THESIS

SEAFLOOR SPREADING IN THE EASTERN GULF OF MEXICO:
NEW EVIDENCE FOR MARINE MAGNETIC ANOMALIES

Submitted by

Philip K. Eskamani

Department of Geosciences

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2014

Master's Committee:

Advisor: Dennis Harry

Sven Egenhoff
Raymond Robinson

UMI Number: 1564450

All rights reserved

INFORMATION TO ALL USERS
The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript
and there are missing pages, these will be noted. Also, if material had to be removed,
a note will indicate the deletion.

UMI 1564450

Published by ProQuest LLC (2014). Copyright in the Dissertation held by the Author.

Microform Edition © ProQuest LLC.
All rights reserved. This work is protected against
unauthorized copying under Title 17, United States Code

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 - 1346

Copyright by Philip K. Eskamani 2014

All Rights Reserved

ABSTRACT

SEAFLOOR SPREADING IN THE EASTERN GULF OF MEXICO: NEW EVIDENCE FOR MARINE MAGNETIC ANOMALIES

Possible sea-floor spreading anomalies are indentified in marine magnetic surveys conducted in the eastern Gulf of Mexico. A symmetric pattern of lineated anomalies can be correlated with the geomagnetic time scale using previously proposed opening histories for the Gulf of Mexico basin. Lineated magnetic anomalies are characterized by amplitudes of up to 30 nT and wavelengths of 45-55 km, and are correlatable across 12 different ship tracks spanning a combined distance of 6,712 km. The magnetic lineations are orientated in a NW-SE direction with 3 distinct positive lineations on either side of the inferred spreading ridge anomalies. The magnetic anomalies were forward modeled with a 2 km thick magnetic crust composed of vertically bounded blocks of normal and reverse polarity at a model source depth of 10 km. Remnant magnetization intensity and inclination are 1.6 A m^{-1} and 0.2° respectively, chosen to best fit the magnetic observed amplitudes and, for inclination, in accord with the nearly equatorial position of the Gulf of Mexico during Jurassic seafloor spreading. The current magnetic field is modeled with declination and inclination of and 0.65° and 20° respectively. Using a full seafloor spreading rate of 1.7 cm/yr, the anomalies correlate with magnetic chrons M21 to M10. The inferred spreading direction is consistent with previous suggestions of a North-East to South-West direction of sea-floor spreading off the west coast of Florida beginning 149 Ma (M21) and ending 134 Ma (M10). The opening direction is also consistent with the counter-clockwise rotation of Yucatan proposed in past models.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to Dr. Dennis Harry, Geosciences Department, for serving as my advisor, and for the very beneficial input and guidance which has been invaluable to the completion of this ongoing project. I would also like to thank Sven Egenhoff and Raymond Robinson for serving on my master's committee, as well as Michal Ruder of Wintermoon Geotechnologies for her supplemental education in the field of gravity and magnetic SEG continuing educational course and Darren Mortimer of Geosoft Inc. for his technical support and education using the Oasis montaj software. I would also like to thank The Petroleum Research Fund, The Geological Society of America, The Society of Exploration Geophysics and the Edward M. Warner Graduate Research Fellowship for their funding and invaluable education tools used for this research. Finally, I would like to thank my Dad and Mom for their encouragement and loving support during the preparation of this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: PURPOSE OF THESIS

The opening history of the Gulf of Mexico and nature of the deep crust is poorly understood, in spite of the immense economic value of the hydrocarbon resources in the basin and the continuous exploration effort intended to locate them. Seafloor spreading anomalies, which have been used elsewhere to map ocean spreading, have not been observed in the Gulf of Mexico. Although large amounts of literature and detailed geologic history is available in the region, identifying high-amplitude seafloor magnetic anomalies prove to be problematic in the Gulf.

Since the seafloor spreading history of an ocean basin can often be determined from its magnetic anomaly patterns, marine track geophysical surveys in the northeastern Gulf are herein analyzed for evidence of seafloor spreading within the basin. Bouguer gravity and aeromagnetic gridded data are also utilized in order to better define and constrain basement crust types in the region. In this thesis I analyze the results of both gridded magnetic and gravity data as well as a high resolution ship track magnetic survey taken in the eastern Gulf and discuss possible implications of the observed magnetic anomalies for the tectonic evolution of the region.

We hypothesize that all or parts of the deep Gulf of Mexico were created by ocean spreading that is recorded in previously unrecognized high amplitude seafloor magnetic anomalies that are present in these areas. These lineated magnetic anomalies may be formed by a) traditional seafloor spreading and creation of new oceanic crust or b) intrusion or serpentinization of exhumed mantle or c) syn-rift intrusion of highly extended Florida crust. The alternative (null) hypothesis is that the deep Gulf of Mexico does not contain oceanic crust produced by seafloor spreading or new crust/stretched crust created during rifting in which case we would expect no lineated magnetic anomalies.

To test the hypothesis, a magnetic block model was constructed using the geomagnetic time-scale of Gradstein et al. [2004] and opening model for the Gulf of Mexico of Pindell and Kennan [2001]. The observed magnetic data from shipborne magnetic surveys were compared with the modeled magnetic anomalies to identify magnetic polarity reversals that correlate with the geomagnetic time scale. The model is used to establish a putative spreading axis and spreading orientation in the northeastern Gulf.

To further search for seafloor or tectonic fabrics consistent with Pindell and Kennan's [2001] interpretation, we also searched for systematic trends in the regional gravity and magnetic fabrics by producing directionally filtered Bouguer gravity and aeromagnetic maps. The Bouguer gravity and aeromagnetic grids were also frequency filtered to highlight any wavelength-dependent features consistent with oceanic crust.

CHAPTER 2: REGIONAL GEOLOGIC BACKGROUND OF THE GULF OF MEXICO

2.1 Structural Evolution of Continental Margins Bounding the Gulf of Mexico

The northern Gulf of Mexico continental margin underwent two Wilson Cycles during formation of Laurentia and assembly and breakup of Pangea [Pindell and Dewey, 1982; Salvador, 1991a; Thomas, 1991]. The first of these cycles began with the late Precambrian Grenville orogeny along southern Laurentia. This was followed by Precambrian through early Cambrian rifting and subsequent formation of a passive margin extending through the middle Paleozoic. The post-Grenville rifting away from the Argentine Precordillera formed a passive pre-Ouachita margin on southern Laurentian that consists of northeast trending rift segments present in east Texas and Alabama that are connected by a southeast trending transform margin [Thomas, 1989] [Fig. 1]. Syn- and postrift strata preserving a record of this rift margin include a Lower Cambrian basal clastic unit (Rome and Conasauga Formations) and overlying Upper Cambrian through Lower Mississippian predominantly carbonate-shelf facies (Ketona through Tuscumbia Formations) [Fig. 2].

The northern Gulf of Mexico margin changed from a passive to a convergent margin during the late Mississippian. The transformation in the regional tectonic framework from a passive to a convergent margin is shown by progradation of synorogenic clastic sediments onto the shelf in the Black Warrior Basin during the late Mississippian [Thomas, 1989]. Convergence resulted in formation of the Ouachita fold-and-thrust belt and several associated foreland basins (Val Verde Basin, Fort Worth Basin, Arkoma Basin, Black Warrior Basin). South-verging subduction of the Laurentian plate beneath an allocthonous continental block or island arc is the favored model for the region during this time [Pindell, 1985]. Convergence ended with docking of Laurentia and Gondwana in the late Mississippian (320 Ma), forming the Pangea supercontinent.

The culminating tectonic event in the region was associated with the breakup of Pangea, resulting in Mesozoic extension and formation of the Gulf of Mexico passive margin on the Northern Gulf Coast margin. In the central northern Gulf of Mexico coastal plain, the northern boundary of Mesozoic extension coincides with the location of the Gilbertown-Pickens fault zone, which outlines the northern boundary of the Mississippi Interior Salt Basin, on the southern flank of the Ouachita orogen [Ewing, 1991]. The Mississippi Interior Salt Basin and Gilbertown-Pickens fault zone are parts of larger Mesozoic extensional systems known as the Interior Basin and Peripheral Fault trend, respectively, that resulted from the breakup of Pangea along the southern boundary of the Ouachita orogen from western Florida to central Texas [Fig. 1] [Buffler and Sawyer, 1985; Dobson and Buffler, 1991]. The Mississippi Interior Salt Basin contains more than 10 km of sedimentary rocks [Sawyer et al., 1991; Mancini et al., 1999] consisting of Triassic–Lower Jurassic synrift clastic and evaporitic sequences (the basal Eagle Mills Formation and Werner Anhydrite Formation), a Middle through Upper Jurassic transitional evaporite and carbonate sequence (Norphlet and Smackover Formations), and Upper Jurassic through Holocene predominantly clastic rocks of the passive-margin shelf and coastal plain (the Haynesville Formation and younger deposits) [Fig. 2]. The Mississippi Interior Salt Basin is bounded on the south by a basement horst with relatively thick crystalline crust known as the Wiggins Arch [Pindell, 1985; Salvador, 1987; Thomas, 1989] that separates the Salt Basin from the major locus of Mesozoic extension in the Gulf Coast Basin farther south. The Gulf Coast Basin is underlain by highly stretched crystalline crust distributed over a 500 km-wide region extending from the southern edge of the Wiggins Arch southward beneath the continental rise

[Buffler and Sawyer, 1985; Sawyer et al., 1991; Mickus and Keller, 1992; Harry and Londono, 2004] and contains Triassic and Jurassic clastic and evaporitic sedimentary rocks (Eagle Mills Formation, Werner Anhydrite, and Louann Salt) deposited on the subsiding Gulf of Mexico passive continental margin [Salvador, 1991b]. The trend of the Eagle Mills redbeds follows the shape of the Ouachita orogenic belt, and it roughly coincides with the underlying successor-basin deposits [Marton and Buffler, 1994]. This relationship suggests that, at least partially, these redbeds are related to extensional collapse of the orogenic belt [Buffler and Thomas, 1994].

Eastern Mexico forms the western margin of the Gulf of Mexico. Evolution of this margin differs from the other margins around the edge of the basin. During the Phanerozoic, this area hosted an Andean-type (continental) arc created by the ongoing east vergent subduction of the Pacific oceanic plates [Ortega-Gutierrez et al., 1994]. Mesozoic NW-SE extension related to the opening of the Gulf of Mexico was relatively minor along this margin. Instead, the margin formed dominantly by right-lateral strike slip motion associated with counterclockwise rotation of Yucatan away from the southern North American margin. Eastern Mexico acted as a continental barrier to marine influence up to the late Middle Jurassic, the time when widespread salt deposition occurred in the Gulf of Mexico [Salvador, 1987]. Pre-Triassic basement in northeastern and east-central Mexico consists of metamorphic rocks of probable Precambrian and/or early or mid-Paleozoic age, Paleozoic sedimentary rocks, and Permian-Triassic granitic intrusions [Woods et al., 1991]. Upper Triassic-Lower Jurassic redbeds and volcanics are known around the western, northern, and eastern margins of the Gulf of Mexico, and often are interpreted as the evidence for the onset of rifting [Salvador, 1991a, 1991b]. The distribution of the Upper Triassic-Lower Jurassic Huizachal redbeds essentially coincides spatially with the Permian-Triassic plutonic belt, and they occur in a 400-km-long and 50- km-wide zone

[Salvador, 1991a, 1991b]. It is interpreted that the western margin of the Gulf of Mexico was established on a newly consolidated orogenic belt/arc underlain mostly by composite Precambrian to Paleozoic terranes.

The Yucatan Block's role in the opening history of the Gulf of Mexico-Caribbean is a first-order one, not only because of its size, but also because this small plate forms a continental ribbon between the two oceanic basins [Marton and Buffler; 1994]. Affinity and tectonic significance of the pre-Mesozoic rocks of Yucatan is uncertain, but some observations can be reached. Old basement rocks, named the Chuacus Series, crop out just north of the Late Cretaceous Motagua suture zone (located at the southern edge of the Yucatan block, west of the Chortis Block) and chiefly consist of schists, gneiss with minor marble, and scattered metavolcanic and quartzite units [Donnelly et al., 1990]. The age of the Chuacus Series can be established only as pre-Late Paleozoic. Metamorphic grade of these rocks can be defined as amphibolite and garnet amphibolite, whereas south of the suture zone phyllite and schists are of the greenschist facies [Bishop, 1980] and are interpreted as part of a separate Chortis block. In general, pre-Late Paleozoic rocks of the Yucatan block, represented by the Chuacus series, are not correlatable with terranes of Mexico and North America [Donnelley, 1989]. The only documented significant post-Paleozoic and pre-Cretaceous sedimentary suite is the Late Jurassic to Neocomian Todos Santos formation [Marton and Buffler, 1994]. These redbeds were deposited in a NW-trending graben system that developed during the early stages of Gulf of Mexico rifting, and are restricted to an area in southwestern Yucatan.

The large continental region represented by the Florida peninsula and the submerged west Florida shelf (which forms the eastern margin of the Gulf of Mexico) can be interpreted as an allochthonous terrane that accreted to North America during Late Paleozoic assembly of

Gondwana. Similar to the Yucatan block, this area withstood pervasive extensional deformation during the opening of the Gulf of Mexico-Caribbean-Central Atlantic system and represents an unusually strong lithospheric fragment. The evolution of the Atlantic and Gulf of Mexico marginal basins is recorded in the sediment pile overlying the subsiding basement. The Blake Plateau basin (located NE of the Florida Platform), with its thick section of Lower to Middle Jurassic sediments, is typical of the western Atlantic marginal basins [Folger et al., 1979; Grow and Sheridan, 1981], but these units are missing in the south Florida-Bahamas basin, [Barnett, 1975; Tator and Hatfield, 1975a, b; Applegate et al., 1982]. Callovian Werner Formation anhydrites overlie Late Triassic Eagle Mills red beds around the rim of the Gulf basin. A thick section of clastic sedimentary rock or volcaniclastic rock has been postulated to lie beneath the Upper Jurassic units in the Bahamas [Dietz et al., 1970; Walper, 1974; Sheridan, 1974], but there is no direct evidence for such thick clastic units and the south Florida basin drill hole data indicate only a very thin, basal clastic unit [Popenoe and Zietz, 1977; Chowns and Williams, 1983; Daniels et al., 1983; Klitgord et al., 1983]. The deposition of Upper Jurassic shelf facies sediment in the south Florida and Bahamas basins indicates that the pre- Upper Jurassic surface was near sea level, requiring a tectonic evolution which accounts for the nondeposition or removal of the Lower to Middle Jurassic units followed immediately by Upper Jurassic shallow water deposition [Klitgord et al., 1984].

2.2 Opening of the Gulf of Mexico

The position of the Mesozoic ocean-continent transition on all of the Gulf margins is problematic, but geophysical models suggest that the oldest oceanic crust is most likely positioned beneath the modern North American continental rise [Buffler and Sawyer, 1985; Dobson and Buffler, 1991; Mickus and Keller, 1992; Pindell et al., 2000; Pindell and Kennan, 2001; Harry and Londono, 2004]. Most workers now agree that counterclockwise rotation of the Yucatan Peninsula block away from the North American plate led to the formation of the basin, creating S or SSE extensional fabrics on the southern U.S. margin and right lateral strike slip faulting on the eastern Mexico margin. This rotation is estimated to have occurred between 160 Ma (Callovian) and 137 Ma (Valanginian) about a pole located within 5° of Miami, Florida [Humphris, 1979; Shepherd, 1983; Pindell, 1985, 1994; Dunbar and Sawyer, 1987; Salvador, 1987, 1991a; Burke, 1988; Ross and Scotese, 1988; Christenson, 1990; Buffler and Thomas, 1994; Hall and Najmuddin, 1994; Marton and Buffler, 1994] [Fig. 3, Table 1]. Evidence for this opening model is paleomagnetic data from the Chiapas massif of the Yucatan Peninsula, with interpretations varying from a counterclockwise rotation of 75° [Molina-Garza et al., 1992] to 130° [Gose et al., 1982] with respect to the magnetic north pole.

Other evidence favoring a rotational opening model for Yucatan includes the orientation of fracture zone trends located within the eastern Gulf interpreted from magnetic data [Shepherd, 1983; Hall and Najmuddin, 1994], restoration of extension on the northern Gulf margin based on nonrigid tectonic reconstructions [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]. Table 2 provides a summary of the Gulf of Mexico formation events as proposed by different authors [Bird et al., 2005].

2.3 Seismic Constraints on the Nature of Crust in the Gulf of Mexico

Seismic refraction measurements constitute the most significant geophysical data set that directly addresses the crustal structure and distribution of oceanic crust in the Gulf of Mexico basin. Seismic refraction profiles from the Gulf of Mexico, as well as other oceanic basins, have been collected and compiled from published literature [Fig. 4a] [Ewing et al., 1960; Cram, 1961; Antoine and Ewing, 1963; Del Castillo, 1974; Ebeniro et al., 1986, 1988; White et al., 1992; Srivastava et al., 2000]. Estimates for the velocity structure and thickness of both the crust and overlying sediments are utilized to delineate the distribution and nature of crust in the Gulf of Mexico.

When corrected for variations in the thickness of Layer 2, the seismic velocity structure in areas of the Gulf proposed to be underlain by oceanic crust form two groups [Fig. 4b]. One group of velocity profiles appears similar to typical Jurassic oceanic crust in the North Atlantic (shaded light blue), although the Layer 3 velocity lies near the low end of the typical oceanic range. This group of profiles lies mostly with the central deep Gulf. The second group of profiles has distinctly higher velocity at depths below Layer 2. Velocities in this group of profiles are near or greater than the high range of velocities for oceanic Layer 3, but lie within the range of velocities encountered in transitional crust on the Iberian and Newfoundland margins (shaded light red) [Fig. 4b]. This second group of profiles lies near the proposed spreading ridge in the northeastern Gulf [Fig. 1].

Four main conclusions can be drawn from the seismic refraction profiles. 1) The deep Gulf profiles appear nothing like the velocity profile from the transitional crust. This means that the deep Gulf crust cannot possibly be rifted continental crust due to its high velocity. 2) The central deep Gulf profiles most closely resemble the north Atlantic Oceanic profile ridge. Thus, we conclude here that the central deep Gulf crust is oceanic in nature, despite the change in thicknesses of Layer 2. 3) The velocity profiles in the northeastern deep Gulf are similar to profiles adjacent to the Iberian rifted margin in terms of both the velocity gradient and magnitude. However, the northeastern Gulf profiles lack the steep velocity gradient in the upper

2 km below seafloor that is characteristic of the Iberia profiles. Although the data allow the possibility that this region is underlain by exhumed mantle, it would be anomalous in comparison to Iberia. 4) The velocity gradient and magnitude of the northeastern Gulf profiles are at the very high end of what we would accept as oceanic crust and the very low end of what we would accept as exhumed mantle. Thus, the nature of the crust in the northeastern Gulf is uncertain.

CHAPTER 3: METHODS

3.1 Bouguer Gravity Data

A Bouguer gravity anomaly map of the Gulf of Mexico basin and surrounding region was produced using the National Geophysical Data Center Land and Marine Gravity dataset [Dater, et al., 1999]. The reported data resolution is about 5 mGal in amplitude over 20-km wavelengths. The Bouguer gravity map was directionally filtered at azimuths of 30°, 60°, 120° and 150° using the Oasis Montaj software by Geosoft, Inc. in order to highlight directional fabrics in the gravity field when present. Each directional azimuth encompasses a direction window of +/- 15° (for example, 30° azimuth allows passing of 15°-45°).

3.2 Aeromagnetic Data

A magnetic intensity anomaly map of the Gulf of Mexico was created using the World Digital Magnetic Anomaly Map dataset with a resolution of 3 arc-min [Maus et al., 2007]. The aeromagnetic grid was reduced to the pole (RTP) from total magnetic intensity (TMI) in order to produce a magnetic map that could be interpreted more simply and directly, and was directionally filtered to highlight any regional fabrics in the magnetic field, when present. As with the Bouguer gravity maps, the RTP maps were directionally filtered at 30°, 60°, 120° and 150° with azimuth direction window of +/- 15°.

