Bird, D. E., Burke, K., Hall, S. A., and Casey, J. F., 2011, Tectonic evolution of the Gulf of Mexico basin: *in*, Buster, N. A., and Holmes, C. W. (editors), *The Gulf of Mexico origin, waters, and biota volume 3, geology*, Tunnell, J. W., Felder, D. L., and Earle, S. A. (series editors): Texas A&M University Press, p. 3-16.

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Tectonic Evolution of the Gulf of Mexico Basin

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

The formation of the Gulf of Mexico basin was preceded by the Late Triassic breakup of Pangea, which began with the collapse of the Appalachian Mountains (ca. 230 Ma; Dewey 1988). Gondwanan terranes of the southern part of the Gulf States, eastern Mexico, and the Yucatan Peninsula remained sutured onto the North American continent as it drifted away from the African-Arabian-South American continent (or Residual Gondwana, Burke et al. 2003). Early seafloor spreading in the central Atlantic Ocean, from about 180 Ma to 160 Ma, included 2 jumps of the seafloor-spreading center to new locations. The timing of the latter ridge jump (ca. 160 Ma) correlates with initial rifting and rotation of the Yucatan block.

The Gulf of Mexico ocean basin is almost completely bounded by continental crust. Its shape requires that at least one ocean-continent transform boundary was active while the basin was opening (Fig. 1.1). Evolutionary models differ between those that require the basin to open by rotation along a single ocean-continent transform boundary (counterclockwise rotation of the Yucatan block), and those that require the basin to open by rotation along a pair of subparallel ocean-continent transform boundaries (essentially northwest-southeast motion of the Yucatan block). Although many models have been proposed, most workers now agree that 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; many of these workers suggest that this rotation occurred between 160 Ma (Oxfordian) and 140 Ma (Berriasian-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: (1) paleomagnetic data from the Chiapas massif of the Yucatan Peninsula (Gose et al. 1982; Molina-Garza et al. 1992), (2) fracture zone trends interpreted from magnetic data (Sheperd 1983; Hall and Najmuddin 1994), (3) non-rigid tectonic reconstructions (Dunbar and Sawyer 1987; Marton and Buffler 1994), and (4) 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).

Most workers consider the total counterclockwise rotation of the Yucatan block to be between 42° and 60° (Dunbar and Sawyer 1987; Ross and Scotese 1988; Hall and Najmuddin 1994; Marton and Buffler 1994; Schouten and Klitgord 1994). Differences in the amount of rotation reflect the close proximity of the Yucatan block to its pole of rotation. That is, a small change in this distance can produce a relatively large change in the rotation angle when the plate being rotated is 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

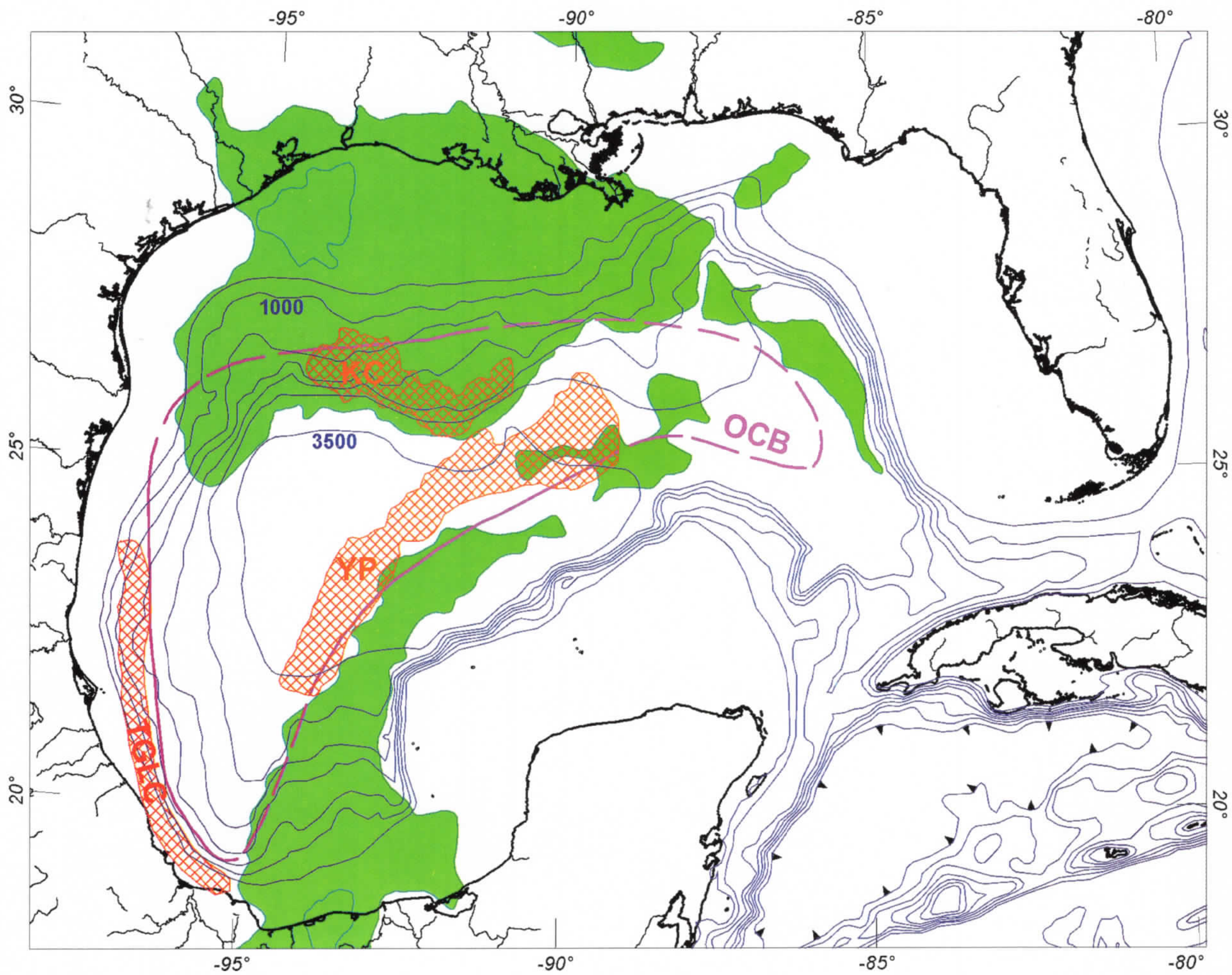


Figure 1.1. Gulf of Mexico basin. The bathymetry contour interval is 500 m. Keathley Canyon (KC) and Yucatan Parallel (YP) free air gravity anomaly outlines show locations of interpreted hotspot tracks. The Tamaulipas-Golden Lane-Chiapas (TGLC) free air gravity anomaly is interpreted to be produced by a marginal ridge. The extent of present-day salt deposits is shaded green (after Martin 1980). OCB is the ocean-continent boundary.

with respect to the magnetic north pole and represents a somewhat larger but more poorly determined rotation of the Yucatan block. Since 42° is roughly twice the rotation that we interpret for seafloor spreading, and this amount brings the Yucatan into a reasonable position after reconstruction, we use this estimate (Marton and Buffler 1994) for our reconstruction.

