Gulf of Mexico tectonic history: Hotspot tracks, crustal boundaries, and early salt distribution

Dale E. Bird, Kevin Burke, Stuart A. Hall, and John F. Casey

ABSTRACT

A Late Jurassic mantle plume may have generated hotspot tracks on the North American plate and the Yucatan Penninsula tectonic block as the Gulf of Mexico opened (ca. 150 Ma). The tracks are identified from deep basement structural highs that have been mapped by integrating seismic refraction and gravity data. They are associated with high-amplitude, distinctive gravity anomalies that provide the basis for a kinematic reconstruction that restores the western ends of the hotspot tracks with a 20° clockwise rotation of the Yucatan block or almost one-half the total rotation required to open the Gulf of Mexico Basin. The duration of track generation is estimated to have been about 8–10 m.y. or almost one-half the total time required to open the Gulf of Mexico Basin. Prior to this rotation, extension of continental crust over a 10–12-m.y. interval was the result of approximately 22° of counterclockwise rotation and crustal thinning. Autochthonous salt appears to be confined to the continental flanks of the hotspot tracks, confirming that salt was deposited during continental extension and not after ocean floor had begun to form. A prominent gravity anomaly along the western boundary of the basin is interpreted to be produced by a marginal ridge, which was created along the ocean-continent transform boundary as the basin opened. The eastern flank of this marginal ridge and the northernmost, easternmost, and southernmost terminations of the hotspot tracks are interpreted to coincide with the oceanic-continental crustal boundary in the basin.

INTRODUCTION

The shape of the Gulf of Mexico requires that at least one ocean-continent transform boundary was active while the basin was opening. Evolutionary models differ between those that require the

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basin to open by rotation along a single ocean-continent transform boundary and those that require the basin to open by rotation along a pair of subparallel ocean-continent transform boundaries. Although many models have been proposed, most workers now agree that the counterclockwise rotation of the Yucatan Peninsula block away from the North American plate, involving a single ocean-continent transform boundary, led to the formation of the basin; and many of these workers suggest that this rotation occurred between 160 Ma (Callovian) and 140 Ma (Valanginian) about a pole located within 5° of Miami, Florida (Humphris, 1979; Shepherd, 1983; Pindell, 1985, 1994; Dunbar and Sawyer, 1987; Salvador, 1987, 1991; Burke, 1988; Ross and Scotese, 1988; Christenson, 1990; Buffler and Thomas, 1994; Hall and Najmuddin, 1994; Marton and Buffler, 1994). Evidence cited for this model of basin evolution includes paleomagnetic data from the Chiapas massif of the Yucatan Peninsula (Gose et al., 1982; Molina-Garza et al., 1992), fracture zone trends interpreted from magnetic data (Shepherd, 1983; Hall and Najmuddin, 1994), nonrigid tectonic reconstruction (Dunbar and Sawyer, 1987; Marton and Buffler, 1994), and kinematic reconstructions making use of geological constraints, well data, and geophysical data, such as seismic refraction, gravity, and magnetics (Pindell, 1985, 1994; Christenson, 1990; Marton and Buffler, 1994).

Determining the tectonic events that contributed to the formation and evolution of the Gulf of Mexico depends on an ability to define the size, shape, and extent of major structures in the basin and at its margins. Integration of gravity and seismic refraction data to interpret the Gulf of Mexico Basin has been practiced since the mid-1960s via two-dimensional (2-D) gravity models constrained by depths and densities derived from the refraction data (Dehlinger and Jones, 1965; Grant and West, 1965; Hales et al., 1970a, b; Moore and del Castillo, 1974; Martin and Case, 1975; Mooney et al., 1983; Ebeniro et al., 1986). This is because the depth to anomaly source ambiguity associated with gravity data can be reduced by refraction depths, and the localized nature of refraction data can be extrapolated away from or interpolated between acquisition locations using the areal coverage provided by gravity data.

Gravity data over the Gulf of Mexico includes onshore Bouguer gravity anomalies compiled by the Society of Exploration Geologists and the U.S. Geological Survey and offshore satellite-derived free-air gravity anomalies (Figure 1). Global satellite-derived gravity data have been calculated from satellite altimetry data acquired during the Geosat Geodetic Mission and the European Remote-Sensing Satellite (ERS-1) Geodetic Phase along closely spaced satellite tracks (Sandwell and Smith, 1997). The reported data resolution is about 5 mGal in amplitude over 20-km (12.4-mi) wavelengths. The resolution is locally better than these reported values for much of the Gulf of Mexico (Bird, 2004).

Seismic refraction data coverage in the Gulf of Mexico region is extensive (Figure 2) (Ewing et al., 1960, 1962; Cram, 1961; Antoine and Ewing, 1963; Antoine and Harding, 1963, 1965; Warren et al., 1966; Hales et al., 1970a, b; Hales, 1973; Del Castillo, 1974;

Moore and Del Castillo, 1974; Keller and Shurbet, 1975; Buffler et al., 1980; Ibrahim et al., 1981; Ibrahim and Uchupi, 1982; Ebeniro et al., 1986, 1988; Nakamura et al., 1988; Kim et al., 2000). In the central parts of the basin, refraction depths and velocities represent oceanic basement and upper mantle. Crustal thicknesses range from about 5 to 8 km (3.1 to 5.0 mi) in these deeper parts of the basin, where water depths are generally greater than 3 km (1.9 mi), indicating the presence of oceanic crust. The data also indicate prominent basement structures, with relief of several kilometers, in deep parts of the basin.

Three prominent positive gravity anomalies over the western part of the Gulf of Mexico are the focus of this work. One is centered over the Keathley Canyon concession area and extends 200 km (124.3 mi) from 26.4°N, 93.9°W along a roughly west-northwest–east-southeast trend to 25.9°N, 91.7°W. This gravity anomaly is here called the Keathley Canyon anomaly. The second gravity anomaly curves for about 630 km (390 mi) north and east from 22°N, 94°W to 24.8°N, 89.8°W concentric with the Yucatan Coast. This gravty anomaly is here called the Yucatan parallel anomaly. The third gravity anomaly is a north-south linear anomaly, concentric with the east coast of central Mexico, and extends from the Rio Grande delta in the north to just offshore Veracruz in the south. It is related to the Tamaulipas–Golden Lane–Chiapas fracture zone defined by Pindell (1985, 1994), and it is referred to here as the Tamaulipas–Golden Lane–Chiapas anomaly.

We have used existing open-file gravity and seismic refraction data to identify these three deep basin structures. These results provide additional constraints for models of tectonic evolution of the Gulf of Mexico Basin involving counterclockwise rotation of the Yucatan Penninsula tectonic block. The basement structures

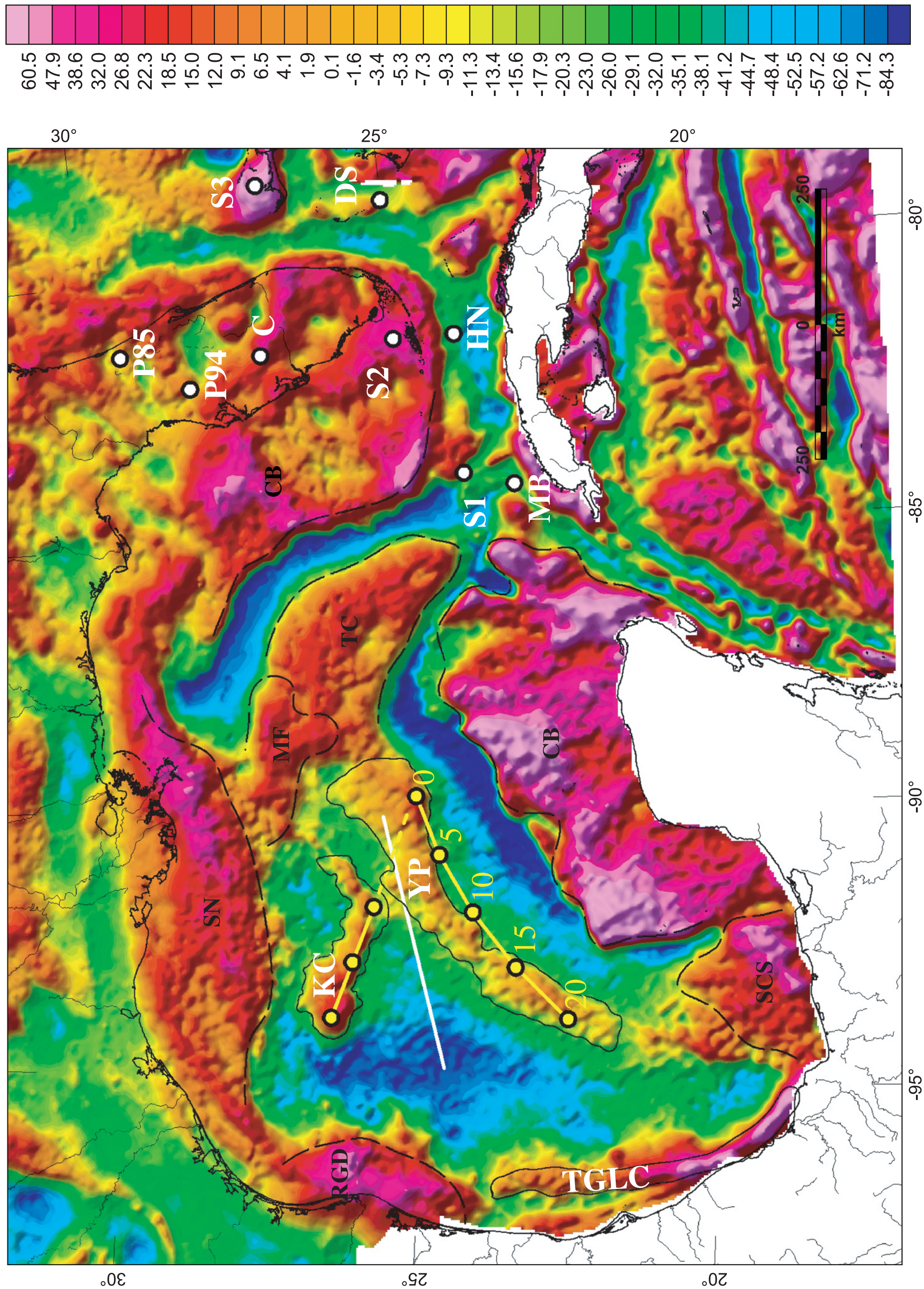
1. are interpreted to include two extinct hotspot tracks, named the Keathley Canyon and Yucatan parallel tracks, which are used as a basis for a 20° clockwise rotation of the Yucatan block to close the oceanic part of the basin;
2. include a north-south–oriented marginal ridge just offshore central Mexico, which formed along the Tamaulipas–Golden Lane–Chiapas transform as the basin opened;
3. define northern, southern, and eastern estimates of the ocean-continent boundary at the hotspot track terminations and the western ocean-continent boundary just outboard of the marginal ridge at the Tamaulipas–Golden Lane–Chiapas fracture zone;
4. define the limits of autochthonous salt deposition prior to sea-floor spreading inboard of the hotspot tracks.

