CRUSTAL TYPE, TECTONIC ORIGIN, AND PETROLEUM POTENTIAL OF THE BAHAMAS CARBONATE PLATFORM

A Thesis Presented to

the Faculty of the Department of Geology

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In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Alex Jefferson Dale

August 2013

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ABSTRACT

I used a compilation of publicly available, free-air and Bouguer-corrected gravity and ship-borne magnetic surveys of the Bahama carbonate platform to determine its underlying crustal type, total sedimentary thickness, plate tectonic history, and petroleum potential. Gravity and magnetic data provide important constraints on the crustal structure of the Bahamas because existing seismic reflection data are unable to penetrate the up-to-7-km-thick carbonate cover of the platform. I created gravity and magnetic models for six 700-1400 km-long, regional dip transects and one 2000-km-long strike transect crossing the Bahamas and the southeastern margin of North America. I generated magnetic models to create a depth-to-basement map that is consistent with a depth-to-basement map that I made independently using gravity data. Both magnetic and gravity maps were combined to create an overall basement depth and structure map for the Bahama platform region. These maps show basement crustal rocks with a density 2.8 g/cm^3 and crustal thicknesses about twice as thick as normal oceanic crust. I interpret most of the Bahama basement to have formed as a southeasterly continuation of the volcanic passive margin of the eastern USA that formed during the Triassic (~201 Ma) eruption of the Central Atlantic Magmatic Province now found on Africa, southeastern North America, and northern South America. Locally thick crustal areas with within the Bahamas are interpreted as seamounts with the volcanic passive margin.

I used variations in sedimentary thicknesses derived from the gravity and magnetic-based depth of basement map along with estimated subsidence from sparse wells and heat flow values based on measurements made in the Bahamas region to calculate the thermal maturity of an inferred Late Jurassic source rock deposited in the Bahamas area. Subsidence modeling supports greater tectonic subsidence over the thinner crust of the large igneous crust areas of the Great Bahama bank than for thicker continental crust beneath eastern Florida. Subsidence models predict peak maturation and generation for Upper Jurassic rocks at modern depths greater than 4500 m occurred in the mid Miocene less than 20 million years ago using an average heat flow of 40 mW/m^2 measured in the Bahamas area. Assuming limited upward vertical migration of hydrocarbons, deeper wells (7-8 km) would be needed to penetrate to the depth of reservoirs where hydrocarbons are mature.

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Chapter 1

Introduction to the thesis

1.1 Unsolved geologic and tectonic problems of the Bahamas carbonate platform

The Bahamas archipelago and carbonate platform consists of over 3,000 islands protruding from a shallow marine carbonate platform covering an area over 14,000 km^2 and forming one of the largest, modern carbonate provinces in the world (Fig. 1.1). The geologic history and crustal origin of the pre-Mesozoic crystalline basement underlying the Bahamas is obscured by as much as 7 km of mainly, shallow-water carbonate rocks that have accumulated from the Late Jurassic age (Walles, 1993).

These thick and massive carbonate lithologies - that overlie crystalline basement rocks - severely reduce the penetration depth of marine seismic reflection data from the bank tops, and therefore limit the value of seismic reflection as a geophysical tool for understanding the crustal types and history underlying the platform. As a consequence of limited geophysical information on the subsurface of the Bahamas carbonate platform, geologic and tectonic models for the early evolution of the Bahamas platform have varied widely over the past 40 years, and have postulated the existence of oceanic, oceanic plateau, and continental basement underlying the carbonate platform (Meyerhoff and Hatten,