Prominent basement features within the Gulf of Mexico basin are interpreted to be hotspot tracks that were created by a single mantle plume as the basin opened (Bird et al. 2005a). During the seafloor-spreading phase, this Late Jurassic mantle plume (ca. 150 Ma to 140 Ma) may have generated the hotspot tracks on the North American Plate and the Yucatan block. 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, distinct gravity anomalies that provide the basis for a plate tectonic 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 (Figs. 1.1, 1.2). The duration of track generation is estimated to have been about 10 Myr, or almost one-half the total time required to open the Gulf of Mexico basin. One gravity anomaly is centered over the Keathley Canyon concession area and is here called the Keathley Canyon anomaly. The second anomaly, which curves for about 630 km concentric with the Yucatan Peninsula continental margin, is here called the Yucatan Parallel anomaly. A third anomaly, oriented

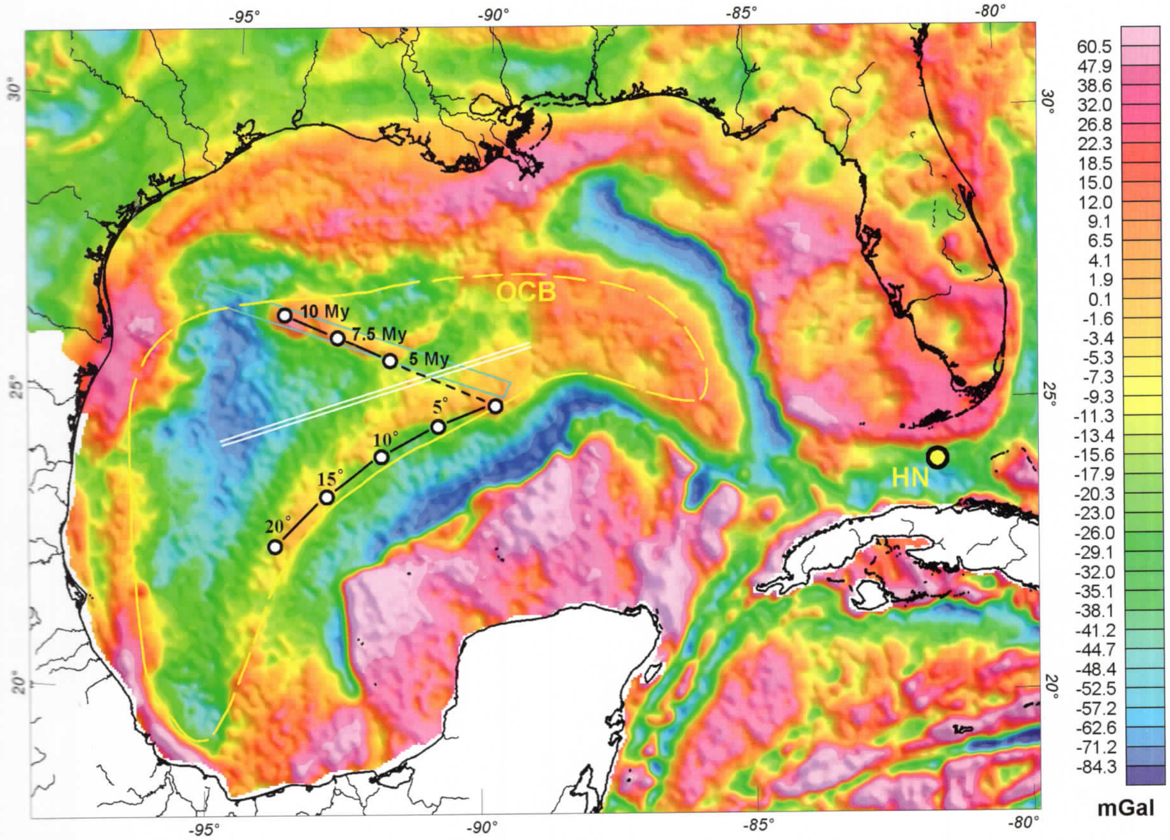


Figure 1.2. Gulf of Mexico gravity anomalies, free air offshore, and Bouguer onshore. Hotspot tracklines over the Keathley Canyon and Yucatan Parallel anomalies (see Fig. 1.1) were based on the rotation pole (HN) described by Hall and Najmuddin (1994). The total hotspot track growth and Yucatan block rotation, during seafloor spreading, are calculated to be 10 My and 20° (italics). The seafloor-spreading center (double white lines) is schematic, and OCB is the ocean-continent boundary.

roughly north-south and concentric with the east coast of central Mexico, extends from the Rio Grande delta in the north to just offshore Veracruz in the south (Figs. 1.1, 1.2). 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.

The Tamaulipas-Golden Lane-Chiapas anomaly was produced by a marginal ridge that was created along this ocean-continent transform boundary as the basin opened. The eastern flank of the 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 (Figs. 1.1, 1.2). Prior to rotation by seafloor spreading, extension of continental crust over an 8 Myr to 10 Myr interval was the result of approximately 22° of counterclockwise rotation and lithospheric 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 (Fig. 1.1).

Pangea Breakup

From Ladinian (Middle Triassic) to Oxfordian (early Late Jurassic), early extension associated with the breakup of Pangea occurred along the Appalachian-collapse rift system (initiated ca. 230 Ma), which extends from east Greenland and the British Isles in the north, through the Appalachian Mountains of North America, to the Takatu Rift of Guyana and Brazil in South America (Burke et al. 2003). North America-Gondwana rifting continued until about 180 Ma when seafloor spreading in the central Atlantic began (Withjack et al. 1988). During this time, the short-lived (about 2 Myr) Central Atlantic Magmatic Province (CAMP) mantle plume erupted (201 Ma), producing about 60 thousand cubic kilometers of flood basalts and associated intrusions over 2.5 million square kilometers in North and South America, Africa, and even Europe (Marzoli et al. 1999).

The growth of ocean basins as continents drift apart is reflected in magnetic data. Bands of linear anomalies flanking spreading centers represent episodic reverses in the polarity of the earth's geomagnetic field. The time intervals between polarity reversals are called chrons, and they have been identified in the world's ocean basins for the Cenozoic Era and Late Cretaceous Period (C-series: C1 to C34), and in the earlier Mesozoic Era to about 167 Ma (M-series: M0 to M41) (Gradstein et al. 2004). Because extensional rifting in passive margins essentially stops once new oceanic lithosphere is created, closing ocean basins along geomagnetic isochrons is an objective method for analyzing reconstructed continental margins.