TWO-DIMENSIONAL MODELING

Modeled cross sections, constrained by seismic refraction and gravity data, have been constructed to interpret the Keathley Canyon and Yucatan parallel structures (Figures 2, 3). Modeled sedimentary rocks, except salt, are divided into layers of constant thickness, concentric with the sea bottom, and assigned densities that approximate a continuous density-depth function (Cordell, 1973; Sykes, 1996). For consistency, density values were held constant for each of the modeled layers for all models. Modeled salt body geometries are largely schematic, and if we assume that salt bodies might include small amounts of clastic sediments, then the density of these salt bodies would be slightly higher than the density of pure halite (2.16 g/cm^3). The modeled crust is divided into three layers representing the upper, middle, and lower crust (Mooney et al., 1998).

Crustal thicknesses from refraction data, roughly north of the Texas–Louisiana shelf edge (near 28°N, 94°W) and south near the Yucatan escarpment (near 23.5°N, 90.5° W), range from 12.5 to 22.5 km (7.8 to 14.0 mi), indicating thinned continental crust (Figure 2). Except for the Keathley Canyon and Yucatan parallel structures, the crustal thickness decreases to about 4–6 km (2.5–3.7 mi) in the center of the basin. South of the Yucatan parallel structure, the crust thickens from 5 to 15 km (3.1 to 9.3 mi), indicating an oceanic to continental crust transition. The crust of the Yucatan parallel structure is 6.5–10 km (4.0–6.2 mi) thick, and it is well-defined by seismic reflection and refraction data along its crest and to the north and south of the structure (Ewing et al., 1960; Antoine and Ewing, 1963; Buffler et al., 1980; Ibrahim et al., 1981).

Thick and complex allochthonous salt over the Keathley Canyon structure masks its shape from seismic reflection data; however, the existence of this large basement structure is supported by observations from seismic refraction data over and near the structure (Ewing et al., 1960; Ibrahim et al., 1981; Ebeniro et al., 1988). Ewing et al. (1960) noted that a large ridge, composed of 5-km/s (3.1-mi/s) material, separates the Sigsbee deep from the Gulf geosyncline. Ebeniro et al. (1988) estimate the thickness of the Keathley Canyon structure to be 12 km (7.5 mi) and reported that the high-velocity layer, associated with the top of the structure, beneath


60.5
47.9
38.6
32.0
26.8
22.3
18.5
15.0
12.0
9.1
6.5
4.1
1.9
0.1
-1.6
-3.4
-5.3
-7.3
-9.3
-11.3
-13.4
-15.6
-17.9
-20.3
-23.0
-26.0
-29.1
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-35.1
-38.1
-41.2
-44.7
-48.4
-52.5
-57.2
-62.6
-71.2
-84.3
30°
25°
20°
-80°
-85°
-90°
-95°
S3
DS
P85
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15
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250
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250
km

the middle Cretaceous unconformity may be shallow basement.

We reference two examples of seismic reflection data that show deep basement structures coinciding with our interpretation of the gravity and seismic refraction data (Figures 2, 4). Buffler et al. (1980, p. 4) interpreted a basement structure, or ''outer basement high,'' from many seismic sections northwest of the Campeche escarpment. They noted that this high is located just north and west of the major salt features. The second example is a newly acquired long-offset (9 km; 5.6 mi), long-record (18 s), large source array line over the southernmost flank of the Keathley Canyon structure (Figure 2), which confirms prominent basement structuring with well-defined onlapping horizontal reflectors at about 12.5-km (7.5-mi) depth (Figure 4). This line is part of the regional GulfSpan survey that was specifically designed to improve imaging of the deep basin structural architecture in the northern Gulf of Mexico.

A primary objective of our modeling is to estimate the shape of the crust beneath the Keathley Canyon and Yucatan parallel anomalies, and we interpret this crust to be modified oceanic crust, similar to seamounts and island chains of other hotspot tracks around the world (Furumoto and Woollard, 1965; Furumoto et al.,1965; Watts and Brink, 1989; Caress et al., 1995; Grevemeyer et al., 2001). In some previous models, based on thickness and location, the crust was interpreted to be either continental, oceanic, or transitional between continental and oceanic (White et al., 1992; Christensen and Mooney, 1995).

Model AA′

This cross section passes through both Keathley Canyon and Yucatan parallel structures and is well constrained by refraction data (Figure 5a). Except for the Keathley Canyon structure and the southeasternmost end, the entire model is controlled by basement and Moho depths from refraction data. Basement depths define only the top of the Keathley Canyon structure. Along-strike extrapolation of basement and Moho depths southeast of the Yucatan parallel anomaly are assumed for the southeastern end of the model. From northwest to southeast, the total crustal thickness decreases from 16.7 to 9.5 km (10.4 to 5.9 mi) at the ocean-continent boundary, then increases to 17 km (10.6 mi) at the crest of the Keathley Canyon structure, then decreases to 4 km (2.5 mi) in the center of the basin, increases again to 12.5 km (7.8 mi) at the crest of the Yucatan parallel structure, and finally decreases to 7.5 km (4.7 mi). We interpret oceanic crust between Keathley Canyon and Yucatan parallel structures and transitional to oceanic crust to lie just northwest of the Keathley Canyon structure and just southeast of the Yucatan parallel structure.

Model BB′

Model BB′ passes through the Keathley Canyon structure (Figure 5b). Basement and Moho depths from refraction data control the southwestern half of the model. Basement control for the northeastern end of the model consists of refraction profiles located about 50 km (31.1 mi) to the west, northwest, and northeast. From northeast to southwest, the total crustal thickness decreases from 12 to 9 km (7.5 to 5.6 mi) at the ocean-continent boundary, then increases to 19 km (11.8 mi) at the crest of the Keathley Canyon structure, and decreases again to 5.5 km (3.4 mi) in oceanic crust. We interpret transitional to oceanic crust to lie immediately northeast of the Keathley Canyon structure along this cross section.

Model CC′

Model CC′ also passes through the Keathley Canyon structure (Figure 5c). Refraction control for this model consists of the basement and Moho depths from about 50 km (31.1 mi) west of the southwestern end,

Figure 1. Gulf of Mexico region gravity anomalies. Offshore satellite-derived free air, and onshore Bouguer gravity anomalies. Open circles around Florida are proposed Euler pole locations given in Table 1, and yellow circles connected by yellow lines along the Keathley Canyon (KC) and Yucatan parallel (YP) hotspot tracks (outlined anomalies) are calculated at 5° increments for a total of 20° counterclockwise rotation of the Yucatan block about an Euler pole interpreted by Hall and Nadjmuddin (1994, HN). A possible spreading center (white line) separates conjugate plume tracks between the North American plate and the Yucatan block. After approximately 10° of rotation, the spreading center is interpreted to have passed over the plume (dashed line connecting open circles between KC and YP anomalies), leaving another approximate 10° of rotation of the Yucatan block over the plume. Gravity anomaly signatures: SN = Sisgbee nappe; MF = Mississippi fan; TC = thin crust; CB = carbonate buildups; SCS = south Campeche salt nappe; RGD = Rio Grande delta; TGLC = Tamaulipas–Golden Lane–Chiapas anomaly; YP = Yucatan parallel anomaly; KC = Keathley Canyon anomaly. Satellite gravity data are available as a 2-arc-minute grid and can be downloaded from the internet at http://topex.ucsd.edu/marine_grav/mar_grav.html; the Society of Exploration Geophysicists gravity data is available as a 4-km grid from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center.