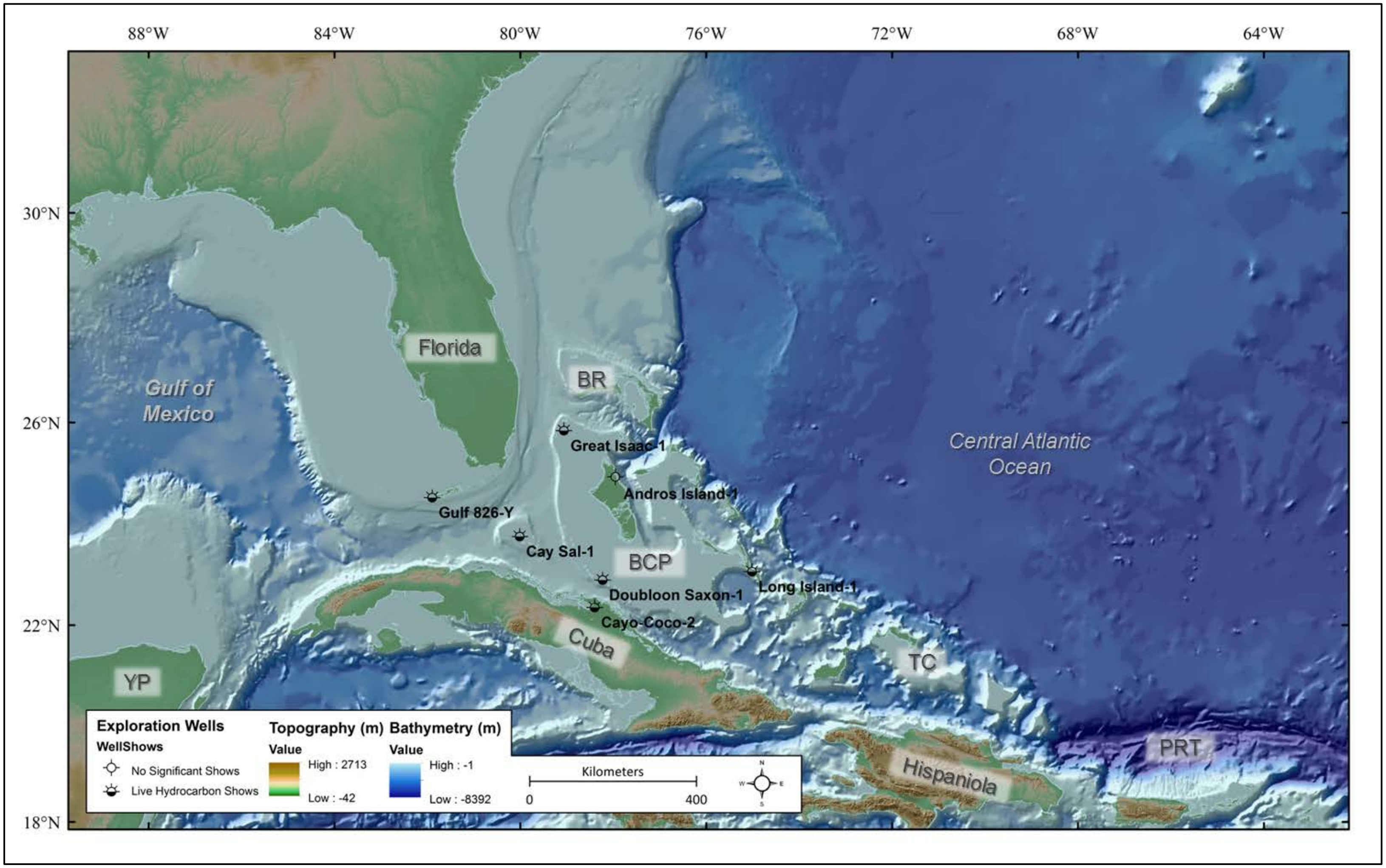


Figure 1.1 Map of southeastern North America and northern Caribbean showing the Bahamas islands and the area of interest for this study. BR = Blake Ridge; YP=Yucatan Peninsula; BCP=Bahamas Carbonate Platform; TC = Turks and Caicos; PRT = Puerto Rico Trench.

1974). The Bahamas carbonate platform is a large, frontier hydrocarbon province where only five, widely-spaced and deep wells have been drilled by the oil industry, with most of this drilling in the 1970’s and 1980’s. The locations of these wells, including key wells from south Florida and key wells from the northern coast of Cuba are shown in Figure 1.1. Of potential economic significance is the occurrence of live hydrocarbon shows within the Lower Cretaceous and Upper Jurassic in three of these five exploration wells (Meyerhoff and Hatten, 1974). Moreover, thick Lower Cretaceous and Upper Jurassic evaporite seal sequences were encountered at depth in all of these wells, with the exception of the Andros Island 1 well, the Long Island-1 well and significant portions of the Doubloon Saxon 1 well (Walles, 1991).

