Structure and origin of the rifted margin of the northern Gulf of Mexico

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ABSTRACT

The wide continental margin of southern Louisiana borders Paleozoic terranes that accreted to Laurentia before Jurassic rifting formed the Gulf of Mexico. It is unclear whether continental rifting here involved widespread or localized crustal extension, or how seafloor spreading in the Gulf of Mexico started. To improve our understanding of this rifting episode, we gathered marine seismic-refraction data along a 396-km-long transect from the continental shelf 50 km off the western Louisiana coast to the central ocean basin as part of the Gulf of Mexico Basin Opening (GUMBO) program. Using travel-time tomography, we imaged the compressional seismic-velocity structure from the shallow sediments to the uppermost mantle. In our geophysical model, the crust tapers in thickness from ~11 km near the Louisiana coast to ~8 km in the deep water of the central Gulf of Mexico. The compressional seismic velocity increases from 5.7 to 5.9 km/s in the shallow basement to 6.8–7.2 km/s above the Moho. The thickness and average wave speed of crust beneath the modern Louisiana coast and continental shelf suggest the presence of uniformly stretched continental crust that was intruded by mantle-derived melts during extension before continental breakup. South of the Sigsbee Escarpment, the crust is thinner with a higher seismic velocity, which is more consistent with thick oceanic crust. A comparison of our seismic-velocity model with coincident seismic-reflection data indicates that the voluminous Louann Salt was likely deposited on rifted continental crust shortly before the onset of seafloor spreading in the Gulf of Mexico.

INTRODUCTION

Rifted margins can exhibit large variations in width and crustal structure due to differences in the mechanical strength and temperature gradient in the continental lithosphere. Other factors that influence the style of rifting are the presence of preexisting weaknesses such as large faults or varying amounts of decompression melting in the rising asthenosphere (Huismans and Beaumont, 2007; Armitage et al., 2009; Van Avendonk et al., 2009; Svartman Dias et al., 2015). We can improve our understanding of rift evolution if we compare the deep structure of mature rifted margins and consider the geological setting.

The Gulf of Mexico is in a unique position in comparative studies of rifted margins. The vast amount of industry seismic-reflection data and decades of drilling results have created a detailed record of sediment routing and basin stratigraphy (Snedden et al., 2018; Zhang et al., 2018), postrift subsidence (Roure et al., 2009), heat flow (Christie and Nagihara, 2016), and salt tectonics (Fort and Brun, 2012; Dooley et al., 2013). However, a consequence of the thick overburden in the Gulf of Mexico is that it makes imaging of the underlying crust more challenging than at sediment-starved margins (Mcintosh et al., 2014; Bayrakci et al., 2016). Potential field data and maps of the top of basement in seismic-reflection data nonetheless agree quite well on the location of the extinct mid-ocean ridge and the landward limit of oceanic crust (LOC) in the Gulf of Mexico (Pindell and Kennan, 2009; Hudac et al., 2013; Christeson et al., 2014; Sandwell et al., 2014) (Fig. 1).

To better understand the nature of the continent-ocean boundary and the variability in crustal structure along the northern Gulf of Mexico margin, we gathered marine seismic-refraction data along four transects as part of the 2010 Gulf of Mexico Basin Opening (GUMBO) program. Seismic-velocity models based on refraction data from GUMBO Line 3 and Line 4 in the northeastern Gulf of Mexico show that the margin has a lower crust with high seismic velocities that may be indicative of a large volume of igneous rock emplaced during rifting (Christeson et al., 2014; Eddy et al., 2014). In contrast, GUMBO Line 1 on the margin of the northwestern Gulf of Mexico exhibits thinner and more heterogeneous crust (Van Avendonk et al., 2015), possibly due to large-scale faulting and sparse magmatism during the Jurassic opening of the basin. The apparent eastward increase in syn-rift magma supply may be due to a larger thickness of the continental lithosphere beneath central Texas than in the Gulf coastal plain of Alabama and northwestern Florida (Van Avendonk et al., 2015).

In this paper, we present seismic-refraction data from GUMBO Line 2, a north-south transect offshore western Louisiana. Regional predictions of the...
Inherited Structure

Figure 1. Bathymetry of the Gulf of Mexico. Outline of Louann and Campeche salt provinces (purple) after Winker and Buffler (1988), Marton and Buffler (1994), and Hudec et al. (2013). The extinct spreading center (gray) as defined by Christeson et al. (2014). Orange, yellow, and green lines mark previous limit of oceanic crust (LOC) interpretations (Pindell and Kennan, 2009; Hudec et al., 2013; Christeson et al., 2014), while white rectangles mark the LOC interpreted in the GUMBO seismic-refraction data. Approximate location of Sabine Block in white. The solid blue line marks the Ouachita-Appalachian thrust front along the southern margin of Laurentia. LU—Llano Uplift; MCS—multichannel seismic reflection; SE—Sigsbee Escarpment.