Mesozoic chrons from M0 to M40, including several in the Jurassic Magnetic Quiet Zone (JMQZ, from ca. 167 Ma to 155 Ma, or M41 to M26), have been identified and mapped between the Atlantis and Fifteen-Twenty fracture zones on the North American Plate, and between the Atlantis and Kane fracture zones on the African Plate (Fig. 1.3A) (Bird 2004). Chron M40 (167.5 Ma) is mapped about 65 km outboard of the African S1 magnetic anomaly and its conjugate, the Blake Spur Magnetic Anomaly (BSMA), over the eastern and western flanks of the central Atlantic (Figs. 1.3B, 1.3C). Another pair of conjugate anomalies, the S3 magnetic anomaly and East Coast Magnetic Anomaly (ECMA), are respectively located about 30 km and 180 km inboard of the S1-BSMA pair. For that reason the shift in the seafloor-spreading center, or "ridge jump," about 90 km to the east between the BSMA and the ECMA anomalies at about 170 Ma (Vogt et al. 1971) is supported by this study. Between the Atlantis and Kane fracture zones the width of the African JMQZ

A)

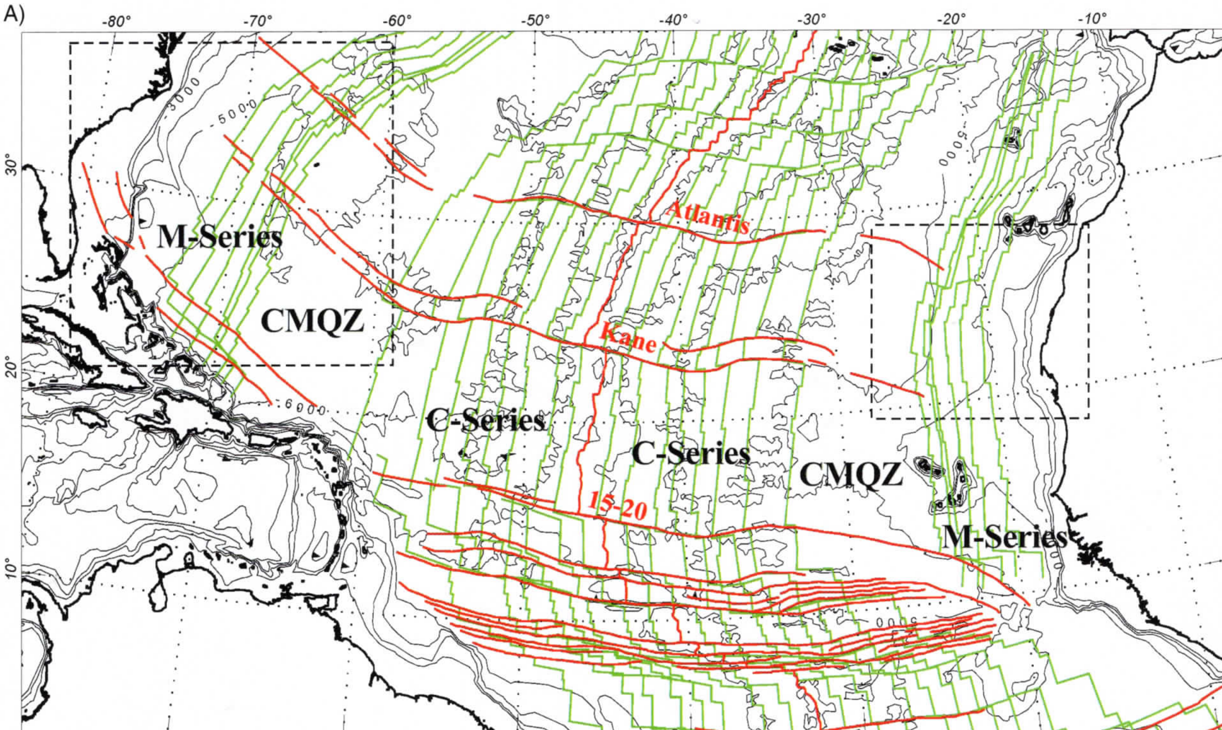
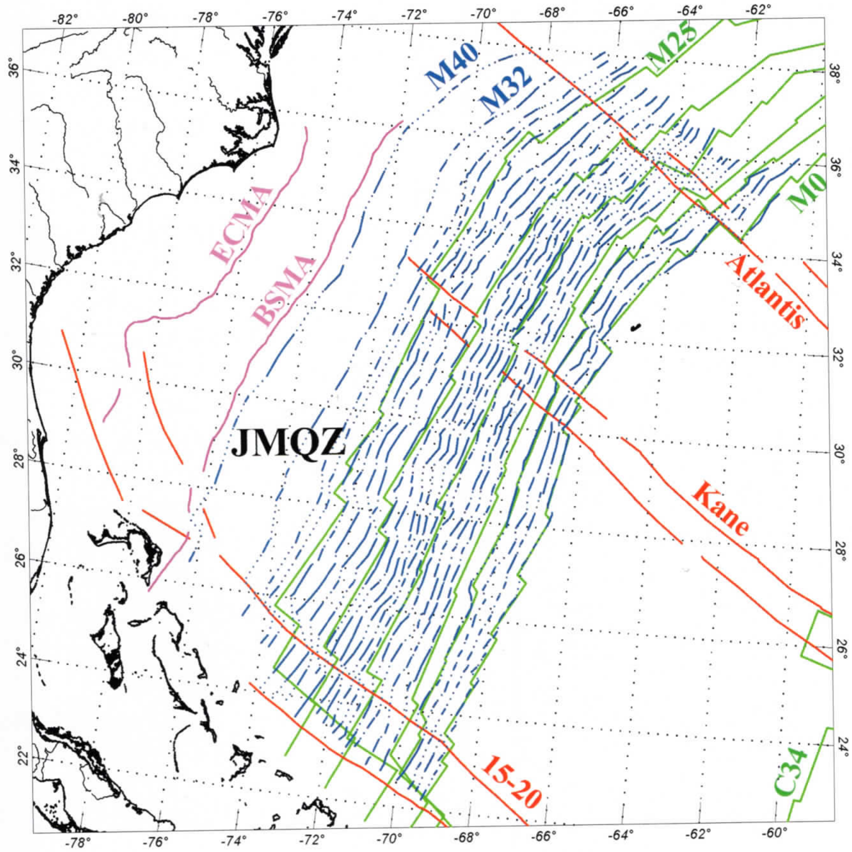


Figure 1.3. (A) Central Atlantic Ocean magnetic isochrons and fracture zones. The Mid-Atlantic Ridge (MAR) and main fracture zones are red; Atlantis, Kane, and Fifteen-Twenty (15–20) are fracture zones used to reconstruct the basin (Bird et al. 2005b). Bands of identified isochrons include the Cenozoic C-series that flank the MAR, then the older Cretaceous Magnetic Quiet Zone (CMQZ, no magnetic polarity reversals occurred during this time), then the Mesozoic M-Series (Muller et al. 1997). (B) and (C) Chron M40 is mapped about 65 km outboard of the conjugate Blake Spur Magnetic Anomaly (BSMA)–S1 Anomaly (Bird 2004) indicating that a ridge jump occurred between the conjugate East Coast Magnetic Anomaly (ECMA)–S3 Anomaly (ca. 170 Ma). Repeated chron M38 over the African flank, and absent over the North American flank, indicates a ridge jump. The Jurassic Magnetic Quiet Zone (JMQZ) is characterized by a relatively weak magnetic field.