3.3 Marine Trackline Data

Marine magnetic data was also obtained via the NOAA National Geophysical Data Center (NGDC). All marine magnetic profiles in the NGDC database were analyzed to search for lineated, symmetric, or periodic anomaly patterns that might be indicative of seafloor spreading magnetic lineations. Of these, data from R/V FARNELLA cruises FRNL85-1, 85-2, and 85-3 in the U.S. Gulf of Mexico EEZ [Lubinski and Twichell, 1989] is the only one found to exhibit strongly lineated magnetic anomalies. These lineations are symmetric and periodic, occurring along profiles perpendicular to previously proposed seafloor spreading ridge orientations [Pindell and Dewey, 1982; Klitgord et al., 1984; Buffler and Sawyer, 1985; Pindell, 1985; Sawyer et al., 1991; Schouten and Klitgord, 1994; Pindell et al., 2000; Pindell and Kennan, 2001; Stern and Dickinson, 2010].

Twenty two individual profiles oriented perpendicular to the Florida Escarpment and the strike of the putative spreading ridge were extracted from the tracklines from survey FRNL85 in order to compare profiles to observe any periodic patterns [Fig. 5]. Portions of the ship track trending perpendicular to the inferred ridge axis were plotted in order from north to south with latitude serving as the x-axis. The magnetic anomalies on these profiles were correlated based on similarity of amplitudes, wavelengths, and their lateral proximity to one another [Fig. 6].

3.4 2-D Magnetic Modeling

Synthetic seafloor spreading magnetic profiles were constructed using the Geosoft, Inc. software package Oasis montaj. Using the GM-SYS software extension, a block model was created in which each block corresponds to region of oceanic crust emplaced during a period of constant polarity in the geomagnetic time scale. GM-SYS was used to calculate the magnetic signature for each block and the anomalies for each block were summed to create the synthetic magnetic profile.

Seafloor spreading anomalies are thought to be produced by dikes intruded at the mid-ocean ridge axis at the time of the crust is formed. The magnetic anomalies create distinctive patterns that depend on the width of the dikes, how strongly magnetized the dikes, their depth, and their latitude. Understanding the impact of these factors on the shape of the magnetic anomalies can be gained by considering the solution for the simple case of a single magnetized dike, which is in the form of one rectangular prism that extends infinitely parallel to the ridge. [Fig 7]. The equation for this solution is

$$T = 2M\left[(\cos^2 i\ \sin^2 k - \sin^2 i)\ (\theta 2 - \theta 1) + 2\sin i \cos i \sin k\ \ln\left(\frac{r1r4}{r2r3}\right)\right]$$

where T is the total anomalous field, M is the total magnetic dipole moment, i is the inclination, k is the remnant declination. For thetas and r's, refer to Fig. 7 [Harry 1983].

As the latitudes change from polar to mid-latitudes, skewness develops. For a positively magnetized dike located at the North Pole, a symmetric anomaly is centered over the magnetic source with most of the power in the positive part of the anomaly [Fig. 8a]. At the latitudes between the North Pole and mid-latitude, the power progressively shifts from the positive peak to the negative peak. At mid-latitude an asymmetric anomaly exists with the power split between the positive and the negative parts of the wavelet [Fig. 8b]. At the equator, we have a symmetric anomaly centered over the magnetic source, but the polarity reversed compared to the dike at the North Pole [Fig. 8c]. As the depth increases, the amplitude decreases and the wavelength increases [Fig 8d]. However, in this research, the latitude and the depth are known. The variables are the width of the anomaly and the intensity of magnetization. The width of the anomaly is determined by the spreading model, specifically the spreading rate and the period of time.

Magnetic blocks were constructed to correspond to geomagnetic epochs, consisting of alternating blocks of normal and reverse magnetic polarities corresponding to the period of seafloor spreading (160 Ma through 137 Ma) suggested by Pindell and Kennan [2001] and the geomagnetic time scale of Gradstein et al. [2004]. The widths of the blocks were determined by multiplying the duration of the constant polarity geomagnetic epoch by the half spreading rate.

The full spreading rate was initially chosen to be a uniform 1.7 cm/yr based on the model of Pindell and Kennan [2001], but this was varied during the modeling to achieve a best fit between the modeled and observed magnetic profiles. Model source is 10 km deep and 2 km thick, corresponding to the depth and thickness of interpreted oceanic Layer 2 in the northeastern Gulf. Remnant magnetization intensity and inclination are 1.6 A m^{-1} and 0.2° respectively, chosen to best fit the magnetic observed amplitudes and, for inclination, in accord with the nearly equatorial position of the Gulf of Mexico during Jurassic seafloor spreading. The current magnetic field is modeled with declination and inclination of 0.65° and 20° respectively, coinciding with the magnetic field parameters in the northeastern Gulf in 1985 when the survey was conducted.

A separate model was created to the east of the spreading ridge from geochron M10 to geochron M26. This was done because the current version of GM-SYS limits the number of blocks in a model, thus the two sides of the ridge were modeled separately. The model east of the ridge was then spliced together with the western model in order to create a model which encompasses both sides of the inferred spreading ridge to see how the observed data matches with the calculated data on either side of the ridge. A third model was also constructed encompassing both sides of the inferred spreading ridge but only includes geochron M10 to geochron M18. This model was created to verify that no artifacts were introduced near the ridge axis when the northeastern and central models were spliced together.

CHAPTER 4: RESULTS

4.1 Seismic Velocity/ Bouguer Gravity and Aeromagnetic Maps

Seismic velocities derived from refraction surveys show that the deep central Gulf is underlain by crust with velocities more similar to that of North Atlantic oceanic crust than transitional crust or exhumed mantle [Fig 4] [Ewing et al., 1960, 1962; Cram, 1961; Antoine and Ewing, 1963; Antoine and Harding, 1965; Buffler and Sawyer, 1985; Ebeniro et al., 1988; Ewing, 1991; Buffler and Thomas, 1994]. The deep northeastern Gulf is characterized by a distinct positive (~ 150 mgal) Bouguer gravity anomaly that narrows toward the southeast (labeled A in Fig. 9) and encompasses portions of the Gulf with seismic refraction velocity profiles which do not resemble North Atlantic oceanic crust or Iberia exhumed mantle seafloor. The nature of the underlying crust in the region encompassed by this positive gravity anomaly is uncertain. Gravity anomalies associated with this region become increasingly negative towards the west, reaching -300 mgal in the central Gulf and -600 mgal in the western Gulf.

The region associated with the gravity high is separated from the continental crust of Yucatan and Florida by distinct gravity lows, which are interpreted to mark the seaward edge of attenuated continental crust (labeled B in Fig. 9). The inferred edge of attenuated continental crust is also associated with a strong gravity gradient along the northwestern margin of Yucatan and along the western margin of Florida, which is interpreted to be related to the continental shelf edge formed mainly by the underlying carbonate platform margins. Positive gravity anomalies are more abundant in the northeastern Gulf margin than elsewhere, reaching ~200 mGal (labeled C in Fig. 9). A prominent but irregular gradient can be observed along the eastern Mexican margin (labeled D in Fig. 9), which may be interpreted to represent the continent-ocean transition. Plate reconstructions indicate that the western Gulf (Mexican) margin is a transform fault margin, unlike the rifted margins that surround the rest of the Gulf [Buffler and Sawyer, 1985; Pindell, 1985; Dunbar and Sawyer, 1987; Ortega-Gutierrez et al., 1994]. The directionally filtered Bouguer gravity maps enhance the distinct continental gravity signatures of Yucatan and the Florida platform in the vicinity of the inferred ocean-continent boundary, but do not otherwise reveal any strong directional fabrics [Fig. 10a, b, c, d].

The magnetic anomalies in the deep Gulf of Mexico are fairly weak (-20 nT) in comparison to continental areas such as the Florida Platform and Yucatan [Fig. 11]. The most plausible cause for the seaward truncation of these anomaly trends is the juxtaposition of the Jurassic oceanic crust with the continental areas [Marton and Buffler; 1994]. The relatively high amplitude anomaly on the Texas coast (labeled A in Fig. 11) is interpreted by Mickus et al., [2009] to be a large volume of magma emplaced at the time of breakup. The lower field strength in the deeper parts of the central Gulf (labeled B in Fig. 11) may reflect the great thickness of the non-magmatic Mesozoic-Cenozoic sedimentary section, but it also may reflect weaker or more homogeneous magnetization of the oceanic crust [Marton and Buffler; 1994].

The contrast between low (-80 nT) and high (70 nT) magnetic anomalies in the eastern Gulf is coincident with the location of the large Bouguer gravity gradients, and clearly defines the seaward edge of continental crust (labeled C in Fig. 11). A prominent north-trending magnetic high and low are truncated by a NW-trending magnetic low near the base of the Campeche escarpment near Yucatan (labeled D in Fig. 11). This dipolar magnetic anomaly is interpreted to be associated with unmapped pre-Mesozoic tectonic structures in Yucatan, but its origin is uncertain and it is not continuous with recognizable similar features in the aeromagnetic maps on the conjugate North American margin. The directional filtered magnetic maps do not display any potential field fabrics consistent with sea-floor spreading anomalies, with the exception of the 60° directionally filtered map [Fig. 12a, b, c, d]. This map [Fig. 12b] displays magnetic fabrics parallel to the spreading center proposed by Pindell and Kennan [2001].

4.2 Shipborne Magnetic Profiles

The ship-paths of the Woods Hole FRNL1985 marine geophysical survey are nearly perpendicular to a bathymetric high that is interpreted here to be the morphological expression of a remnant spreading ridge. This region corresponds with a Bouguer gravity high (~180 mGal) and a region of relatively low magnetic field strength (-50 nT). The symmetry of the magnetic anomalies surrounding the inferred spreading ridge offer the best evidence of seafloor spreading magnetic anomalies provided by the Woods Hole survey. Of the FRNL 1985 ship-track profiles, one in particular (labeled as Model Line in Fig. 6) seems to provide strong potential evidence of seafloor spreading magnetic anomalies centered about a bathymetric ridge. As discussed below, magnetic geochrons corresponding to these anomalies are determined for the Model Line through forward modeling. The Model Line, when then correlated to surrounding survey profiles, demonstrates that magnetic anomalies consistent with seafloor spreading are present throughout the surveyed region [Fig. 13].

4.3 2-D Magnetic Models

Forward modeling using the timescale of Gradstein et al. [2004] shows that the anomalies roughly correlate with chrons M21r-M10r (149-134 Ma), assuming a half spreading rate of 8.5 mm/yr on either side of the ridge. In the model profile west of the inferred spreading ridge [Fig. 14], the model and data match relatively well between M10n (134.62 Ma) through M21r (148.92 Ma). The model and data fail to correlate significantly with one another beyond ~148 Ma. At the M21r geochron (148.92 Ma), the observed magnetic data shows a positive anomaly, whereas the model predicts a negative anomaly. The observed magnetic data remains at higher field strength than the calculated data until around 150.8 Ma (M23 anomaly) where the observed and calculated data intersect. Beyond the M23 anomaly, the observed magnetic data remains at a lower value than the calculated data. The difference in the calculated and observed magnetic data beyond the M23 anomaly may be explained by a number of possibilities: a change in magnetic susceptibility in the oceanic crust, a variation in the intensity of magnetization, or a possible change in spreading rate.

In the model profile east of the inferred spreading ridge [Fig. 15], the model and data match relatively well until about geochron M17n (142.84 Ma). Beyond that geochron, the model again predicts a negative magnetic anomaly where the data shows a positive anomaly. The calculated data dips to ~ -40 nT while the observed data peaks at around 0 nT. The observed and calculated data intersect at M19r only to diverge from one another and fail to correlate with one another for the remainder of the model. The poor correlation between the model and data at ages greater than 142.84 Ma may be explained by the proximity to the Florida shelf edge, or by a change in spreading rate.

When the two magnetic forward models are stitched together assuming a constant half-spreading rate (8.5 mm/yr) the entire model can be compared with the data [Fig. 16a, b]. Although this model provides a reasonable approximate fit to the observed magnetic profile, it does not produce a symmetric set of anomalies on either side of the ridge. In particular, the model predicts anomaly M17 to be present west of the spreading ridge, but absent on the east side. The observed magnetic profile shows compelling similarity in the character of magnetic anomalies on either side of the ridge, suggesting that the uniform spreading model does not accurately identify all anomalies present. A better fit to the magnetic anomaly pattern is obtained by assuming asymmetric spreading, with a half spreading rate of 9.9 mm/yr on the western side and a half spreading rate of 8.8 mm/yr on the eastern side of the ridge [Fig. 16c]. In this model, the first two magnetic highs on either side of the spreading ridge correspond to anomalies M12 and M17, in agreement with the similarity in character of the magnetic profile.

CHAPTER 5: IMPLICATIONS FOR THE NATURE OF THE CRUST IN THE NORTHEASTERN GULF OF MEXICO

Based on the seismic refraction profiles, Bouguer gravity data, aeromagnetic data and magnetic forward models, three main plausible scenarios exist regarding the nature of the crust in the northeastern Gulf of Mexico:

1) The northeastern Gulf is underlain by oceanic crust.
2) The northeastern Gulf is underlain by exhumed mantle.
3) The northeastern Gulf is underlain by extended Florida crust intruded by dikes during rifting.

By utilizing all of the geophysical data presented here, a series of arguments can be made for and against each of these possibilities. Arguments that can be made for oceanic crust are as follows: A set of lineated magnetic anomalies are evident in the eastern Gulf in magnetic profiles collected from the Woods Hole R/V Farnella FRNL85-2 cruise [Lubinski and Twitchell, 1989]. These anomalies cover over a 400 km wide region that crosses a bathymetric high, that is interpreted to be the morphological expression of a remnant spreading ridge [Fig 16a]. Forward modeling using the timescale of Gradstein et al. [2004] shows that the anomalies roughly correlate with chrons M21r-M10r (149-134 Ma), assuming a half spreading rate of 8.5 mm/yr on either side of the ridge [Fig. 16b]. The anomalies correlate better with chrons M21r-M10r in the asymmetric spreading model, which provides a more realistic model for sea floor spreading [Fig. 14c]. The lack of high amplitude anomalies (~1000 nT) in the northeastern Gulf may be attributed to rapid magnetic field polarity reversals during the Jurassic, which are associated with weak seafloor spreading magnetic anomalies in ocean basins across the globe [e.g., Hall and Najmuddin, 1994], the equatorial position of the Gulf during Jurassic, which would be associated with a relatively low magnetic field strength, and the great depth to basement in the deep Gulf (>10 km), which could result in subdued anomaly amplitudes.

Likewise, a series of arguments can be made against the northeastern Gulf of Mexico being underlain by oceanic crust. The lineated magnetic anomalies in the northeastern Gulf of Mexico differ from high-amplitude (~1000 nT) lineated magnetic anomalies such as those typically associated with creation of oceanic crust. Instead, magnetic anomalies in the deep Gulf are low-amplitude (<100 nT) [Fig. 17]. These low-amplitude magnetic anomalies are also bounded by more subdued magnetic gradients than is typical of similar age oceanic crust. The interval of crust with oceanic Layer 2 p-wave velocities (4.6-5.2 km s^{-1}) is 2.7-6.0 km-thick, much thicker than is typical of Layer 2 in most ocean basins, and velocities at greater depths are, in much of the eastern Gulf, higher than typical oceanic crust [Fig. 4a]. The northeastern Gulf is overlain by an anomalous Bouguer gravity high that is not present elsewhere in the Gulf which has been interpreted to be underlain by oceanic crust (the central Gulf). The half spreading rate of 8.5 mm/yr clearly suggests that the ridge is characteristic of a slow spreading center. Typically, slow spreading centers around the globe are regions where we expect to find exhumed mantle instead of traditional oceanic crust [Chian et al., 1995; Whitmarsh and Miles, 1995; Louden and Chian, 1999; Manatschal and Bernoulli, 1999; Pérez-Gussinyé et al., 2003; Russell and Whitmarsh, 2003; Reston and Perez-Gussinye, 2007; Reston, 2009].

Data used to argue for exhumed mantle are as follows: The magnetic anomalies in the eastern Gulf of Mexico are similar in amplitude to those observed off the west coast of Iberia and its conjugate Newfoundland margin, where the seafloor is known to be formed by exhumed mantle [Fig 17]. Exhumed subcontinental mantle is characteristic of non-volcanic rifted margins, which are also typically associated with slow spreading rates [Chian et al., 1995; Whitmarsh and Miles, 1995; Louden and Chian, 1999; Manatschal and Bernoulli, 1999; Pérez-Gussinyé et al., 2003; Russell and Whitmarsh, 2003; Reston and Perez-Gussinye, 2007; Reston, 2009], as is the case in the northeastern Gulf of Mexico.

The velocity profiles in the northeastern Gulf are similar to profiles adjacent to the Iberian rifted margin in terms of both the velocity gradient and magnitude. The seismic velocity, gravity, and magmatic characteristics of the crust in the area encompassed by these magnetic data are similar to those adjacent to rifted margins where subcontinental lithosphere is exhumed during slow amagmatic rifting.

Despite the fact that the velocity profiles in the northeastern Gulf are more similar to the profiles adjacent to the Iberian rifted margin, the northeastern Gulf profiles lack the steep velocity gradient in the upper 2 km below seafloor that is characteristic of the Iberia profiles. The velocity gradient and magnitude of the northeastern Gulf profiles are at the very low end of what we would accept as exhumed mantle. Although the data allows the possibility that this region is underlain by exhumed mantle, it would be anomalous in comparison to Iberia.

Lastly, diking during the late stages of extension may produce low-amplitude low-gradient lineated magnetic fabrics such as is observed in the eastern Gulf. Such dikes, if emplaced sequentially toward the rift axis, may provide a chronology of the late stages of rifting, much as seafloor spreading anomalies [Lizarralde et al., 2007]. The present data does not allow for distinguishing between the exhumed mantle or intruded Florida crust models.

CHAPTER 6: CONCLUSIONS

Several conclusions can be drawn regarding the nature of the crust in the deep Gulf of Mexico. Since deep central Gulf seismic velocity profiles appear nothing like the velocity profile from the transitional crust, the deep Gulf crust cannot possibly be rifted continental crust unless it is highly intruded. The seismic refraction profiles within the central Gulf are consistent with those from oceanic crust in the North Atlantic. Thus, we conclude that the central Gulf of Mexico is underlain by oceanic crust.

The northeastern Gulf of Mexico is enigmatic and the nature of the underlying crust is problematic. The identification of lineated magnetic anomalies and their correlation to chrons M21n-M10r certainly suggest that the northeastern Gulf may be underlain by oceanic crust. However, the northeastern Gulf magnetic anomalies are lower in amplitude and are bounded by more subdued magnetic gradients than is typical of similar age oceanic crust. Also, the interval of crust with oceanic Layer 2 p-wave velocities is much thicker than is typical of Layer 2 in most ocean basins, and velocities at greater depths are higher than typical oceanic crust. The magnetic and gravity fields in the northeastern Gulf are anomalous in comparison to the central Gulf underlain by oceanic crust, with distinctively higher gravity and lower magnetic field strengths. The half spreading rate of 8.5 mm/yr obtained from the magnetic models suggests a slow spreading center that is more typical of exhumed mantle than traditional oceanic crust.

Although the high velocity in the northeastern Gulf is similar to the Iberia profiles in terms of both its gradient and velocity, it lacks the steep velocity gradient in the shallow section of the profile. The velocity gradient and magnitude of the northeastern Gulf profiles are at the very low end of what we would accept as exhumed mantle and are at the very high end of what we would accept as oceanic crust. Thus, the nature of the crust in the northeastern Gulf of Mexico remains unknown.