During the early 1970’s through the 1990’s, petroleum exploration of the Bahamas region continued in a desultory way according to the rise and fall in world oil prices. Overall, the distribution of seismic surveys and wells were scattered across the vast region with most seismic data being collected from deeper water reentrants into the carbonate platform areas where finer-grained and less massive carbonate lithologies allowed the acquisition of higher-quality seismic data. The geologic association of thick bank carbonates, reefs, Jurassic source rocks, and evaporites help maintain the interest of petroleum explorationists in the area from up to ongoing petroleum exploration in the Bahamas (Ramirez and Dames, 2011). Thick carbonate and evaporitic rocks of the same ages - Miocene through Late Jurassic - produce commercial hydrocarbons at similar latitudes in Mexico, the southern United States, and the Middle East.

None of the test wells in the Bahamas carbonate platform that have been drilled to date have resulted in commercial economic oil or gas discoveries. However, promising source rocks of Early Cretaceous – Late Jurassic age were discovered in the Great Isaac -1, Long Island -1, Doubloon Saxon-1, and Cay Sal-1 wells at depths ranging from 3868 m (12,690 ft.) in the Cay Sal-1 well to 5400 m (17,720 ft) in the Great Isaac-1 well (all Bahamas deep well results are reviewed by Meyerhoff and Hatten (1974), Mullins and Lynts (1977), Walles (1993) and in Chapter 3 of this thesis).

These carbonate-evaporite seal sequences delineate the extent of a Early Cretaceous and Jurassic lagoonal and restricted marine evaporite basin that extends from the northern coastal wells of Cuba, across the Bahamas platform, to the margins and interior of south Florida (Meyerhoff and Hatten, 1974). Based on regional well log correlations of these carbonate-evaporite sequences, this Mesozoic basin encompassed an area of at least 150,000 km^2.

I was motivated to carry out this thesis to understand the crustal types underlying this large but poorly understood basin and the tectonic mechanisms which led to the formation and subsidence of its underlying crust. This type of fundamental crustal information is also important to guide future hydrocarbon exploration efforts. For example, my analysis of the regional gravity and magnetic data, presented in Chapter 2 has shown that the total sediment thickness (Paleozoic to present) ranges from 2 km on the northern basin margin in the South Florida Basin to over 14 km in the central basin area, along the northern coast of Cuba, and near the Doubloon Saxon well (Fig. 1.1). Critical questions include: 1) what tectonic environments led to this extreme subsidence to the southeast yet more modest subsidence in the Florida area, and 2) whether these large sediment thicknesses have immature or overmatured source rocks of Jurassic and Early Cretaceous age that are were found near the base of the sedimentary succession in the deep wells described by Meyerhoff and Hatten (1974).

1.2 Background of this master's thesis

I graduated from Baylor University in Waco, Texas in 2011 with a bachelor's degree in geology. At Baylor I gained a general knowledge of the different specialties within geosciences, especially those based on outcrop studies. This broad knowledge of geology motivated me to seek a master's degree and to become a petroleum geologist focused on subsurface exploration using modern geophysical methods.

Following completion of my geology B.S. in 2011, I was accepted by the Department of Earth and Atmospheric Sciences at the University of Houston into their two-year MS program in geology in August, 2011. After taking a tectonics seminar during the first semester led by Dr. Paul Mann for University of Houston graduate students interested in that area of geosciences, I became interested in

Caribbean tectonics and the Bahamas area. Dr. Mann hired me as a graduate research assistant starting in my second semester in the spring of 2012 as a graduate student working with his industry-funded group, Caribbean Basins, Tectonics and Hydrocarbons (CBTH). Together with Dr. Dale Bird, we developed the idea of a subsurface study of the Bahamas platform that would rely mainly on publicly available gravity and magnetic data that could be quickly assembled for the study at no cost and analyzed using the Montaj software package licensed to the University of Houston.