LOC, which are based either on the basement topography (Hudec et al., 2013) or on the horizontal gravity gradient (Christeson et al., 2014), differ by more than 100 km in this area. Marine seismic-refraction data can help determine the nature of crystalline basement and improve tectonic models for the opening of the Gulf of Mexico. The seismic-velocity structure along this transect appears consistent with a margin that experienced intermediate amounts of magmatism. Widely stretched, thinned, and magmatically intruded continental crust may lie up to 300 km offshore southwestern Louisiana in the northern Gulf of Mexico.

The Mesozoic rift that formed the Gulf of Mexico region initiated along the southern edge of Laurentia (Pindell and Dewey, 1982; Stern et al., 2010) (Fig. 1), where older orogenies created a structural fabric that still persists in the deep lithosphere of modern passive margins (Gao et al., 2008; Ainsworth et al., 2014). Given that the reactivation of inherited structural weaknesses can influence the development and localization of continental rifts (Corti et al., 2007; Chenin et al., 2015), the crustal structure beneath the Gulf coastal plain between Texas and Florida may reflect the geometry of the adjacent Ouachita front, the Paleozoic suture between Laurentia, and accreted terranes of the southeastern United States (Wilson, 1966; Thomas, 2004; Poole et al., 2005; Huerta and Harry, 2012).

In central Texas, where high-standing Laurentian basement of the Llano Uplift flanks extended lithosphere of the northwestern Gulf of Mexico basin (Fig. 1) (Young and Lee, 2009; Raye et al., 2011), the Mesozoic rift may have localized in thickened crust of the Ouachita orogenic belt (Culotta et al., 1992). To the east, the Ouachita suture lies farther north in Arkansas, ~500 km north of the Gulf coast (Houseknecht and Matthews, 1985; Keller et al., 1989). The pronounced Louisiana magnetic anomaly (Fig. 2) suggests that the continent-ocean transition approximately follows the present-day coastline (Mickus et al., 2009; Kneller and Johnson, 2011). Igneous rocks found in the Five Islands salt domes in southern Louisiana also indicate that low-degree melts were produced here in the Late Jurassic (158–160 Ma) in the final stages of rifting (Stern et al., 2011). The Mesozoic rift therefore did not exploit the ancient Ouachita suture in the Mississippi Embayment (Wilson et al., 1982; Mickus and Keller, 1992; Harry and Londono, 2004), but instead localized extension in the crust that presently lies deep beneath the sediments of the Gulf coastal plain (Fig. 1).

The zone of crust between the Ouachita orogen of Oklahoma and Arkansas in the north and the Louisiana Gulf of Mexico margin to the south may include Paleozoic volcanic arc terranes and fragments of continental lithosphere that accreted to Laurentia during the closure of the Iapetus and Rheic oceans (Thomas, 2004; Nance and Linnemann, 2009). Near the Texas-Louisiana border, crust of Sabine Block (Fig. 1) tapers southward in thickness from ~35 km to ~15 km (Hales et al., 1970; Mickus and Keller, 1992) toward the present-day shoreline. This crustal thickness trend may be explained by increasing amounts of stretching of the basement toward the distal margin before continental breakup. Seismic-velocity images from Earthscope data (Schmandt et al., 2015) show that the accreted crust of the southeastern United States appears to be consistently thinner than the Laurentian crust north of the Ouachita suture. Furthermore, south of the Ouachita front, the upper mantle has shear-wave seismic velocities of 4.5–4.6 km/s, whereas this wave speed is generally higher than 4.7 km/s beneath Laurentia (Schmandt et al., 2015). The lower-mantle seismic velocities of the Sabine Block suggest that it is less depleted and, therefore, not as strong as the cratonic mantle to the north and west (Poupin et al.,...
2003). Such structural differences along the southern margin of Laurentia may have influenced the style of rifting during the opening of the Gulf of Mexico.

Opening the Gulf of Mexico

The timing of major events in the geological evolution of the Gulf of Mexico is less certain than at some of the Atlantic margins, because seafloor-spreading anomalies appear absent in the central portion of this small ocean basin. Despite this challenge, regional plate tectonic reconstructions that are constrained by basement-stratigraphic relationships offer a consensus on the rifting and seafloor-spreading history of the Gulf of Mexico (Pindell and Dewey, 1982; Salvador, 1987; Marton and Buffler, 1994; Pindell and Kennan, 2009; Hudec et al., 2013; Christeson et al., 2014; Eddy et al., 2014). Kneller and Johnson (2011) have presented an alternative model, where plate kinematics in the Gulf of Mexico are similar, except that opening of the basin started 20–25 million years earlier.