Despite the complications regarding the exact nature of the crust in the northeastern Gulf, the half-spreading rate (8.5 mm/yr), duration of seafloor spreading (149 Ma through 134 Ma), oceanic crustal thickness (2 km) and depth of oceanic crust (10 km) used in the model are all consistent with the tectonic model proposed by Pindell and Kennan [2001]. The orientation of magnetic anomalies obtained via the Woods Hole survey is also consistent with the trend of seafloor spreading magnetic anomalies predicted by Pindell and Kennan [2001]. This model involves the counterclockwise rotation of the Yucatan block from away from the northern Gulf margin, and is consistent with previously proposed models by other authors as well [Buffler and Sawyer, 1985; Dickinson and Lawton, 2001].

The observed magnetic lineations within the northeastern Gulf have a roughly N-S to NE-SW trend. This orientation of magnetic anomalies is consistent with the trend of seafloor spreading magnetic anomalies predicted by the previously proposed kinematic opening models of Buffler and Sawyer [1985], Hall and Najmuddin [1994], and Pindell and Kennan [2001]. The magnetic data obtained by the Woods Hole survey are consistent with models for the formation of the Gulf of Mexico which involve a counterclockwise rotation of the Yucatan block from a position adjacent to the northern Gulf margin to its current location [e.g., Pindell and Dewey, 1982; Pindell, 1985; Buffler and Sawyer, 1985; Pindell and Kennan, 2001]. Due to the scarcity of seismic data, and the lack of recognized sea-floor spreading anomalies elsewhere in the Gulf, the exact boundary of the proposed oceanic crust is problematic, as is the nature of the crust in the northeastern Gulf.

Table 1: Poles for Counterclockwise Rotation of the Yucatan Block
[Bird et al., 2005]

Source	Longitude	Latitude
Marton and Buffler, 1994	-84.24°	23.18°
Hall and Najmuddin, 1994	-81.50°	24.00°
Pindell, 1985	-81.40°	29.50°
Pindell, 1994	-82.10°	28.40°
Dunbar and Sawyer, 1987	-79.00°	25.00°
Shepherd, 1983	-84.00°	24.00°
Shepherd, 1983	-81.50°	25.00°
Shepherd, 1983	-78.50°	27.00°
Christenson, 1990	-81.60°	27.20°

Table 2: Summary of Gulf of Mexico Formation Events
[Bird et al., 2005]

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	Berrisian, 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	Winkler 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	Berrisian, 140 Ma	Bird et al., 2005

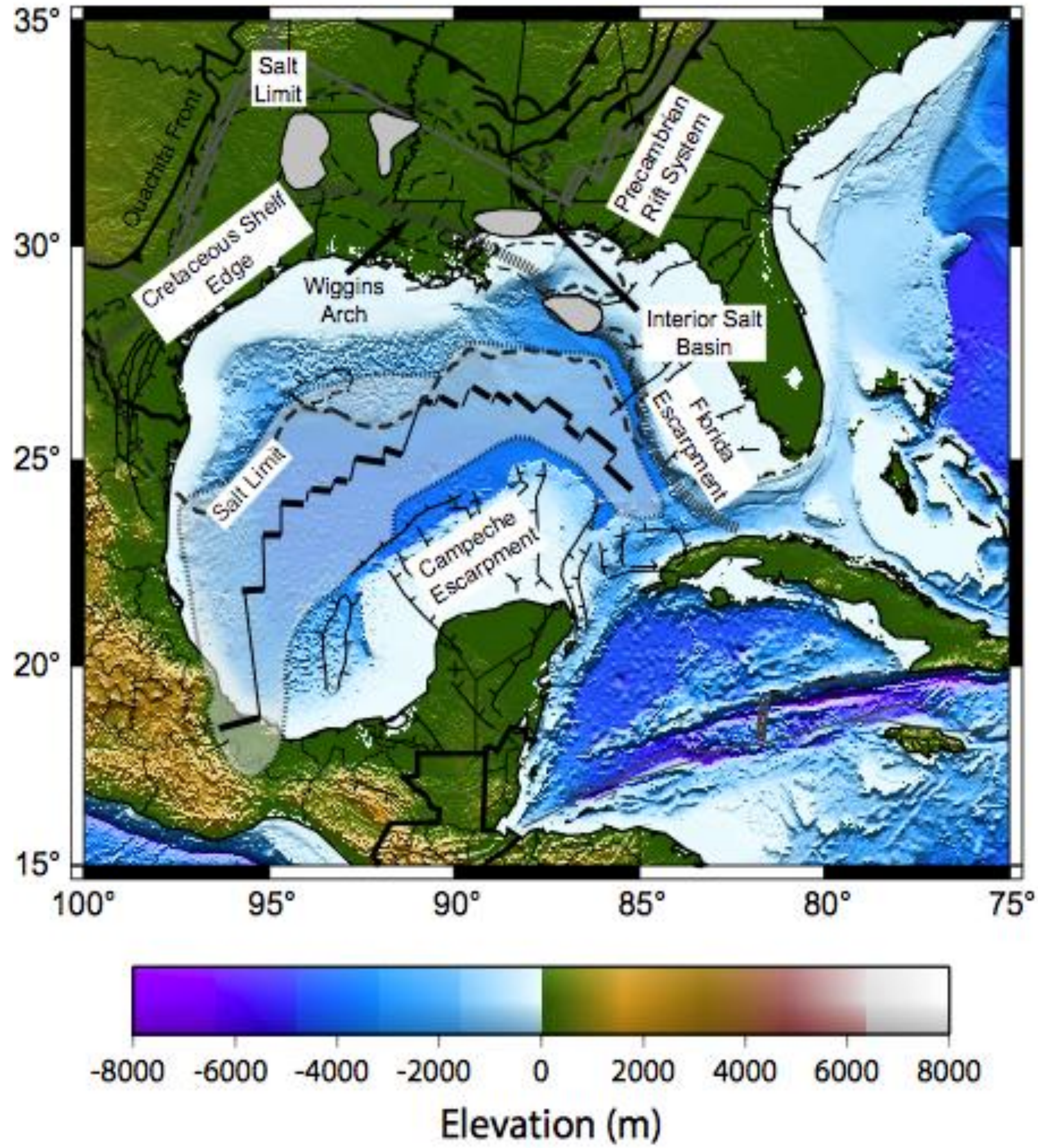


Figure 1: Key Tectonic Elements of the Gulf of Mexico Region

Thin black lines: major Mesozoic normal fault systems; Thick black lines: previously proposed Gulf of Mexico and Caribbean seafloor spreading structures; gray shaded polygons: rift-related Mesozoic arches and uplifts. Shaded regions within the basement represent interpretation of oceanic crust. Modified after Pindell and Kennan [2009].

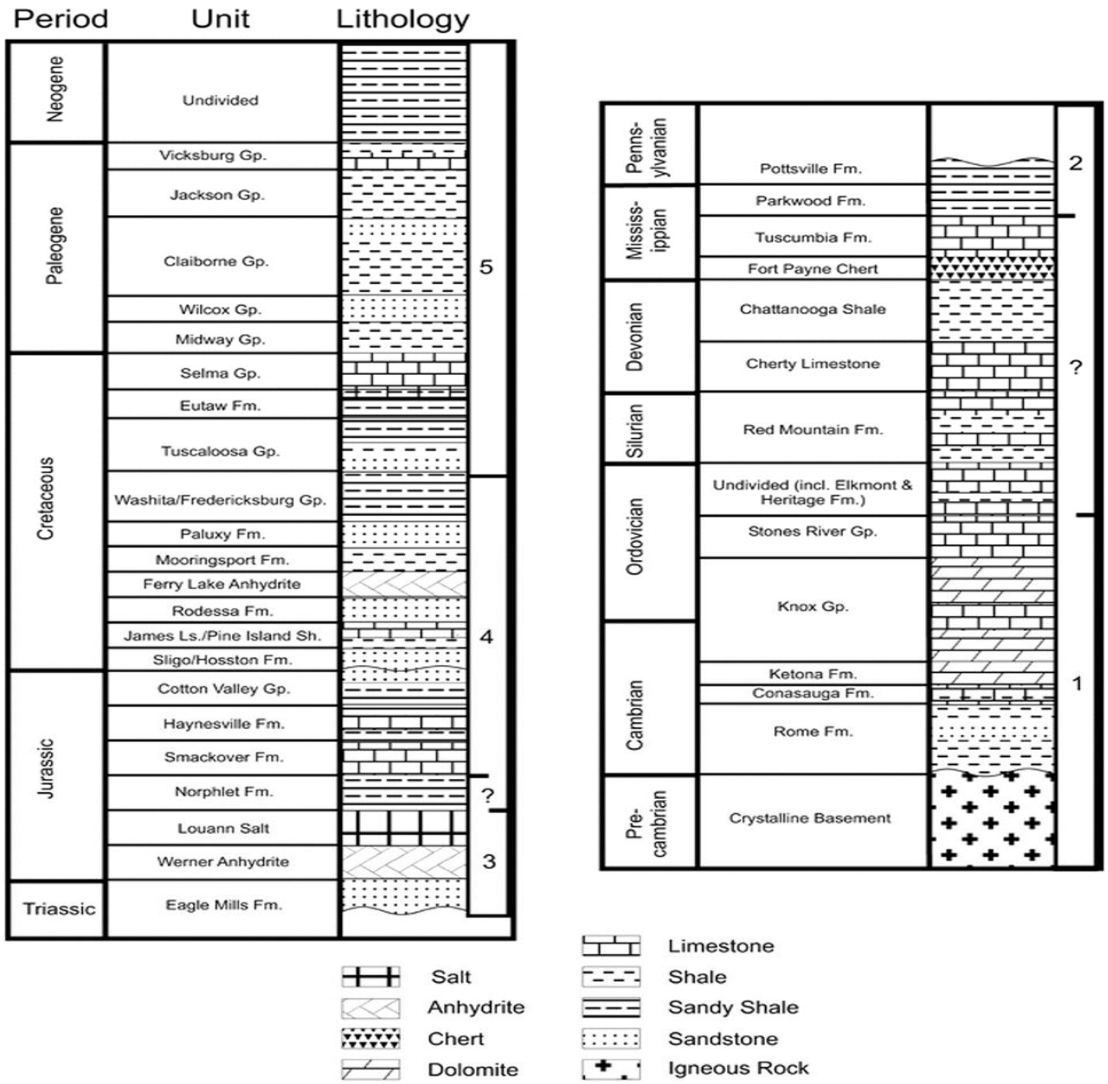


Figure 2: Composite Stratigraphic Column of Mississippi

Paleozoic strata are typically present in the southeastern North American platform and are mostly absent south of the Ouachita fold-and-thrust belt. Triassic through Paleogene strata are present in the Gulf Coast Basin and Mississippi Interior Salt Basin. Cretaceous through Paleogene strata progressively pinch out north of the Salt Basin. The Rome and Conasauga Formations are synrift deposits associated with rifting along the southern Laurentian margin. The Ketona through Tuscumbia Formations primarily record ensuing postrift passive-margin subsidence and carbonate-shelf buildup. The Parkwood and Pottsville Formations are synorogenic strata primarily deposited in the foreland of the Ouachita fold-and-thrust belt. The Eagle Mills Formation through Louann Salt are synrift strata deposited during opening of the Gulf of Mexico. Overlying strata record primarily passive-margin subsidence punctuated by eustatic sea-level changes. Triassic and younger stratigraphy based on Mancini et al. [1999]. Pre-Triassic stratigraphy adapted from Raymond and Copeland [1987].

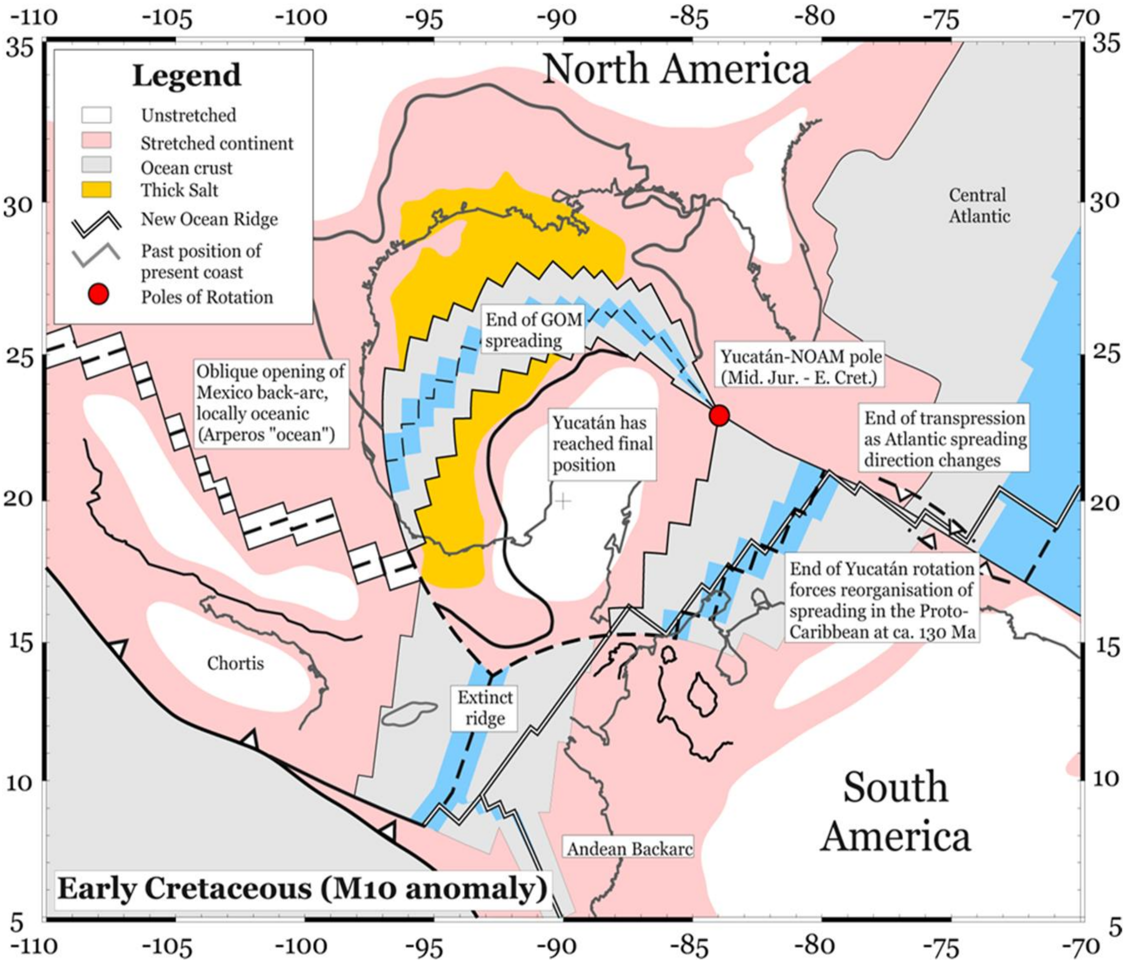


Figure 3: Tectonic Reconstruction of the Gulf of Mexico Basin during Final Seafloor Spreading Phase

[Pindell and Kennan, 2001].

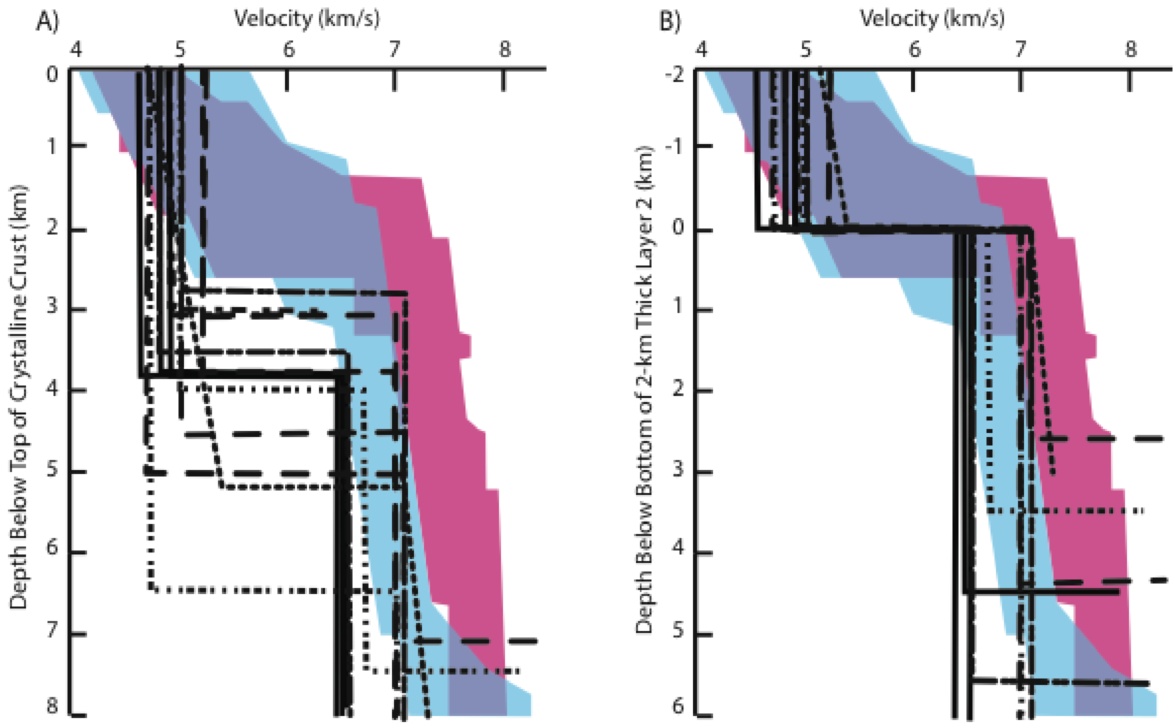


Figure 4: Seismic Velocity Profiles from Central and Eastern Gulf of Mexico

A) Dashed and dotted lines indicate profiles from the eastern Gulf of Mexico. Solid black lines indicate profiles from the central Gulf of Mexico. (sources: Ewing et al., 1960; Cram, 1961; Antoine and Ewing, 1963; Del Castillo, 1974; Ebeniro et al., 1986, 1988). Crust with oceanic Layer 2 velocities (4.6-5.1 km s-1) ranges from 2.8-5.1 km thick. Light blue: typical range of velocities for Jurassic Atlantic oceanic crust (White et al., 1992). Light red: range of velocities for Iberian and Newfoundland transitional crust thought to consist of exhumed mantle (as compiled by Srivastava et al., 2000). B) Gulf of Mexico profiles are shifted to align at the base of Layer 2. A 2 km-thick Layer 2 is included for comparison to typical oceanic crust. Velocities below Layer 2 indicate two groups of profiles. One group has velocities close to the slow limit of typical oceanic crust Layer 3. This group consists of profiles from the north-central and western Gulf. The other group has velocities that are near or above the high limit of typical Layer 3 velocities, and overlap Iberia/Newfoundland transitional crust velocities at depths above 2.5 km below Layer 2. This group consists of profiles from the south-central and eastern Gulf.

