackson, 1992a, 1992b; Schultz-Ela and Jackson, 1996; Fort et al., 2004; Mount et al., 2007; Dooley et al., 2008).

A second usage of the term raft refers to blocks of material found trapped within large, inflated salt bodies and in salt diapirs. This rafted material, sometimes referred to as stringers or floaters (Reuning et al., 2008), most commonly consists of strata originally interbedded with the salt during deposition (Talbot and Jackson, 1987), but not always. Such rafted material appears to be

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found in salt basins worldwide. The Ara carbonate, found within salt diapirs in Oman, is a well-known example and a productive exploration target (Peters et al., 2003; Callot et al., 2006; Reuning et al., 2008). The presence of rafted sediment inclusions in diapirs of South Australia were noted and described by Webb (1961), Coats (1965), Dalgarno and Johnson (1968), and Lemon (1985). Hearon et al. (2014, their Figure 8) illustrated a 10 km+ (6 mi+) body of non-evaporite lithologies entrained and folded within the pedestal of the Witchelina Diaper in the Willouran Ranges, South Australia. The inflated and intensely folded layered evaporite sequence of the Sao Paulo Plateau in the Santos Basin, Brazil, which contains halite intercalated with anhydrite, carnalite, and tachyhydrite beds, is another example of this style of rafting (Fiduk and Rowan, 2012, their Figures 8 and 10). In the Gulf of Mexico, metaigneous clasts are part of the insoluble detritus shed from the El Gordo, El Papalote, and La Popa diapirs in the La Popa Basin, Mexico (Garrison and McMillan, 1999; Giles et al., 2004). At Alderdice Bank in the outer shelf of Louisiana in South Marsh Island South Extension, 80 million year old basalt columns stick up above the sea floor protruding out of a salt dome (Rezak and Tieh, 1984; Schmal et al., 2003).

A third usage of the term raft refers to isolated blocks of unconformable strata at the base, within, or above an allochthonous salt canopy. In the Gulf of Mexico, these blocks originate as strata deposited as parallel layers, we assume conformably, over autochthonous salt that is later inflated or on actively inflating salt highs (Kilby et al., 2008). After inflation of the salt high, raft blocks are eventually transported laterally (usually basinward) by allochthonous salt movement. Our Gulf of Mexico seismic observations reveal these rafted bodies to be condensed sections compared to similar age strata below the canopy. This third usage conforms closely to the term "carapace" as introduced by Hart et al. (2004). They specifically give carapace the key attribute of "being readily rafted along by spreading salt." As with the term raft, the term carapace has been used in many connotations by Gulf of Mexico geologists. Carapace most commonly refers to the generally thin condensed cover above diapirs and/or shallow allochthonous salt (McGuinness and Hossack, 1993; Harrison and Patton, 1995; Fletcher et al., 1995; Jackson, 1997). However, carapace thickness may vary considerably between structures, reaching up to 1500 m (5000 ft) thick (Hart et al., 2004).

There are some key characteristics that Hart et al. (2004) identified for carapace that rafts share: (1) strata deposited on salt highs, (2) principally comprised of fine grain sediment, (3) initially form a protective cover to salt, and (4) are readily rafted by spreading salt. We acknowledge that the seismic criteria used by Hart et al. (2004) to identify carapace can be used equally well to help identify rafts: (a) tabular sequences of subparallel beds above salt or weld, (b) lateral and vertical changes from isopachous to non-isopachous, converging/diverging strata, (c) boundaries that are unconformities, truncations, or downlap/onlap surfaces, and (d) deformation as semi-rigid or brittle blocks rather than like more ductile and flexible minibasin fill. The critical difference we see between rafts and the carapace of Hart et al. (2004) is that rafts can begin forming above autochthonous salt as pre-kinematic or syn-kinematic strata (Kilby et al., 2008). Hart et al. (2004) purposefully excluded these strata from their carapace definition to emphasize geomorphic traits that allow carapace strata a unique seismic identification. We believe there may be some overlap in this area. However, for the purpose of this study, we intentionally restricted our focus to those bodies that have been vertically elevated, laterally displaced, and contain Mesozoic carbonates (the "chips" of Kilby et al., 2008). Rafts that include Mesozoic carbonate have a more consistent seismic character aiding visual recognition and are identifiable using tomographic velocity analysis.

DATA

Published literature by Hart et al. (2004), Kilby et al. (2008), Liro et al. (2009), and Liro and Holdaway (2011) composed the initial starting point for this study. From these papers, it was learned that wells in Garden Banks (GB) (Norton, GB 754; Vienna, GB 840; and Sumatra, GB 941) and Keathley Canyon (KC) (Ponza, KC 774) Outer Continental Shelf (OCS) protraction areas had encountered blocks of strata containing anomalously old section within or at the base of the shallow salt canopy (Fig. 1). Additional wells in KC (Bass, KC 596; Lucius, KC 875; and Hadrian, KC 919) and Walker Ridge (WR) (Logan, WR 969) were added later based on seismic correlations. These wells formed the anchor points for our seismic characterization of carbonate rafts.

Narrow azimuth, wide azimuth, and dual coil 3D seismic data were used to identify and map the extent of raft blocks away from well locations. In excess of 100,000 sq. km (62,000 sq. mi) of seismic data covering all or parts of Alaminos Canyon (AC), East Breaks (EB), GB, KC, Sigsbee Escarpment (SE), Amery Terrace (AmT), WR, Green Canyon (GC), Atwater Valley (AT), and Ewing Bank (EwB) OCS protraction areas were examined (Fig. 1). Much of northern EB, GB, and GC are still being thoroughly investigated and work in these areas is ongoing.

OBSERVATIONS AND INTERPRETATION

Well Ties

The first physical proof of vertically and horizontally displaced Mesozoic carbonate strata in the northern Gulf of Mexico comes from the Norton well, GB 754 (Hart et al., 2004). Publicly available data from the well document a condensed Miocene (185 m [600 ft]), Oligocene (245 m [810 ft]), Eocene (165 m [540 ft]), upper Wilcox (85 m [270 ft]), lower Wilcox (190 m [630 ft]), lower Paleocene (18 m [60 ft]), Cretaceous (490 m [1620 ft]) and Upper Jurassic (195 m [640 ft]) section sitting on top of the shallow salt canopy. This is the only available well that shows a raft known to contain Jurassic-aged Tithonian source rocks (Hart et al., 2004).

The Vienna well, GB 840, lies approximately 10–12 km (6–7 mi) southwest of Norton. This well also encountered a Mesozoic carbonate raft (Liro et al., 2009). Data from the well show a condensed Cenozoic section similar to Norton's, but the well stopped after reaching the Upper Cretaceous. Seismic correlations between the two wells show a very similar seismic character for each raft (Fig. 2). It is likely that these two rafts were originally part of one larger body and that the Vienna well would have encountered Jurassic strata if the well had drilled to the salt canopy. The condensed nature of the raft stratigraphy becomes apparent when compared to equivalent section below the canopy. On the left side of Figure 2, the thickness of Wilcox (>1370 m [4500 ft]) and Cretaceous (>2745 m [9000 ft]) strata are expanded more than 5:1 compared to the Wilcox (275 m [900 ft]) and Cretaceous (495 m [1620 ft]) in the Norton well despite being buried 4600–6100 m (15,000–20,000 ft) deeper.

The Sumatra well, GB 941, was drilled 58–63 km (36–39 mi) east of Norton and Vienna. The well encountered a Mesozoic carbonate raft (Liro et al., 2009; Liro and Holdaway, 2011) and this raft has a complex history. First, the raft does not lie on top of the canopy. Instead, it sits on a weld at the canopy base so that rafted Cretaceous strata overlie Oligocene subsalt strata (Liro and Holdaway, 2011). Second, allochthonous salt of the canopy has overrun the raft so that it is now almost completely encased in salt. Third, the raft has a 145 m (470 ft) thick salt layer within itself, separating Eocene from Upper Cretaceous strata. The raft has been involved with at least three allochthonous salt bodies: one that carried it to this location, a second with an Eocene carapace that overran the raft and then partially deflated, and a third that is still present on top of the raft today. More complicated histories for this raft are possible.