The common view is that a northwest-southeast-oriented continental rift initiated between Yucatan and North America in the Late Triassic (ca. 210 Ma). After the continental crust stretched and thinned, large volumes of salt filled the young Gulf of Mexico basin to sea level around Callovian time (163–161 Ma). At approximately the same time (166–154 Ma), the opening direction changed, and seafloor spreading commenced in a northeast-southwest direction, as the Yucatan block rotated to its current position. During this spreading phase, the salt body split into a northern Louann province and a southern Campeche province (Fig. 1). Seafloor spreading ceased ca. 140–135 Ma. Over the course of the Cretaceous and Paleogene, the wide continental shelf on the northern Gulf of Mexico margin subsided and formed large carbonate reefs, and large volumes of clastic sediment arrived from the North American interior (Winker and Buffler, 1988). Subsequently, the Callovian salt migrated upward from its deep-lying stratigraphic position to salt domes on the inner margin and massive diapiric salt bodies along the Sigsbee escarpment (Jackson et al., 1994; Galloway, 2008).

## DATA AND METHODS

Seismic-Refraction Data

The 396-km-long north-south GUMBO Line 2 extends from a northern end point at ~50 km offshore the western Louisiana coastline to the deep-water central Gulf of Mexico basin (Fig. 1). The seismic line crosses the Louisiana shelf, the salt minibasin province on the continental slope, and the Sigsbee Escarpment (Bryant et al., 1990; Hall, 2002). Unlike GUMBO Line 3 and Line 4, the south end of GUMBO Line 2 does not cross the east-west-trending extinct spreading center, which lies ~40 km farther south (Christeson et al., 2014; Nguyen and Mann, 2016).

The vessel R/V Iron Cat towed three strings each with 12 air guns at 9–10 m water depth, providing an average source capacity of 774 L. Air-gun shots fired every 150 m were recorded on 38 short-period ocean-bottom seismometers (OBSs) at 10 km spacing along GUMBO Line 2. Thirty-four of these instruments were recovered with useful data. Each OBS recorded data on a three-component geophone and on a hydrophone. The hydrophone channels produced the highest quality receiver gathers from instruments on the Louisiana shelf, whereas the vertical channel showed arrivals more clearly on instruments located in the salt minibasins and outboard of the Sigsbee Escarpment.

We describe the characteristics of wide-angle events in the seismic-refraction data from receiver gathers of instruments on the shallow Louisiana shelf where the seafloor is less than 250 m deep to the central Gulf of Mexico outboard of the Sigsbee Escarpment, where seafloor depths exceed 2400 m. By comparing wide-angle OBS records along GUMBO Line 2, we consistently recognize three seismic-refraction phases (P1–P3) and two wide-angle seismic
reflections (R1 and R2) in the receiver gathers (Figs. 3A–3C). These phases are classified based on the source-receiver offset and travel times at which they are observed, and they have distinct apparent velocities in x-t space. In contrast to seismic-refraction data in the eastern Gulf of Mexico, where salt and sediment cover are relatively thin (Christeson et al., 2014; Eddy et al., 2014), the OBS data along GUMBO Line 2 generally have a lower signal-to-noise ratio. However, the data from GUMBO Line 2 are similar in quality to the seismic-refraction data from GUMBO Line 1 (Van Avendonk et al., 2015). Coherent seismic arrivals can be determined at source-receiver offsets no greater than 60–100 km (Fig. 3).

We observe the first-arriving seismic-refraction phase P1 on all 34 receiver gathers, at offsets up to ~40 km. The apparent velocity of P1 arrivals is mostly consistent across all water depths and increases gradually with source-receiver offset from ~2.2–3.5 km/s. However, in some areas, the presence of shallow salt diapirs coincides with P1 arrivals with apparent velocity greater than 4.0 km/s. All but one of the instruments on GUMBO Line 2 recorded the refracted arrival P2. This event appears 0.5–1.0 s later than P1 at near offsets, but P2 is usually the first-arriving phase at ranges of 30 km to 60 km from the OBS. Instruments on the Louisiana shelf and in the salt minibasins recorded P2 refractions with relatively consistent apparent velocities of 4.5–6.0 km/s (Figs. 3A–3C), while seismic records outboard of the Sigsbee Escarpment show P2 arrivals with faster apparent velocities (5.5–70 km/s) at nearer source-receiver offsets (20–40 km; Fig. 3D). Due to a poorer signal-noise ratio at larger offsets, the P3 phase can be distinguished on just 25 of the 34 OBS records of GUMBO Line 2. Phase P3 shows at offsets greater than 50 km on most of the receiver gathers with an average apparent velocity of ~8.2 km/s; but south of the Sigsbee Escarpment,
it appears at offsets of ~40 km. We recognize wide-angle seismic reflections R1 and R2 in the receiver gathers as retrograde travel-time branches. On several OBS records, we observe seismic-reflection R1 shortly after the crossover point of P1 and P2 refractions (Fig. 3D). Reflection R2 is a later, high-amplitude phase that we commonly see after the P2 at offsets between 35 km and 65 km.