B)



C)

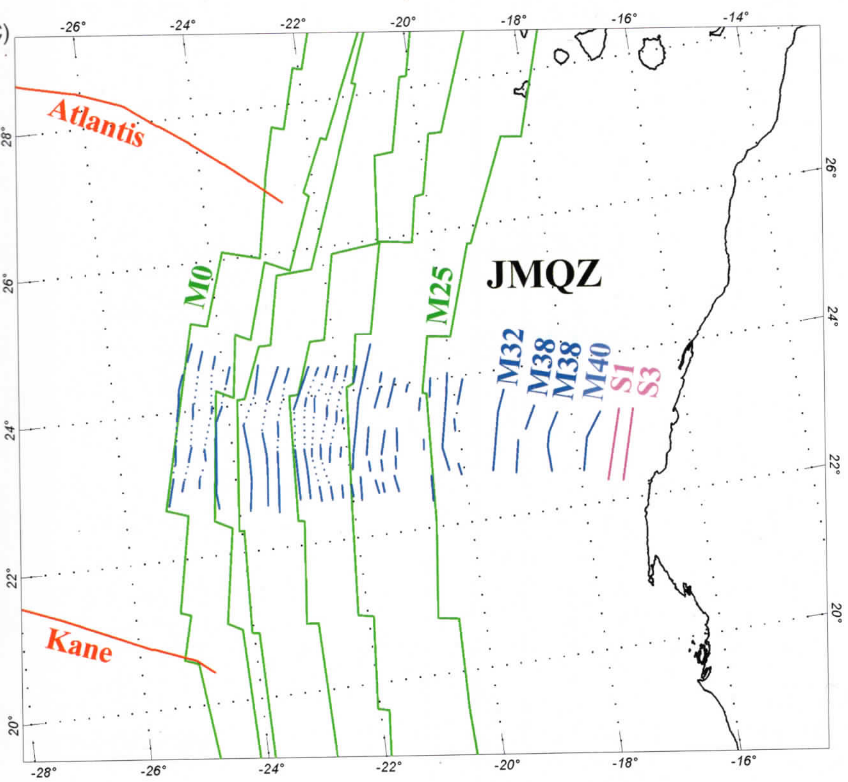


Figure 1.3. *(continued)*

is about 70 km greater (22%) than the North American JMQZ. Inspection of magnetic anomalies over this range reveals that additional correlatable anomalies exist over Africa (Bird 2004), suggesting a second ridge jump of about 35 km to the west. Modeling results indicate that this jump occurred between 159 Ma and 164 Ma (chrons M32 and M38). These ridge jumps could have coincided with North American-Gondwana plate reorganizations including rifting of the Yucatan block away from North America and seafloor spreading in the Gulf of Mexico. The second ridge jump in the central Atlantic (ca. 160 Ma) roughly coincides with the initiation of Yucatan block rotation followed by the formation of the Gulf of Mexico (Dunbar and Sawyer 1987; Burke 1988; Ross and Scotese 1988; Salvador 1991; Buffler and Thomas 1994; Hall and Najmuddin 1994; Marton and Buffler 1994; Pindell 1994).

The 2 ridge jumps described here are consistent in dimensions and duration with other ridge jumps observed around the world (Bird 2004). Ridge jumps have been documented along the Mid-Atlantic Ridge near the Ascension fracture zone (Brozena 1986), at 7 locations west of the East Pacific Rise including 2 currently underway (Luhr et al. 1986; Mammerickx and Sandwell 1986; Morton and Ballard 1986; Mammerickx et al. 1988), south of the Chilean Ridge (Mammerickx et al. 1988), and at 3 locations in the north Pacific (Mammerickx et al. 1988).

Our closest North American-Gondwana fit (Fig. 1.4A) illustrates that final closure (to form pre-breakup Pangea) requires that: (1) the Yucatan block rotated over 40° clockwise from its present position to close the Gulf of Mexico, (2) the southern edge of the Florida shelf was contiguous with the Demerara Rise of South America and the Guinea Nose of Africa as suggested by Pindell and Dewey (1982), and (3) the Bahama Island chain must have formed while the central Atlantic was opening supporting the idea that the islands overlie a hotspot track, as was first suggested by Dietz (1973). That track is recognized here to be that of the Early Jurassic Central Atlantic Magmatic Province (CAMP) mantle plume that initially erupted at 201 Ma (Marzoli et al. 1999).

Dickinson and Lawton (2001) reported that the Gondwanan Coahuila crustal block, which consists of the southern half of Texas and the northeastern corner of Mexico, was accreted onto Laurentia during the Permian along the Ouachita-Marathon suture. Farther south, and separated by the northwest-oriented Coahuila Transform fault, the Gondwanan Tampico, Del Sur, and Yucatan-Chiapas blocks form the eastern half of Mexico (shaded yellow, Fig. 1.4A). As Pangea began to break up, the Mezcalera Plate was consumed by the advancing Farallon Plate west of the Gondwanan terranes and south of the Coahuila Transform (Dickinson and Lawton 2001).

Gulf of Mexico Rifting and Continental Extension

From Oxfordian (early Late Jurassic) to Tithonian (Latest Jurassic), the Yucatan block appears to have rotated about 22° counterclockwise, while extensive salt was deposited on extended and attenuated continental crust, from the time of the second ridge jump in the central Atlantic to about 150 Ma (Fig. 1.4B). The block was rotated about a pole located presently at 24°N, 81.5°W (Hall and Najmuddin 1994). This rotation requires a north-south oriented transform fault offshore of eastern Mexico (Marton and Buffler 1994; Pindell 1994). We interpret the westward ridge jump in the central Atlantic at about 160 Ma to be linked to the clearing by the Florida shelf of the "Trinidad corner" on the north coast of South America. That change, which created space for the Gulf of Mexico to open, was coeval with the onset of Yucatan block rotation.

Salt in the Gulf of Mexico generally can be divided into 2 large regions, the northern Gulf of Mexico salt basin and the Campeche salt basin (Fig. 1.1), 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 could be restored by clockwise rotation. They reasoned that the landward morphology of the southern Campeche salt margin, and the northern Gulf salt basin, represent rift valley walls that formed as the continental blocks separated.

