**Summary**

Two drastically different oceanic crustal domains are interpreted in the eastern Gulf of Mexico based on the integrated analysis of seismic, gravity, and magnetic data. The 2D profile modeling confirmed the ridge propagation in the Eastern Gulf of Mexico inferred from the prior spatial analysis of satellite gravity. The modeling suggests that the older oceanic crust represents a uniform layer of moderately dense and highly magnetic rocks resulting from an ultra-slow spreading presumably in Late Jurassic. In contrast, the younger oceanic crust toward the center of the basin (produced during slow spreading in Early Cretaceous) is thicker and has a characteristic two-layered structure. The presence of two drastically different domains is consistent with seismic refraction data and suggests the major ridge reorganization that occurred during the opening of the Gulf of Mexico presumably around 150 Ma. The two-phase spreading explains the known asymmetry of the eastern part of the basin that is challenging to explain with a single-stage opening, as well as observed crustal seismicity that was previously interpreted as “intraplate”. The ridge propagation during the opening of the eastern Gulf of Mexico offers a novel way of the basin reconstruction.

**Introduction**

The tectonic story of the Gulf of Mexico remains puzzling despite the long exploration history and an enormous amount of geological and geophysical data acquired in the basin. Up to date, many tectonic models are developed describing the formation of the basin; among the most recent ones are Eddy et al. (2014), Nguyen and Mann (2016), Pindell et al. (2016), and Minguez et al. (2018). Several authors used satellite gravity data of Sandwell et al. (2104) to map the segments of extinct ridges offset by transform faults (Sandwell et al., 2014; Christeson et al., 2014; Nguyen and Mann, 2016). The overall location of the ridge agrees between multiple interpretations (see gray polygon in Figure 1) and generally suggests a significant degree of asymmetry in the eastern Gulf of Mexico as the oceanic crust to the north of the interpreted extinct spreading center is drastically wider than the one to the south. In 2014, Eddy et al. and Christeson et al. published two refraction profiles through the eastern part of the basin (GUMBO3 and GUMBO4, Figures 1 and 2) suggesting strikingly different structures of the oceanic crust in the eastern Gulf of Mexico. The integrated geophysical analysis along these two profiles performed by Liu and Filina (2018) suggested that the thinner crust (imaged by profile GUMBO4) requires dense and magnetic material in order to explain the observed gravity and magnetic fields. It also showed that the crust along GUMBO3 is composed of two layers – less dense and less magnetic upper layer (presumably basalts) over denser and more magnetic layer (presumably gabbro). The consequent spatial analysis of gravity data allowed outlining the boundaries of the two different crustal domains (Filina et al., 2020), concluding the two-phase formation of oceanic crust in the Gulf of Mexico. The first spreading episode lasted approximately from 160 Ma to 150 Ma (based on ages from Snedden et al., 2014), and produced a thin oceanic crust with a uniform seismic velocity profile imaged by GUMBO4 line.

![Image](Image)

**Figure 1**: The eastern Gulf of Mexico with the location of key seismic lines; burnt orange are GUMBO refraction lines from Eddy et al. (2014) and Christeson et al. (2014), yellow lines are reflection data from Snedden et al. (2014). The thick white line marks the location of the Ocean-Continental Boundary (OCB) from Filina et al., 2020. The yellow circles show the OCB from integrated geophysical models (Liu and Filina, 2018; Filina, 2019; Liu et al., 2019, and Filina and Hartford, in review). The integrated geophysical model for Line 1 is presented in Figure 4. White circles show the vintage refraction points from Ibrahim et al. (1981) used to constrain the model. The location of the DSDP well that has penetrated the upper continental crust (Buffler et al., 1984) is shown with the red circle. Two distinct crustal domains from Filina et al., 2020 are also shown: red lines illustrate the locations of the extinct Late Jurassic spreading centers (before ridge reorganization near 150 Ma), while black ones illustrate the Early Cretaceous ones; the boundary between those domains, the pseudofault, is shown as a thin white line. Red squares are two recent crustal earthquakes from USGS.
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Figure 2: The oceanic portions of seismic refraction lines (a) GUMBO3 (from Eddy et al., 2014) and (b) GUMBO4 (Christeson et al., 2014). The distance between Ocean Bottom Seismometers (inverted white triangles) was 12 km. Note strikingly different velocity structures of oceanic crust in these profiles. The dotted white line shows the location of pseudofault—the boundary between two distinct crustal domains (see Figure 1). The vertical black arrows mark the crossings with the Line 2 (see Figures 1 and 3) over the Early Cretaceous extinct ridges expressed in both refraction lines as regions of lower seismic velocity. The thick white lines show the basement and Moho interpreted in the original publications. The depths to those boundaries were used to constrain integrated geophysical modeling for the seismic line shown in Figure 3a.