We manually picked 15,517 travel times of all wide-angle phases on the OBS record sections of GUMBO Line 2. We verified the accuracy of all picks by cross-checking arrival times of reciprocal source-receiver pairs. Such reciprocity tests were particularly important to distinguish the P2 and P3 phases from the deeper R2 reflection on records of relatively poor quality. The uncertainty of travel-time picks generally increases with source-receiver offset. We assigned errors of 25–125 ms uncertainties to P1 arrivals. For the P2 refraction, these errors range from 50 ms to 225 ms. The average assigned errors for R1, R2, and P3 are 112 ms, 123 ms, and 203 ms, respectively.

Seismic-Reflection Data

Joint interpretation of marine multichannel seismic (MCS) reflection and refraction data has greatly advanced our understanding of rifted margins worldwide, since these data sets are often designed to complement each other (e.g., Morgan et al., 1989; Dean et al., 2000; Lester et al., 2014). Likewise, the GUMBO marine seismic-refraction project benefitted from the existence of many regional marine seismic-reflection lines in the Gulf of Mexico that have been acquired by geophysical companies. GUMBO Line 2 lies approximately in the same location as GulfSPAN Line 2000, which was gathered by ION/GXT (Fig. 2). GulfSPAN Line 2000 was collected with a 9-km-long streamer and imaged to 16 seconds. A reverse-time prestack depth migration of the MCS data produced a reflection profile across the margin offshore Louisiana (Fig. 4).

An interpretation of GulfSPAN Line 2000 in pink (Radovich et al., 2011) shows the widespread extent of salt structures in the north-central Gulf of Mexico. The mobilized salt and deformed sediments can be interpreted in the MCS image, whereas they are mostly outside the resolution of our wide-angle refraction data. At the landward side of marine seismic profiles, the base of autochthonous Louann salt appears as a nearly continuous horizon beneath sedimentary reflections at or near the top of acoustic basement (Hall, 2002; Hudec et al., 2013). This horizon dips toward the salt minibasin province to ~15 km depth at a distance of 200 km in the profile (Fig. 4), and it rises to ~13 km depth at the Sigsbee Escarpment (350 km in profile). Along GulfSPAN Line 2000, we find several bodies of salt at depths of less than 10 km, some a few kilometers thick. These massive salt structures evacuated seaward and upward from their original stratigraphic position (Jackson et al., 1994; Hall, 2002) when large volumes of clastic sediments arrived at the passive margin in the Cenozoic (Galloway, 2008).

The thick salt and sediment layers in the north-central Gulf of Mexico strongly attenuate acoustic energy in the MCS data, such that few coherent reflections are found below the base of autochthonous salt (Fig. 4). However, we observe reflectivity at ~15 km depth beneath the salt minibasins at 180 km, 215 km, and 260 km model distance along GulfSPAN Line 2000, which could mark the top of basement (labeled Ba on Fig. 4). Seaward of the Sigsbee Escarpment, the acoustic basement can be seen as a coherent reflection at ~13 km depth.

Tomographic Inversion

The observation of wide-angle seismic reflections (R1 and R2) and refractions (P1–P3) on most of the OBS receiver gathers on GUMBO Line 2 suggests the presence of at least two prominent layer boundaries in the subsurface. We therefore build a seismic-velocity model that consists of three layers, divided by two reflecting interfaces. The arrival times of the wide-angle reflection R1 phase in the OBS data correspond well with the depth of acoustic basement in the reflection image for GulfSPAN Line 2000 (Fig. 4), or otherwise with the base of autochthonous salt. We refer to the R1 phase as $P_{bb}$ in our data interpretation, a wide-angle reflection from a relatively shallow interface. The first-arriving phase P1 must be a refracted wave turning above this interface in the sediments ($P_{sed}$). The P2 and P3 phases appear to represent crustal refractions.
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Before we incorporate all wide-angle reflections and refractions in our analysis of the seismic-velocity structure, we build a preliminary velocity model for GUMBO Line 2 by inverting first-arriving seismic refractions from our travel-time data set. A tomographic inversion of first-arriving phases generally leads to a robust, smoothly varying seismic-velocity image (Zelt et al., 2003). Using the seismic-reflection image of GulfSPAN Line 2000, we subsequently estimate the top of basement and the Moho as first-order velocity discontinuities in our model. For each of the observed phases, we calculate ray paths and travel times in the starting velocity model using the shortest path method and ray bending (Van Avendonk et al., 2001). We then iteratively invert travel-time residuals using a linearized tomography method with smoothness constraints (Van Avendonk et al., 2004). The inversion method simultaneously adjusts the seismic velocities and layer boundary depths until the data misfit is comparable to the assigned errors.