The original distribution of salt deposits in the Gulf of Mexico is probably closely related to the areal extent of attenuated continental crust. Prior to seafloor spreading between 160 Ma and 150 Ma, rotation of the Yucatan block and continental crustal extension allowed intermittent seawater influx that produced massive salt deposition. The lack of evidence for autochthonous salt (Peel et al. 1995; Hall 2001) beneath the Keathley Canyon anomaly probably means that the Keathley Canyon and Yucatan Parallel structures formed seaward boundaries for autochthonous Louann and Campeche salt as seafloor spreading continued until about 140 Ma. The Keathley Canyon structure is now hidden beneath a Plio-Pleistocene

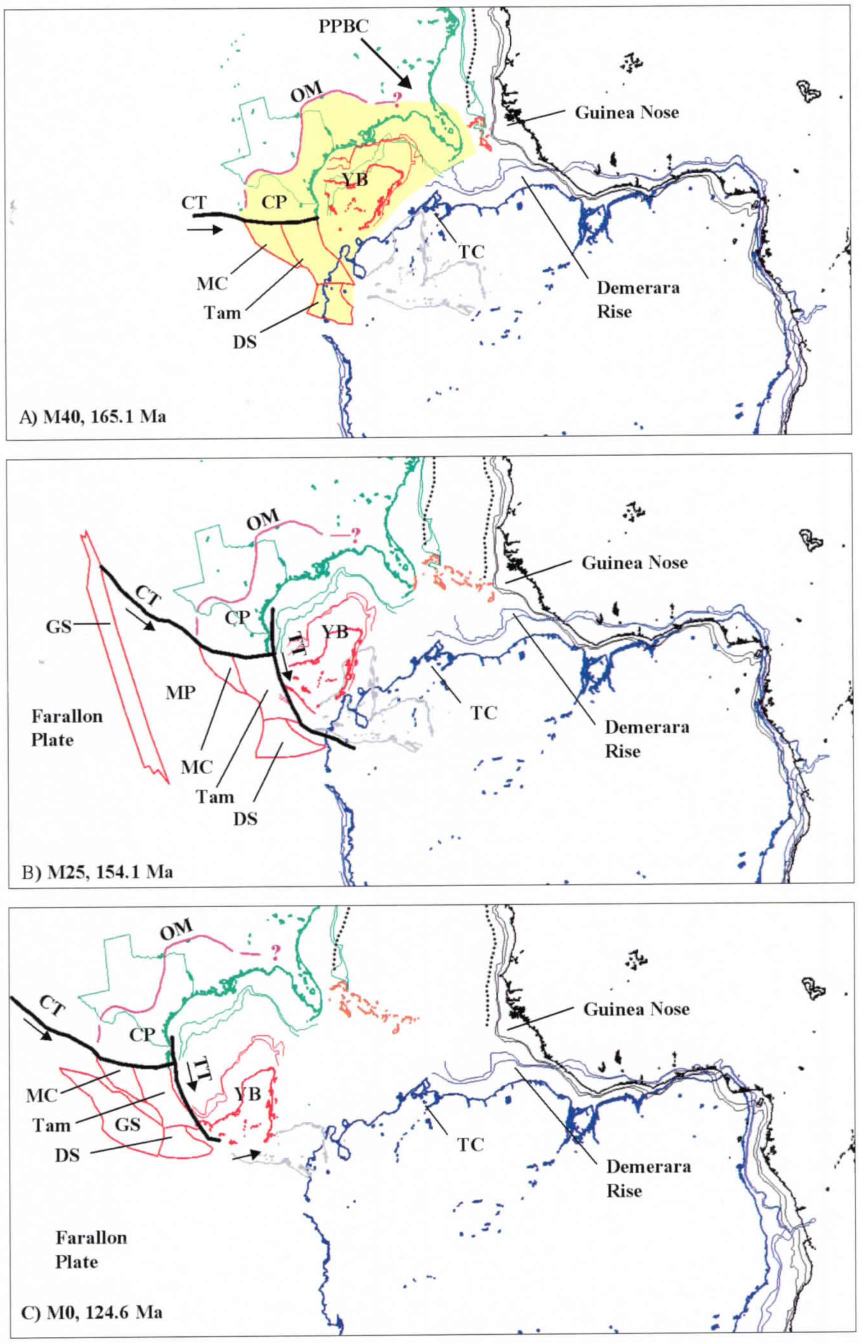


Figure 1.4. Formation of Mexico, Gulf of Mexico, and the central Atlantic Ocean after Pangea breakup: (A) M40 (165.1 Ma), (B) M25 (154.1 Ma), and (C) M0 (124.6 Ma). Present western and northern coastlines of South America (west of TC) have been used for ease of geographic reference. Jurassic and Cretaceous coastlines in those regions, although poorly known, were certainly very different. North America (green) and South America (blue) are relative to Africa (black); South America-Africa closest-fit position for M40 and M25, and for M0 as South America drifted away from Africa, after Bird et al. (2005b); and present-day Yucatan and Chortis blocks relative to North America are light gray. One kilometer and 2 km isobaths, and estimated positions of abandoned central Atlantic seafloor-spreading centers (dotted lines), are plotted. Mexico crustal blocks (red), Ouachita-Marathon Suture (OM, magenta), and transform faults (heavy black) are modified after Dickinson and Lawton (2001). Bahama Islands (red) may overlie seamounts produced by the Central Atlantic Magmatic Province mantle plume. Yellow represents Gondwanan terranes. CP = Coahuila Platform, CT = Coahuila Transform, DS = Del Sur block, GS = Guerrero Superterrane, MC = Mesa Central Triassic subduction complex, MP = Mezcalara Plate, Tam = Tampico block, TC = "Trinidad corner," TGLC = Tamaulipas-Golden Lane-Chiapas transform fault, and YB = Yucatan block. The heavy arrow, PPBC = the direction of Pre-Pangea Breakup Closure.

allochthonous salt nappe, but the Yucatan Parallel structure is clearly a boundary that separates the Campeche salt from the oceanic center of the basin.

Gulf of Mexico Seafloor Spreading

By about 140 Ma, Tithonian (Latest Jurassic) to Berriasian-Valanginian (earliest Cretaceous), the Gulf of Mexico appears to have been completely formed after another 20° (42° total) of counterclockwise rotation by seafloor spreading (Fig. 1.4C). Crustal thicknesses from refraction data (Fig. 1.5) indicate typical passive margin continental thicknesses of over 20 km thinning to typical oceanic thicknesses of 4 to 8 km towards the center of the basin (Bird et al. 2005a). Crustal thicknesses under the Keathley Canyon and Yucatan Parallel gravity anomalies range from over 6.5 to 13 km and are similar to the thicknesses of crusts of seamounts produced by mantle plumes elsewhere in the world's ocean basins (Bird et al. 2005a). Modeled cross sections (Fig. 1.5) constrained by seismic refraction and gravity data constructed for the Keathley Canyon and Yucatan Parallel structures indicate that the structures have similar dimensions to other hotspot structures (Bird et al. 2005a). The Keathley Canyon and Yucatan Parallel anomalies are similar in wavelength and