Downslope near the Sigsbee Escarpment are five other wells that encountered rafts: Bass, KC 596; Ponza, KC 774; Lucius, KC 875; Hadrian, KC 919; and Logan, WR 969. The Bass well encountered a raft on the salt canopy that contains Paleogene section, but is missing any high amplitude Mesozoic carbonate reflections. With seismic data alone, it would be difficult to distinguish this raft from other more common and much younger carapace. The Ponza well encountered a raft that now sits where the canopy has welded out. Well data suggest a highly con-

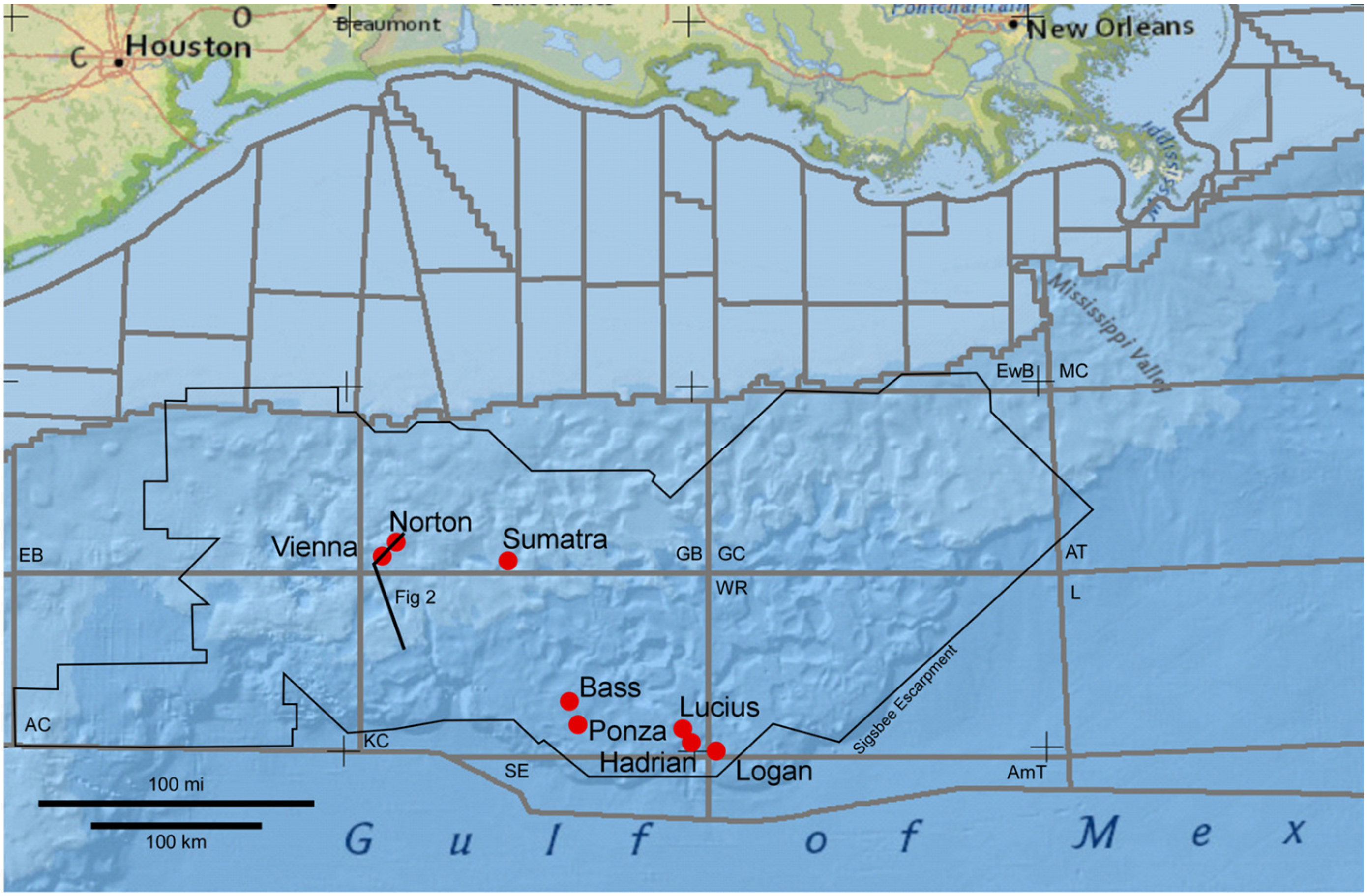

Figure 1. Bathymetric map of the northern Gulf of Mexico, showing locations where wells are known to have penetrated rafted Mesozoic/Paleogene section at the level of the shallow salt canopy. Those wells are: Norton, GB 754; Sumatra, GB 941; Vienna, GB 840; Hadrian, KC 919; Bass, KC 596; Ponza, KC 774; Lucius, KC 875; and Logan, WR 969. A black line shows the composite outline of seismic surveys included in the study. All of the data have not been thoroughly examined to date, and the study is ongoing.

densed Cretaceous and Paleogene section on the weld above Miocene subsalt strata. Seismic data show that some of the apparently condensed section is due to structural thinning. The raft is in the process of being extended and segmented.

The Lucius, Hadrian, and Logan wells all encountered rafts that are close together, seismically quite similar, and very possibly genetically related. These rafts and others nearby display what might be called a typical or diagnostic "carbonate raft" seismic character (Fig. 3). Each raft contains a package of continuous, high amplitude reflections (Cretaceous) overlain by alternating low and very low amplitude events (Paleogene), all which are of limited mappable extent. Biostratigraphic age data from these wells are not public, thus it is unknown whether or not Jurassic sediment is present. But if the Jurassic is present, the raft on the right side of Figure 3 suggests it may crop out at the sea floor along with the Cretaceous and Wilcox.

Model for Raft Development

Empirical well data tells us that Cretaceous and Paleogene strata are present within the shallow allochthonous salt canopy. Seismic imagery shows us and seismic correlations tell us that these strata are repeated below the canopy at or near their regional level. Thus, the raft bodies did not come from where they are presently located. This conundrum forces us to ask the questions: where did these bodies originate and how did they get to where they are located today? By addressing the second question first, we can gain some insight on possible answers for the first question.

A geomechanical model for displacing blocks of Mesozoic carbonate strata from their original depositional position and transporting them as rafts to a shallower stratigraphic level mirrors the creation of the allochthonous salt canopy. As salt inflates to form large, broad, diapiric structures, overlying strata are lifted above adjacent subsiding minibasins containing equivalent strata (Figs. 4A–4E). Strata deposited above the inflating salt are thinner and tend to be finer grained than in adjacent basins. Along the edges of the inflating structures, the thinner strata becomes fractured, faulted, and extended (Figs. 4B and 4C). Eventually salt breakout occurs, which may isolate blocks of the diapir's overburden (Figs. 4C and 4D). With continued diapiric inflation, the isolated blocks of overburden can be lifted above surrounding minibasins and transported along with the allochthonous salt (Figs. 4E) (Hudec and Jackson, 2006). In this manner, we can reproduce the repeated section observed on seismic data. If shortening were to occur during the growth of the diapiric structure, this process would be rendered even easier to accomplish (Figs. 5A–5E).