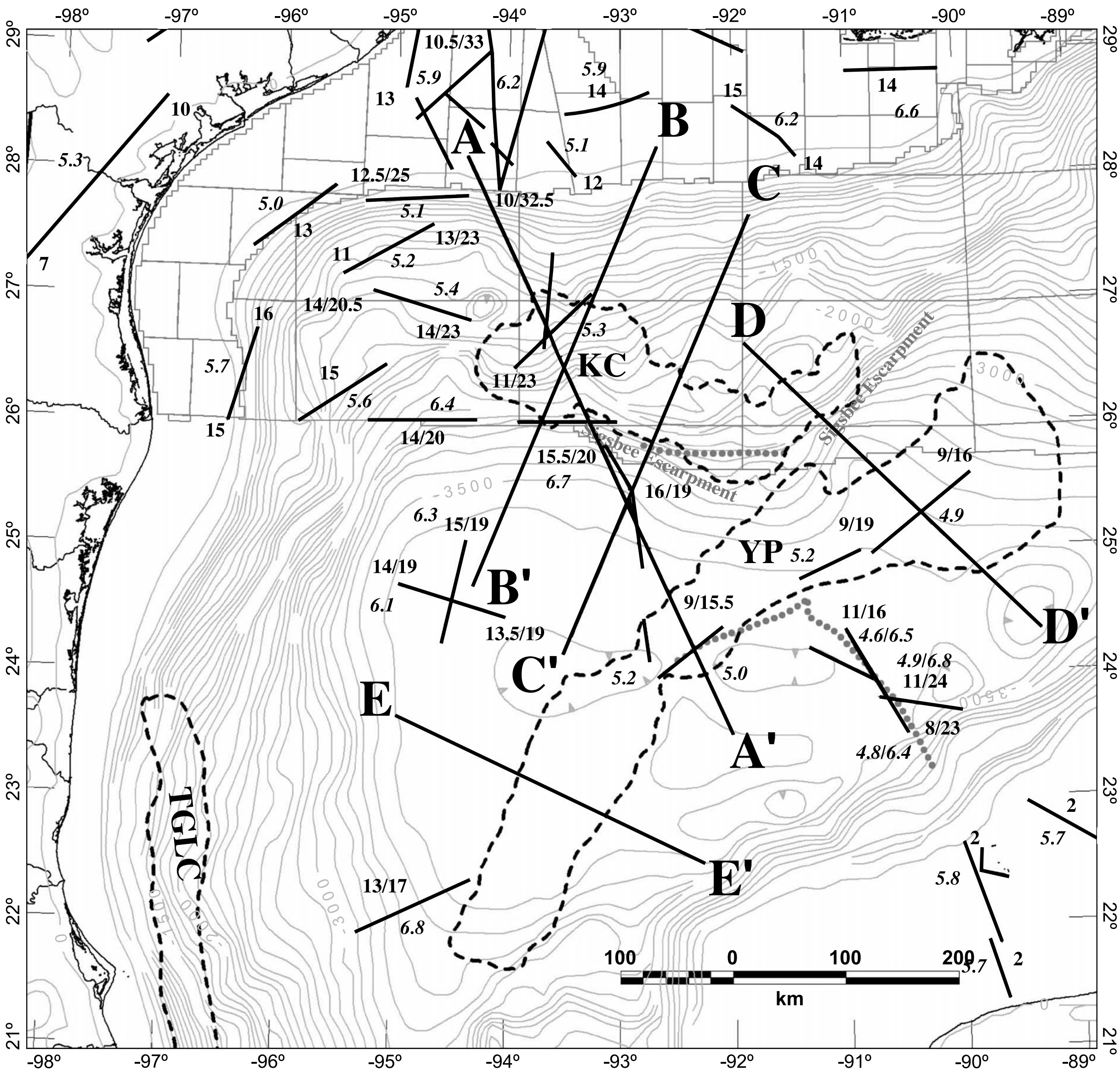

Figure 2. Seismic control and modeled gravity cross section locations in the western Gulf of Mexico. Bathymetry and topography contour interval = 200 m (660 ft), Keathley Canyon (KC), Yucatan parallel (YP), and Tamaulipas–Golden Lane–Chiapas (TGLC) gravity anomaly outlines (dashed), 2.5-D model locations (AA′, BB′, CC′, DD′, and EE′), and seismic refraction information. Short solid line segments coincide with seismic refraction profiles. Nonitalic numbers expressed as fractions are generalized from literature sources and indicate depths in kilometers to the top and base of the crust; single numbers indicate depths to the top of crust only. Italics numbers are upper crustal P-wave velocities generalized from literature sources in kilometers per second. Thick gray dotted lines are the locations of seismic reflection interpretations shown in Figure 4.

the basement and Moho depths just south of the Keathley Canyon structure, and the basement depths about 50 km (31.1 mi) beyond the northeastern end of the model. From northeast to southwest, the total crustal thickness decreases from 11 to 6.5 km (6.8 to 4.0 mi) at the ocean-continent boundary, then increases to 15 km (9.3 mi) at the crest of the Keathley Canyon structure, and decreases again to 5 km (3.1 mi). Except for the northeasternmost part of this model, which we interpret to be continental crust, we interpret the thin crust northeast and southwest of the Keathley Canyon structure along this profile to be oceanic.

Model DD′

This model passes through the relatively smaller northeast-trending dogleg of the eastern part of the Keathley Canyon anomaly and then through the Yucatan