(Christeson et al., 2014; Figure 2). The extinct spreading centers associate with this initial spreading have E-W orientation (red segments in Figure 1), implying the N-S extensional stresses. Around 150 Ma, the ridge propagation occurred related to a change to the NE-SW extension and a jump in Euler pole (consistent with Pindell et al., 2016). The younger spreading centers have NW-SE trends (black segments in Figure 1) and the crust of this second phase is generally thicker and has a typical two-layered structure (Eddy et al., 2014, Figure 2). The estimates of Filina et al. (2020) suggest that the full rate of the initial Late Jurassic spreading was 0.9 cm/yr, while the younger Early Cretaceous event, despite the apparent increase in magma supply, was also a slow-spreading one with an estimated full rate of 1.1 cm/yr. The boundary between the two oceanic domains (referred to as pseudofault, thin white line in Figure 1) is coincident with two deep earthquakes in the eastern Gulf of Mexico (shown as red squares in Figure 1) that were previously not associated with any geological structure. Moreover, this two-phase spreading model with ridge reorganization explains the observed dramatic asymmetry of the basin that was noted by previous authors (Hudec et al., 2013; Nguyen and Mann, 2016).

The study presented in this paper builds on the previous analysis of Filina et al. (2020) and reports the results of the integrated geophysical analysis for seismic reflection profile from Snedden et al., 2014 (Figures 1 and 3). Line 1

Figure 3: Seismic cross-sections from Snedden et al. 2014.

(a) Line 1 was used for integrated geophysical modeling; it is referred to as line 3b in the original paper. This line crosses the well LL399 and trends southward toward the Yucatan Peninsula, although does not reach the OCB on the Mexican side (see Figure 1 for location). Please note that the top portion of Line 1 (including bathymetry) is missing in the seismic cross-section in the original paper, presenting a challenge with determining the vertical scale. Line 3c from the original paper (shown in panel b, referred here as Line 2) was utilized for determining the vertical scale. The red marks show the corresponding horizons in the crossing point of two profiles. For this study, only the portion to the south of the well LL399 was modeled.

(b) Line 2 (line 3c in the original paper) strikes from the east to the west and crosses mostly the younger oceanic crust (see Figure 1 for location). The bathymetry data from Smith and Sandwell (1997) were used to validate the horizontal and vertical scales of this line. The overall excellent correlation between seismic reflections in the crossing points gives confidence in proper spatial positioning and the depth of both lines. A through E mark the location of extinct spreading centers and corresponding transform faults (see Figure 1 for location).
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Table 1. Physical properties of subsurface rocks for integrated geophysical analysis

<table>
<thead>
<tr>
<th>Layer</th>
<th>Density, kg/m³</th>
<th>Magnetic Susceptibility, μcgs</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1030</td>
<td>0</td>
<td>Telford et al., 1990</td>
</tr>
<tr>
<td>Sedimentary section</td>
<td>2250 to 2550</td>
<td>0</td>
<td>Hilterman (1998), Filina et al. (2015), Filina (2019), Liu et al. (2019), Filina and Hartford (in review)</td>
</tr>
<tr>
<td>Upper continental crust</td>
<td>2780</td>
<td>2500</td>
<td>Buffer and Shipboard Scientific Party (1984), Hunt et al. (1995)</td>
</tr>
<tr>
<td>Lower continental crust</td>
<td>2900</td>
<td>5500</td>
<td>Christensen and Mooney (1995), Hunt et al. (1995)</td>
</tr>
<tr>
<td>Older oceanic crust (uniform, 1 layered)</td>
<td>2850</td>
<td>6000</td>
<td>Hunt et al. (1995)</td>
</tr>
<tr>
<td>Younger oceanic crust, basalts</td>
<td>2650</td>
<td>3000</td>
<td>Carlson and Herrick (1990), Christesen et al. (2019), Hunt et al. (1995)</td>
</tr>
<tr>
<td>Younger oceanic crust, gabbro</td>
<td>2950</td>
<td>4000</td>
<td></td>
</tr>
<tr>
<td>Lithospheric mantle</td>
<td>3300</td>
<td>0</td>
<td>To be consistent with Filina et al. (2015), Liu and Filina (2018), Filina (2019) and Filina and Hartford (in review)</td>
</tr>
</tbody>
</table>

(Figure 3a) crosses both older (thin and uniform) and younger (thick and layered) oceanic crustal domains, allowing further validate the ridge propagation during the formation of the Gulf of Mexico.