During the summer between my first and second years of graduate school in 2012, I was hired as a summer intern by Statoil in Houston to work in their gas shale team developing plays in the Eagle Ford shale of Texas. My mentor at Statoil, Luis Canales, also allowed me the opportunity to interpret a grid of widely spaced 2D seismic data from the Bahamas with Dr. Magnus Edvardsson but I found these data to not be useful since their penetration was limited to only the upper part of the carbonate platform. In the meantime I moved ahead with collecting publicly available gravity and magnetic data from the Bahamas area which ultimately became the topic of MS thesis supervised by Drs. Mann, Bird, and van Wijk. Dr. Mann and the CBTH project continued to fund me as a research assistant during the fall, spring, and summer of my second year in the MS program. During this time, I presented the evolving thesis as posters and oral presentations at two AAPG annual meetings and two, year-end meetings for the CBTH sponsors.

1.3 Summary of thesis chapters 2 and 3

In this thesis, **Chapter 2** provides an overview of the history surrounding the controversy surrounding the nature of the underlying Bahamas crystalline basement and its structure and tectonic evolution using summaries of published literature. This is followed by my original analysis of gravity and magnetic data from the region and my proposed constraints on the nature of the underlying crust and its evolution as part of the Central Atlantic Magmatic Province or CAMP (McHone, 2006). I also used PaleoGIS software to modify existing plate reconstructions by Norton and Escalona (in preparation) using the new constraints from my gravity and magnetic interpretations. These reconstructions were able to place the basement blocks of the Bahamas platform into the context of the early opening of the central Atlantic Ocean and its relation to hotspot activity related to CAMP.

Chapter 3 focusses on the implications of regional maps of total sedimentary thickness on potential maturation of deeply buried Jurassic and Lower Cretaceous source rocks previously described by Meyerhoff and Hatten (1974). My map of regional sedimentary thickness map updates an earlier map by Meyerhoff and Hatten (1974) that is poorly documented but apparently based on widely-spaced seismic reflection lines. In this chapter I present two subsidence and burial history plots for deep wells in the Bahamas and Florida to illustrate variations related to thicker, continental crust beneath Florida and thinner, large igneous plateau and seamount crust beneath the Bahamas platform. Both chapters 2 and 3 were written as stand-alone manuscripts for submission and therefore some of the introductory parts, especially those related to the tectonic and geologic setting of the Bahamas, are repeated in both chapters.

Chapter 2

Crustal structure and tectonic origin of the Bahamas carbonate platform based on modeling of regional gravity and magnetic data

2.1 Previous work on the tectonic origin of the Bahamas carbonate platform

Because geologic and geophysical constraints are few, three tectonic origins have been postulated for the nature of the crystalline crust underlying up to 14 km of carbonate rocks covering the Bahamas area. In Figure 2.1, I summarize three models postulating continental basement (Fig. 2.1, A, B), oceanic basement (Fig. 2.1, C, D), and thickened oceanic - or large igneous province and seamount crust – underlying the Bahamas (Fig. 2.1, E, F). Each hypothesis and its main supporting observations are discussed below (Summaries from Meyerhoff and Hatten, 1974).

Hypothesis for thinned continental crust underlying the Bahamas platform

This hypothesis was first proposed by Field et al. (1931, p. 763-765) using early gravity measurements:

> *"…the Great Bahama Bank is not underlain by igneous rocks, and probably did not originate as the result of submarine igneous activity. It would seem that the Bahamas are continental in character. There seems to be good evidence that the Bahama Bank and the*