A second scenario involving diapiric inflation is likely to occur in the Gulf of Mexico. In this scenario, the inflating structure is near/at the extended continental crust–oceanic crust boundary (Figs. 6A–6E). Evolutionary steps are similar to the first model except for the beginning setup. Initial emplacement and thermal subsidence of oceanic crust would tilt the basin. This could lead to an early allochthonous salt tongue out onto the oceanic crust (Fig. 6A). Following the Gulf of Mexico evolution model of Hudec et al. (2013a), this might be expected. If we allow varying rates of salt inflation and basinward deposition,

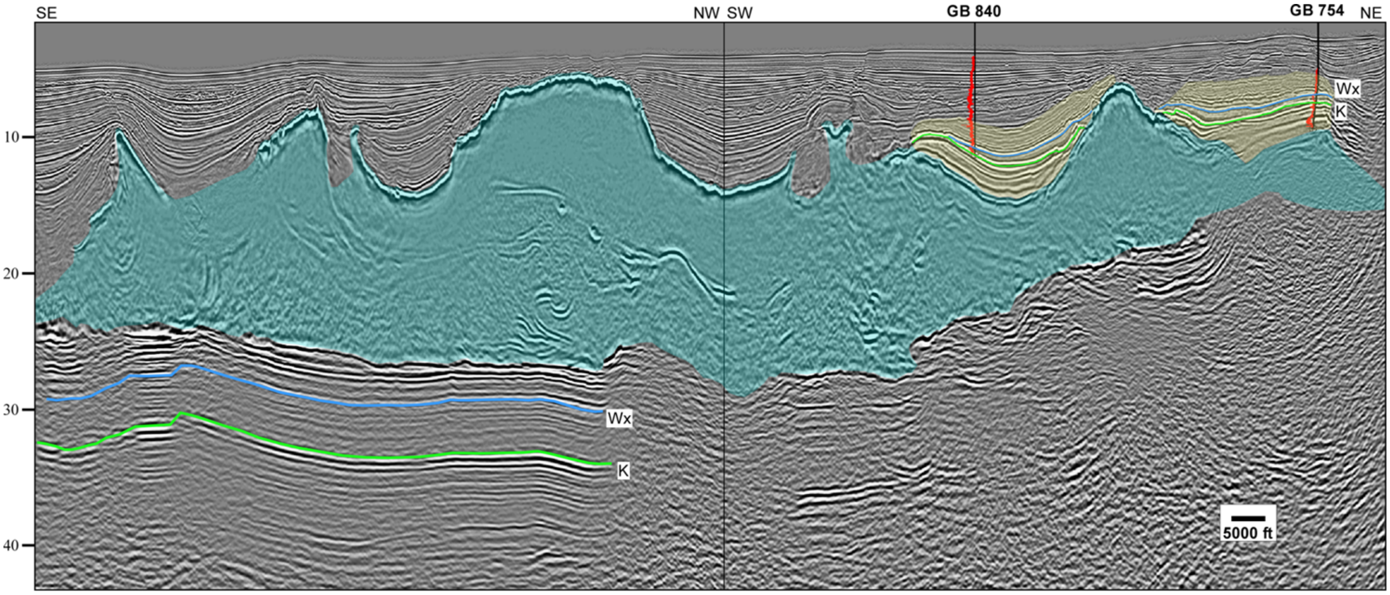

Figure 2. A composite depth seismic line showing the seismic character of condensed rafted sections at Norton GB 754 and Vienna GB 840, which are highlighted in yellow. An equivalent stratigraphic section is found just to the southeast in Keathley Canyon. The Wilcox (Wx) and Cretaceous (K) intervals here are at their regional levels and much thicker. Depth scale in 10,000 ft increments. Vertical exaggeration, 2:1. Seismic data provided courtesy of Schlumberger Multiclient.

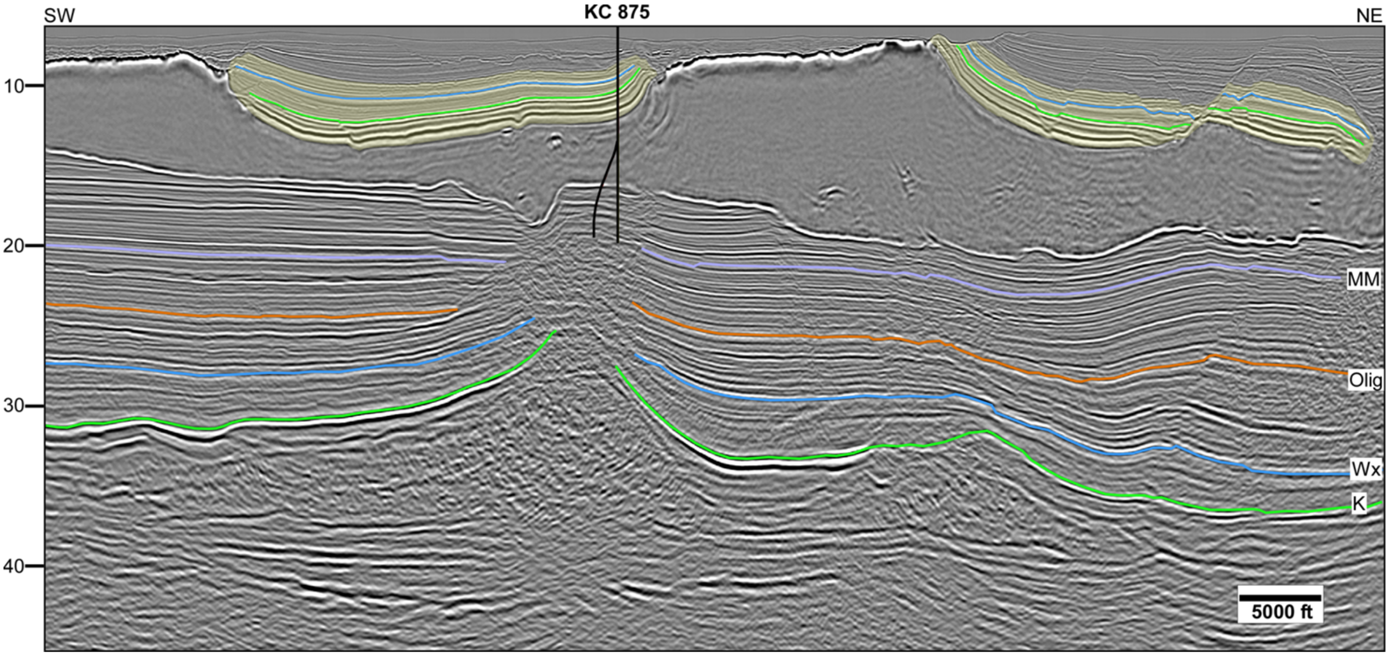

Figure 3. The Lucius well encountered a raft that is only modestly deformed and very well imaged. This raft and those nearby display what might be called a typical or diagnostic "carbonate raft" seismic character (i.e., a package of continuous, high amplitude reflections overlain by alternating low and very low amplitude events, all which are of limited mappable extent). Mesozoic strata of raft on right hand side appear to outcrop on the sea floor. Depth scale in 10,000 ft increments. Vertical exaggeration, 1:1. MM = Middle Miocene, and Olig = Oligocene. Seismic data provided courtesy of Schlumberger Multiclient.

then more than one early salt extrusion event may have been possible. As with the first model, if shortening were to occur during the growth of the diapiric structure, this process would be rendered even easier to accomplish (Fig. 7A–7E).

We are not the first to observe or model Mesozoic carbonate rafts. A few investigators such as Rowan and Inman (2011) and Hudec et al. (2013b) showed rafted carapace in their schematic restorations. Pilcher et al. (2011) showed a regional cross section restoration that includes Mesozoic carbonate rafts. We have used their ideas as a starting point to add more detail to the evolution of carbonate rafts. With that detail, we hope to answer some specific questions about raft origins, movement, and deformation.

Raft Deformation

Once a raft has moved away from its home diapir and joined the salt canopy, there are many possible fates. A raft may not be transported very far before the canopy deflates, leaving the raft on the underlying weld (e.g., Sumatra). Alternately, a raft may be transported far downslope before coming to rest. Some rafts