Our final compressional seismic-velocity model (Fig. 5) shows three layers with seismic velocities increasing steadily with depth from 2.0 km/s near the seafloor to more than 8.0 km/s at depths varying between 25 km nearshore and 20 km in the central Gulf of Mexico. There are lateral variations in seismic velocity and layer boundary depth as well. After the last iteration of the inversion, the model has a $\chi^2$ relative data misfit of 1.5 and a root mean square (RMS) travel-time misfit of 130 ms. The match between picked and calculated travel times for the final model is shown for OBSs 204, 213, 226, and 237 (Fig. 6) together with the ray paths for each of the observed wide-angle seismic phases. The largest misfits (>100 ms) are associated with wide-angle refraction $Pn$ and reflections $PbP$ and $PmP$. The travel-time picks for these phases were generally assigned the largest uncertainties as well.

Resolution Test

To determine which parts of the seismic-velocity model (Fig. 5) can be interpreted with confidence, we carry out resolution tests. A byproduct of the least-squares inversion is the resolution matrix (Jackson, 1972), from which we can examine the spatial resolution of seismic velocities and layer boundaries in our GUMBO Line 2 tomographic model. Specifically, we test the degree to which a model feature of fixed size can be resolved. We perform this calculation for an elliptical body in model space of 8 km × 3 km and for a larger ellipse of 16 km × 6 km in size (Van Avendonk et al., 2004). If such structure can be fully reproduced with the ray geometry and travel-time constraints of our data set, the local resolution is 1. Conversely, if no part of the test ellipse is imaged, the local resolution is 0. We consider a resolution value of 0.5 adequate for interpretation.
We find excellent spatial resolution of the GUMBO Line 2 seismic-velocity model at the 16 km x 6 km scale from the seafloor to the uppermost mantle (Fig. 7A). Measured over such a large area of our model, the average seismic velocity must be well determined. The resolution of basement and Moho depth in the tomographic inversion are also very good on a scale of 16 km. The interpretation of fine structure in the model (Fig. 5) requires adequate resolution at the 8 km x 3 km scale. These smaller length scales are well resolved in the shallow sediments and partially resolved in the upper crust (Fig. 7A). Some of the strong seismic-velocity heterogeneity in the sediments, which is likely related to salt tectonism (Fig. 4), may therefore also be within the resolution of our tomographic inversion. On the other hand, small-scale velocity variations (~8 km) in the deep crust and uppermost mantle of GUMBO Line 2 cannot be uniquely determined.

**SEISMIC-VELOCITY STRUCTURE**

Our seismic-velocity model for GUMBO Line 2 (Fig. 5A) consists of three layers divided by two boundaries that are constrained by the travel times of wide-angle seismic reflections and refractions. The \( PmP \) reflections that we observe in the GUMBO seismic-refraction data are of high amplitude, and seismic velocities beneath the deeper interface exceed 8 km/s. We therefore have confidence that this layer boundary represents the Moho, and its depth varies from 26 km at the landward end of the profile to 20 km depth at the southern end. The upper model interface, which is in part constrained by the \( PbP \) wide-angle reflections, decreases in depth from 15 km to 12 km along GUMBO Line 2. A comparison with the marine seismic-reflection data (Fig. 5C) shows that these weaker reflections could be from the top of crystalline basement beneath the...
continental shelf. Between 140 km and 250 km distance in the model, the base of salt approximately coincides with the top of basement. Farther south, the Sigsbee Escarpment is a mobilized salt ridge that lies several kilometers above the top of basement (Fig. 4). We therefore infer that the middle layer of our model mostly consists of crystalline crust, although it may also include some pre-rift and early syn-rift sediments beneath the salt minibasins.

The upper layer in our model comprises salt and sediments, up to 15 km thick, with seismic velocities increasing from 2.0 km/s near the surface to almost 5.5 km/s near the top of basement. Some shallow salt bodies have seismic velocities approaching 4.5 km/s, whereas clastic sediments in the first two kilometers beneath the seafloor have seismic velocities of 2–3 km/s. Small-scale heterogeneity in velocity structure increases from the continental shelf (0–140 km in our model) to the salt minibasins (140–350 km) along our seismic-velocity profile (Fig. 5A). This trend is consistent with the distribution of salt diapirs and welds (Fig. 5C) that are imaged in the seismic-reflection data of GulfSPAN Line 2000 (Radovich et al., 2011). The greater occurrence of allochthonous salt beneath the minibasins compared to the inner margin is a common feature of the northern Gulf of Mexico (Peel et al., 1995; Hall, 2002;...
Galloway, 2008). Seaward of the Sigsbee Escarpment, we observe flat-lying, laterally continuous sediments in the seismic-reflection and seismic-refraction data over a distance of 40 km.