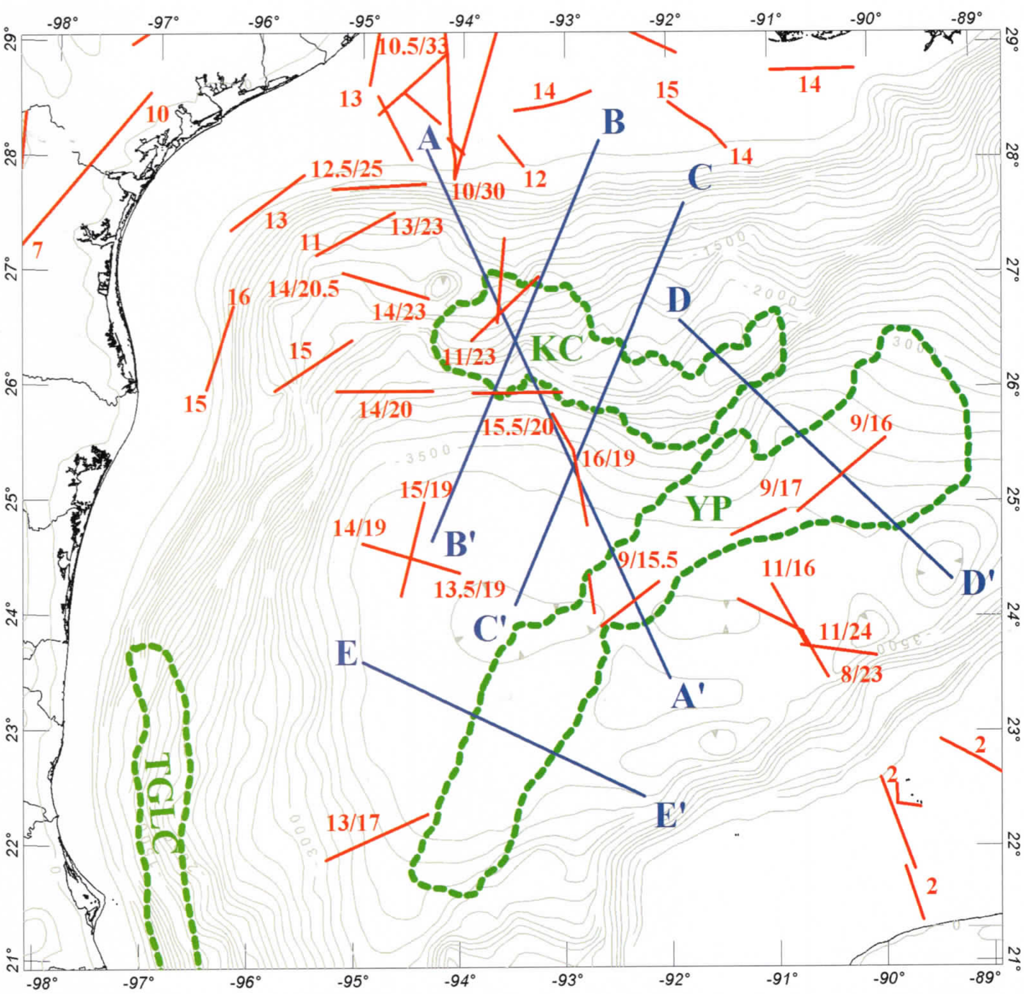


Figure 1.5. Seismic refraction control and modeled gravity cross-section locations in the western Gulf of Mexico. Bathymetry and topography contour interval=200 m, Keathley Canyon (KC), Yucatan Parallel (YP), and Tamaulipas-Golden Lane-Chiapas (TGLC) gravity anomaly outlines (dashed), 2.5-D model locations (A-A′, B-B′, C-C′, D-D′, and E-E′; Bird et al. 2005a), and seismic refraction information. Short solid-line segments coincide with seismic refraction profiles. 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.

amplitude to other anomalies produced by hotspot tracks such as the Galapagos Islands, New England Seamounts, Walvis Ridge, Rio Grande Rise, Ninetyeast Ridge, Hollister Ridge, Emperor Seamounts, and the Hawaiian Islands (Bird et al. 2005a).

Thick and complex allochthonous salt over the Keathley Canyon structure masks its shape from seismic reflection data, but the existence of this large basement structure is clear in seismic refraction data over and near the structure (Ewing et al. 1960; Ibrahim et al. 1981; Ebeniro et al. 1988). Ewing et al. (1960, p. 4096) noted that a large ridge, composed of 5 km/s material, "separates the Sigsbee deep from the Gulf geosyncline." Ebeniro et al. (1988) estimated the thickness of the Keathley Canyon structure to be 12 km and considered that the high-velocity layer associated with the top of the structure, beneath the Mid-Cretaceous Unconformity, may be a basement structure.

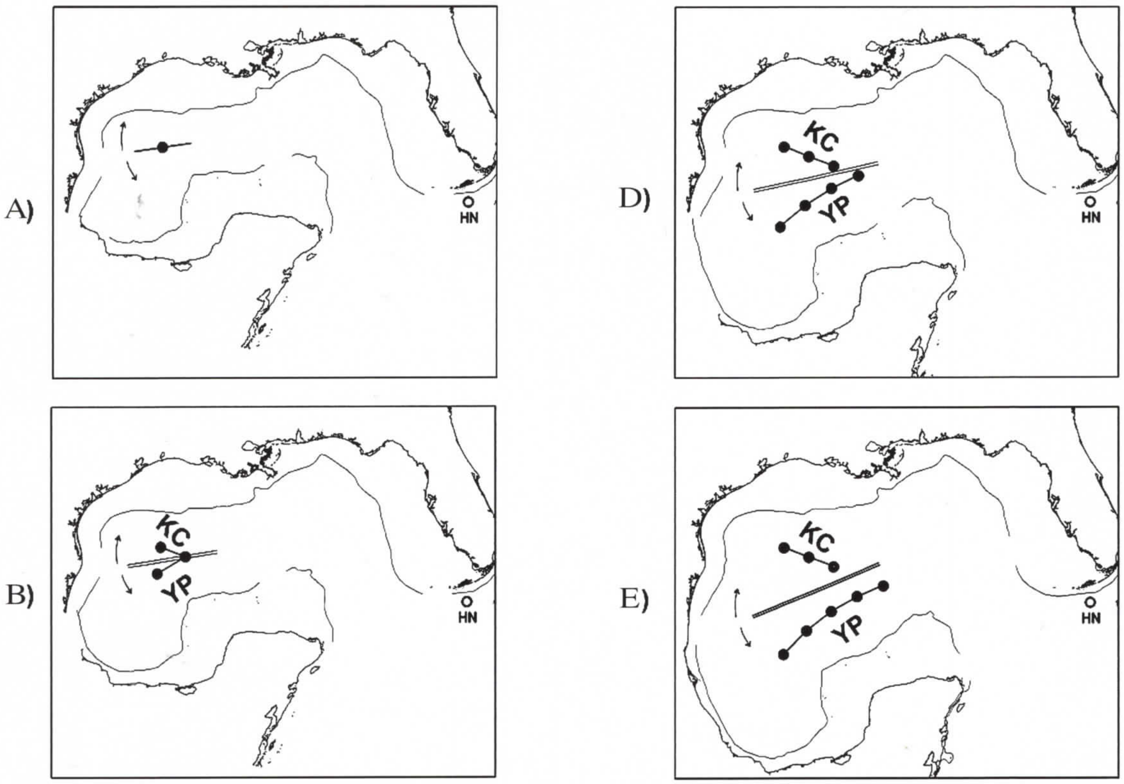
The narrow rectangular box in Figure 1.2 encloses trajectories for hotspot-referenced motion of North America for 140 Ma, 150 Ma, and 160 Ma (Morgan 1983). The trend of these trajectories and the overall trend of the Keathley Canyon anomaly are the same, indicating that if the Keathley Canyon structure is a hotspot track on the North American Plate, then it could have formed between 160 Ma 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.