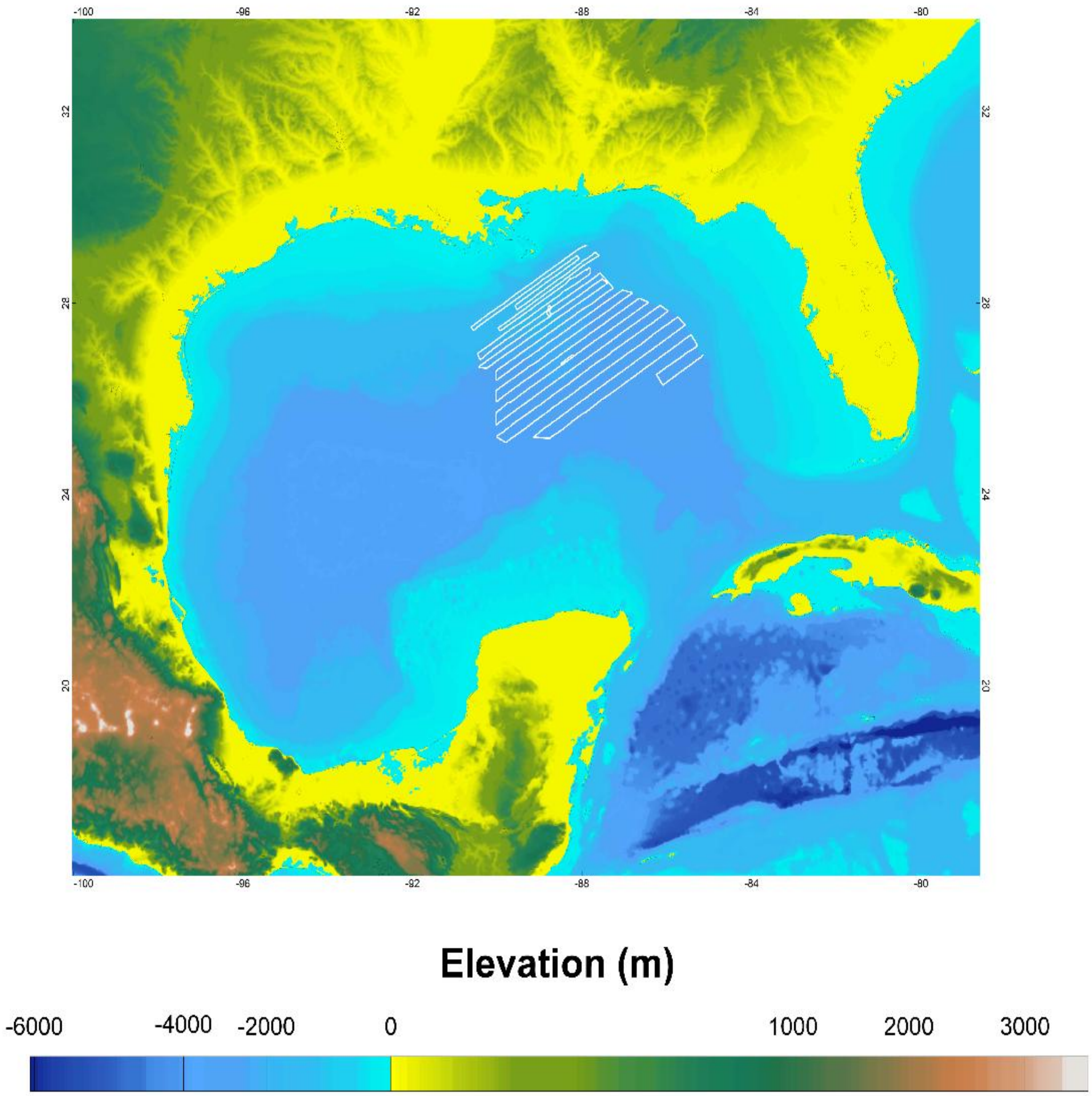


Figure 5: Woods Hole FRNL 1985 Geophysical Shiptrack Locations
[Lubinski and Twitchell, 1989].

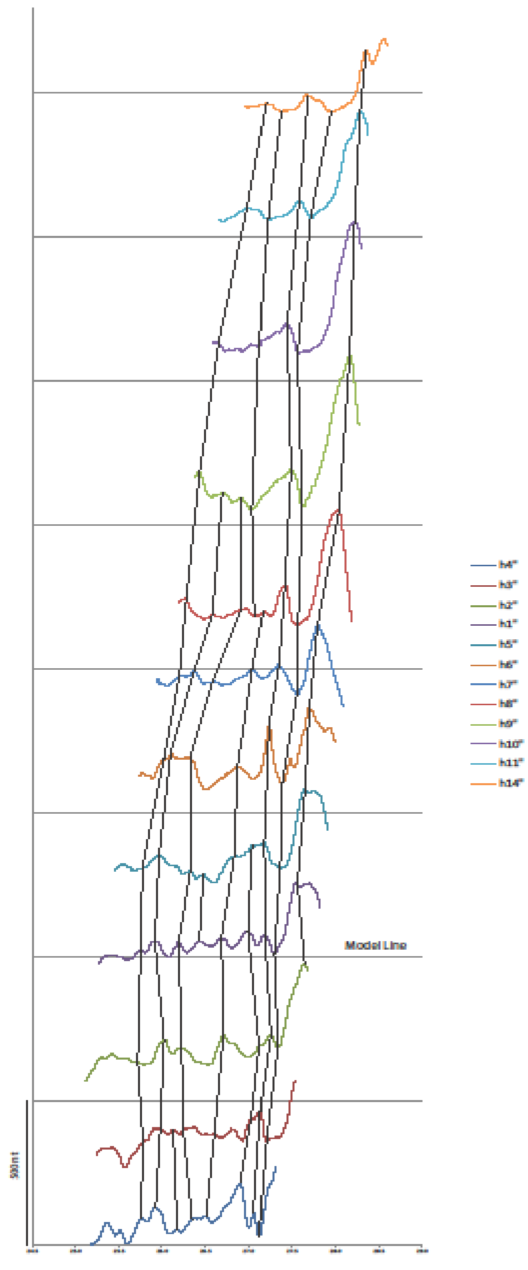


Figure 6: Correlations of Magnetic Anomolies Obtained via the Woods Hole FRNL 1985 Shiptrack