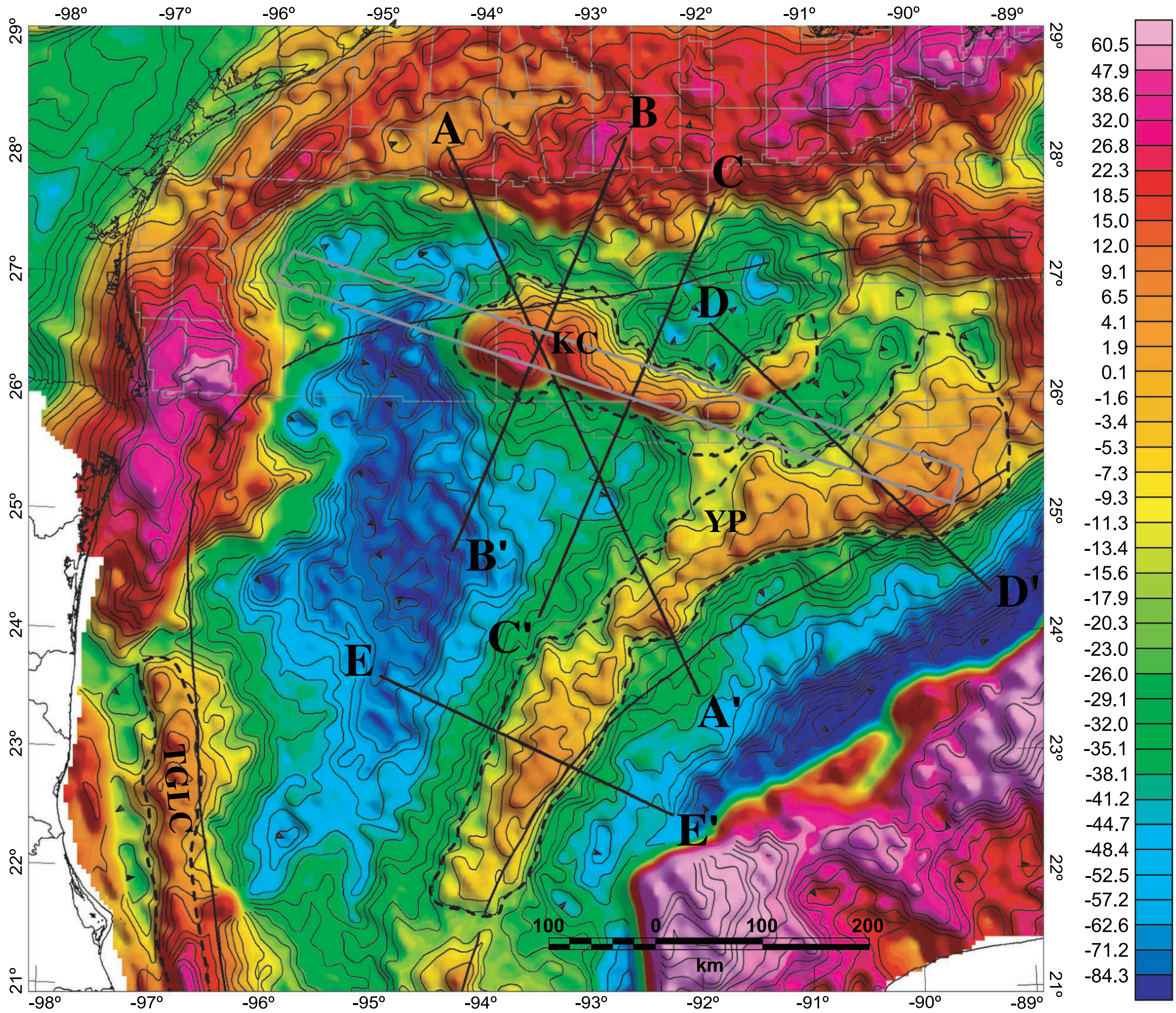

Figure 3. Free air gravity anomalies over the western Gulf of Mexico, contoured at 5 mGal. Lines indicate the locations of 2.5-D gravity models (AA′, BB′, CC′, DD′, and EE′) and the interpreted ocean-continent boundary. Hotspot-referenced trajectories for 160, 150, and 140 Ma (Morgan, 1983) fit in the rectangular gray box. Dashed lines outline the Keathley Canyon (KC), Yucatan parallel (YP), and Tamaulipas–Golden Lane–Chiapas fracture zone (TGLC) gravity anomalies and interpreted deep basement structures.

parallel structure (Figure 5d). The only refraction control for this model is the basement and Moho depths of the Yucatan parallel structure. Along-strike extrapolation of basement and Moho depths southeast of the Yucatan parallel anomaly is assumed for the southeastern end of the model. From northwest to southeast, the total crustal thickness increases from 7 to 11 km (4.3 to 6.8 mi) beneath the Keathley Canyon anomaly dogleg, then decreases to 8.5 km (5.3 mi), then increases again to 12 km (7.5 mi) at the crest of the Yucatan parallel structure, and finally decreases to 9 km (5.6 mi). The crustal structure modeled beneath the Keathley Canyon anomaly dogleg is different from those of the larger part of the Keathley Canyon structure and the Yucatan parallel structure. That is, it has less relief and width, and it is not rooted. This part of the Keathley Canyon anomaly could be an anomalous crustal element such as an extinct spreading ridge segment. We interpret all the crust along this profile, except that of the Yucatan parallel structure, to be oceanic.

Model EE′

Model EE′ passes through the southern part of the Yucatan parallel structure (Figure 5e). Refraction control for this model consists of basement and Moho depths from more than 100 km (62.1 mi) to the north and south of the western end of the model, and along

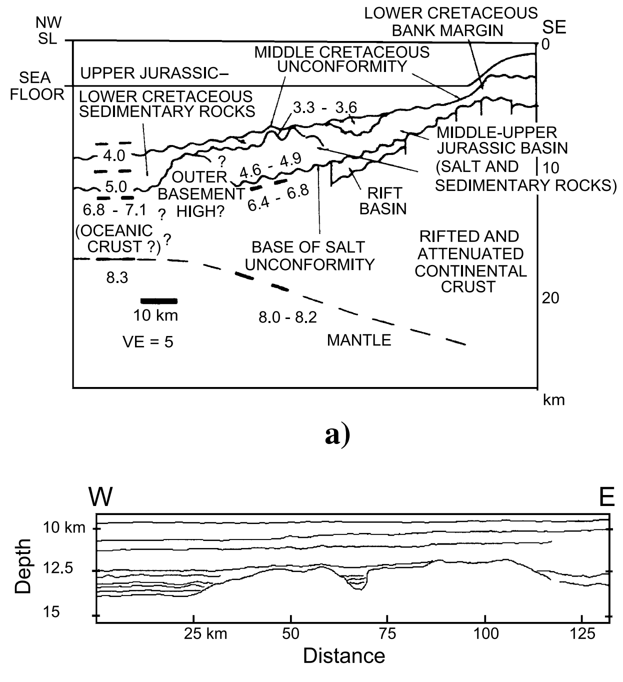

Figure 4. Seismic reflection interpretations, see Figure 2 for line locations. (a) The Yucatan parallel (YP) structure identified from seismic reflection data. The outer basement high(?) of this schematic cross section of the central Gulf of Mexico (after Buffler et al., 1980, p. 4) corresponds with the Yucatan parallel structure. (b) Line drawing of a recently acquired data over the southernmost flank of the Keathley Canyon (KC) structure shows deep sediment onlapping deep basement structures.

strike extrapolation (more than 200 km, 124.3 mi) from the southeast of the Yucatan parallel structure to the northeast of the eastern end of the model. This modeled cross section is not as well constrained as the other models; however, its construction is consistent with the other models in this study. From west to east the total crustal thickness increases from 7 to 11.5 km (4.3 to 7.1 mi) at the crest of the Yucatan parallel structure, and then decreases to 6.5 km (4.0 mi). We interpret all the crust along this profile, except for the Yucatan parallel structure, to be oceanic.

INTERPRETATION

Basement Structures

Prominent, long-wavelength free air gravity anomaly highs over the Gulf of Mexico Basin include (1) those over deltas and regions of recent deposition, (2) carbonate buildups, (3) thin oceanic crust, and (4) major basement structures (Figure 1). Anomaly categories 1 and 2 describe anomalies that are produced by relatively shallow density contrasts. In the case of deltas and areas of relatively recent sedimentation, long wavelengths are related to isostatic effects. Anomaly categories 3 and 4 represent anomalies that are produced by crustal variations and deep structures.

The large triangular-shaped gravity high centered around 26.5°N, 87.5°W is related to thin oceanic crust bounded to the east and south by the thick continental carbonate-laden crusts of Yucatan and Florida. Shorter wavelength anomalies superimposed on the northwestern corner of this triangular high are produced by the southern lobes of the Mississippi fan. The crust of the west-central area of the Gulf, between the Keathley Canyon and Yucatan parallel structures, is also oceanic, but it is characterized by relatively low gravity values because the basement in this part of the basin is more than 14 km (8.7 mi) deep or much deeper than the basement beneath the eastern triangular-shaped gravity high (about 9 km [5.6 mi]).

As the Yucatan Penninsula tectonic block rotated, a shear margin was created along the east coast of central Mexico (Pindell, 1985, 1994; Marton and Buffler, 1994). Shear margins are continent-ocean transform or fracture zone boundaries and typically form after (1) the rupture of the continental crust and rifting and the formation of a continental transform boundary such as the San Andreas fault; (2) the development of an active oceanic transform boundary between ridge axes and off-axes fracture zone boundaries, as the continental blocks separate transtensionally; and (3) passive-margin formation via thermal subsidence along the fracture zones that also separate oceanic and continental crust (Lorenzo, 1997). Several examples of shear margins reveal that high-standing marginal ridges, rising 1–3 km (0.6–1.8 mi) over the abyssal sea floor and ranging from 50 to 100 km (31.1 to 62.1 mi) wide, form along the continental sides of these margins (Bird, 2001). The formation of marginal ridges has been attributed to the absorption of heat from juxtaposed very thin (essentially zero at the spreading center) oceanic lithosphere as the ridge transform intersection moves past the relatively very thick (more-than-30-km [18.6-mi]) continental lithosphere (Todd and Keen, 1989; Lorenzo, 1997).

Marginal ridges can be topographic features, such as the Ivory Coast–Ghana marginal ridge, the Davie Ridge, and the Queen Charlotte Islands; or, depending on sedimentation rates, they can be completely buried by sediments, such as in the southern Exmouth plateau