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, causing conjugate hotspot tracks to form on both the North American Plate and the Yucatan block (Figs. 1.6B, 1.6C). 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 records only part of the total opening history of the Gulf. The Yucatan Parallel track records the total rotation history during the seafloor-spreading phase of the evolution of the Gulf of Mexico (Figs. 1.6D, 1.6E). Reconstruction tracks from our opening scenario, with tracks calculated in 2.5° increments totaling 20° of seafloor spreading using an Euler pole from Hall and Nadjmuddin (1994) located about 100 km south of Key West at 24°N, 81.5°W (Fig. 1.6E), are superimposed on free air gravity anomalies in Figure 1.2.

As the Yucatan block rotated, a sheared margin was created along the east coast of central Mexico (Pindell 1985, 1994; Marton and Buffler 1994). Shear margins are ocean-continent transform or fracture zone boundaries and typically form after: (1) rupture of continental crust, rifting, and the formation of an intracontinental transform boundary, (2) the development of a seafloor-spreading center and a continent-oceanic transform boundary as the continental blocks slide past each other, and (3) thermal subsidence of the fracture-zone margin that separates oceanic from continental crust (Lorenzo 1997). Several examples of shear margins reveal that high-standing marginal ridges, rising 1 to 3 km over the abyssal seafloor and ranging from 50 to 100 km 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, thin (essentially zero at the spreading center), oceanic lithosphere as the ridge transform intersection moves past thick (over 100 km) continental lithosphere (Todd and Keen 1989; Lorenzo 1997).

Marginal ridges can be topographic features such as the Côte d' Ivoire-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 and the Agulhas-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). 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 (free air gravity data derived from global satellite, Sandwell and Smith 1997). The anomalies are approximately 30 milligals (mGal) to 80 mGal in amplitude, 20 to 70 km in wavelength, and oriented parallel to bounding oceanic transforms or fracture zones.

If the plume was active only during seafloor spreading, then the southern and 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. 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. The location of the oceanic-continental crustal boundary in the Gulf of



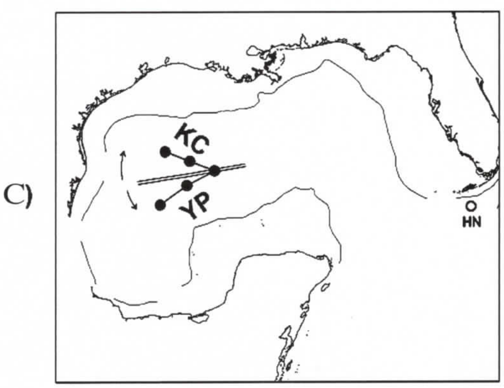


Figure 1.6. Hotspot referenced, seafloor-spreading phase of the opening of the Gulf of Mexico with a mantle plume. (A) Seafloor spreading is initiated over the mantle plume and the earliest formation of the hotspot tracks. (B) through (E) show the expected hotspot track geometry, and a schematic position of the spreading center (double lines), with four 5° steps. The seafloor 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 Myr (Figs. 1.6A–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 (Figs. 1.6D, E), seafloor spreading slowed relative to hotspot growth and the mantle plume ended up beneath the Yucatan block (another 5 Myr). Rotations were calculated using an Euler pole (HN) described by Hall and Najmuddin (1994).

Mexico is interpreted along these areas as solid lines that are then connected by dashed lines in Figures 1.1 and 1.2.

Discussion

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 about 10 Myr (Morgan 1983), or nearly one-half the total time interval required for the Gulf of Mexico to open (Salvador 1987, 1991; Marton and Buffler 1994). Since about 20° of clockwise rotation is needed to restore the western ends of the Keathley Canyon and Yucatan Parallel tracks, and this rotation must have occurred over the 10-Myr interval, then the rotation of about 20° should be roughly one-half the total rotation required to open the basin. These results, that the total time and rotation are approximately 20 Myr and 42° (Fig. 1.7), are consistent with evolutionary data presented by other workers. Exactly when this 20-Myr period occurred is difficult to determine, but stratigraphic relationships indicate that the basin must have been completely formed by ca. 140 Ma.