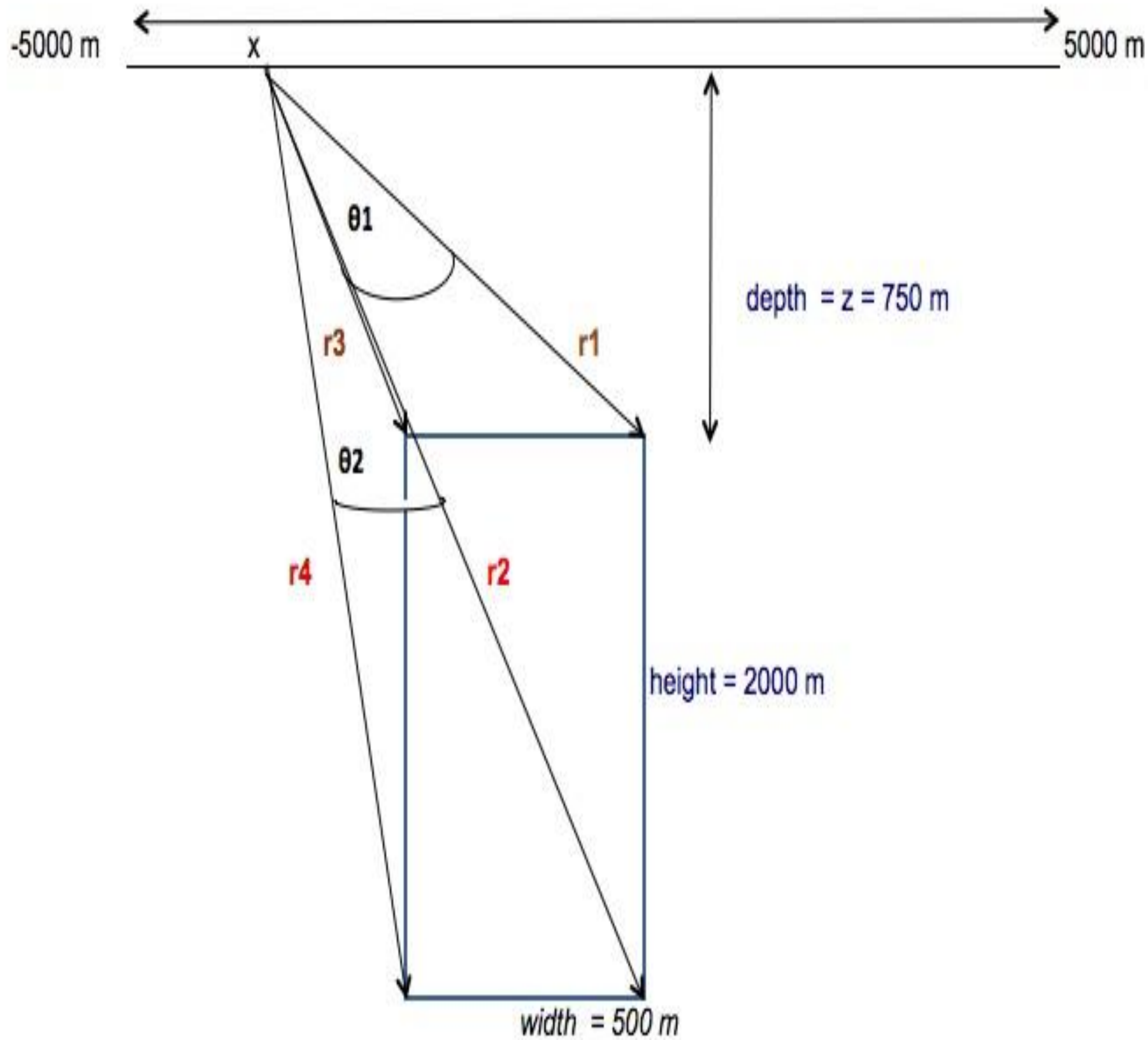


Figure 7: Diagram of a Single Magnetized Dike

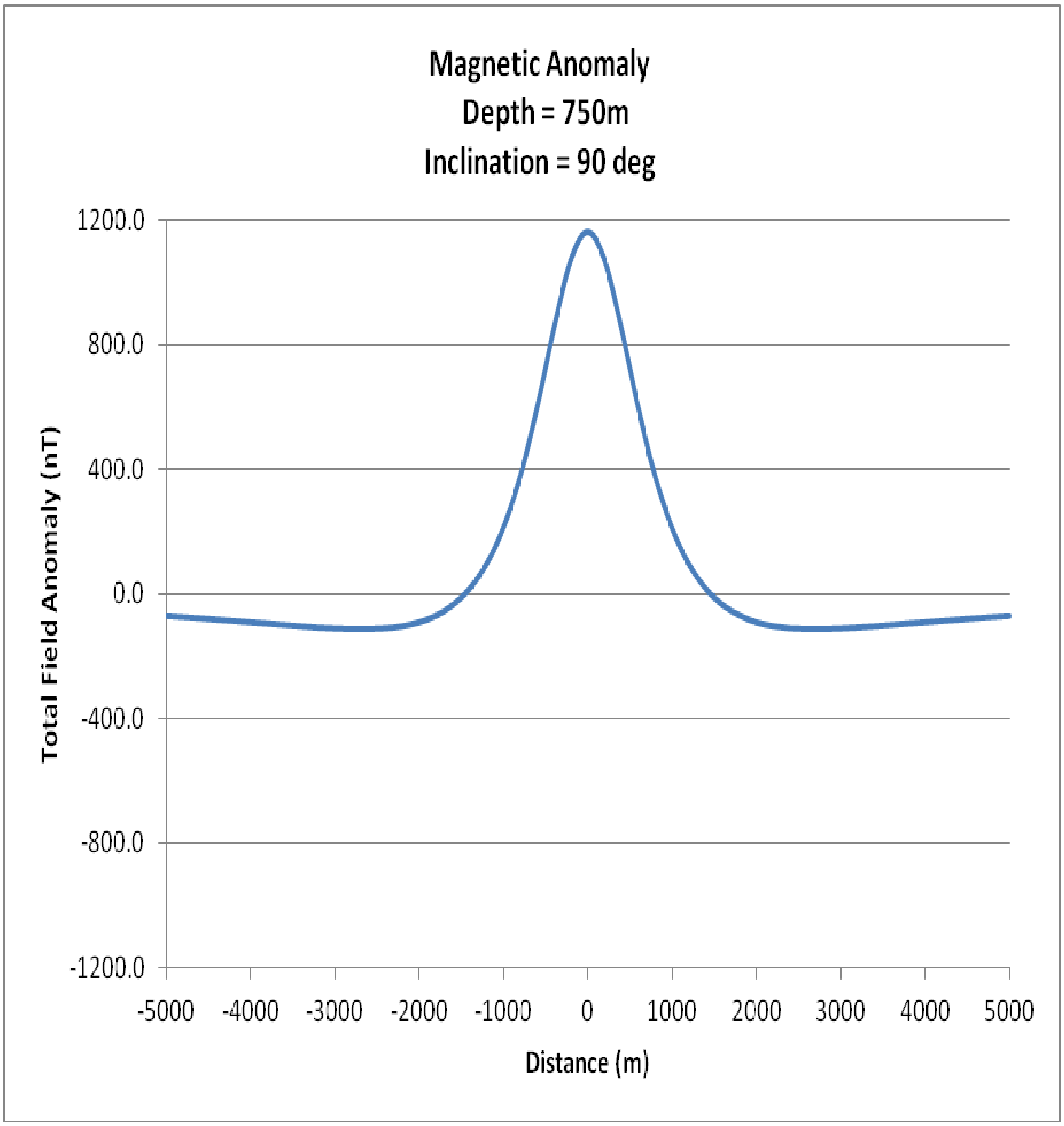


Figure 8a: Anomalous Field Strength at the North Pole

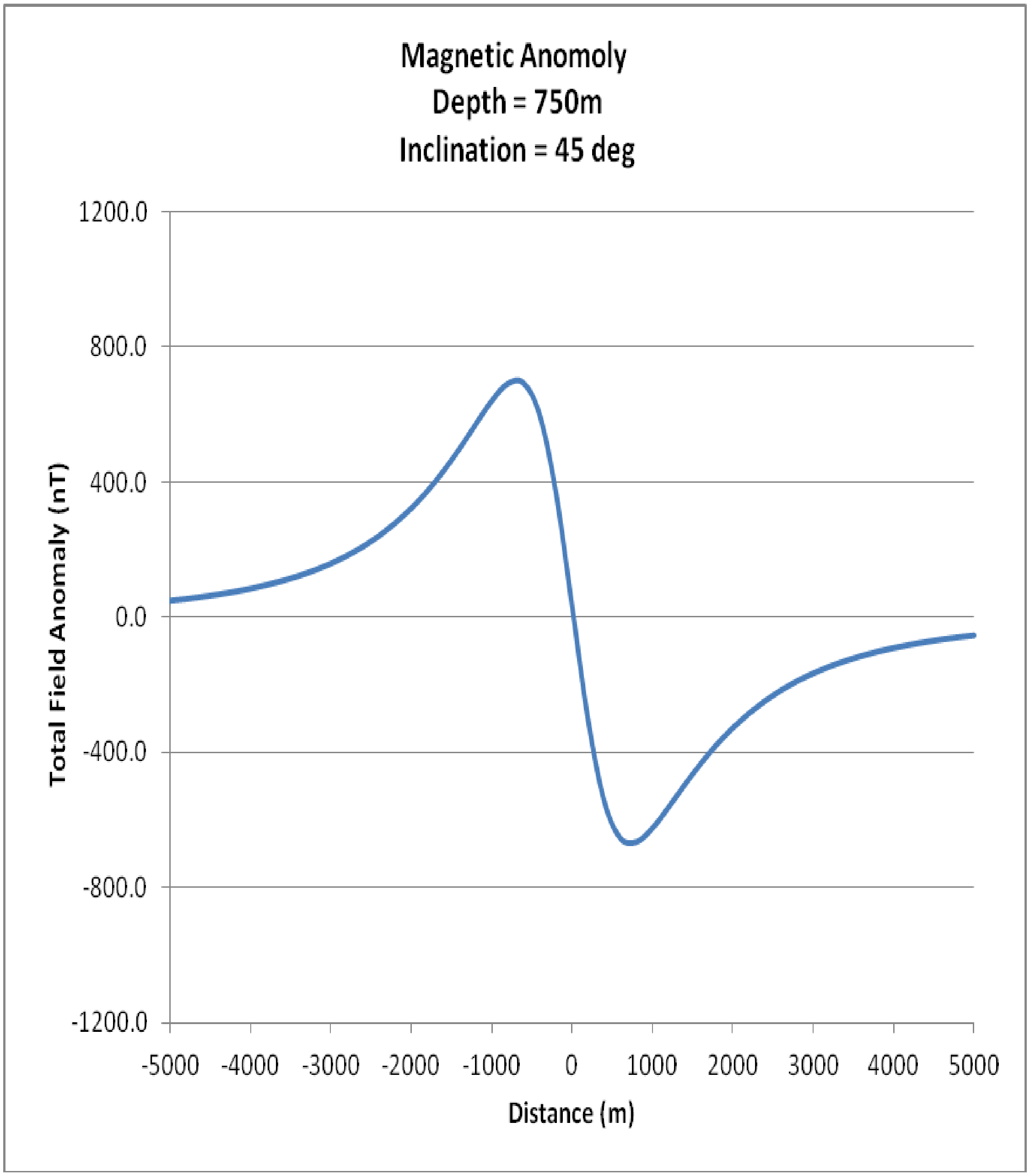


Figure 8b: Anomlous Field Strength at Mid-latitude

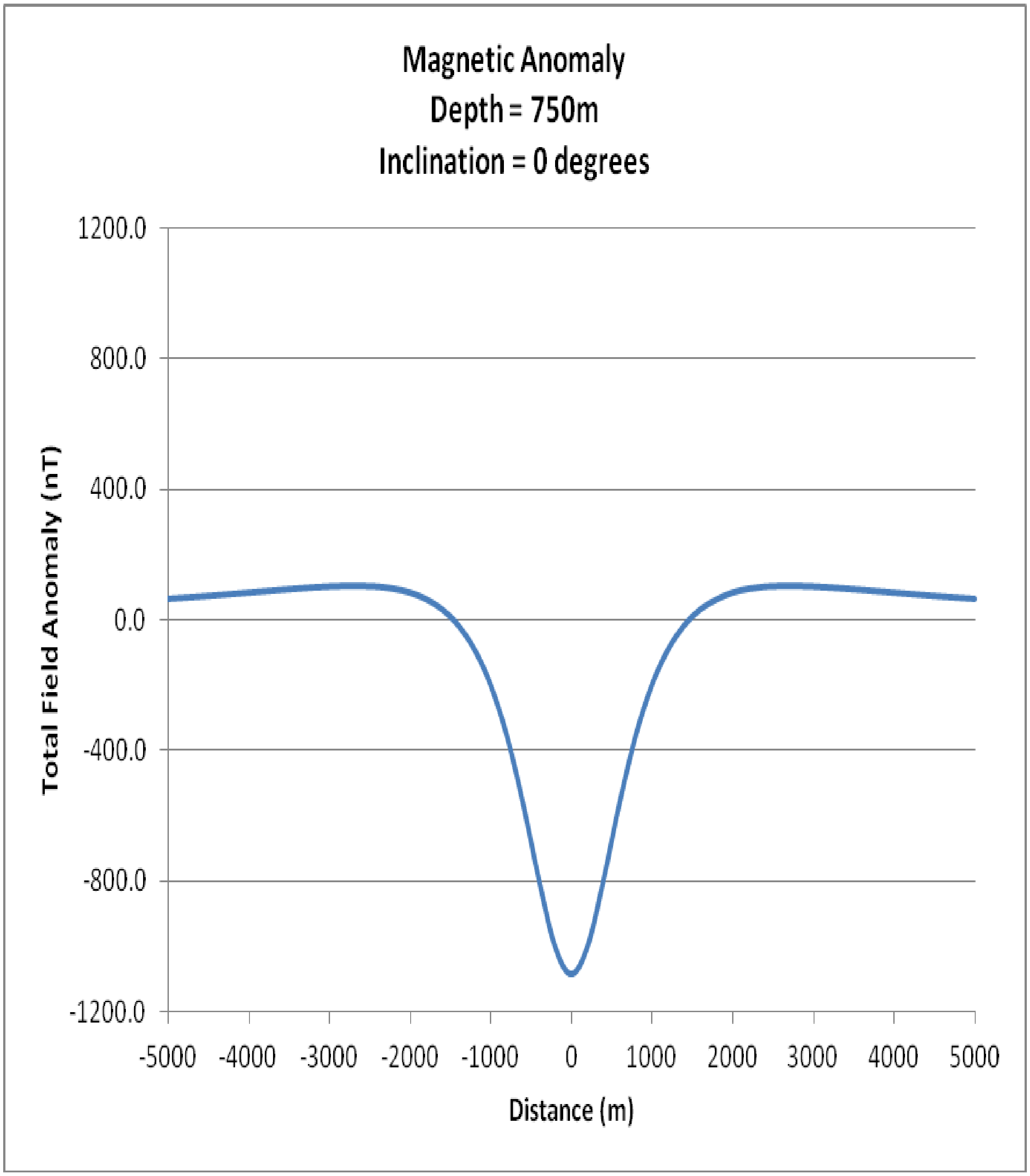


Figure 8c: Anomalous Field Strength at the Equator

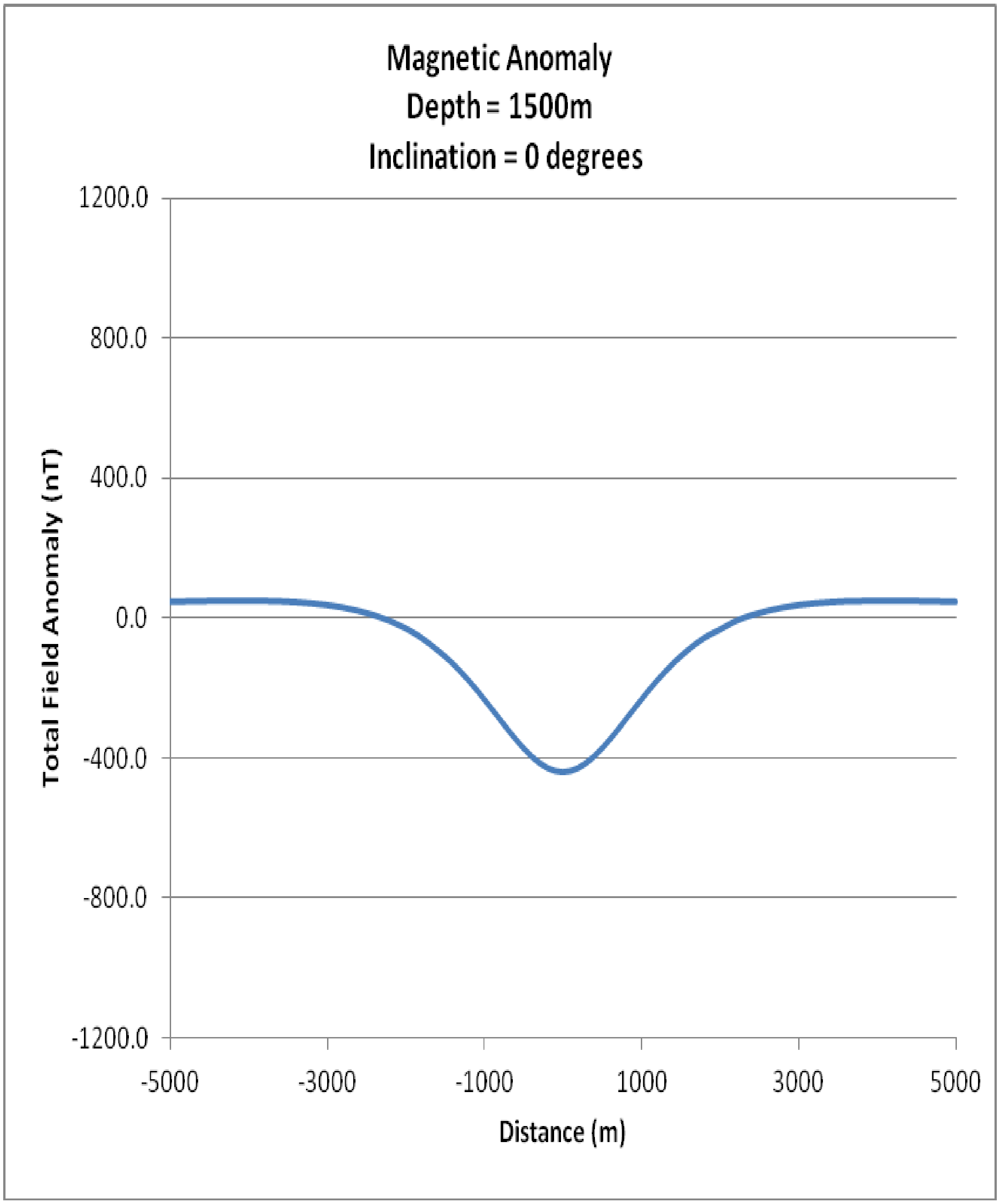


Figure 8d: Anomalous Field Strength at the Equator, Depth at 1500m

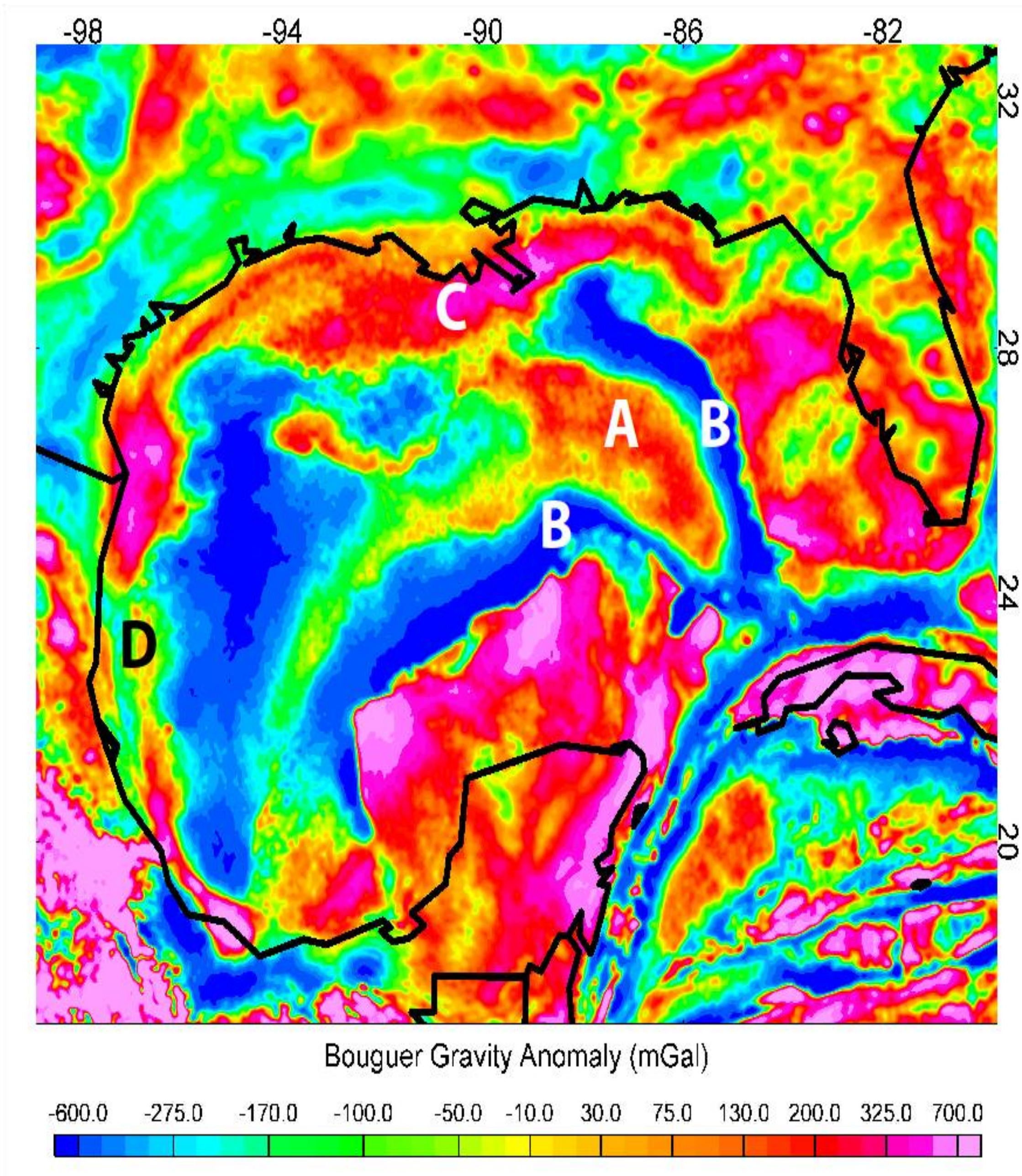


Figure 9: Bouguer Gravity Map of the Gulf of Mexico at 6km Resolution
Features A, B, and C are discussed in the text.

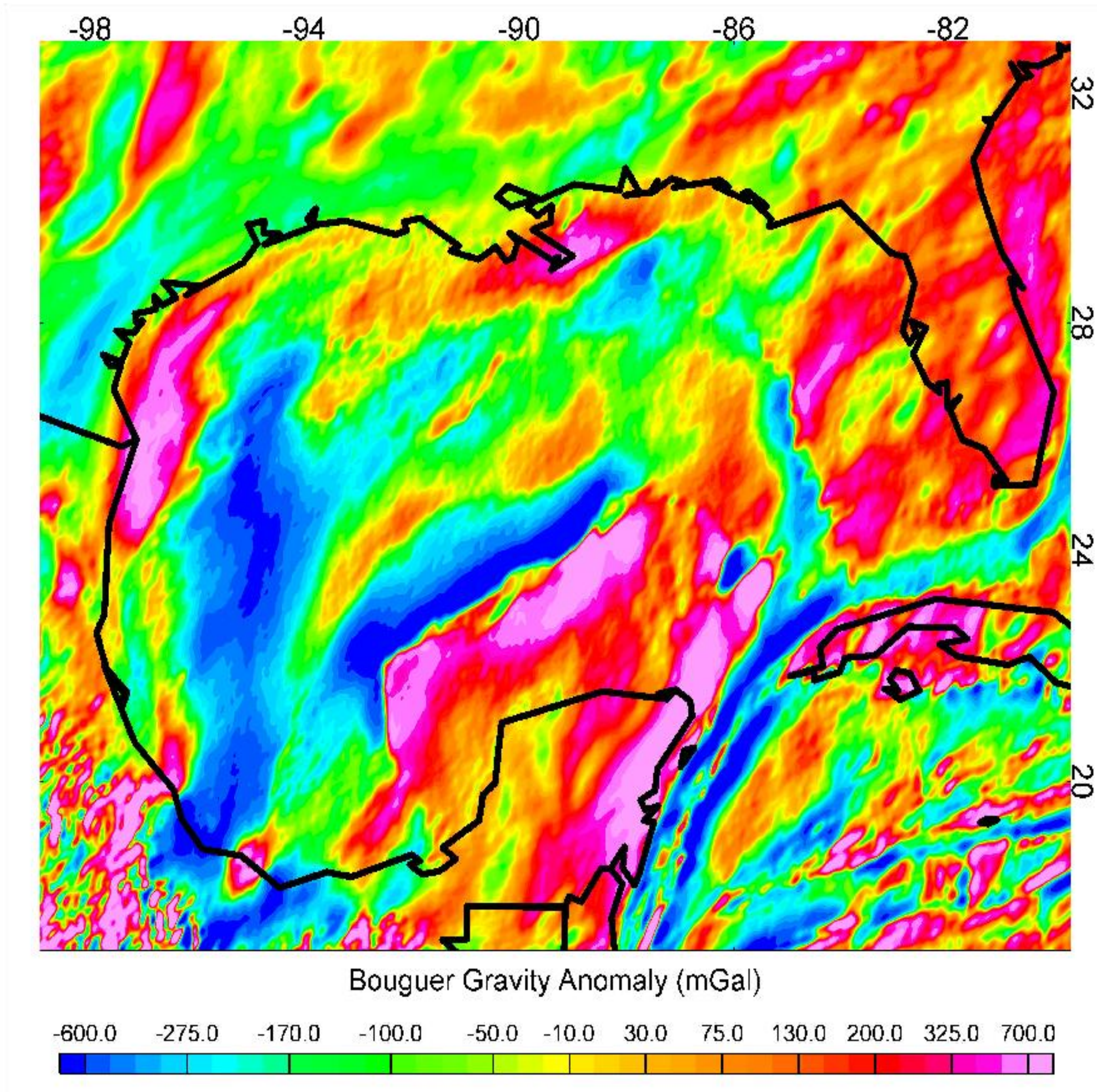
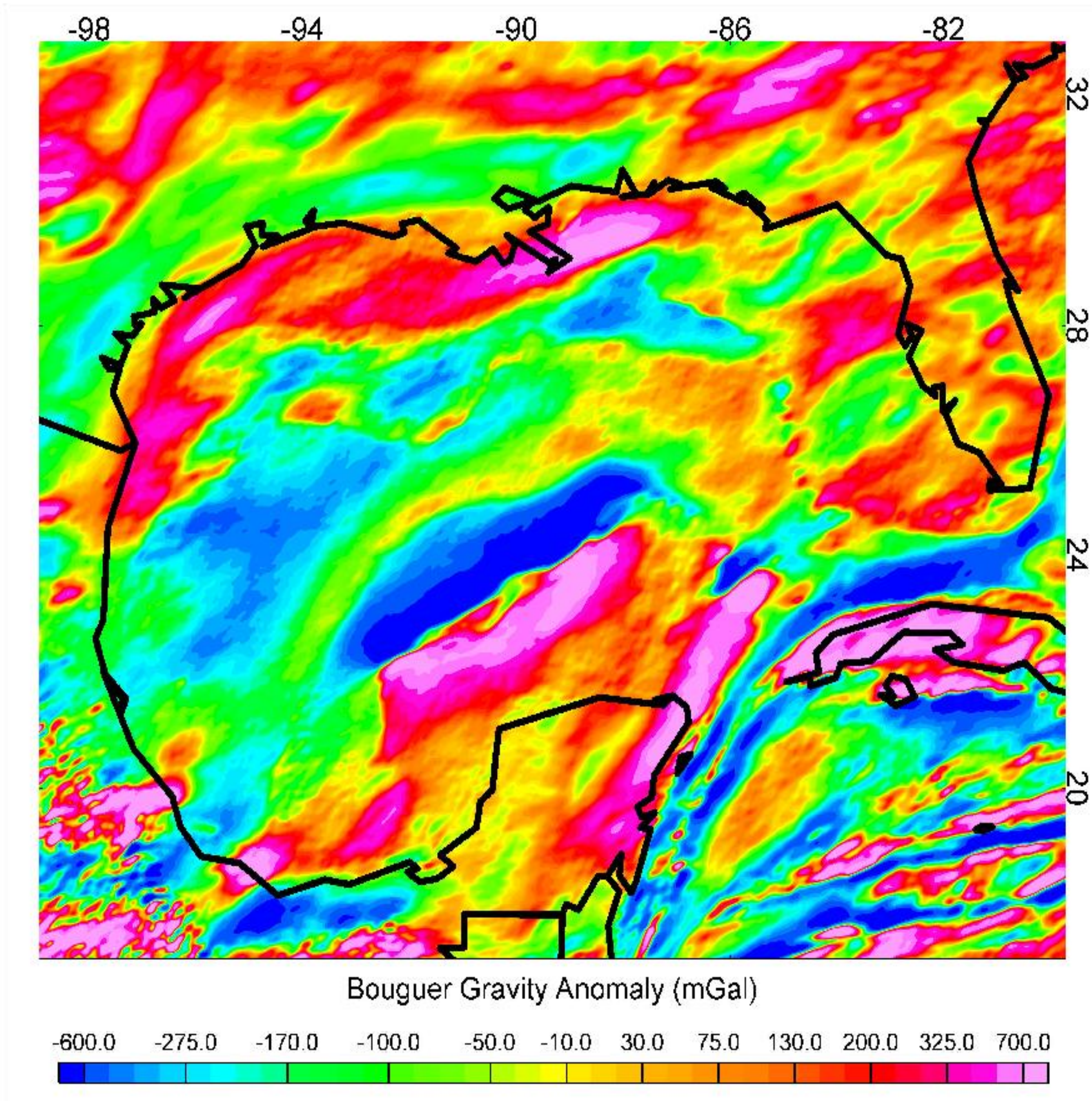