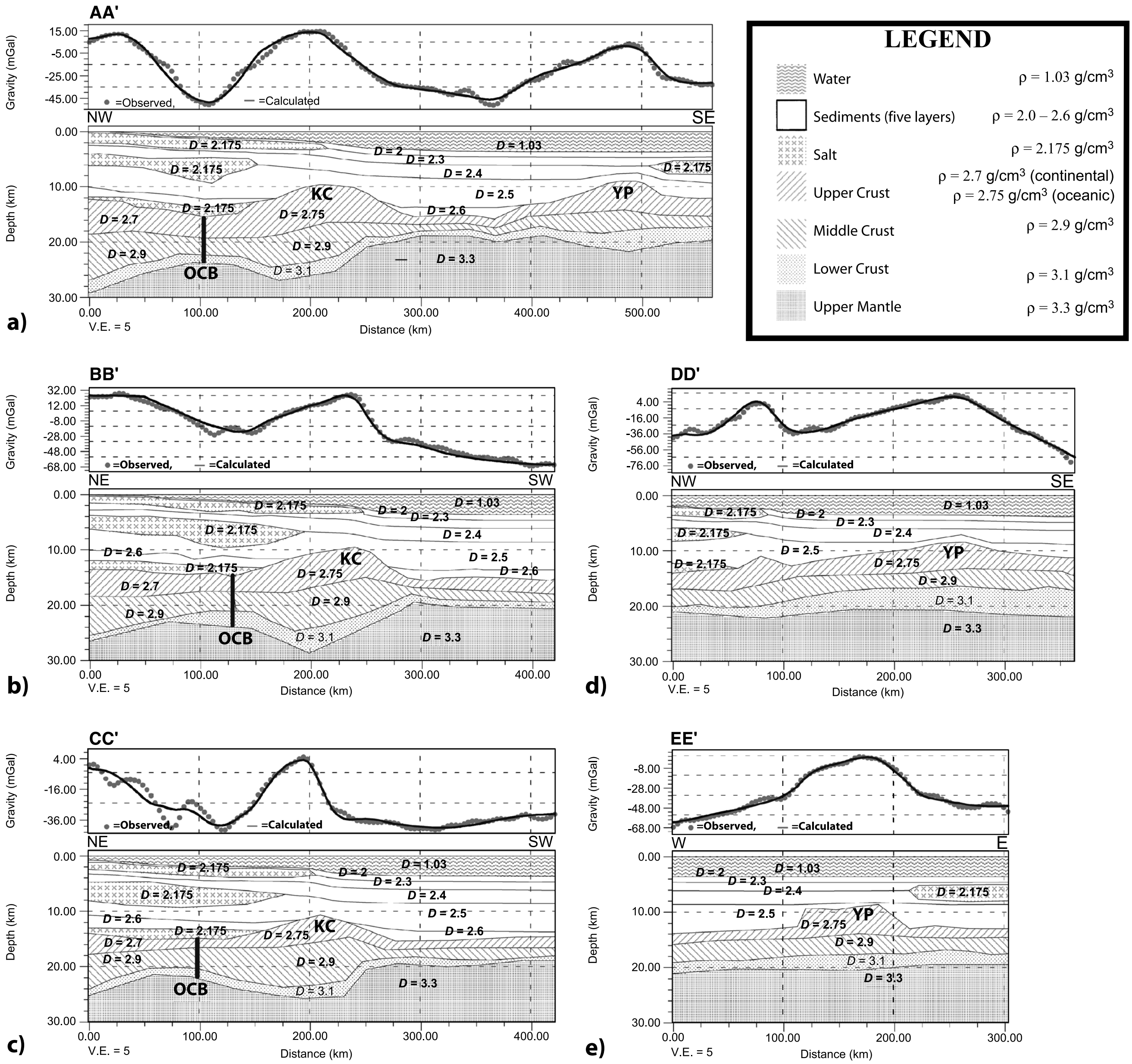

Figure 5. Two-dimensional modeled cross sections. All models have the same scale: vertical exaggeration is 5; observed and calculated free air gravity anomalies are dotted and solid lines, respectively. Densities used in modeling are displayed in the legend. The ocean-continent boundary (OCB) is marked with thick vertical lines through upper and lower crust. Models are located in Figures 2 and 3.

and the Agulhas and Diaz ridges (Mascle et al., 1987; Mackie et al., 1989; Lorenzo et al., 1991; Ben-Avraham et al., 1997; Edwards et al., 1997; Lorenzo and Wessel, 1997). Similarly, the Tamaulipas–Golden Lane–Chiapas anomaly in the Gulf of Mexico is not correlated with bathymetric relief and, therefore, must be attributed to a density contrast at depth. In both cases, marginal ridges produce prominent free air gravity anomaly highs that are similar in amplitude, wavelength, and orientation to the Tamaulipas–Golden Lane–Chiapas anomaly (global satellite-derived free air gravity data; Sandwell and Smith, 1997). The anomalies are approximately 30–80 mGal in amplitude, 20–70 km (12.4–43.5 mi) in wavelength, and oriented parallel to bounding oceanic transforms or fracture zones.

Gravity anomaly amplitudes and wavelengths over hotspot tracks can vary widely: 20–160 mGal and 20–140 km (12.4–87 mi), respectively, over Galapagos Islands, New England seamounts, Walvis Ridge, Rio Grande Rise, Ninetyeast Ridge, Hollister Ridge, Emperor seamounts, and the Hawaiian Islands (global satellite-derived free air gravity data; Sandwell and Smith, 1997). These relatively long and narrow curvilinear volcanic chains of islands and seamounts, commonly displaying an increase in age-with-distance relationship, are distinctive features common to ocean basins. The Keathley Canyon and Yucatan parallel gravity anomaly amplitudes and wavelengths range from 30 to 80 mGal and 30 to 100 km (18.6 to 62.1 mi), respectively.

The Yucatan parallel structure underlies flat ocean floor, and the lack of correlation with topography indicates that the gravity anomaly is produced by deeper density contrasts. In contrast, the southern flank of the Keathley Canyon anomaly corresponds with the Sigsbee escarpment (Figure 2). An offshore Bouguer correction essentially replaces the water density with a density equal to the shallowest sediments, such that the effect of the density contrast at the sea bottom is minimized. Although the amplitude of the Keathley Canyon anomaly is decreased after the Bouguer correction is applied, the anomaly remains prominent when compared with other anomalies over the basin (Bird, 2004).

The crustal structure of hotspot tracks is similar to that of oceanic crust but with greater variability in thickness and velocity (Furumoto and Woollard, 1965; Furumoto et al., 1965; Watts and Brink, 1989; Caress et al., 1995; Grevemeyer et al., 2001). Refraction data from several seamounts along hotspot tracks indicate that they typically rise 2–5 km (1.2–3.1 mi) above the ocean floor, are deeply rooted, and range in total thickness from 14 to 24 km (8.7 to 14.9 mi). The shape and velocity structure of the Keathley Canyon and Yucatan parallel structures differ greatly from those of continental fragments such as the Rockall Bank, Seychelles Bank, Broken Ridge, Lord Howe Rise, and those that surround the South China Sea (Bird, 2004). These continental fragments are nearly circular or square in shape. The dimensions of the Keathley Canyon and Yucatan parallel structures are less than 100 km (62.1 mi) wide and hundreds of kilometers in length, which is consistent with the shapes of other hotspot tracks around the world.

A comparison of gravity anomalies over other hotspot tracks with the Keathley Canyon and Yucatan parallel anomalies and crustal structures of other hotspot tracks with 2-D modeling results indicates that the Keathley Canyon and Yucatan parallel anomalies are produced by deep basement structures that are similar to seamounts created by mantle plumes. We suggest that these structures are hotspot tracks that were created by a single Late Jurassic mantle plume during the formation of the Gulf of Mexico Basin (Bird et al., 2001; Bird, 2004), and that the Tamaulipas–Golden Lane–Chiapas structure is a marginal ridge located just inboard of the Tamaulipas–Golden Lane–Chiapas transform, which also formed during the opening of the basin (Figures 1–3).

Formation Kinematics

Winker and Buffler (1988) summarized the Gulf of Mexico evolutionary models and divided them into six categories. All but one of these categories fall into one of two groups: either those that require rotation of the Yucatan block along two subparallel ocean-continent transform boundaries or those that require rotation of the Yucatan Penninsula tectonic block along a single ocean-continent transform boundary. The Yucatan Penninsula tectonic block is not included in the remaining model. The prevailing consensus favors rotation with a single ocean-continent transform boundary, or shear margin, located just offshore and subparallel to the eastern coast of central Mexico (Burke, 1988; Hall and Najmuddin, 1994; Marton and Buffler, 1994; Pindell, 1994). Proposed rotation poles for these models and additional published poles are shown in Figure 1 and listed in Table 1 (Shepherd, 1983; Pindell, 1985; Dunbar and Sawyer, 1987; Christenson, 1990).

Most workers consider the total counterclockwise rotation to be between 42 and 60° (Dunbar and Sawyer, 1987; Ross and Scotese, 1988; Hall and Najmuddin, 1994; Marton and Buffler, 1994; Schouten and

Table 1. Poles for Counterclockwise Rotation of the Yucatan Block*

	Longitude	Latitude	Symbol, Figure 1
Marton and Buffler, 1994	−84.24	23.18	MB
Hall and Najmuddin, 1994	−81.50	24.00	HN
Pindell, 1985	−81.40	29.50	P85
Pindell, 1994	−82.10	28.40	P94
Dunbar and Sawyer, 1987	−79.00	25.00	DS
Shepherd, 1983	−84.00	24.00	S1
Shepherd, 1983	−81.50	25.00	S2
Shepherd, 1983	−78.50	27.00	S3
Christenson, 1990	−81.60	27.20	C

*Located in Figure 1.