The E-W trending Line 2 crosses mostly the younger oceanic crust. The seismic cross-section (Figure 3b) clearly illustrates five basement valleys (labeled A through E in Figure 3b) that correlate to the segments of the extinct spreading centers identified from spatial analysis of potential fields shown as black lines in Figure 1. The 3D seismic reflection survey of Deighton et al. (2017) in the eastern Gulf of Mexico also revealed that both extinct spreading centers and corresponding transform faults are expressed as basement valleys. This morphology of extinct spreading centers further confirms the slow-spreading regime concluded by Filina et al., 2020.

The locations of the lines shown in Figure 3 were derived by georeferencing the map from the original paper. Please note, that the top portion of Line 1 (line 3b in Snedden et al., 2014) is not shown in the original publication, so the vertical scale was constrained with the crossing point of the east-west line (Line 2, in the original paper it is referred as line 3c). Overall, the positioning and depth errors of these cross-sections are estimated to be within 5 and 0.1 km respectively, which is considered relatively small and not affecting the overall modeling.

The subsurface model (Figure 4) was composed of multiple rock layers listed in Table 1. The physical properties – densities and magnetic susceptibilities – were either constrained from wells (namely the sedimentary layers and the upper continental crust) or published measurements (water, basalts, gabbro) or assigned to be consistent with the previous models in the Gulf of Mexico.

The thickness of modeled rock layers was constrained with seismic reflection sections (Figure 3), seismic refraction data for GUMBO3 (Figure 2) and with several vintage seismic refraction points from Ibrahim et al. (1981) shown as white circles in Figure 1. The potential fields for the composed subsurface model were calculated and compared with observed free-air gravity from Sandwell et al. (2014) and magnetic data from Lubinski and Twichell, (1989). The model was that adjusted to fit both gravity and magnetic fields while complying with all available constraints, namely seismic reflections and refractions, as well as having reasonable physical properties (Table 1) and remaining geologically valid.

Results

The N-S portion of Line1 crosses both old (thin and uniform) and young (thicker and layered) oceanic domains. According to the integrated geophysical model (Figure 4), the OCB is immediately outboard of the well LL399 (Figure 3a). The continental crustal layers require relatively high magnetic susceptibilities, which is consistent with the conclusion of Liu et al. (2019). The thickness of oceanic crust in the older domain varies from 7 km near OCB to ~ 5 km near the pseudofault – the boundary between two different crustal domains located at a range of ~100 km of Line 1. The younger oceanic crust is thicker (up to 9 km) and consists two layers, presumably basalts and gabbro. The variation in thickness between these two crustal domains is consistent not only with the results of the GUMBO experiment (Figure 2) but also with vintage refraction data (Figures 1
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The modeling requires the uniform crust produced during the initial Late Jurassic spreading to have a moderate density and a relatively high magnetic susceptibility (Table 1). Remarkably, the gravity modeling demands the bottom layer of the younger oceanic crust to be denser than the older oceanic crust. This is consistent with the higher seismic velocities (> 7 km/s) observed in GUMBO3 with respect to GUMBO4 (~7 km/s), as shown in Figure 3.

The derived model (Figure 4) confirms the ridge propagation during oceanic spreading in the eastern Gulf of Mexico. The two phase spreading clarifies several puzzling facts that cannot be explained with a single spreading model, namely dramatic basin asymmetry with respect to a single spreading center, the “intraplate” crustal seismicity and the variations in structure and thickness of oceanic crust in the eastern part of the basin revealed from the GUMBO experiment.

The integrative approach to geophysical analysis (Filina et al., 2019) used in this study allowed deriving a more robust and confident model that honors several geophysical datasets, namely seismic, gravity and magnetic fields, as well as obeys geological constraints and agrees with the well data.

Conclusions

The two-dimensional integrated geophysical modeling confirms the ridge propagation during the opening of the eastern Gulf of Mexico proposed by Filina et al. (2020) based on spatial analysis of potential fields. The model built on the seismic line from Snedden et al. (2014) supports the presence of two distinct crustal domains in the eastern Gulf of Mexico. The older oceanic crust, presumably resulted from the Late Jurassic ultra-slow N-S spreading, is thin and uniform with moderate density and high magnetic susceptibility. In contrast, the younger crust resulted from the second NE-SW slow-spreading phase in the Early Cretaceous produced thicker crust with a typical two-layered structure. This two-phase spreading with the ridge reorganization of the eastern Gulf of Mexico explains not only the presence of two distinct crustal zones in the oceanic domain but also the observed dramatic asymmetry of the basin and recent crustal seismicity.

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