The crustal thickness beneath the Louisiana continental shelf is nearly constant at 10.0–10.5 km along GUMBO Line 2. In the salt minibasin province, between 140 km to 350 km in our model, the crust varies in thickness between 8.9 km and 11.5 km. Beneath the Sigsbee Escarpment (350 km), crust thins to a minimum thickness of 6.1 km (Fig. 5A), and it increases in the seaward direction to ~8.0 km in the central Gulf of Mexico. Seismic velocities in the crust increase gradually with depth from 5.4 km/s at the top of basement to 7.2 km/s at its base. Lateral variations in the deep crustal seismic velocities appear to correlate with the magnetic anomalies (Fig. 5B) along GUMBO Line 2. Near the Louisiana coast (0–50 km in our model), the seismic velocity in the lower crust averages 6.9 km/s, but it increases to 7.3 km/s at 120–150 km at the shelf edge (Fig. 5A). Coincidentally, the magnetic anomaly increases by 50 nT in the seaward direction. Farther south, both the seismic velocity and magnetic anomaly decrease toward the Sigsbee Escarpment (at 300 km in our model), but both are also higher at the southern end of GUMBO Line 2 in the central Gulf of Mexico.

The mantle seismic velocities along GUMBO Line 2 are not very well constrained (Fig. 7). In our final image (Fig. 5A), we find that seismic velocity beneath the Moho averages 8.2 km/s, which indicates that our model clearly identifies the base of crust along the refraction profile. Between 170 km and 220 km, these velocities are below 7.8 km/s, and seaward of the Sigsbee Escarpment, we obtained values as great as 8.5 km/s. Though these values are within range of possible seismic velocities in the uppermost mantle (White et al., 1992; Christensen, 2004), some lateral variations in mantle wave speed may not be well resolved due to the low signal/noise ratio of mantle seismic refractions at large offsets (Fig. 3).

**DISCUSSION**

**Tectonic Interpretations**

To get better insight into the structure and origin of the Gulf of Mexico, scientists have gathered marine seismic-refraction data in the basin since the...
mid-twentieth century. Early explosion seismic studies showed good depth penetration of seismic refractions at large offsets (Ewing et al., 1960; Hales et al., 1970; Ibrahim et al., 1981). Interpretation of seismic-refraction phases in these vintage OBS shot gathers is nonetheless difficult due to large gaps between explosive shot locations. In later years, air-gun arrays offered much denser shot coverage in marine seismic-refraction experiments. However, the acoustic source volume in these second-generation seismic-refraction studies of the northern Gulf of Mexico was small, which resulted in OBS refraction data of limited quality (Ebeniro et al., 1988). The 2010 GUMBO study benefitted from a large acoustic array as well as a large number of OBS instruments. The resulting seismic-velocity models for Line 2 and three previously published GUMBO transects (Christeson et al., 2014; Eddy et al., 2014; Van Avendonk et al., 2015) provide full coverage of the crustal structure, even beneath thick salt structures of the Sigsbee Escarpment. Given that the GUMBO seismic-velocity images have good resolution (Fig. 7), we can make comparisons with the seismic-velocity structure of other rifted margins where the sediment cover is thinner and the basement morphology is better known (e.g., Dean et al., 2000; Lester et al., 2014).

Based on the available geophysical data, several scientists suggest that thinned continental crust extends offshore Louisiana (Buffler and Sawyer, 1985; Ebeniro et al., 1988; Pindell and Kennan, 2009; Nguyen and Mann, 2016). Conversely, others prefer a model where the Houston magnetic anomaly and Louisiana magnetic anomaly (Fig. 2) mark the continent-ocean transition along the Gulf coast (Mickus et al., 2009). A few geological considerations support the latter model. Firstly, plate reconstructions for Pangea allow for a tight fit between Yucatan and North America (Kneller and Johnson, 2011); so a large mass of thick continental crust offshore in the northwestern Gulf of Mexico would be difficult to explain. Secondly, there is evidence for rift-related volcanism near the magnetic anomaly in southern Louisiana (Stern et al., 2011). The arrival of mantle-derived melts in the Jurassic may have reduced the yield strength in the extending lithosphere (Bialas et al., 2010), which could have led to rapid continental breakup and seafloor spreading offshore Louisiana. The seismic-velocity structure along GUMBO Line 2 (Fig. 5) correlates well with the gridded magnetic anomalies in the northwestern Gulf of Mexico (Maus et al., 2009). High seismic velocities imaged in the lowermost crust of the continent-ocean transition zone correspond to magnetic-high anomalies on a scale of ~50 km. This suggests that high seismic velocities (>7.0 km/s) on these profiles may correspond to igneous intrusions in the lower crust, whereas lower seismic velocities (6.0–7.0 km/s) represent a composition that includes rifted continental basement.