Klitgord, 1994). Differences in the amount of rotation reflect the close proximity of the Yucatan block to the rotation pole. That is, a small change in this distance can produce a relatively large change in the rotation angle when the plate being rotated is very close to or contains the rotation pole. Additional support for counterclockwise rotation is provided by paleomagnetic data (Gose et al., 1982; Molina-Garza et al., 1992). The amount of counterclockwise rotation reported by these authors, 75° (Molina-Garza et al., 1992) and 130° (Gose et al., 1982), is with respect to the magnetic north pole and represents a somewhat larger but more poorly determined rotation of Yucatan. Because 42° is roughly two times the rotation that we interpret for sea-floor spreading, and this amount brings the Yucatan into a reasonable position after reconstruction, we use Marton and Buffler's (1994) estimate for our reconstruction. In a contrasting study, M. Steiner (2003, personal communication) reports 105 + 11° clockwise rotation about a Triassic paleomagnetic pole.

Hall and Najmuddin (1994) interpreted discontinuities in linear magnetic anomaly patterns over the eastern Gulf of Mexico to be fracture zones, which they used to calculate a pole of rotation for the Yucatan block. They also observed, as have other workers, that the anomaly patterns are dominated by east-west trends (Hall et al., 1982; Pindell and Dewey, 1982; Shepherd, 1983; Buffler and Sawyer, 1985; Pindell, 1985, 1994; Dunbar and Sawyer, 1987), which again is consistent with counterclockwise rotation of the Yucatan block.

A gap between the current edges of the northern Yucatan shelf and the western Florida shelf exists after reconstruction by the single ocean-continent transform boundary model. Pindell (1985, 1994) and Marton and Buffler (1994) suggested a modification to the model whereby southern Florida is displaced to the southeast along a hypothesized Bahama fracture zone (Klitgord and Popenoe, 1984) prior to the rotation of the Yucatan block. Burke (1988) suggested that the Yucatan was originally longer, thus filling the gap, and that it was later shortened to its present length. This explanation is supported by the Mesozoic Guaniguanico terrane of western Cuba that was sheared from the Yucatan as the Caribbean plate was inserted between North and South America (Pszczolkowski, 1999).

A narrow rectangular box in Figure 3 encloses trajectories for hotspot-referenced motion of North America for 140, 150, and 160 Ma (Morgan, 1983). The trend of these trajectories and the overall trend of the Keathley Canyon anomaly are the same, indicating that if the Keathley Canyon structure is a hotspot track on the North American plate, then it could have formed between 160 and 140 Ma. Furthermore, the easternmost termination of the Yucatan parallel structure also falls along the hotspot-referenced trajectories, indicating no significant relative motion of the Yucatan with respect to North America after this time.

Two velocities need to be considered to reconstruct the relative motion between the North American plate and the Yucatan block for a sea-floor spreading and mantle plume model: the spreading rate between the two plates, and the velocity at which these two plates passed over the proposed mantle plume. Bird (2004) discussed end-member scenarios. As sea floor is accreted from the spreading center, the effect is that the spreading center moves away from North America. Therefore, it is best to reference the motion of the spreading center and hotspot track growth with respect to North America because the growth of the Keathley Canyon hotspot track would also be to the southeast. We interpret the distinctive shapes of the Keathley Canyon and Yucatan parallel anomalies to indicate that, initially, the velocities of the spreading center and hotspot track growth were similar, such that conjugate hotspot tracks formed on both the North American plate and on the Yucatan block (Figure 6b, c). Later, the velocity of hotspot track growth increased relative to the velocity of the spreading center, and the hotspot track continued to grow only on the Yucatan block. Therefore, although the Keathley Canyon track shows the relative motion between North America and the mantle plume, it only records part of the total opening history. It is the Yucatan parallel track that records the total rotation history during the sea-floor spreading phase of the evolution of the Gulf of Mexico (Figure 6d, e).

The two interpreted hotspot tracks are on parts of the basin that are underlain by oceanic crust, and their formation was from the west to the east over time. A line drawn from the northwestern end of the Keathley Canyon anomaly to the eastern end of the Yucatan parallel anomaly is the full length of the hotspot track. Reconstruction diagrams (Figure 6) illustrate our version of the two end-member scenarios: tracks were calculated in 5° increments, totaling 20° of sea-floor spreading, using an Euler pole from Hall and Najmuddin (1994) located about 100 km (62 mi) south of Key West at 24°N, 81.5°W. Reconstruction tracks from our preferred opening scenario (Figure 6e) are superimposed on free air gravity anomalies in Figure 1.

If the plume was active only during sea-floor spreading, then the oceanic crust can be defined with confidence in four locations of the Gulf of Mexico.

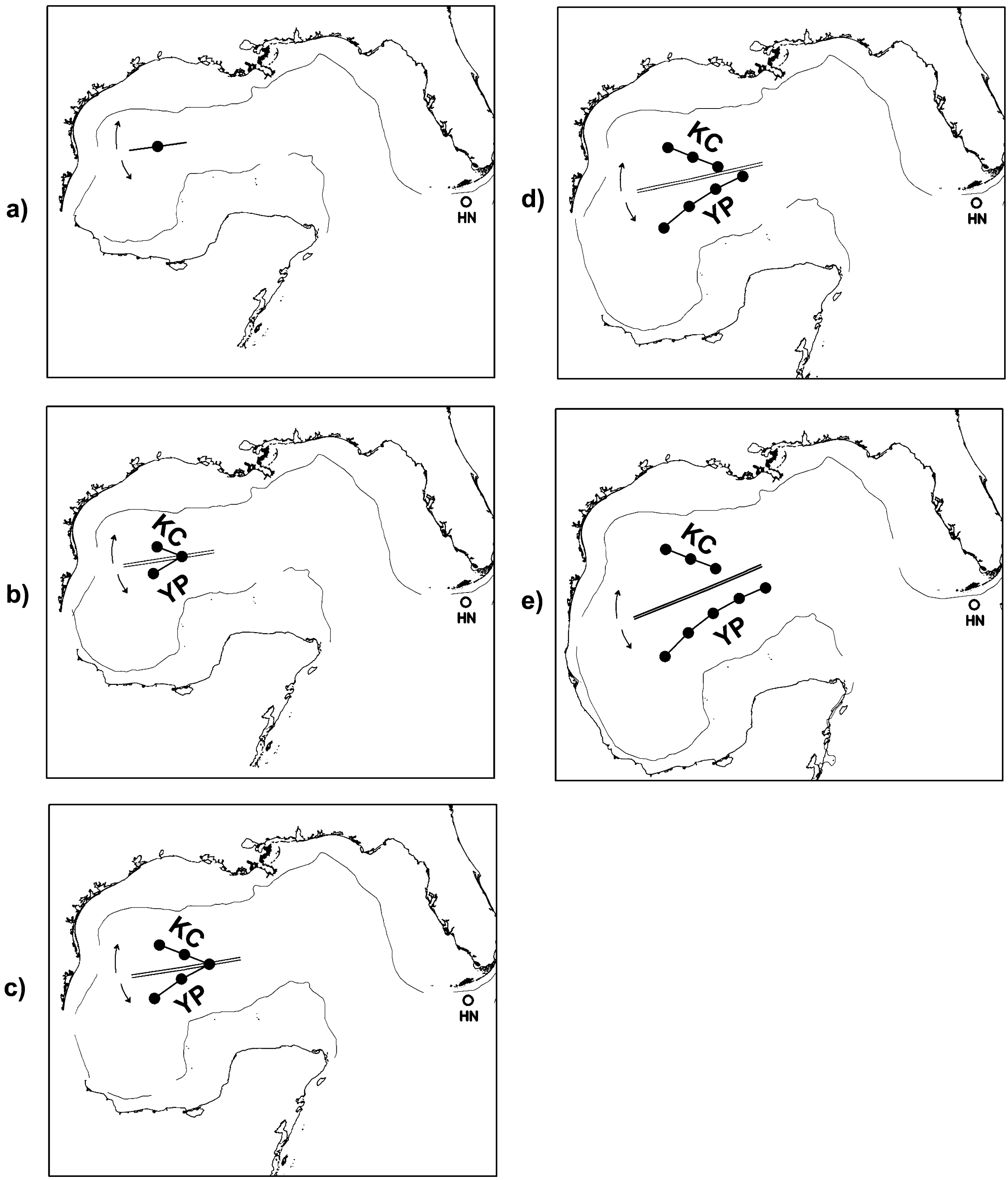

Figure 6. Hotspot-referenced, sea-floor spreading phase of the opening of the Gulf of Mexico with a mantle plume. (a) Sea-floor spreading is initiated over the mantle plume and the earliest formation of the hotspot tracks. Parts (b–e) show the expected hotspot track geometry with four 5° steps. The sea-floor spreading half-rate was roughly equal to the velocity of the North American plate over the mantle plume such that the plume remained beneath the spreading center for about 5 m.y. (a–c), producing conjugate hotspot tracks (the Keathley Canyon [KC] and Yucatan parallel [YP] tracks) on both the North American plate and the Yucatan block. Later (d, e), sea-floor spreading slowed relative to hotspot growth, and the mantle plume ended up beneath the Yucatan block (another 5 m.y.). Rotations were calculated using an Euler pole described by Hall and Nadjmuddin (1994) (HN).