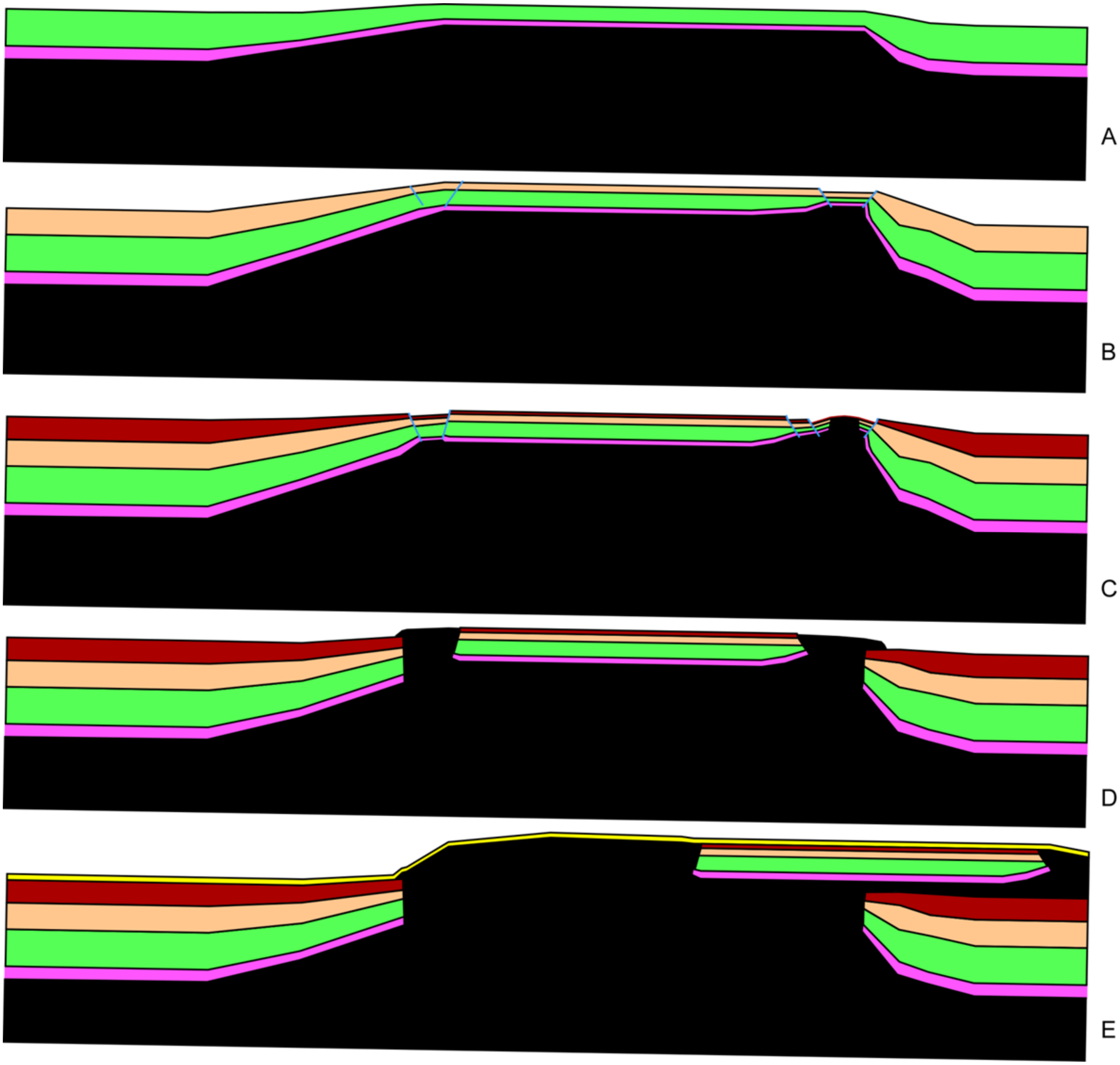

Figure 4. Scenario 1a: Cartoon model for the development of Mesozoic carbonate rafts in the Gulf of Mexico. This shows a generic setting for an inflating salt body on the slope or abyssal plain. (A) Different thicknesses of strata accumulate above inflating salt and in adjacent minibasins. (B) Onset of extension and faulting in strata above inflating salt. (C) Moment of imminent salt breakout. (D) Continuation of salt breakout and isolation of raft on inflating salt. (E) Initial movement of raft away from home diapir over adjacent minibasin. The model contains a one-degree dip from right to left to simulate regional slope.

appear to have little or minor distortions. However, in general, the farther a raft gets moved the better the chances for it to also be dissected and deformed.

Deformation can take on many forms and seems to occur most commonly after a raft begins to lose the salt underneath. Many rafts show subtle flexing and bending due to changes in the salt below, but when the salt gets too thin to isolate fully a raft, frictional forces become important. Once a raft starts frictionally binding against the underlying strata tangible deformation begins.

Folding and thrusting of raft strata are common. Figure 8 shows an arbitrary north-south seismic line on which a raft has begun deforming after grounding at the Sigsbee Escarpment. The front end of the raft has welded, while the back end, still supported by salt, is trying to move basinward. Three types of folds are visible: an isoclinal fold on the left, a slightly asymmetric fold with a basinward thrust in the center, and a box fold with basinward and landward vergent thrusts on the right. The box fold sits at the point where the raft has started welding with the subsalt section. The isoclinal fold was once exposed at the sea floor and eroded. The weaker Paleogene section is gone, but the stronger Mesozoic carbonates resisted erosion. With its forward motion halted, salt is now just starting to overrun the raft from behind (see arrow in Figure 8).

If deformation continues past initial folding and thrusting the raft may break into segments. Figure 9 shows a southwest-northeast oriented line where segmentation has occurred. On this

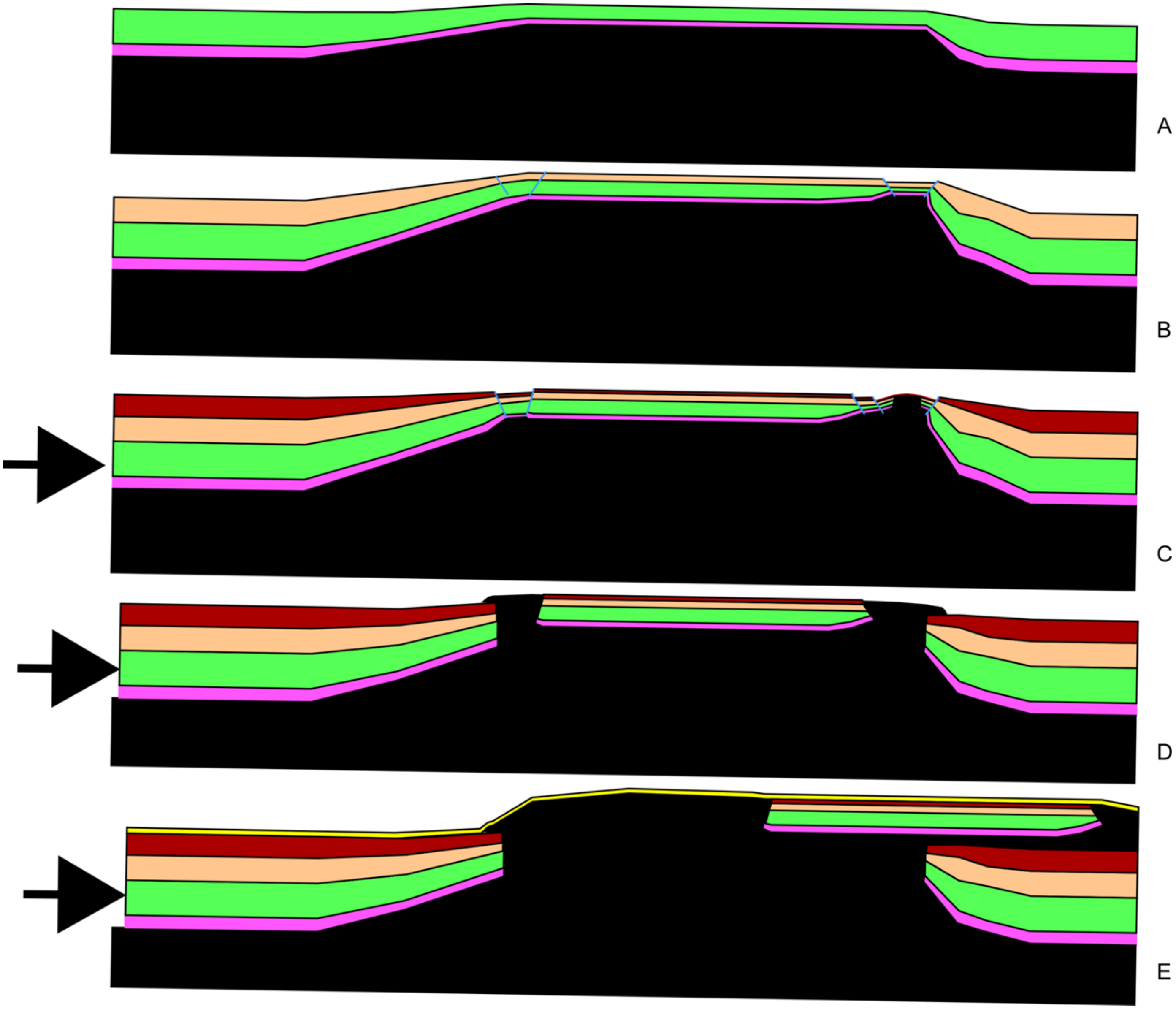

Figure 5. Scenario 1b: Cartoon model for the development of Mesozoic carbonate rafts in the Gulf of Mexico. This follows the same pattern of evolution as Figure 4, except that shortening occurs during diapir growth. The model contains a one-degree dip from right to left to simulate regional slope.

line, a raft has been divided into three segments in an area just short of the Sigsbee Escarpment (to left). Only the back half of raft segment 1 is visible. The front end of each raft segment has touched down, while the back ends were, for a time, being lifted by salt inflation. This eventually led to the raft segment 2 being thrusted over raft segment 3 upslope from it. The process also allowed salt to encapsulate partially the two segments. Poor imaging within and below the canopy on the right indicates that other raft segments are possibly/probably encapsulated there (raft? on Figure 9).