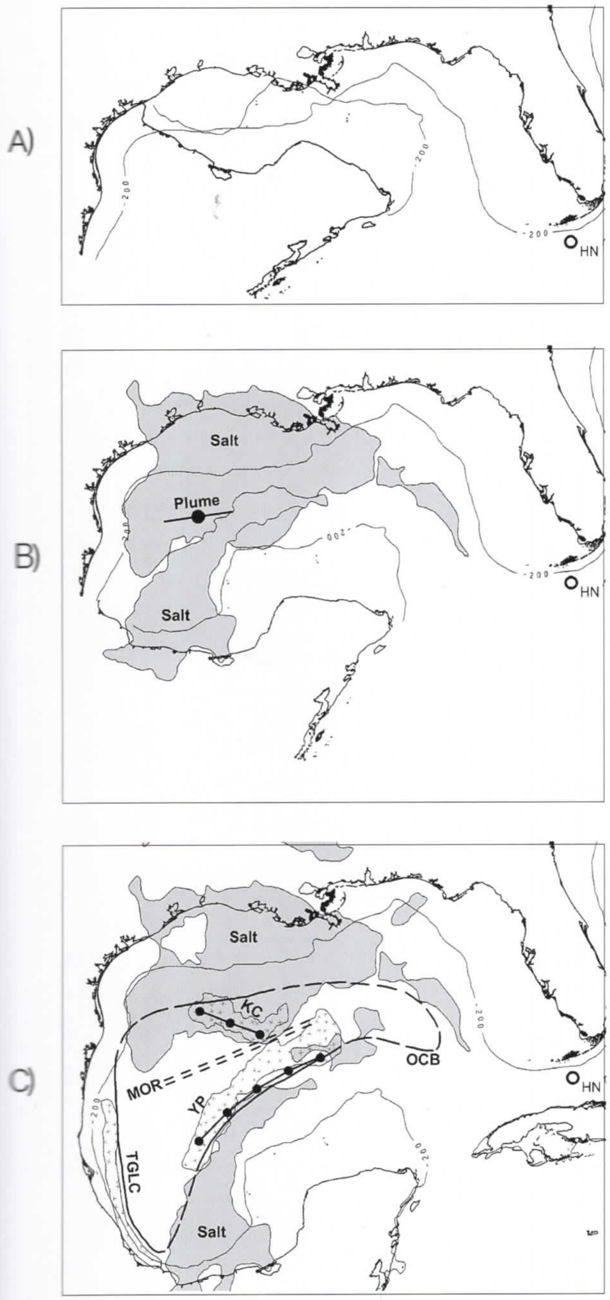


Figure 1.7. Reconstruction of Gulf of Mexico, 20-Myr evolution of Yucatan motion, using rotation pole (HN) described by Hall and Najmuddin (1994). (A) Initial position about 160 Ma. Yucatan occupies what is the Gulf of Mexico basin now. Because the Yucatan was probably longer at that time, there was no gap between the peninsula and western Florida (Burke 1988). (B) 10 to 12 Myr: about 22° of rotation and continental crust extension. Seafloor spreading began at the end of this time when the plume became active. (C) After another 8 to 10 Myr, about 20° of rotation and seafloor spreading until the present geometry is achieved. Keathley Canyon (KC), Yucatan Parallel (YP), and Tamaulipas-Golden Lane-Chiapas (TGLC) gravity anomalies, Mid-Ocean Ridge (MOR), and ocean-continent boundary (OCB).

Our conclusion that seafloor spreading occurred between 150 Ma and 140 Ma implies that the Gulf of Mexico opened about 30 Myr after seafloor spreading began in the central Atlantic Ocean (Withjack et al. 1998). During that 20-Myr interval seafloor spreading between North and South America must also have been in progress. This allows us to distinguish several tectonic events in the evolution of North America and the Gulf of Mexico beginning with the breakup of Pangea (Table 1.1): onset of rifting, salt deposition, onset of Yucatan rotation by continental extension, onset of seafloor spreading, and the end of seafloor spreading.

As Pangea broke up, mantle plumes appear to have found older rifts and erupted before the plates drifted apart (Sleep 1997). The CAMP (200 Ma) and Karroo (183 Ma) plume eruptions preceded the breakup of North America, Australia-India-Antarctica, and Madagascar from Africa; the Bunbury member of the Kerguelen

Table 1.1. Chronology of tectonic events.

Time	Event
230 Ma	Pangea breakup began: collapse of the Appalachians and Ouachitas
230 to 164 Ma	Mesa Central Subduction complex began to form as the Mezcalera Plate is consumed by the Farallon Plate; Gondwanan crustal blocks south of the Coahuila Transform are displaced eastward; extension of the Coahuila block toward the southeast, and stretching of the Yucatan block
200 Ma	CAMP plume erupts
180 Ma	Seafloor spreading began in the Central Atlantic (Withjack et al. 1998)
170 Ma	Eastward ridge jump in the Central Atlantic (abandoning African lithosphere on the western flank)
160 Ma	Westward ridge jump in the Central Atlantic (abandoning North American lithosphere on the eastern flank)
~160 Ma	Yucatan block began to rotate away from North America, 24° counterclockwise continental extension
~150 Ma	Seafloor spreading in the Gulf of Mexico, 20° counterclockwise rotation of the Yucatan block
~140 Ma	Gulf of Mexico formation was complete
~126 Ma	South America began separating from Africa
120 Ma	Guerrero Superterrane was accreted onto western Mexico

(135 Ma) plume cluster preceded the breakup of India and Antarctica-Australia; and the Tristan (133 Ma) plume preceded the opening of the south Atlantic Ocean. Later the Marion, Deccan, and Iceland plumes (85 Ma, 65 Ma, and 60 Ma, respectively), preceded the breakup of the Seychelles from Madagascar, India from the Seychelles, and Greenland from the British Isles. After North America separated from the African-Arabian-South American continent (Residual Gondwana), Gondwanan terranes remained sutured to North America; that is, eastern Mexico, the Yucatan Peninsula, and the southern part of the Gulf States were contiguous from the Pacific to the Atlantic oceans. Only the Yucatan, which was surrounded on 3 sides by similar terranes, broke away to form the Gulf of Mexico. We consider the Gulf mantle plume to have played a similar role as other mantle plumes prior to continental breakup.

Conclusion

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 the seamounts and seamount tracks created by mantle plumes. These structures are not continental fragments as indicated by their size, shape, and crustal structure. 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). 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.

Our proposed plate kinematic model and interpreted basement structures are consistent with established parameters including the pole of Yucatan block rotation, fracture zone, crustal types, the onset of rifting, early salt deposition, and deepwater marine sedimentation. Basin formation began with about 22° of counterclockwise rotation and continental extension (about 160 Ma to 150 Ma), which coincided with early salt deposition. Then another 20° of counterclockwise rotation and seafloor spreading coincided with the formation of hotspot tracks (about 150 Ma to 140 Ma).

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Gulf of Mexico Origin, Waters, and Biota

Volume 3, Geology

Edited by
Noreen A. Buster and
Charles W. Holmes

Texas A&M University Press
College Station

Printed in China by Everbest Printing Co., through FCI Print Group

First edition

This paper meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).
Binding materials have been chosen for durability.
♾ ♻

Library of Congress Cataloging-in-Publication Data
Gulf of Mexico origin, waters, and biota / [edited by John W. Tunnell Jr., Darryl L. Felder, and Sylvia A. Earle]—1st ed.
v. cm.—(Harte Research Institute for Gulf of Mexico Studies series)
Includes indexes.
Taken from the Harte Research Institute for Gulf of Mexico Studies website: Gulf of Mexico origin, waters, and biota, is an updated and enlarged version of the Gulf of Mexico: its origin, waters, and marine life, first published by U.S. Fish and Wildlife Service in Fishery bulletin, v. 89, 1954. Contents: V. 1. Biodiversity / edited by Darryl L. Felder and David K. Camp ISBN-13: 978-1-60344-094-3 (cloth : alk. paper)
ISBN-10: 1-60344-094-1 (cloth : alk. paper)
1. Mexico, Gulf of. 2. Marine biology—Mexico, Gulf of. 3. Geology—Mexico, Gulf of. 4. Oceanography—Mexico, Gulf of. I. Tunnell, John Wesley II. Felder, Darryl L. III. Earle, Sylvia A., 1935–. IV. Camp, David K. V. Series.
QH92.3.G834 2009
578.77'364—dc22

2008025312

Vol. 2, Ocean and Coastal Economy
ISBN-13: 978-1-60344-086-8
ISBN-10: 1-60344-086-0

Vol. 3, Geology
ISBN-13: 978-1-60344-290-9
ISBN-10: 1-60344-290-1