The southern and the eastern endpoints of the Yucatan parallel structure and the northwestern endpoint of the Keathley Canyon structure are the southern, eastern, and northern limits of oceanic crust. However, if the plume ceased to be active before sea-floor spreading ceased, then oceanic crust could exist between the eastern end of the Yucatan parallel structure and the continental crust of the Yucatan block. Therefore, this end of the Yucatan parallel structure marks the farthest seaward limit of the ocean-continent boundary. The eastern flank of the Tamaulipas–Golden Lane–Chiapas structure (marginal ridge) along the east coast of central Mexico defines the western limit of oceanic crust. Using these areas as control (solid lines), the oceanic-continental boundary has been completed using dashed lines in Figures 3, 7, and 8. Our 20° sea-floor spreading phase of basin formation agrees well with Hall and Najmuddin's (1994) calculation of 25°. The 5° discrepancy between our estimate and that of Hall and Najmuddin (1994) may be attributed to differences in method and study area; that is, they mapped fracture zones using aeromagnetic data over the eastern Gulf of Mexico.

The boundary between oceanic and continental crust in the Gulf of Mexico has been interpreted in several ways (Figure 8) using seismic reflection, seismic refraction, gravity, and magnetic data, as well as kinematic reconstructions (Buffler and Sawyer, 1985; Pindell, 1985, 1994; Dunbar and Sawyer, 1987; Ross and Scotese, 1988; Winker and Buffler, 1988; Buffler, 1989; Salvador, 1991; Buffler and Thomas, 1994; Hall and Najmuddin, 1994; Marton and Buffler, 1994; Schouten and Klitgord, 1994). The ocean-continent crustal boundary is interpreted to coincide roughly with the 3000-m (10,000-ft) isobath except where it passes beneath the Pliocene–Pleistocene Sigsbee salt nappe (Pindell, 1985, 1994; Dunbar and Sawyer, 1987; Ross and Scotese, 1988; Winker and Buffler, 1988; Salvador, 1991).

Formation Chronology

Mesozoic tectonic and geologic events that occurred in the history of the Gulf of Mexico are summarized in Table 2 (Pindell, 1985, 1994; Salvador, 1987, 1991; Winker and Buffler, 1988; Marton and Buffler, 1994). Intracontinental rifting between the Yucatan and North America began with the collapse of the Appalachians and Ouachitas in the Middle to Late Triassic (230 Ma) (Olsen et al., 1982) and is thought to have continued until about 160 Ma, with salt being deposited in the rift basins before sea-floor spreading began. The cessation of sea-floor spreading in the basin coincided with geomagnetic chron M16 (Winker and Buffler, 1988; Pindell, 1994), corresponding to about 138 Ma (Channell et al., 1995).

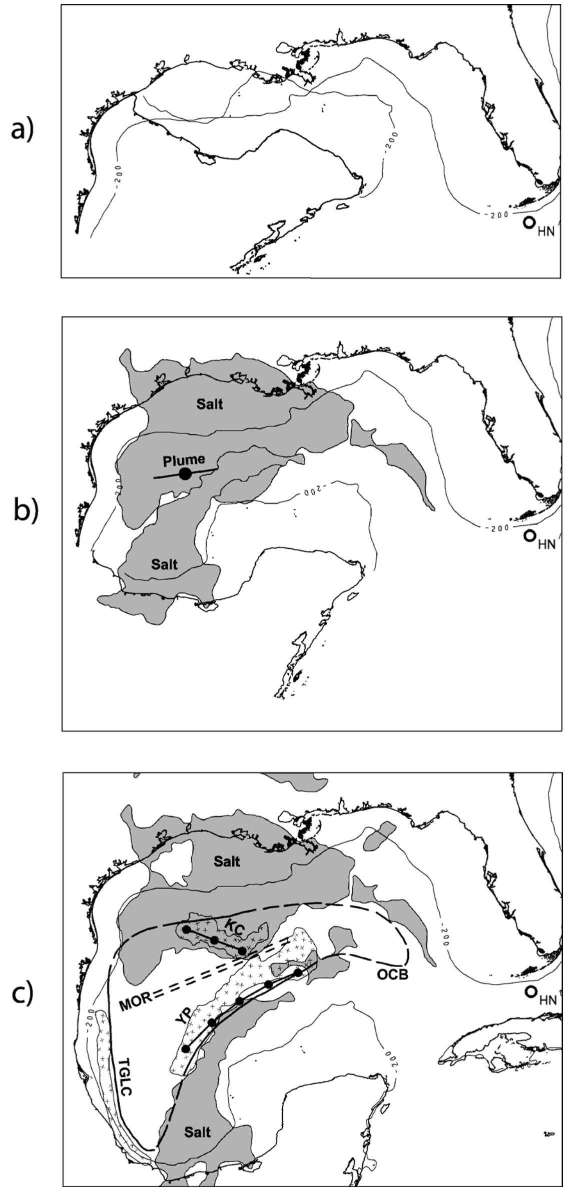

Figure 7. Reconstruction of Gulf of Mexico, 20-m.y. evolution of Yucatan motion. Pole used by Hall and Najmuddin (1994) = HN. (a) Initial position: about 160 Ma (exact age unknown). Yucatan occupies what is the Gulf of Mexico Basin now. Because the Yucatan was probably longer at that time, no gap was present between the peninsula and western Florida (Burke, 1988). (b) 10–12 m.y. coinciding with 22° of rotation and continental crust extension (about 150–152 Ma). Sea-floor spreading began at the end of this time when the plume became active. (c) 20 m.y. and 42° total rotation (adding 20° by rotation of sea-floor spreading), present position achieved (about 140 Ma).

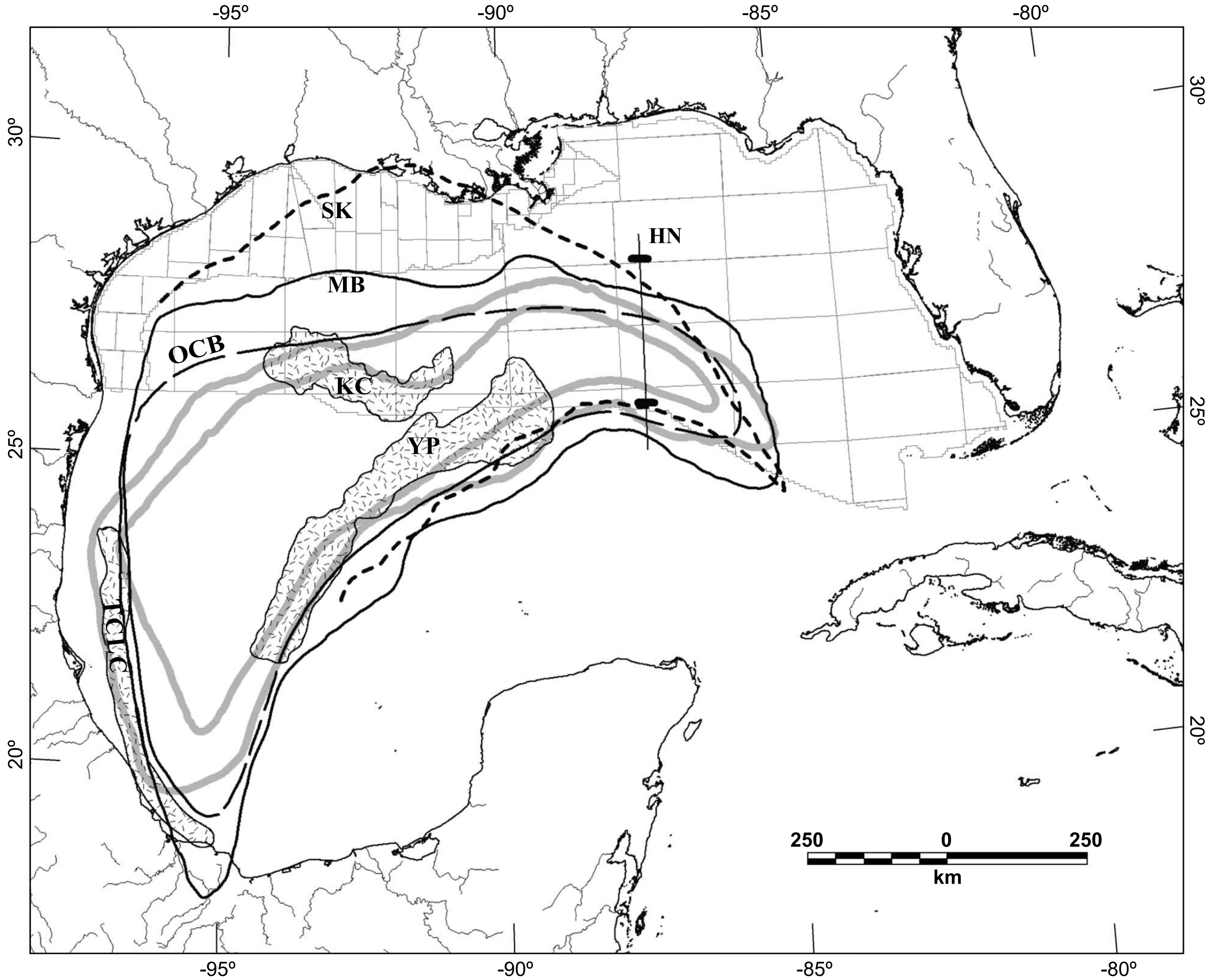

Figure 8. Gulf of Mexico ocean basin interpreted ocean-continent crustal boundaries (OCB). From this work = OCB; SK = from DNAG magnetic anomaly grid (Schouten and Klitgord, 1994); HN = along a 2-D magnetic model (tick marks, Hall and Najmuddin, 1994); MB = from seismic refraction data (Marton and Buffler, 1994); heavy gray lines = an envelope of several interpreted boundaries (Buffler and Sawyer, 1985; Ross and Scotese, 1988; Winker and Buffler, 1988; Salvador, 1991; Buffler and Thomas, 1994; Pindell, 1994). TGLC = Tamaulipas–Golden Lane–Chiapas marginal ridge; YP = Yucatan parallel structure; KC = Keathley Canyon structure.