There are more unusual fates for rafts in the Gulf of Mexico than just folding, thrusting, and segmentation (Fig. 10). On this west-east oriented seismic line in WR, a raft has been pulled down into a salt diapir. In the process of moving basinward with the allochthonous salt in the canopy, part of this raft passed over the diapir. The initial motion for salt in the canopy is to move down into the diapir as salt in the diapir is displaced out and basinward (Dooley et al., 2012). When the raft passed over, it apparently moved down into the diapir but could not move back up out of the diapir. The raft folded but did not break and basinward movement of the raft stopped. Eventually, more salt from upslope flowed over the raft encasing it within the diapir. At the canopy level the raft is mostly but not completely welded. Theoretically, the interaction between salt bodies such as this is not unprecedented. Modeling of allochthonous salt flow over diapirs done at the Advanced Geodynamics Laboratory in Austin, Texas, shows the same relationships as described above (Tim Dooley, 2014, personal communication).

Distribution of Rafts

The distribution of carbonate rafts that we have identified so far is asymmetric. Most of the rafts are located on the lower slope near the terminus of the canopy system along the Sigsbee Escarpment (Fig. 11). Only a few rafts like those at Norton, Vienna, and Sumatra are seen in the middle to upper slope. It is thought that these bodies have not moved too far from where they originated. The authors acknowledge that the asymmetric distribution shown could be an artifact of our observations and raft identification methodology. However, it could equally sug-

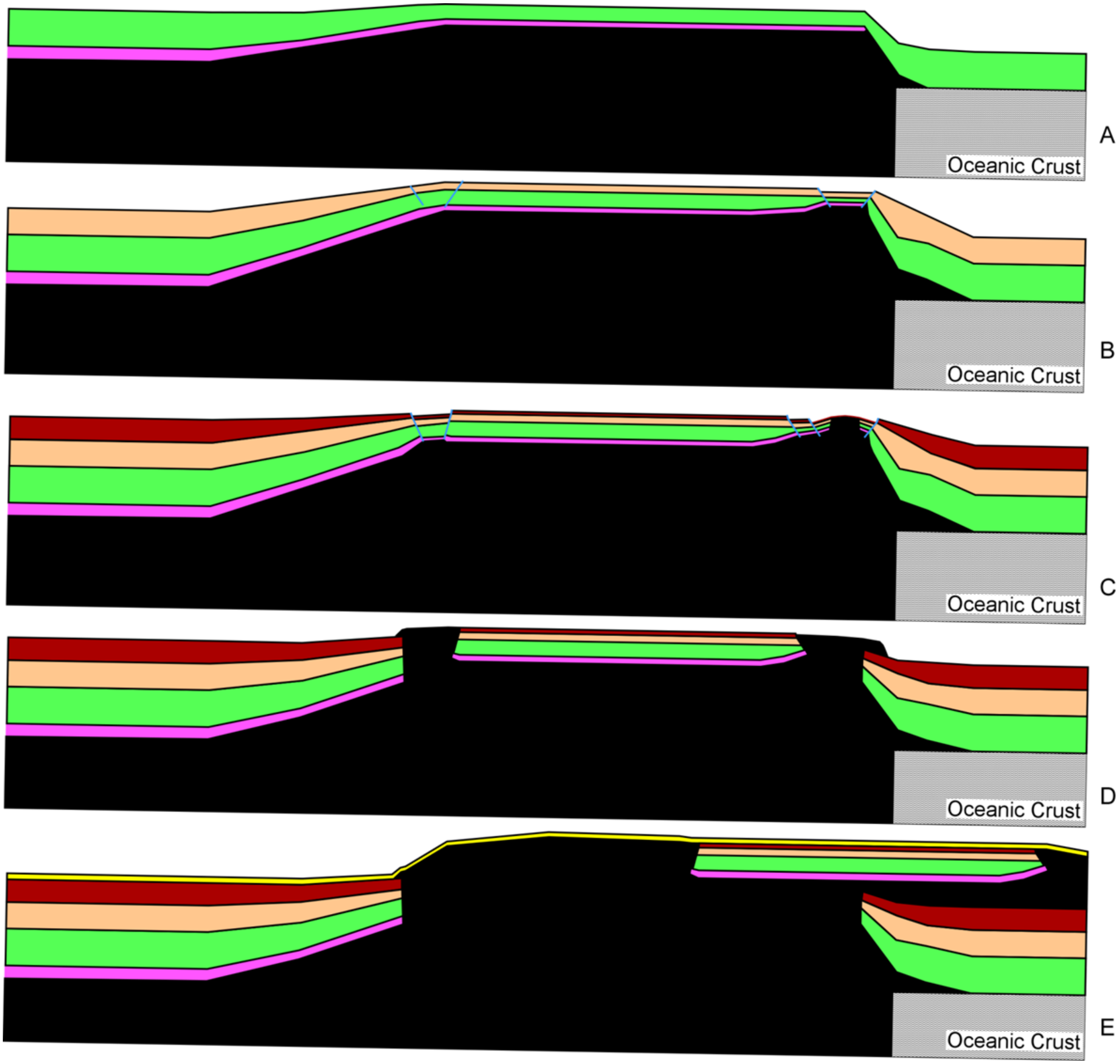

Figure 6. Scenario 2a: Cartoon model for the development of Mesozoic carbonate rafts in the Gulf of Mexico. This follows the same pattern of evolution as Figure 4, except that the inflating salt body is near/at the extended continental crust–oceanic crust boundary. The model contains a one-degree dip from right to left to simulate regional slope.

gest that allochthonous salt is very efficient at transporting overburden to its distal limits.

The total area covered by carbonate rafts is surprisingly large, approximately 3100 sq. km (1200 sq. mi). This total is necessarily a minimum, as we have since found that other rafted bodies lie hidden within the canopy. Individual rafts vary considerably in size, but can be up to about 500 sq. km (200 sq. mi). Rafts this large typically show numerous faults and extensional features. The two large rafts in AC display these characteristics and appear to be somewhat thinner than rafts to the east. However, a thinner section may reflect their different point of origin. Large rafts commonly have much smaller satellite rafts that have calved off the larger body during the transportation process. We strongly suspect that the salt canopy is littered with dismembered raft pieces that are too small for positive identification.