Global Comparison of Seismic-Velocity Structure

To test the most common interpretations of the nature of basement offshore Louisiana, we compare our new seismic-velocity model for GUMBO Line 2 with seismic-velocity depth curves that represent other tectonic settings that are relevant to our study. First, we divide our seismic-velocity image in four regions based on the variations in the magnetic anomalies across the margin (Fig. 8A): (1) On the inner continental shelf, magnetic anomalies are very weak (~10 nT), which we use to distinguish it from (2) the shelf edge (100–150 km), which has a +50 nT anomaly. (3) The salt minibasins province (150–300 km) forms a broad magnetic low (~80 nT), while (4) the area south of Sigsbee Escarpment (350 km) has a much weaker negative anomaly (~25 nT).

We calculate the average one-dimensional (1-D) seismic-velocity profiles for each of the four mentioned regions of GUMBO Line 2, and first compare these with average mature Atlantic oceanic crust (White et al., 1992) and with average continental crust (Christensen and Mooney, 1995). The seismic velocities of the three regions north of the Sigsbee Escarpment do not match either continental or oceanic crust, but the velocity-depth curve of the southermmost portion of GUMBO Line 2 mostly lies within the bounds of mature oceanic crust (Fig. 8B). In the first kilometer beneath the top of basement, we observe a significant discrepancy between the 1-D velocity curves from the GUMBO project and global averages of seismic-velocity structure (Fig. 8). We can attribute this difference to the large sediment load in the Gulf of Mexico. The weight of sediments results in a higher confining pressure in the upper crust, which reduces pore space and increases the seismic wave speed in sediment-covered basement.

Neither of the 1-D velocity profiles for GUMBO Line 2 fit the structure of magma-poor margins, such as those from the Newfoundland-Iberia rift (Fig. 8C). On the other hand, the three profiles from the shelf and salt minibasins correspond quite well with the seismic-velocity structure of the northern margin of the South China Sea (Lester et al., 2014), where stretched and faulted continental basement was overprinted with volcanism and lower-crustal magmatic intrusions (Fig. 8D). We also display velocity-depth curves from the volcanic rifted margins of eastern Greenland (Hopper et al., 2003) and central Norway (Mjelde et al., 2005), where basement is covered by thick sections of lava flows, expressed as seaward-dipping reflections in seismic-reflection data. The crust of these volcanic margins is thicker and of higher seismic velocity (>7.4 km/s) than the crust of the offshore Louisiana margin (Fig. 8E). The seismic-velocity structure of the crust beneath the continental shelf and salt minibasins along GUMBO Line 2 may therefore be described as an intermediate volcanic rifted margin. This would imply that the Louisiana magnetic anomaly represents an important syn-rift volcanic event, but that Jurassic lithospheric breakup occurred farther offshore.

In our interpretation of the seismic structure along GUMBO Line 2, the LOC lies at ~310 km in our profile (Figs. 5 and 8). The suggested location of the continent-ocean transition is in good agreement with the LOC proposed by Hudec et al. (2013), who used industry seismic-reflection data to map an upward step in the basement from the rifted margin toward the central Gulf of Mexico (Fig. 1). According to our model, the crust thickens southward from 6.1 km beneath the Sigsbee Escarpment to 8.0 km at the south end of the transect. The southward crustal thickness increase provides isostatic support for the basement...
ramp, which may have formed the seaward limit of the Louann salt province at the onset of seafloor spreading (Hudec et al., 2013).

Rifted Margin Evolution

The four GUMBO seismic-refraction transects (Fig. 1) show along-strike differences in the deep crustal structure from east to west on the northern Gulf of Mexico margin. The seismic velocities of the rifted crust along GUMBO Line 2 are higher than those observed on GUMBO Line 1. The seismic-velocity structure is also notably rougher on GUMBO Line 1 offshore South Texas than on the three GUMBO transects to the east. Van Avendonk et al. (2015) suggested that the crustal heterogeneities on Line 1 are consistent with faulted and extended continental crust with local igneous intrusions. Relatively sparse synrift magmatism and more localized deformation may have resulted from rifting of the strong and thick Grenvillian lithosphere in central Texas, which would have hampered decompression melting (Armitage et al., 2009).

The high average seismic velocity (~6.6 km/s) and smooth lateral variations in crustal structure on GUMBO Line 2 can be explained by widespread igneous intrusions that may make up a large fraction of the crust offshore southern Louisiana. During Mesozoic extension and breakup of the relatively thin lithosphere of the Sabine Block and other Paleozoic terranes of the southeastern United States, upwelling asthenosphere passed through the solidus at relatively shallow depth, producing a larger melt volume along GUMBO Line 2 than along GUMBO Line 1 offshore South Texas (Van Avendonk et al., 2015). The inherited continental lithospheric thickness along the northern margin of the Gulf of Mexico may therefore have controlled the amount of syn-rift magmatism. To the east, data from GUMBO Line 3 (Eddy et al., 2014) and GUMBO Line 4 (Christeson et al., 2014) support the presence of a volcanic rifted margin. Here the lower crust has a higher seismic velocity (7.2 km/s) than along GUMBO Line 2, which suggests that the mantle potential temperature at the time of mantle melt production was higher in the northeastern Gulf of Mexico than offshore Louisiana.