The time required to span the distance from the northwesternmost end of the Keathley Canyon anomaly to the eastern end of the Yucatan parallel anomaly in the hotspot reference frame is 8–10 m.y. (Morgan, 1983), or nearly one-half the time interval required for the Gulf of Mexico to open (Salvador, 1987, 1991; Marton and Buffler, 1994). Because a 20° counterclockwise rotation is needed to restore the western ends of the Keathley Canyon and Yucatan parallel tracks, and it occurred over 8–10 m.y., then this 20° of rotation should be roughly one-half the total rotation required to open the basin, which makes the total rotation and total time of approximately 42° and 20 m.y., consistent with evolutionary data presented by other workers. Exactly when this 20-m.y. period occurred is difficult to determine, but stratigraphic relationships indicate that the basin must have been completely formed by ca. 140 Ma. Therefore, we choose the 160–140-Ma period for the basin to open, emphasizing that this time interval is not well constrained.

Our conclusion that sea-floor spreading occurred between 160 and 140 Ma implies that the Gulf of Mexico opened about 20 m.y. after sea-floor spreading began in the central Atlantic Ocean (Withjack et al., 1998). During that 20-m.y. interval, sea-floor spreading between North and South America must also have been in progress. This allows us to distinguish several tectonic events, including early salt deposition, of North

Table 2. Summary of Gulf of Mexico Formation Events

Rifting Begins	Salt Deposition	Yucatan Rotation Begins	Sea-Floor Spreading Begins	Sea-Floor Spreading Ends	Source
Late Triassic to Early Jurassic	completed by Oxfordian, 160 Ma	late Middle Jurassic (Callovian)	Callovian, 166 Ma	Berriasian, 140 Ma	Marton and Buffler, 1994
Late Triassic, 200 Ma	Callovian (or earlier) to middle Oxfordian, by 160 Ma		early Oxfordian, 160 Ma	Berriasian, 137.85 Ma (M16)	Pindell, 1994
Late Triassic, 210 Ma	late Callovian, by 160 Ma		late Callovian, 160 Ma	Berriasian, 140 Ma	Pindell, 1985
Late Triassic to Early Jurassic	late Middle Jurassic to early Late Jurassic		latest Callovian or early Oxfordian	early Late Jurassic but not later than middle Oxfordian	Salvador, 1991
Late Triassic to end of Middle Jurassic	late Middle Jurassic		Late Jurassic	early part of Late Jurassic	Salvador, 1987
Late Triassic	Callovian, ~168–163 Ma		early Oxfordian, 160 Ma	Berriasian, 140 Ma	Winker and Buffler, 1988
Middle to Late Triassic, 230 Ma	late Callovian–early Oxfordian to Kimmeridgian, 160–150 Ma	late Callovian to early Oxfordian, 160 Ma	Kimmeridgian, 150 Ma	Berriasian, 140 Ma	this paper

America beginning with the breakup of Gondwana (Table 2): onset of rifting, salt deposition, onset of Yucatan rotation and continental extension, onset of sea-floor spreading, and the end of sea-floor spreading.

Salt Distribution

Salt in the Gulf of Mexico can be generally divided into two large regions, the northern Gulf of Mexico salt basin and the Campeche salt basin (Figure 7), which are interpreted to have formed contemporaneously (Winker and Buffler, 1988; Salvador, 1991; Angeles-Aquino et al., 1994; Marton and Buffler, 1994; Pindell, 1994). Using the distribution of Jurassic evaporite deposits as a geometrical constraint, White (1980) and White and Burke (1980) showed that the Yucatan block can be restored by counterclockwise rotation. They reasoned that the landward morphology of the southern Campeche salt margin and the northern Gulf of Mexico salt basin represent rift valley walls that formed as the continental blocks separated.

The original distribution of salt deposits in the Gulf of Mexico are probably closely related to the areal extent of the continental crust. Exhaustive studies of salt structures in the Gulf of Mexico have led workers to categorize the northern Gulf of Mexico and Campeche salt provinces into smaller provinces based on size, shape, occurrence, timing, and stratigraphic relationship of salt structures and surrounding clastic rocks (Martin, 1980; Diegel et al., 1995; Peel et al., 1995; Hall, 2001). Salvador (1991) suggested that salt was deposited coeval with rift sediments; however, Peel et al. (1995) suggested that salt deposition was controlled by postrift geometries. The Campeche salt was deposited in the Callovian and mobilized during the Oligocene, with deformation continuing to the earliest Miocene (Angeles-Aquino et al., 1994).

Hall (2001) interprets the lack of salt-related sedimentary structures in the Keathley Canyon concession area as evidence that little or no autochthonous salt was deposited. Furthermore, he reports that thick allochthonous salt sheets in the Keathley Canyon concession area were probably sourced from the north. Peel et al. (1995) also suggest that the seaward extent of autochthonous salt in the northern salt basin did not extend over the Keathley Canyon area.

Prior to sea-floor spreading, continental crustal extension of the Yucatan, as it rotated about 22° counterclockwise between 160 and 150 Ma, allowed intermittent seawater influx, producing massive salt deposition. The lack of evidence for autochthonous salt in the Keathley Canyon (Peel et al., 1995; Hall, 2001) supports our interpretation for the formation of Late Jurassic hotspots and probably means that the Keathley Canyon and Yucatan parallel structures formed seaward boundaries for autochthonous Louann and Campeche salt as sea-floor spreading continued until about 140 Ma. The Keathley Canyon structure is now hidden beneath the Pliocene–Pleistocene allochthonous salt nappe; however, the Yucatan parallel structure is clearly a boundary that separates the Campeche salt from the center of the basin.

CONCLUSION

The economic importance of the Gulf of Mexico has led to the acquisition of vast amounts of geophysical data. These data have, in turn, led to extensive geologic studies, but complexly structured salt has masked important details of the great thickness of sediments in the basin. It is ironic that this richness of data cannot fully explain first-order parameters, such as the depth to the crystalline basement, distribution of source rocks, details of deep structures related to salt withdrawal basins and carbonate platform development, or even the tectonic evolution of the basin. A full understanding of these parameters would provide the bases for superior integrated basin analyses and petroleum system modeling.

The first-order knowledge required for mapping and interpreting deep geologic elements in the Gulf of Mexico, as well as its tectonic evolution, is an understanding of the nature of major basement structures. This is especially true for areas in the Gulf of Mexico that are hidden beneath near-opaque, complex, and extensive allochthonous salt bodies. Once the shape of the basement is known, then an evolutionary model can be developed, followed by mapping and interpretation of smaller geologic elements and processes. Using this approach, we have integrated and interpreted gravity and seismic refraction data and have also done the following:

1. Constructed 2-D cross-sectional models that indicate two deep basement structures in the Gulf of Mexico (the Keathley Canyon and Yucatan parallel hotspot tracks) that are similar to hotspot tracks around the world produced by mantle plumes, including crustal structure (velocity and thickness) and areal gravity signatures. These structures are not continental fragments as indicated by their size, shape, and crustal structure. Another deep basement structure (the Tamaulipas–Golden Lane–Chiapas marginal ridge) is consistent in size and shape with other marginal ridges around the world. The eastern flank of this ridge and the northern, eastern, and southern terminations of the hotspot tracks coincide with the oceanic-continental crustal boundary.
2. Proposed a plate kinematic model that is consistent with established parameters, including rotation pole, fracture zone and boundary, and crustal types. Basin formation began with about 22° of counterclockwise rotation and continental extension, which coincided with early salt deposition. Then, another 20° of counterclockwise rotation and sea-floor spreading coincided with the formation of hotspot tracks.
3. Demonstrated that the interpreted basement structures and kinematic reconstruction are consistent with established tectonic and depositional events, including the onset of rifting, early salt deposition, and deepwater marine sedimentation. Continental extension occurred roughly between 160 and 150 Ma, and seafloor spreading occurred between 150 and 140 Ma.

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