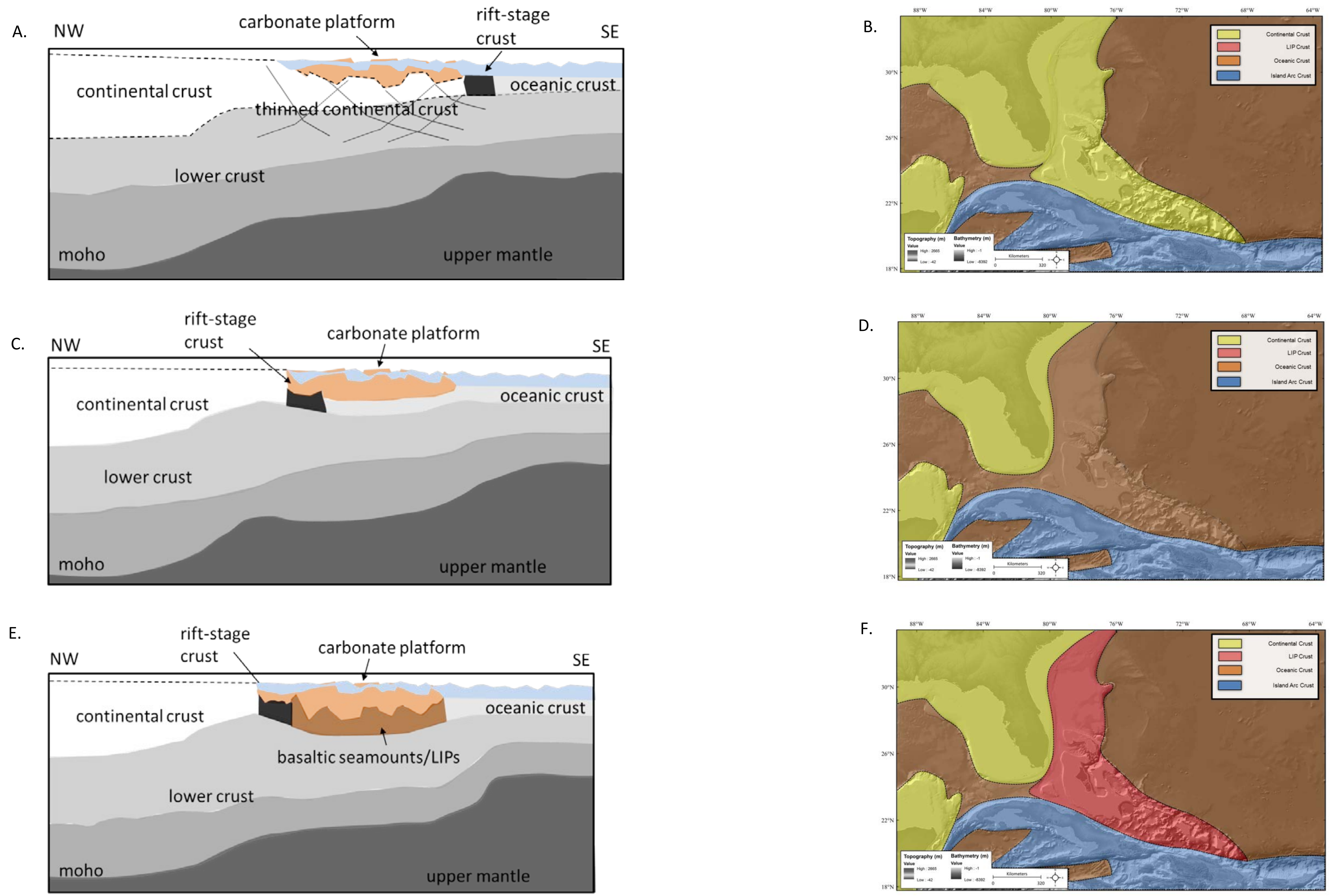


Figure 2.1 **(A)** Schematic NW-SE-oriented cross section from Florida to the Bahamas. This cross section shows the widely accepted hypothesis of thinned, faulted continental crust beneath the Bahamas. **(B)** Regional topographic map showing the crustal boundaries proposed in the thinned continental crustal model shown in Fig. 1A. **(C)** Schematic NW-SE-oriented cross section from Florida to the Bahamas showing the hypothesis of normal oceanic crust beneath the Bahamas. **(D)** Regional topographic map showing the crustal boundaries proposed in the normal oceanic crustal model. **(E)** Schematic NW-SE-oriented cross section from Florida to the Bahamas showing the proposed hypothesis of a thickened, large, igneous plateau beneath the Bahamas. **(F)** Regional topographic map showing the crustal boundaries proposed in the basaltic crustal model.

surrounding areas are in isostatic equilibrium to a marked degree, and that the anomalies at several stations are probably due to abnormally light material close to the stations."