The question that remains is "where do the rafts originate?" We attempted to answer the question by looking at the base of the salt canopy. The base of the salt canopy records the basinward movement of salt from the deep primary autochthonous salt basins to the modern Sigsbee Escarpment. That movement is punctuated by flats (time where salt advance is relatively unimpeded) and ramps (time when sedimentation forces salt to inflate before further advancement can proceed). The timing of salt advance is known from the age of sediment cutoffs below the salt base. The ramps and flats also contain linear flow lines, which radially diverge from their points of origin. We used these flow

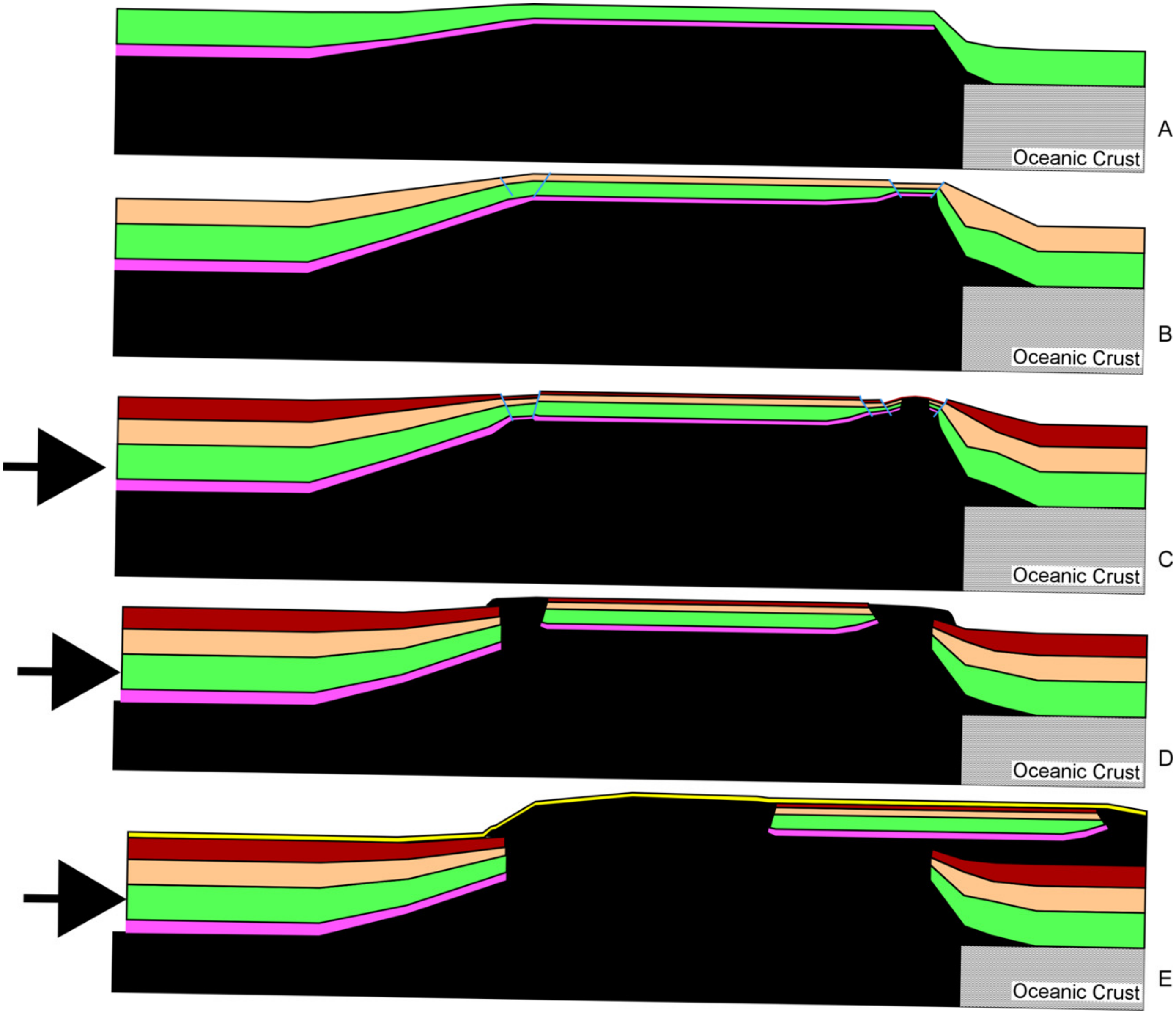

Figure 7. Scenario 2b: Cartoon model for the development of Mesozoic carbonate rafts in the Gulf of Mexico. This follows the same pattern of evolution as Figure 4, except that the inflating salt body is near/at the extended continental crust–oceanic crust boundary and that shortening occurs during diapir growth. The model contains a one-degree dip from right to left to simulate regional slope.

lines to project the rafts back towards their potential points of origin.

Figure 12 shows our raft body interpretation posted on the top primary basins map from Pilcher et al. (2011). The map shows numerous deep withdrawal basins (dark blue) in their bucket-weld province on the middle to upper slope. Bucket-welds occur where former diapirs, feeders to the shallow salt canopy, have collapsed. The present day position of interpreted carbonate rafts are shown in yellow shading, just as they are in Figure 11. Black arrows show the direction of transportation suggested by flow lines at the base of the salt canopy. White shaded rafts show the projected locations where each raft may have originated. By evaluating the two sets of locations on the map, an interesting correlation becomes apparent. At the rafts' present locations, there are very few or no candidates likely to have produced a raft (i.e., deep withdrawal basins, identified feeders, or collapsed feeders), but the projected points of origin, as suggested by flow lines at the base of the salt canopy, have numerous obvious candidates. Almost all of the rafts project back up into the bucket-weld province. This does not prove we have identified the exact sites where the rafts originated, but it does suggest that the rafts have been transported downslope at least as far as we have predicted.

CONCLUSIONS

Rafted bodies containing Mesozoic and Paleogene strata have been vertically displaced, often 3050–4600 m (10,000–15,000 ft), above equivalent aged strata found in adjacent basins or directly below the shallow salt canopy. The rafted strata are a condensed version of normal thickness strata found at regional level and expanded thicknesses found in salt withdrawal basins. The rafted strata have been transported large distances down slope from their sites of origin by allochthonous salt. A geomechanical model for displacing blocks of Mesozoic strata from their original depositional position and transporting them as rafts to a shallower stratigraphic level mirrors the creation of the allochthonous salt canopy. As salt inflated to form large, broad,

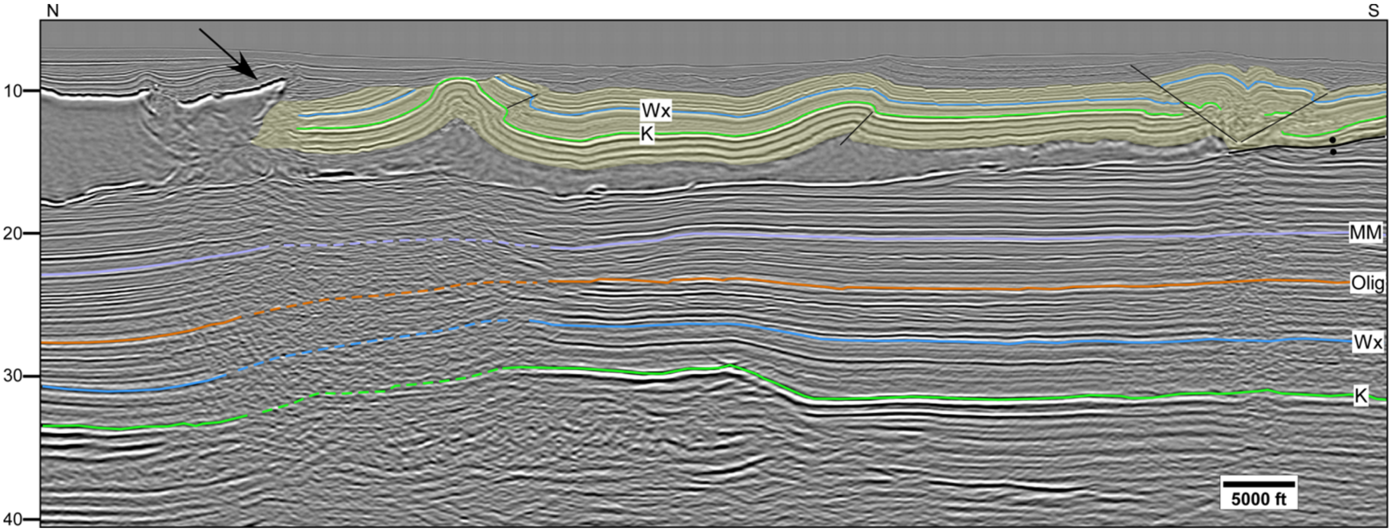

Figure 8. An arbitrary north-south seismic line that shows deformation of raft grounding at the Sigsbee Escarpment. The front end of the raft has welded while the back end is still trying to move basinward. Three types of folds are visible: an isoclinal fold, a slightly asymmetric fold with a basinward thrust fault, and a box fold with basinward and landward vergent thrust faults. The isoclinal fold was once exposed at the sea floor and eroded. The Paleogene section is gone but the Mesozoic carbonates resisted erosion. Black arrow points to where salt is starting to flow over back end of raft. Depth scale is in 10,000 ft increments. Vertical exaggeration, 1:1. Seismic data provided courtesy of Schlumberger Multiclient.