Figure 10a: Directional-Filtered Bouguer Gravity Anomaly Map: 30°



F

igure 10b: Directional-Filtered Bouguer Gravity Anomaly Map: 60^o

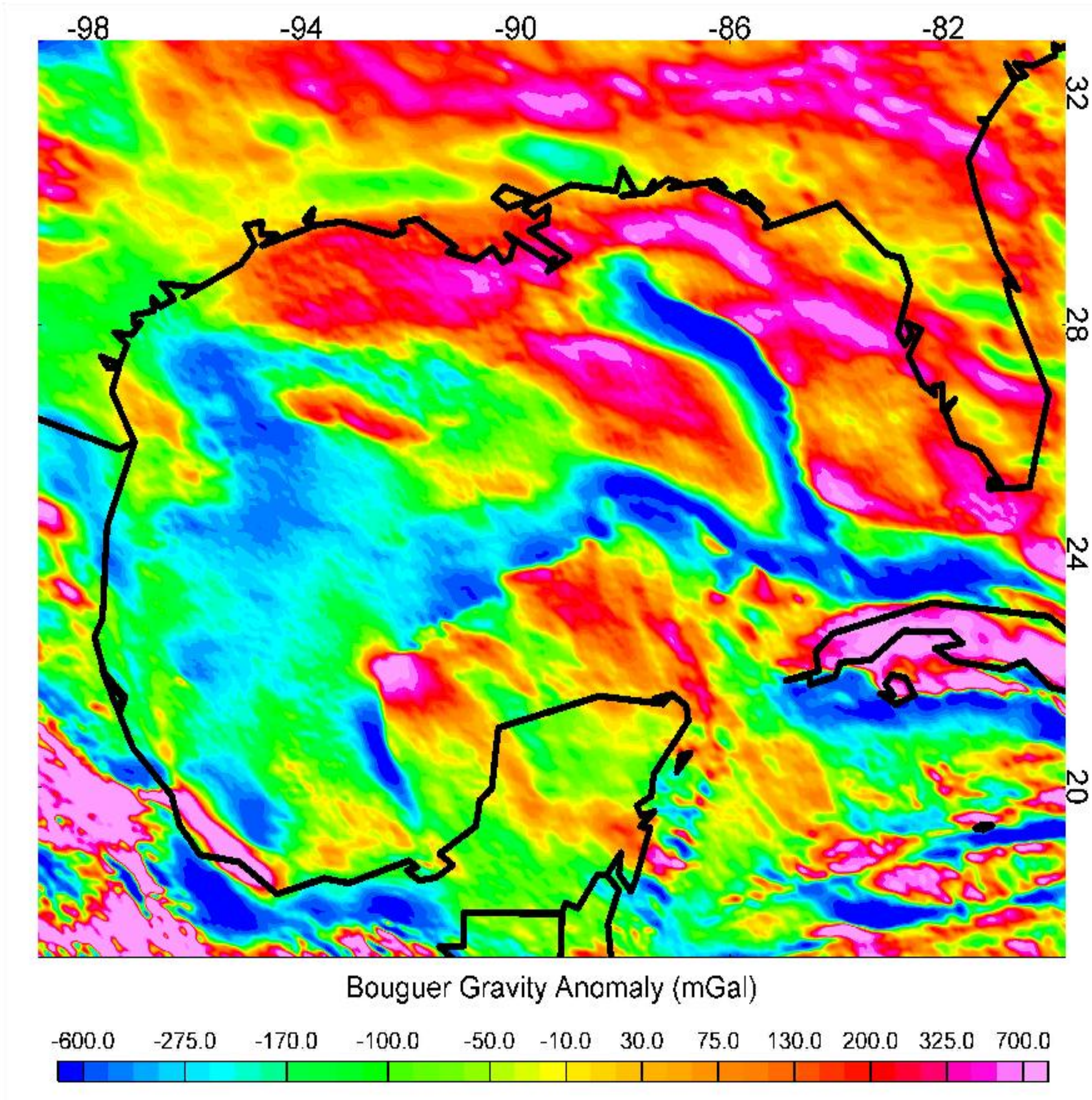


Figure 10c: Directional-Filtered Bouguer Gravity Anomaly Map: 120^{o}

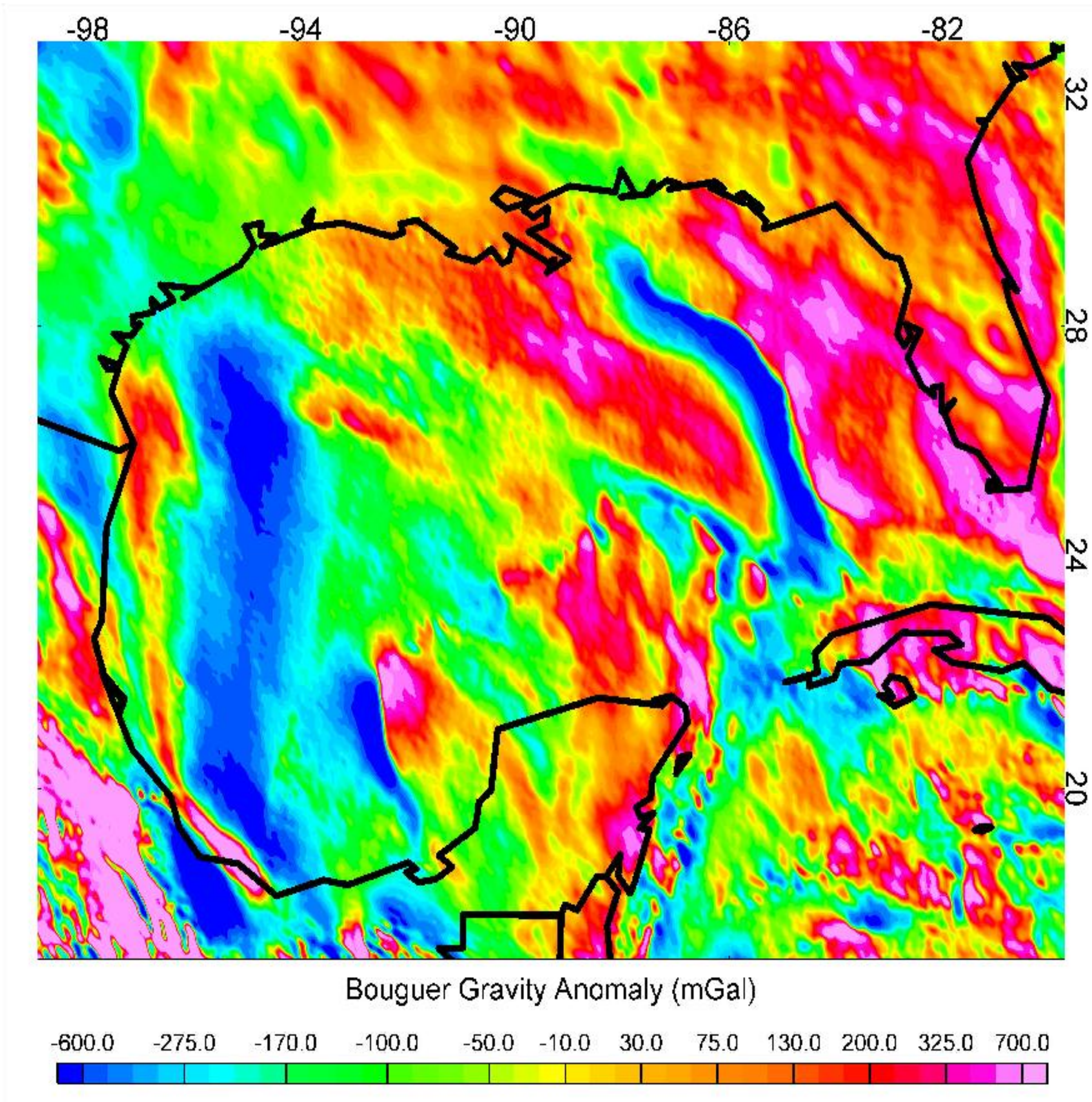


Figure 10d: Directional-Filtered Bouguer Gravity Anomaly Map: 150°

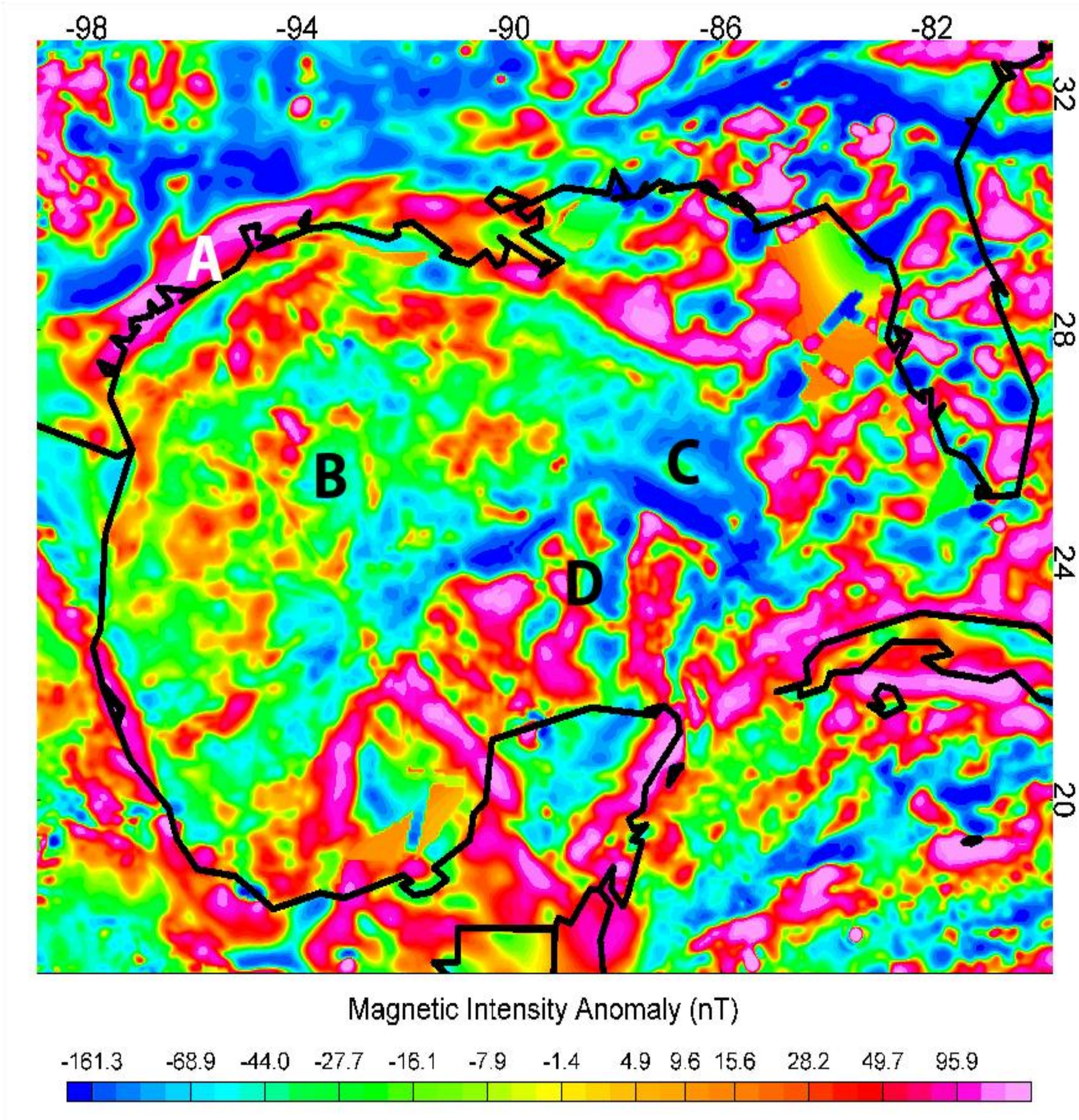


Figure 11: Reduced to Pole Magnetic Intensity Map of the Gulf of Mexico

RTP magnetic intensity anomaly is at an altitude of 5 km above average sea level at 3 arc min resolution. A, B, and C are explained in text.

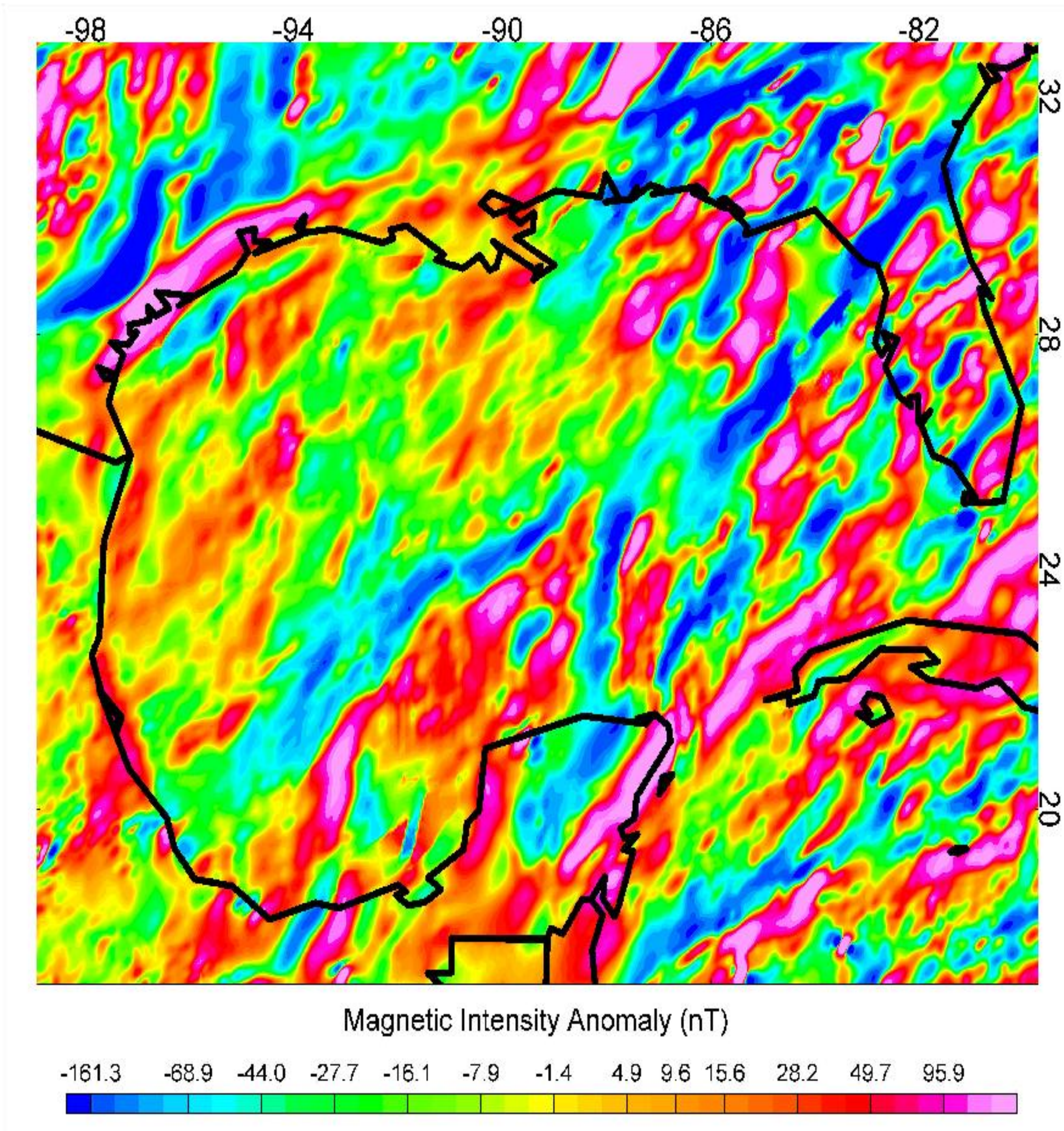


Figure 12a: Directional-Filtered Regional Magnetic Reduced to Pole Intensity Map: 30^o

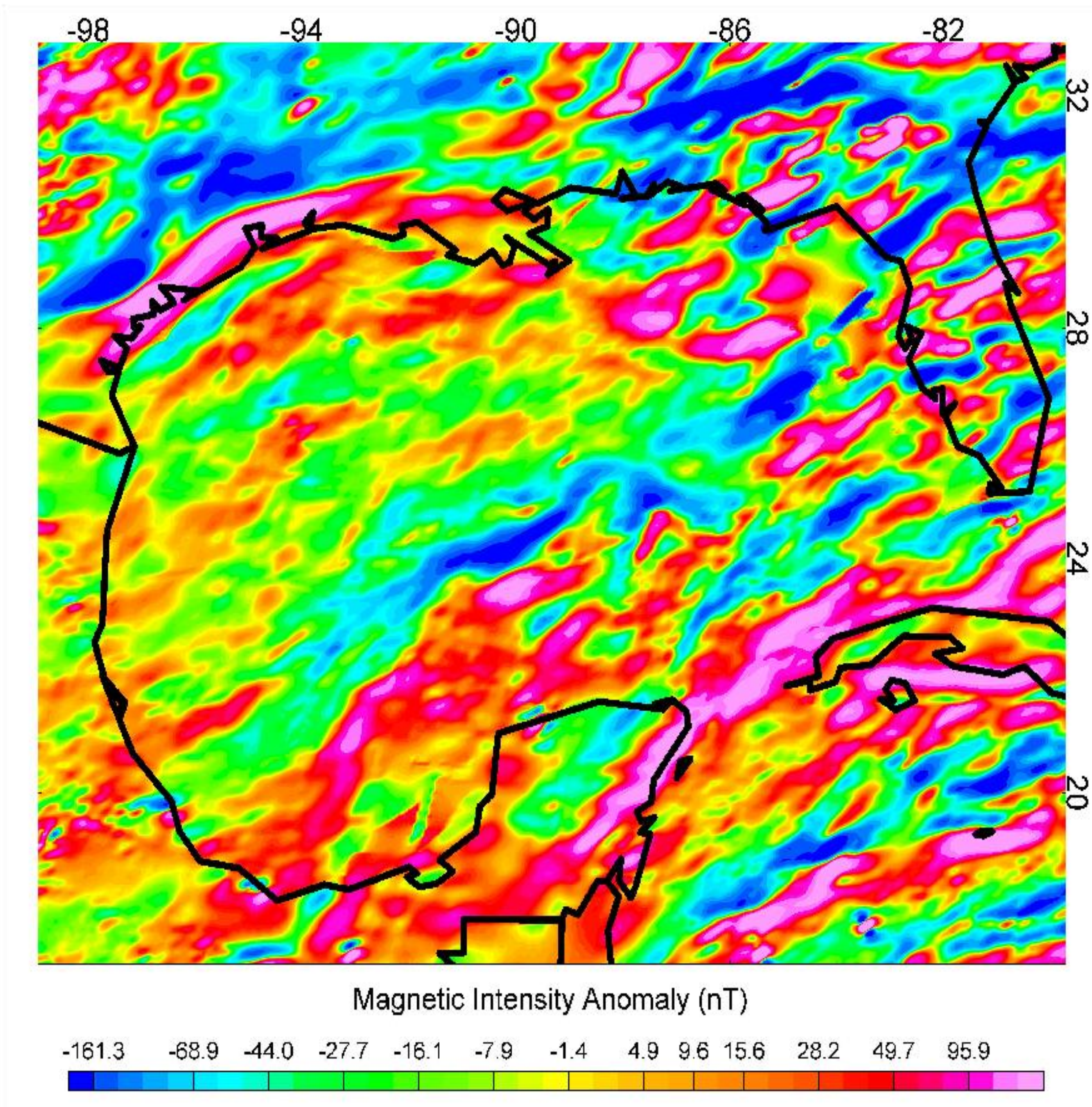


Figure 12b: Directional-Filtered Regional Magnetic Reduced to Pole Intensity Map: 60°

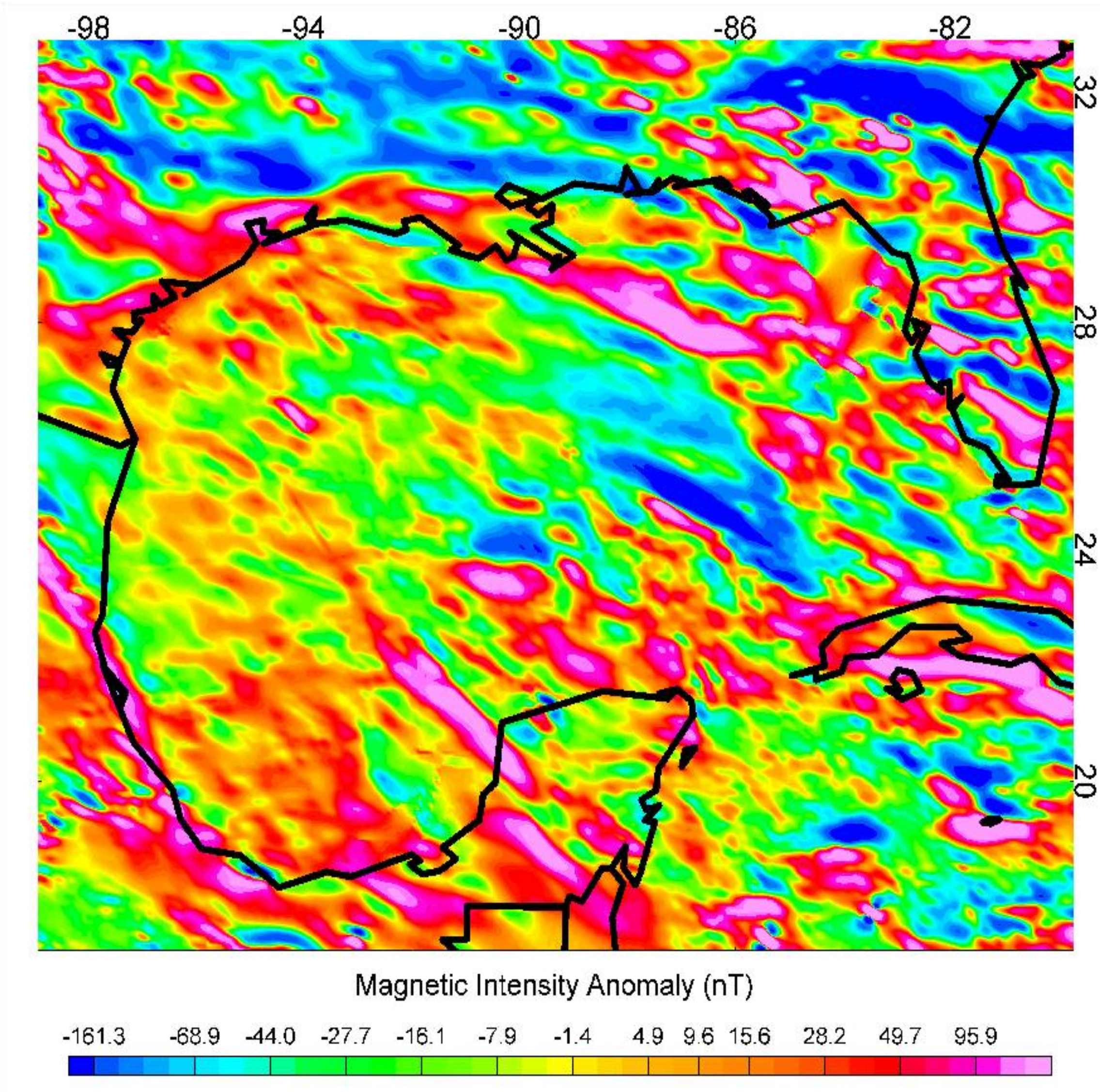


Figure 12c: Directional-Filtered Regional Magnetic Reduced to Pole Intensity Map: 120°