Ball (1967) also proposed the presence of continental crust beneath the Bahamas using results from seismic reflection data from the offshore areas and by stratigraphic correlations with known continental rocks exposed by Paleogene thrusting in Cuba. Schuchert (1935, p. 26-27) also endorsed the viewpoint of earlier workers that the central and western Bahamas were built on continental crust, but went on to suggest that the deeper water, eastern and southeastern parts of the platform were built on Cretaceous or Tertiary volcanoes. This contrast was envisioned as produced from greater extension related to rifting of the thinner crust to the southeast and less extension related to the thicker crust to the northwest as shown schematically in Figure 2.1A. Despite the lack of evidence in a time when geophysics was in its infancy, this continental to northwest and oceanic to southeast interpretation became the widely accepted explanation of the origin of the Bahamas and remained unchallenged for the following two decades.

In the 1960's and 1970's improved mapping of the geology of Cuba and improved reflection and refraction surveys in the Old Bahama Channel separating Cuba the Bahamas carbonate platform showed that the Bahamas carbonate platform was present in Cuba and collided with the Great Arc of the Caribbean in Paleogene time. Most of these workers adopted the continental origin of the Bahamas to account for its tectonic role as a "backstop" for the

Paleogene collision of the Cuban segment of the Great Arc of the Caribbean (e.g., Mattson, 1972). They also noted the presence of localized outcrops of folded and thrusted Paleozoic and Precambrian crystalline rocks as evidence for a continental basement of the same age extending to the northeast beneath the Bahamas carbonate platform (Wassall, 1956; Furrazola *et al.,* 1964; Hatten, 1967; Khudoley, 1967; Meyerhoff and Hatten, 1968; Khudoley and Meyerhoff, 1971).

Mullins and Lynts (1977) used newly available compilations of existing seismic reflection, refraction, gravity, and magnetics data to attempt to shed light on the Bahamas crustal controversy after a lull in research in the area. They used gravity and magnetic data to conclude that the Bahamas are underlain by continental crust that was pervasively intruded by rift-related, Lower Triassic-Early Jurassic ultramafic rocks which increased its crustal density and produced anomalous gravity and magnetic signatures that differ from normal continental crust.

Hypothesis for normal oceanic crust underlying the Bahamas platform

Using scattered reflection and refraction data, Uchupi *et al.,* (1971) proposed that the northwestern Bahamas was underlain by continental crust, as earlier postulated by Dietz *et al.,* (1970), but that the thinner crust of the southeastern Bahamas formed later than thicker crust of the western and northern Bahamas. According to Uchupi *et al.,* the existence of a thin (~20 km) crust underlying the southeastern Bahamas suggests that the carbonate platform of that area is younger and grew to sea level above normal oceanic crust, in contrast to the thicker continental crust (~30 km) present in the western and central Bahamas. In the Uchupi *et al.,* model, oceanic crust in the southeastern Bahamas began to develop along a transtensional fracture zone as sea-floor spreading began to separate North America and Africa.

Klitgord *et al.,* (1984) proposed that the underlying crust beneath Florida and the Bahamas region was composed entirely of normal oceanic crust cut by linear, oceanic fracture zones that could be traced on regional gravity and magnetic maps as continuous, linear features from undisputed oceanic crust of the western Atlantic Ocean, across deeply buried oceanic crust of the Bahamas Platform, across continental rocks in Florida, and into the deeply buried oceanic crust in the Gulf of Mexico.

Hypothesis for a large igneous province and associated seamounts underlying the Bahamas platform

Newell (1955, p. 304-314) postulated that the entire Bahamas platform was built on oceanic crust characterized by large volcanoes or seamounts, and that the present carbonate platform developed as individual carbonate atolls surrounding the volcanoes built upward and outward and gradually coalesced as the volcanoes became inactive and subsided.