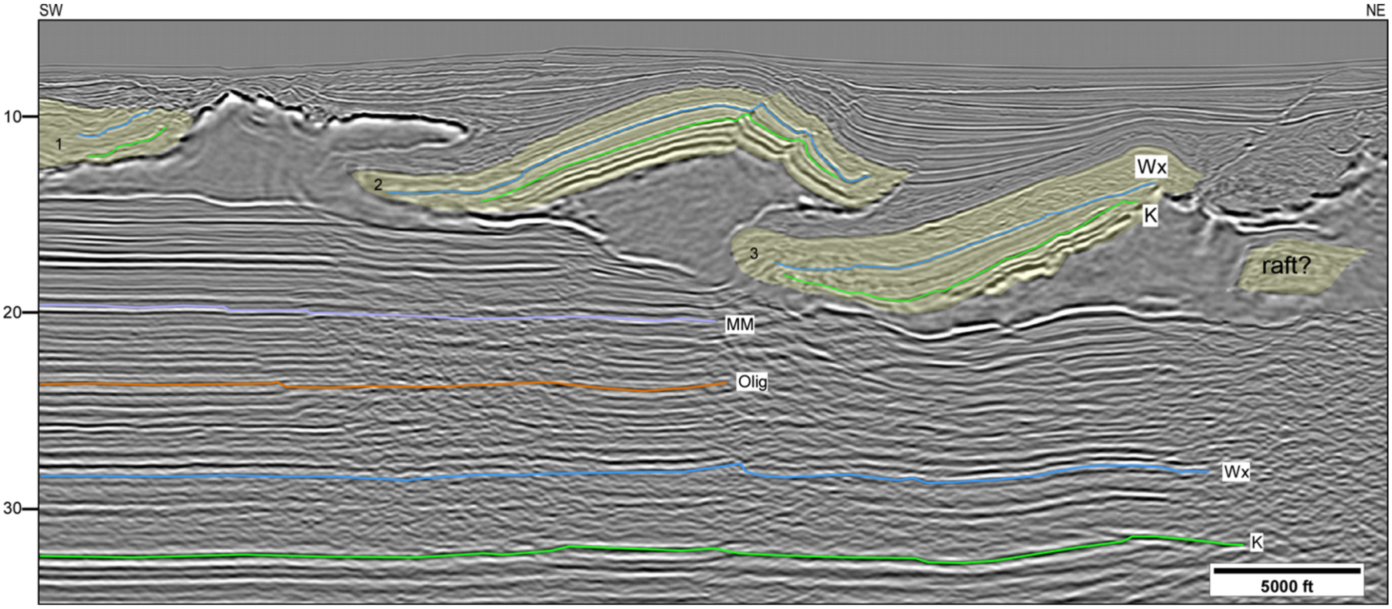

Figure 9. On this southwest-northeast seismic line, a raft has been divided into three segments just short of the Sigsbee Escarpment (to left). The front end of each segment has touched down, while the back ends were, for a time, being lifted by salt inflation. This eventually led to the middle raft segment being thrusted over the one upslope from it. The process also allowed salt to encapsulate partially the two segments. Poor imaging within and below the canopy on the right indicates that other raft segments are possibly/probably encapsulated (raft?). Depth scale is in 10,000 ft increments. Vertical exaggeration, 1:1. Seismic data provided courtesy of Schlumberger Multiclient.

diapiric structures, overlying strata were lifted above adjacent subsiding minibasins containing equivalent strata. Then, at later times in the Eocene, Oligocene, and Miocene, salt from the inflated structures broke out to form shallow canopies, carrying the rafts/overburden with it. During the transportation process, rafted bodies are subject to potentially intense deformation including normal faulting, thrusting, folding, stratal delamination, and segmentation or dismemberment. It is likely that many rafted segments have been encased in salt or become unrecognizable and lost. A minimum of 3100+ sq. km (1200 sq. mi) of area updip are missing Mesozoic carbonate strata and possibly the potential for Jurassic-aged source rocks. The total raft area identified by this study represents a minimum amount of possible raft material.

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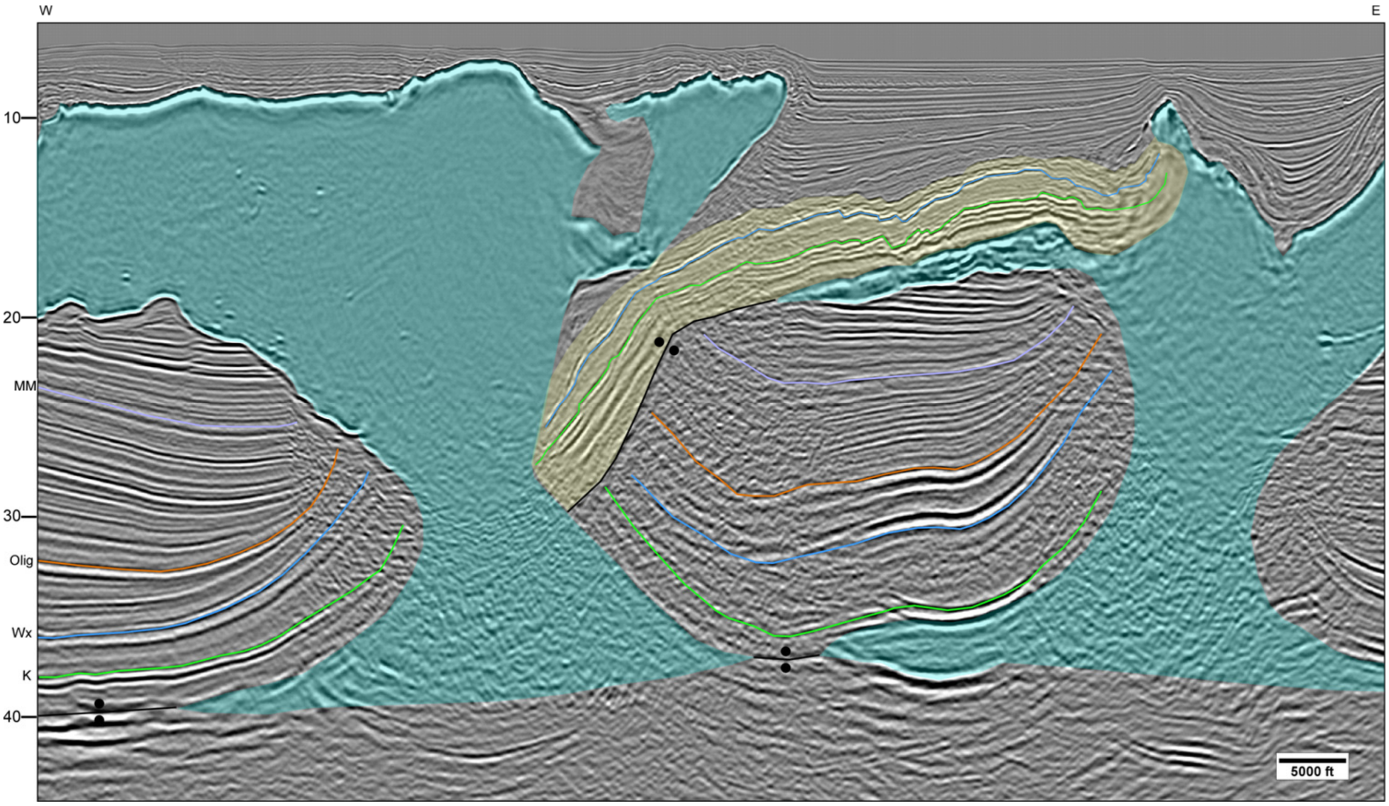

Figure 10. West-east oriented seismic line in Walker Ridge showing where a raft has been pulled down into a salt diapir. Depth scale is in 10,000 ft increments. Vertical exaggeration, 1:1.5. Seismic data provided courtesy of Schlumberger Multiclient.