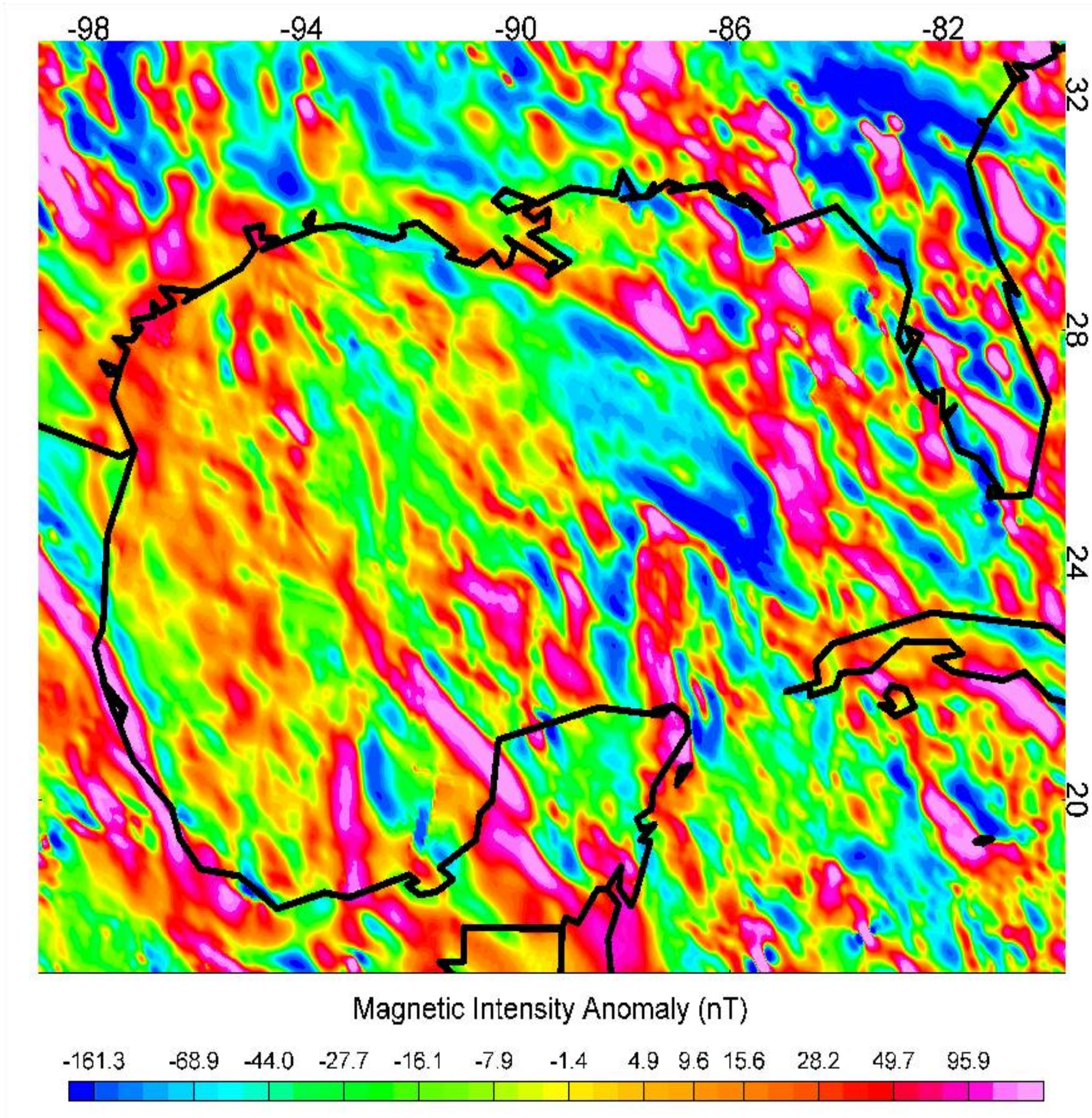


Figure 12d: Directional-Filtered Regional Magnetic Reduced to Pole Intensity Map: 150°

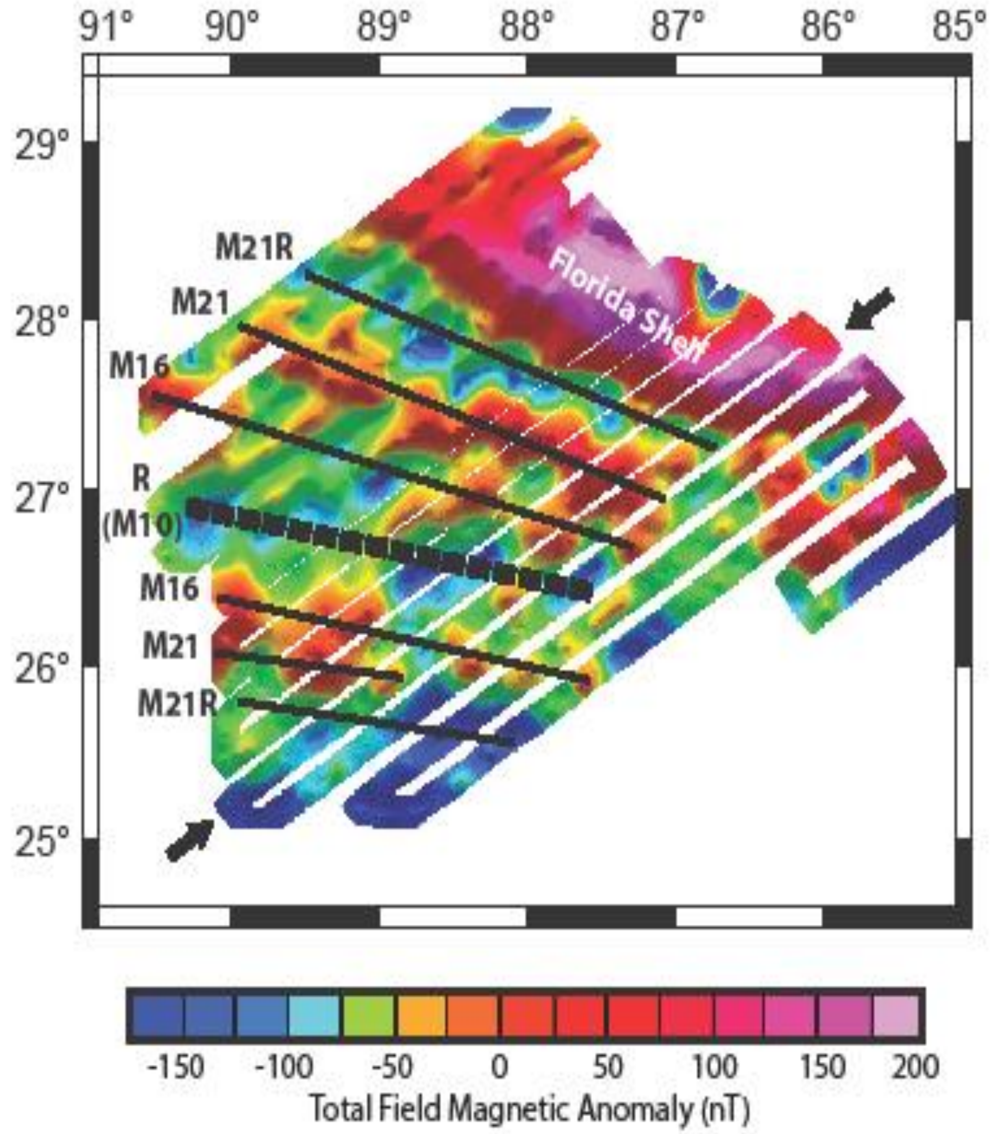


Figure 13: Magnetic Profiles from Woods Hole R/V Farnella FRNL-2 Survey [Lubinski and Twitchell, 1989]. Solid black lines and numbers indicate geochrons identified from forward modeling of profile marked by arrows, as shown in Figure 6. Thick dashed line (labeled R) indicates inferred extinct spreading axis.

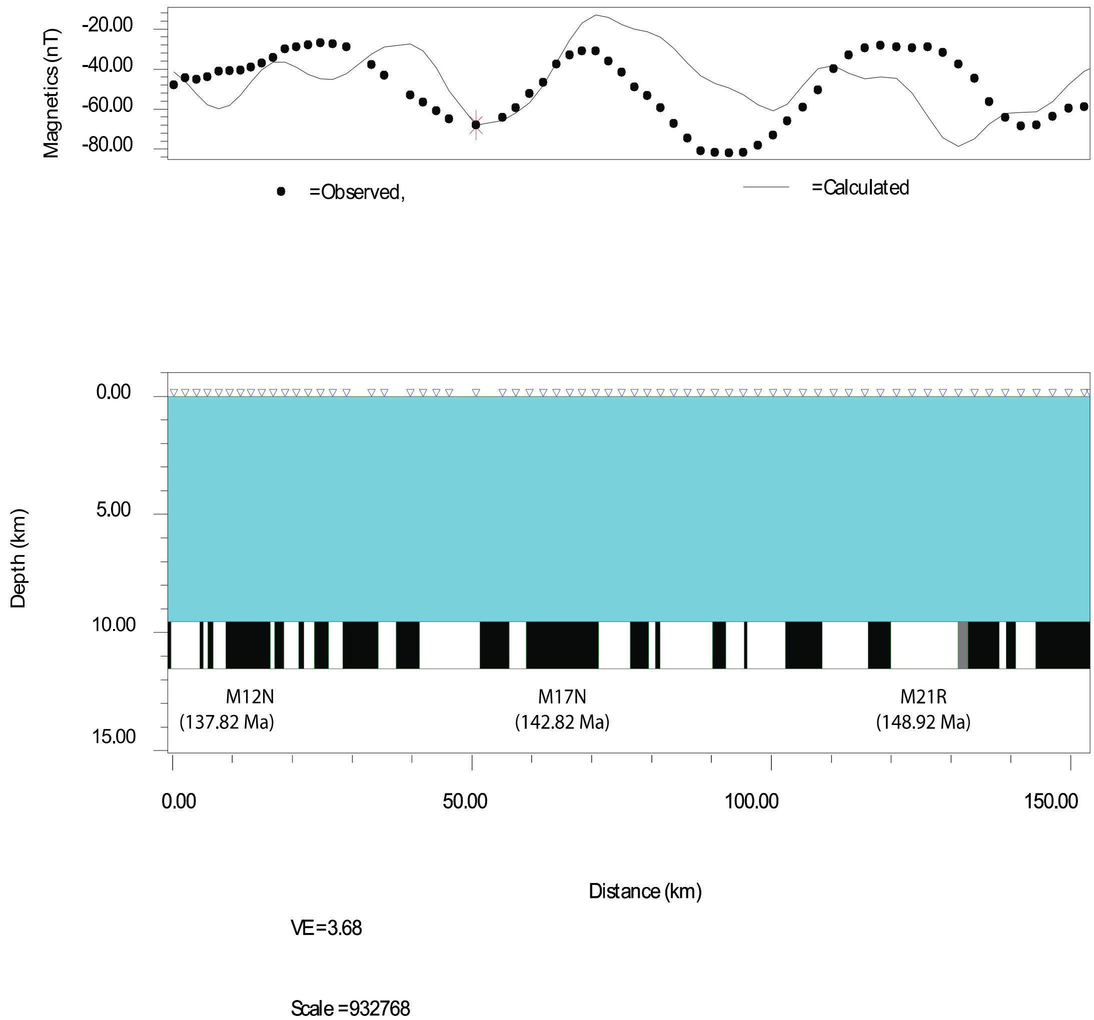


Figure 14: GM-SYS Model of Crust Profile West of the Inferred Spreading Ridge
Black blocks represent periods of normal magnetic polarity, while the white blocks represent periods of reversed magnetic polarity. The width of the blocks were determined by the uniform half spreading rate (8.5 mm/yr) and spreading duration (149 Ma through 134 Ma) which were proposed by Pindell and Kennan [2001], as well as the geomagnetic time scale of Gradstein et al. [2004]. The observed magnetic data collected in the marine survey is shown as a series of dots, while the models calculated data is shown as the thin solid line.

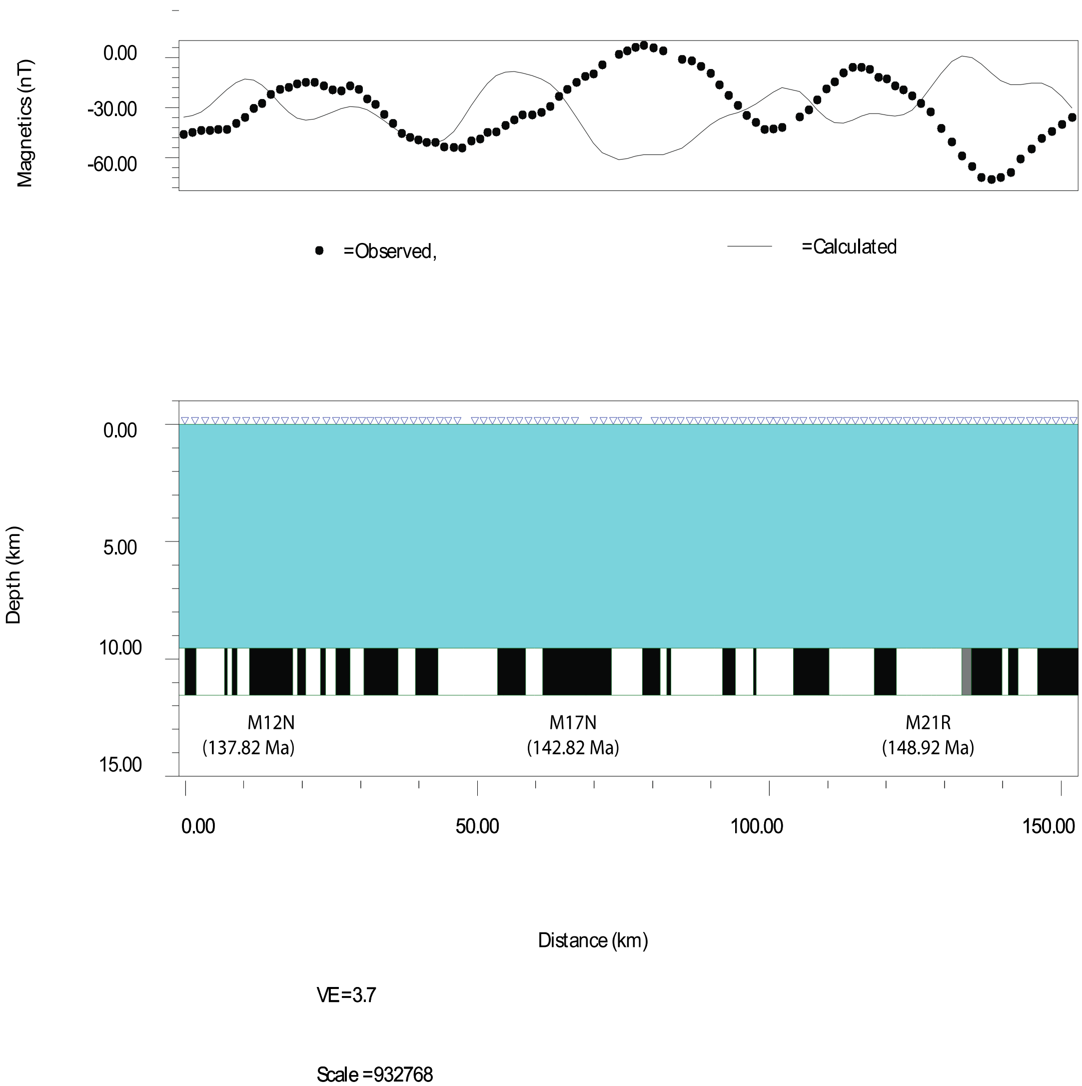


Figure 15: GM-SYS Model of Crust Profile East of the Inferred Spreading Ridge

Black blocks represent periods of normal magnetic polarity, while the white blocks represent periods of reversed magnetic polarity. The width of the blocks were determined by the uniform half spreading rate (8.5 mm/yr) and spreading duration (149 Ma through 134 Ma) which were proposed by Pindell and Kennan [2001], as well as the geomagnetic time scale of Gradstein, et al., [2004]. The observed magnetic data collected in the marine survey is shown as a series of dots, while the models calculated data is shown as the thin solid line.

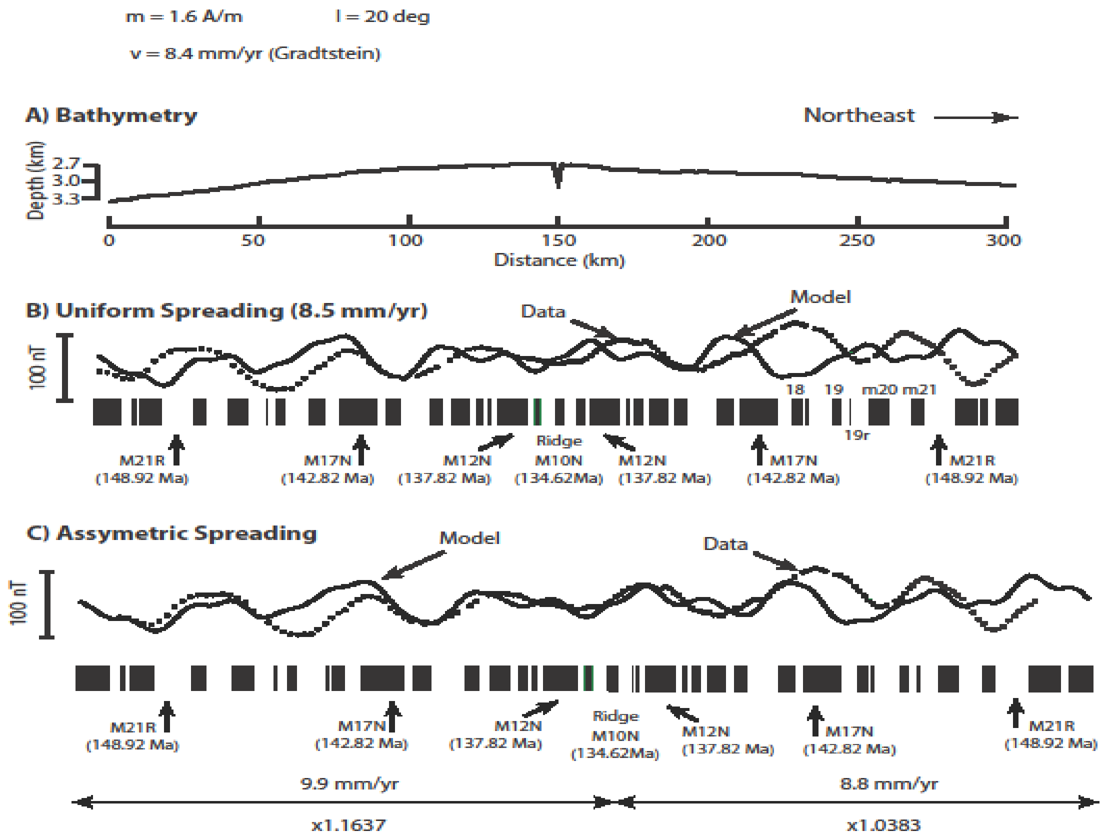


Figure 16: Synthetic Magnetic Anomaly Profiles along FRNL85-2 Line

Shown in Figure 6. A) Bathymetry. B) Model with uniform spreading half-rate of 8.5 mm/yr showing approximate fit to observed anomaly pattern with extinct ridge coinciding with chron M10r. Note anomaly M17 is present on the west side of the profile, but is apparently missing on the east side. C) Asymmetric spreading model, with spreading half-rate of 8.8mm/yr in eastern part of profile and 9.9 mm/yr on the western profile. Remnant magnetization intensity and inclination are 2 A m^{-1} and 0.2° respectively, chosen to best fit the magnetic observed amplitudes and, for inclination, in accord with the nearly equatorial position of the Gulf of Mexico during Jurassic seafloor spreading. The current magnetic field is modeled with declination and inclination of and 0.65° and 20° respectively, coinciding with the magnetic field parameters in the eastern Gulf in 1985 when the survey was conducted.