The lateral homogeneity of the seismic-velocity structure offshore Louisiana may also indicate that (1) the crust of the Sabine Block had a weak rheology prior to rifting, which led to a wide volcanic rift zone (Armitage et al., 2018) during opening of the Gulf of Mexico, and (2) extension here was accommodated mostly by pure-shear stretching. In our interpretation, stretched continental crust was intruded by mantle-derived melts from the coast (Stern et al., 2011) to 300 km offshore southwestern Louisiana. In contrast, the conjugate margin offshore Yucatan appears relatively narrow (Nguyen and Mann, 2016). Lithospheric breakup between the U.S. and Yucatan margins must therefore...
have been asymmetric. Hudé et al. (2013) attributed differences in the amount of crustal stretching offshore Texas and Louisiana to margin segmentation at the right-lateral Brazos transform fault. Though we mostly agree on the location of the LOC, we propose that the additional extension that created the Walker Ridge salient (Fig. 2) is due to the weak rheology. We prefer this explanation because continental transform faults rarely offset rifted margins into the oceanic domain (Taylor et al., 2009).

We propose that the oldest true oceanic crust of the basin lies near the western Sigsbee Escarpment, and early seafloor spreading in the central Gulf of Mexico was approximately symmetrical. According to our model, the oceanic crust at the south end of GUMBO Line 2 is ~8.0 km thick (Fig. 8B). This is much thicker than the average of crust formed at present-day mid-ocean ridges, but it is not unusual for oceanic crust that formed in the mid-Jurassic after the breakup of Pangaea. The mantle beneath the supercontinent was probably ~20 °C hotter than the global average due to the effect of continental insulation (Van Avendonk et al., 2017), which led to more decompression melting and thicker oceanic crust after continental breakup.

Since the Louann and Campeche salt basins of the Gulf of Mexico are mostly confined to the transitional crust of its northern and southern margins (e.g., Marton and Buffler, 1994; Pindell and Kennan, 2009; Nguyen and Mann, 2016), it is often assumed that Callovian salt deposition ended when continental rifting gave way to seafloor spreading. However, it appears that the rift-drift transition may not have occurred simultaneously across the Gulf of Mexico. On GUMBO Line 1 (Van Avendonk et al., 2015), the base of Louann salt appears to lie several kilometers above the acoustic basement of the transitional crust. Along GUMBO Line 2, we could also interpret some pre-rift sediments beneath the salt structures of the continental shelf. However, in the salt minibasins province, the base of salt appears to lie directly on the basement, which implies that the final stage of rifting developed slightly later offshore Louisiana than offshore Texas. Furthermore, salt deposits are much less voluminous in the northeastern Gulf of Mexico, indicating that much of the extension and thinning of the crust at that margin took place after Callovian time. In general, the Gulf of Mexico rift appears to have progressed from west to east, which is consistent with plate tectonic reconstructions (e.g., Marton and Buffler, 1994; Eddy et al., 2014).

## CONCLUSIONS

We developed a two-dimensional (2-D) seismic-velocity model of the rifted margin offshore southwestern Louisiana using OBS data from GUMBO Line 2. The new seismic-velocity model of the crust beneath the Louisiana shelf and salt minibasin province is interpreted as thinly stretched continental crust with significant amounts of rift-related igneous intrusions and volcanism. True oceanic crust lies 300 km offshore, near the Sigsbee Escarpment. In the final stage of rifting, Callovian (ca. 163 Ma) salt was deposited directly on the distal margin offshore Louisiana. Seafloor spreading in the central Gulf of Mexico subsequently split the Louann salt province of the northern margin from the Campeche salt province of the conjugate Yucatan margin.

We attribute the difference in crustal structure between rifted margins offshore Texas (GUMBO Line 1) and offshore Louisiana (GUMBO Line 2) to the nature of the preexisting continental lithosphere. The stronger rheology of the Grenvillian basement of central Texas led to less magmatism and more focused deformation during Mesozoic extension and breakup. In contrast, the relatively smooth lateral variations in the crustal seismic velocities along GUMBO Line 2 suggest that the rifted crust of the Louisiana margin was weak, and extensional deformation and magmatism were widely distributed. Seismic velocities in the lower crust of the rifted margins increase farther east (GUMBO Line 3), concordant with an eastward increase in syn-rift magmatism and mantle potential temperatures.

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