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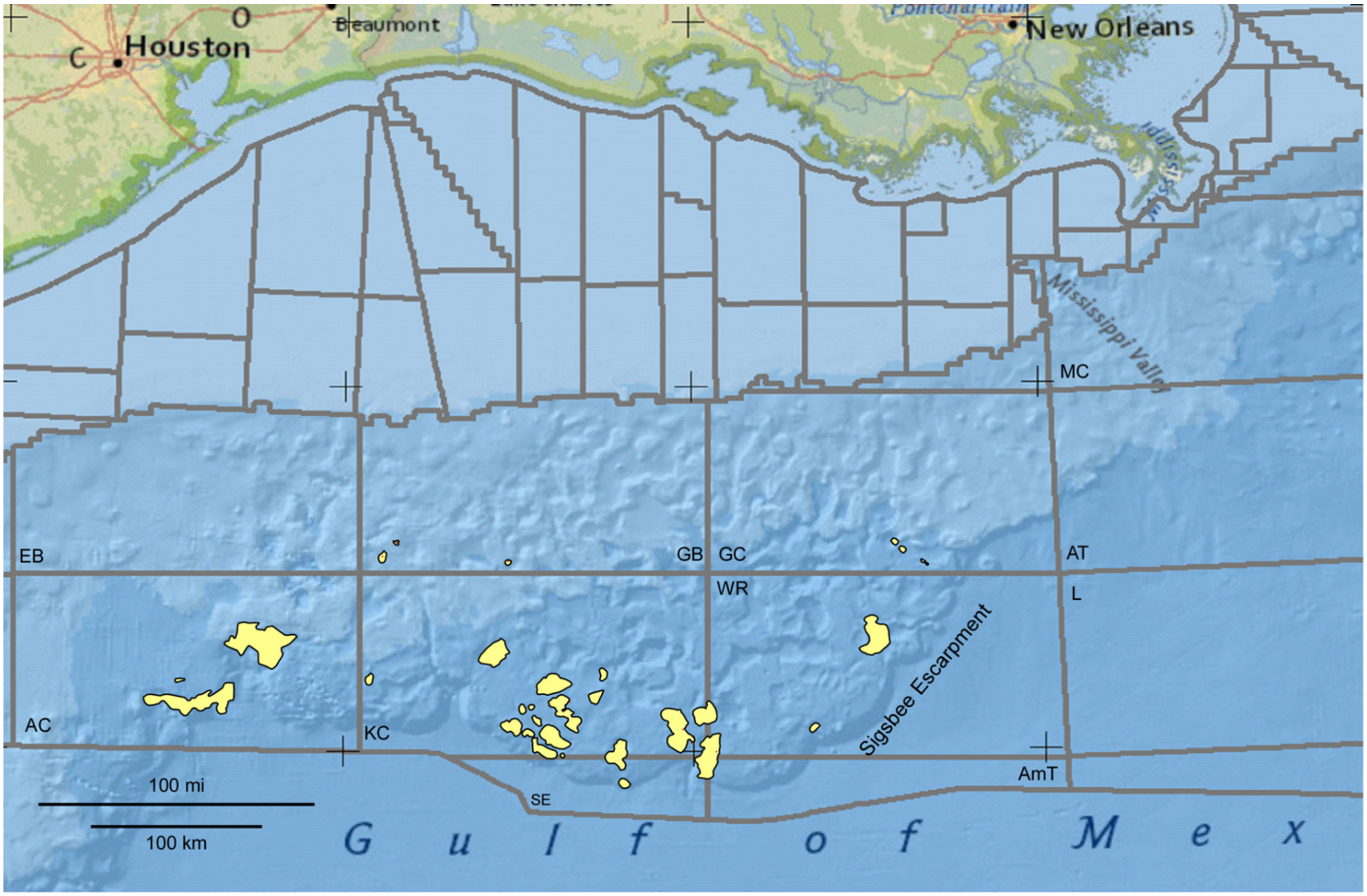

Figure 11. Material interpreted to be rafted Mesozoic carbonates has been identified on seismic data in GB, GC, WR, KC, and AC OCS protraction areas. The distribution of raft material is shown in yellow and amounts to slightly more than 3100 sq. km (1200 sq. mi). Most of the rafted strata are found near the terminus of the canopy system along the Sigsbee Escarpment.

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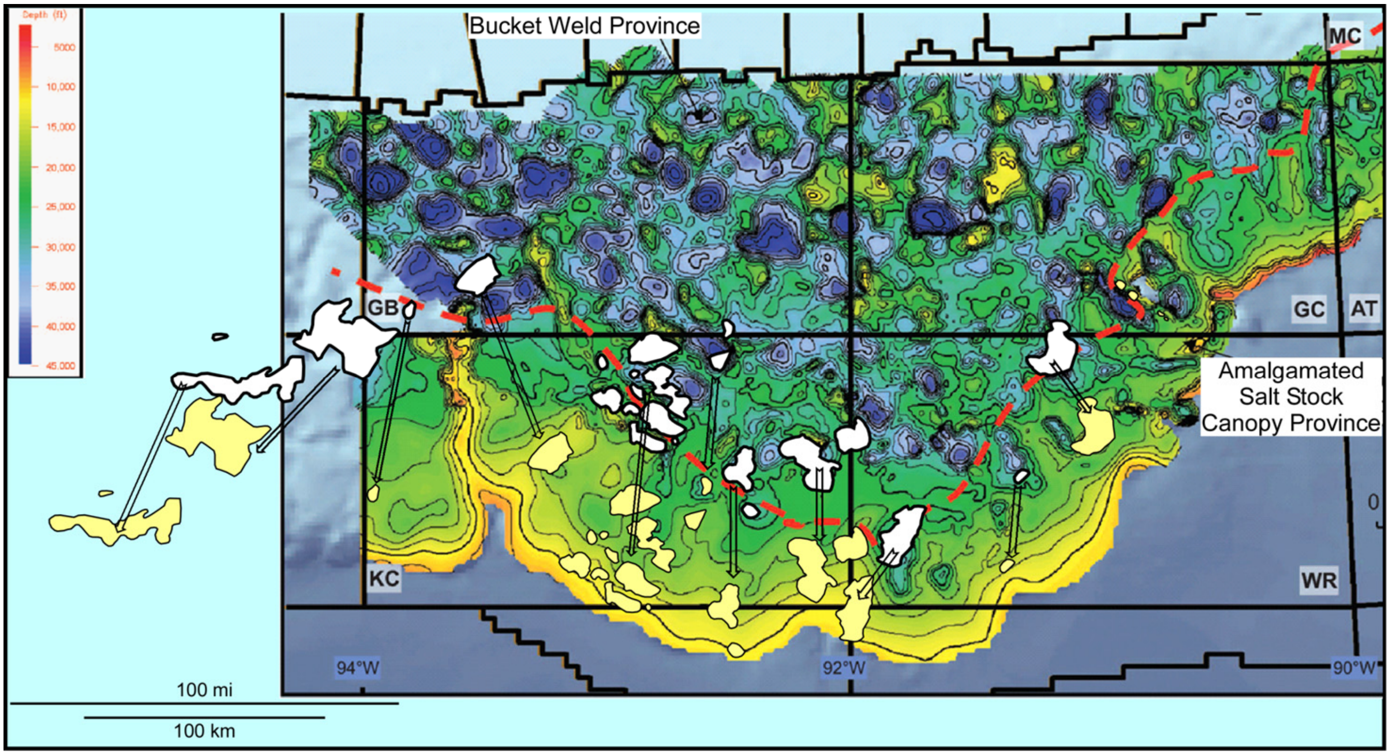

Figure 12. Top primary basins map from Pilcher et al. (2011) with present locations of rafts (yellow) and projected points of origin (white). Black arrows show the direction of transportation suggested by flow lines at the base of the salt canopy. Projection of rafts updip into the bucket-weld province provides many candidate diapirs for the origin of the rafts.

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