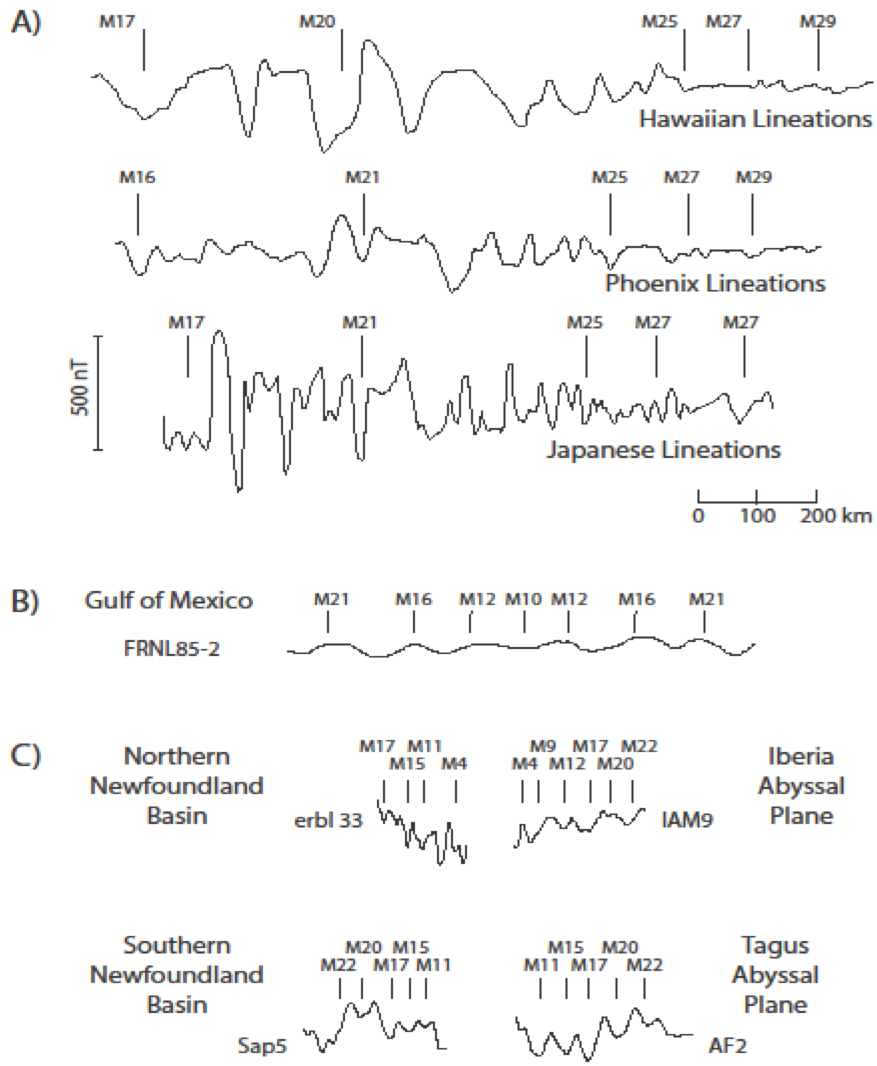


Figure 17: Comparison of Jurassic Marine Magnetic Anomalies from Eastern Gulf of Mexico and other Ocean Basins

A) Oceanic crust in the western Pacific [Cande et al., 1978]. B) Gulf of Mexico (profile shown in Figure 4). C) Iberia-Newfoundland transitional crust [Srivastava et al., 2000].

REFERENCES

Antoine, J., and Ewing, J. (1963). Seismic refraction measurements on the margins of the Gulf of Mexico. *Journal of Geophysical Research*, *68*(7), 1975-1996.

Antoine, J. W., and Harding, J. L. (1965). Structure beneath continental shelf, northeastern Gulf of Mexico. *AAPG Bulletin*, *49*(2), 157-171.

Applegate, A. V., Winston, G. O., and Palacas, J. G. (1982). Subdivision, stratigraphy of pre-Punta Gorda Florida rocks (lowermost Cretaceous-Jurassic?). *Oil Gas J*, *80*(17), 207-216.

Barnet, R.S., (1975), Basement structure of Florida and its tectonic implications, *Trans. Gulf Coast Assoc. Geol. Soc., 25*, 122-142.

Bird, D. E., Burke, K., Hall, S. A., and Casey, J. F. (2005). Gulf of Mexico tectonic history: Hotspot tracks, crustal boundaries, and early salt distribution. *AAPG bulletin*, *89*(3), 311-328.

Bishop, W. F. (1980). Petroleum geology of northern Central America. *Journal of petroleum Geology*, *3*(1), 3-59.

Buffler, R. T., and Sawyer, D. S. (1985). Distribution of crust and early history, Gulf of Mexico Basin, *Gulf Coast Association of Geological Societies Transactions, 35,* 333-334.

Buffler, R. T., and Thomas, W. A. (1994). Crustal structure and evolution of the southeastern margin of North America and the Gulf of Mexico basin. *Phanerozoic evolution of North American continent-ocean transitions: Boulder, Colorado, Geological Society of America, Decade of North American Geology, Continent-Ocean Transect Volume*, 219-264.

Burke, K. (1988). Tectonic evolution of the Caribbean. *Annual Review of Earth and Planetary Sciences*, *16*, 201-230.

Cande, S. C., Larson, R. L., and LaBrecque, J. L. (1978). Magnetic lineations in the Pacific Jurassic quiet zone. *Earth and Planetary Science Letters*, *41*(4), 434-440.

Chian, D., Keen, C., Reid, I., and Louden, K. E. (1995). Evolution of nonvolcanic rifted margins: New results from the conjugate margins of the Labrador Sea. *Geology*, *23*(7), 589-592.

Chowns, T. M., and Williams, C. T. (1983). *Pre-Cretaceous rocks beneath the Georgia Coastal Plain: regional implications*. US Department of the Interior, Geological Survey.

Christenson, G. (1990). The Florida lineament. *Gulf Coast Associaton of Geol societies Transactions, 40,* 99-115.

Cram, I., Jr. (1961). A crustal structure refraction survey in south Texas, *Geophysics, 26*(5), 560–573.

Daniels, D. L., Zietz, I., and Popenoe, P. (1983). *Distribution of subsurface lower Mesozoic rocks in the southeastern United States, as interpreted from regional aeromagnetic and gravity maps*. US Department of the Interior, Geological Survey.

Dater, D., D. Metzger, and A. Hittleman (1999), Land and Marine Gravity Data on CD-ROM: 1999 Edition, Natl. Geophys. Data Cent., Boulder, Colo.

Del Castillo, L. G. (1974). Marine geophysics along the Gulf of Mexico and the Yucatan peninsula coastal area in Mexico. *Physics of the Earth and Planetary Interiors*, *9*(3), 227-248.

Dickinson, W. R., and Lawton, T. F. (2001). Carboniferous to Cretaceous assembly and fragmentation of Mexico. *Geological Society of America Bulletin*, *113*(9), 1142-1160.

Dietz, R. S., Holden, J. C., and Sproll, W. P. (1970). Geotectonic evolution and subsidence of Bahama platform. *Geological Society of America Bulletin*, *81*(7), 1915-1928.

Dobson, L. M., and Buffler, R. T. (1991). Basement rocks and structure, northeast Gulf of Mexico, Transactions *of the Gulf Coast Association of Geological Societies, 41*, 191-204.

Donnelly, T. W. (1989). Geologic history of the Caribbean and Central America. *The Geology of North America, Vol. A, An Overview*, 299-321.

Donnelly, T. W., Horne, G. S., Finch, R. C., and López-Ramos, E. (1990). Northern Central America; the Maya and Chortis blocks. *The Caribbean region: Boulder, CO, Geological Society of America, The Geology of North America, v. H*, 37-76.

Dunbar, J. A., and Sawyer, D. S. (1987). Implications of continental crust extension for plate reconstruction: An example from the Gulf of Mexico. *Tectonics*, *6*(6), 739-755.

Ebeniro, J. O., O'Brien Jr, W. P., and Shaub, F. J. (1986). Crustal structure of the South Florida Platform, eastern Gulf of Mexico: An ocean-bottom seismograph refraction study. *Marine geophysical researches*, *8*(4), 363-382.

Ebeniro, J. O., Nakamura, Y., Sawyer, D. S., and O'Brien, W. P. (1988). Sedimentary and crustal structure of the northwestern Gulf of Mexico. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *93*(B8), 9075-9092.

Ewing, T. E. (1991). Structural framework. *The Gulf of Mexico Basin: Geological Society of America, The Geology of North America, v. J*, 31-52.

Ewing, J., J. Antoine, and M. Ewing (1960), Geophysical measurements in the western Caribbean Sea and in the Gulf of Mexico, *J. Geophys. Res.*, *65*(12), 4087–4126.

Ewing, J. I., J. L. Worzel, and M. Ewing (1962), Sediments and oceanic structural history of the Gulf of Mexico, *J. Geophys. Res.*, *67(*6), 2509–2527.

Folger, D. W., Dillon, W. P., Grow, J. A., Klitgord, K. D., and Schlee, J. S. (1979). Evolution of the Atlantic continental margin of the United States. *Maurice Ewing Series*, *3*, 87-108.

Gose, W. A., Belcher, R. C., and Scott, G. R. (1982). Paleomagnetic results from northeastern Mexico: Evidence for large Mesozoic rotations. *Geology*, *10*(1), 50-54.

Gradstein, F. M., Ogg, J. G., and Smith, A. G. (Eds.). (2004). *A geologic time scale 2004* (Vol. 86). Cambridge University Press.

Grow, J. A., and Sheridan, R. E. (1981). Deep structure and evolution of the continental margin off the eastern United States. *Oceanol. Acta C*, *3*, 11-19.

Hall, S. A., and Najmuddin, I. J. (1994). Constraints on the tectonic development of the eastern Gulf of Mexico provided by magnetic anomaly data. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *99*(B4), 7161-7175.

Harry, D. L. (1983). Inversion of Marine Magnetic Anomalies. Master's Thesis, Texas A&M University.

Harry, D. L., and Londono, J. (2004). Structure and evolution of the central Gulf of Mexico continental margin and coastal plain, southeast United States. *Geological Society of America Bulletin*, *116*(1-2), 188-199.

Humphris, C. C. (1979). Salt movement on continental slope, northern Gulf of Mexico. *AAPG Bulletin*, *63*(5), 782-798.

Klitgord, K. D., Dillon, W. P., and Popenoe, P. (1983). *Mesozoic tectonics of the southeastern United States Coastal Plain and continental margin*. US Department of the Interior, Geological Survey.

Klitgord, K. D., Popenoe, P., and Schouten, H. (1984). Florida: A Jurassic transform plate boundary. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *89*(B9), 7753-7772.

Lizarralde, D., Axen, G. J., Brown, H. E., Fletcher, J. M., González-Fernández, A., Harding, A. J., and Umhoefer, P. J. (2007). Variation in styles of rifting in the Gulf of California. *Nature*, *448*(7152), 466-469.

Louden, K. E., and Chian, D. (1999). The deep structure of non–volcanic rifted continental margins. *Philosophical Transactions A*, *357*(1753), 767.

Lubinski, D.J., and Twitchell, D.C. (1989). Magnetic and bathymetric data from R/V FARNELLA cruises FRNL85-1, 85-2, and 85-3 in the *U.S. Gulf of Mexico EEZ, USGS Open File Report*, 89-156.

Manatschal, G., and Bernoulli, D. (1999). Architecture and tectonic evolution of nonvolcanic margins: Present-day Galicia and ancient Adria. *Tectonics*, *18*(6), 1099-1119.

Mancini, E. A., Puckett, T. M., Parcell, W. C., and Panetta, B. J. (1999). Topical reports 1 and 2, basin analysis of the Mississippi Interior salt basin and petroleum system modeling of the Jurassic Smackover Formation, eastern Gulf coastal plain: US Department of Energy Technical Report. *Project Number DE-FG22-96BC14946*.

Marton, G., and R.T. Buffler, (1994), Jurassic reconstruction of the Gulf of Mexico Basin, International Geology Review, 36(6), 545–586.

Maus, S., Sazonova, T., Hemant, K., Fairhead, J. D., and Ravat, D. (2007). National geophysical data center candidate for the world digital magnetic anomaly map. *Geochemistry, Geophysics, Geosystems*, *8*(6).

Mickus, K. L., and Keller, G. R. (1992). Lithospheric structure of the south-central United States. *Geology*, *20*(4), 335-338.

Mickus, K., Stern, R. J., Keller, G. R., and Anthony, E. Y. (2009). Potential field evidence for a volcanic rifted margin along the Texas Gulf Coast. *Geology*, *37*(5), 387-390.

Molina-Garza, R. S., van der Voo, R., and Urrutia-Fucugauchi, J. (1992). Paleomagnetism of the Chiapas Massif, southern Mexico: Evidence for rotation of the Maya Block and implications for the opening of the Gulf of Mexico. *Geological Society of America Bulletin*, *104*(9), 1156-1168.

Ortega-Gutiérrez, F., Sedlock, R. L., Speed, R. C., and Geol. Soc. of Amer. (1994). Phanerozoic tectonic evolution of Mexico. *Phanerozoic evolution of North American Continent-Ocean Transition*, 265-306.

Pérez-Gussinyé, M., Ranero, C. R., Reston, T. J., and Sawyer, D. (2003). Mechanisms of extension at nonvolcanic margins: Evidence from the Galicia interior basin, west of Iberia. *Journal of Geophysical Research*, *108*(B5), 2245.

Pindell, J. L. (1985). Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas, and Proto-Caribbean. *Tectonics*, *4*(1), 1-39.

Pindell, J. L. (1994). Evolution of the Gulf of Mexico and the Caribbean. *Caribbean geology: an introduction*, 13-39.

Pindell, J., and Dewey, J. F. (1982). Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/ Caribbean region. *Tectonics*, *1*(2), 179-211.

Pindell, J. L., and Kennan, L. (2001, December). Kinematic evolution of the Gulf of Mexico and Caribbean. In *Transactions of the Gulf Coast Section Society of Economic Paleontologists and Mineralogists (GCSSEPM) 21st Annual Bob F. Perkins Research Conference, Petroleum Systems of Deep-Water Basins, Houston, Texas, December* (pp. 2-5).

Pindell, J. L., and Kennan, L. (2009). Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. *Geological Society, London, Special Publications*, *328*(1), 1-55.

Pindell, J., Kennan, L., and Barrett, S. F. (2000). Regional Plate Kinematics: Arm Waving, or Underutilized Exploration Tool. *American Association of Petroleum Geologists Explorer*.

Popenoe, P., and Zietz, I. (1977). *The nature of the geophysical basement beneath the Coastal Plain of South Carolina and northeastern Georgia*. US Government Printing Office.

Raymond, D. E., & Copeland, C. W. (1987). Selected columnar sections for the coastal plain. *Appalachian plateaus, interior low plateaus, and Valley and Ridge provinces in Alabama: Geological Survey of Alabama Atlas Series*, *20*, 43.

Reston, T. J. (2009). The structure, evolution and symmetry of the magma-poor rifted margins of the North and Central Atlantic: a synthesis. *Tectonophysics*, *468*(1), 6-27.

Reston, T. J., and Pérez-Gussinyé, M. (2007). Lithospheric extension from rifting to continental breakup at magma-poor margins: rheology, serpentinisation and symmetry. *International Journal of Earth Sciences*, *96*(6), 1033-1046.

Ross, M. I., and Scotese, C. R. (1988). A hierarchical tectonic model of the Gulf of Mexico and Caribbean region. *Tectonophysics*, *155*(1), 139-168.

Russell, S. M., and Whitmarsh, R. B. (2003). Magmatism at the west Iberia non-volcanic rifted continental margin: evidence from analyses of magnetic anomalies. *Geophysical Journal International*, *154*(3), 706-730.

Salvador, A. (1987). Late Triassic-Jurassic paleogeography and origin of Gulf of Mexico basin. *Am. Assoc. Pet. Geol., Bull.;(United States)*, *71*(4), 419-451.

Salvador, A. (1991a). Origin and development of the Gulf of Mexico basin. *The Gulf of Mexico Basin*, 389-444.

Salvador, A. (1991b). Triassic-Jurassic. *The Gulf of Mexico Basin: Boulder, Colorado, Geological Society of America, Geology of North America, v. J*, 131-180.

Sawyer, D. S., Buffler, R. T., and Pilger Jr, R. H. (1991). The crust under the Gulf of Mexico Basin. *The Gulf of Mexico Basin: Geological Society of America, The Geology of North America, v. J*, 53-72.

Schouten, H., and Klitgord, K. D. (1994). Mechanistic solutions to the opening of the Gulf of Mexico. *Geology*, *22*(6), 507-510.

Shepherd, A. (1983). *A study of the magnetic anomalies in the eastern Gulf of Mexico* (Doctoral dissertation, University of Houston-University Park).

Sheridan, R. E. (1974). Atlantic continental margin of North America. *The geology of continental margins: New York, Springer-Verlag*, 391-407.

Srivastava, S. P., Sibuet, J. C., Cande, S., Roest, W. R., and Reid, I. D. (2000). Magnetic evidence for slow seafloor spreading during the formation of the Newfoundland and Iberian margins. *Earth and Planetary Science Letters*, *182*(1), 61-76.

Stern, R. J., and Dickinson, W. R. (2010). The Gulf of Mexico is a Jurassic backarc basin. *Geosphere*, *6*(6), 739-754.

Tator, B. A., and Hatfield, L. E. (1975a). Bahamas present complex geology. *Oil Gas J.;(United States)*, *73*(44), 172-176.

Tator, B. A., and Hatfield, L. E. (1975b). Bahamas present complex geology. *Oil Gas J.;(United States)*, *73*(45), 120-122.

Thomas, W. A. (1989). The Appalachian-Ouachita orogen beneath the Gulf Coastal Plain between the outcrops in the Appalachian and Ouachita Mountains. *The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America*, *2*, 537-553.

Thomas, W. A. (1991). The Appalachian-Ouachita rifted margin of southeastern North America. *Geological Society of America Bulletin*, *103*(3), 415-431.

Walper, J. L. (1974). The origin of the Bahama platform. *Trans. Gulf Coast Assoc. Geol. Soc., 24*, 25-30.

White, R. S., McKenzie, D., and O'Nions, R. K. (1992). Oceanic crustal thickness from seismic measurements and rare earth element inversions. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *97*(B13), 19683-19715.

Whitmarsh, R. B., and Miles, P. R. (1995). Models of the development of the West Iberia rifted continental margin at 40 30′ N deduced from surface and deep-tow magnetic anomalies. *Journal of Geophysical Research*, *100*(B3), 3789-3806.

Woods, R. D., Salvador, A., and Miles, A. E. (1991). Pre-Triassic. *The Gulf of Mexico Basin: Geological Society of America, The geology of North America, v. J*, 109-130.