Drake *et al.* (1963) used magnetic data in an attempt to discredit the idea that the Bahamas are built on oceanic crust with subsided volcanoes, except in the southwestern part of the Turks and Caicos area of the southeastern Bahamas where a volcanic structure was inferred from strong and localized magnetic anomalies. In other areas of the Bahamas, Drake et al. (1963) inferred continental basement from a reasonably smooth magnetic field over large areas and the complete absence of sharp, high-amplitude anomalies used to infer the presence of buried volcanoes.

To explain the origin of oceanic basement beneath the Bahamas, Dietz (1973) proposed that the Bahamas formed over a moving hotspot, possibly associated with what is now called the Central Atlantic Magmatic Province (CAMP) plume (Schlische *et al.*, 2002) and is analogous to the modern motion of the Hawaiian hotspot in the Pacific Ocean. In the model by Dietz (1973), effusive volcanics were extruded to build tall seamounts protruding above the surrounding seafloor upon which a tropical “carbonate factory” developed to keep pace with subsidence of the seamount and its surrounding oceanic crust related to thermal cooling.

Ideas for the tectonic origin of the Bahamas in the framework of evolving plate models and plume models

Plate reconstructions by Klitgord *et al.,* (1984), Pindell (1985), Bird et al. (2006) all agree that the Bahamas formed in a triple junction region defined by the confluence of the Demerara Rise, a spur of continental crust on the northwestern South American plate; the Guinea nose, a continental spur on the African plate; and the tip of modern-day Florida peninsula, a spur of continental crust on the North American plate. This confluence of these three, continental pre-rift trends in the area of the Bahamas platform led early workers like Dietz *et al.,* (1973) to postulate the presence of a Mesozoic mantle plume that thinned continental crust beneath Florida during the early stages rifting in Jurassic time and emplaced volcanics onto newly formed oceanic crust that became the substrate for the Bahamas carbonate platform.

The Mesozoic plume inferred in the Bahamas area was linked to the early formation of the Central Atlantic Magmatic Province (CAMP) (Marzoli *et al.,* 1999). It was thought to have initiated continental breakup in this area with its three rift arms propagating northward into the central Atlantic, northwestward into the Gulf of Mexico, and southward into the south-central Atlantic.

During the 1990’s and early 2000’s systematic isotopic dating of Mesozoic, rift-related igneous rocks in southeastern North America, the Gulf of Mexico, northeastern South America, and Africa showed that long and linear dikes of Triassic to late Jurassic age were intruded on all three continents in a huge, radial pattern that spanned North America, African and South America. The centerpoint of this radial pattern was found to the northeast of the present-day Bahamas Platform (Schlische, 2002). Dike ages and trends were used as evidence to propose the short-lived - but intense - existence of a large mantle plume that initiated as a broad plume that was followed by a more localized hotspot track.

The plume and hotspot track is collectively called the Central Atlantic Magmatic Province or CAMP. Systematic isotopic dating in all areas shows that the plume and diking event initiated in Triassic time about 201 Ma (Marzoli *et al.,* 1999). The rise and surface eruption of this plume was proposed to have initiated early rifting in the central Atlantic Ocean. The CAMP hypothesis follows the earlier hypothesis of Dietz (1973) that predicted the presence of a large igneous province and/or seamounts beneath the Bahamas carbonate platform from which more superficial dikes and sills in the upper crust radiated in all directions from the hotspot location.

2.2 Objectives of this chapter

The above summary of hypotheses about the origin of the underlying Bahamas crust makes it clear that after 80 years of study these fundamental questions about the nature of the crust underlying the area are far from being solved. Moreover, a successful program of hydrocarbon exploration in this region begins with an improved understanding of the basement type and heat flow of the crust underlying the 7-km-thick carbonate platform.

Ship-based gravity data compiled by the Decade of North American Geology (DNAG) in 1994 (Fig. 2.2) and ship-based magnetic data compiled by the Geophysical Data System in (2001) (Fig. 2.3) are combined with previously published seismic refraction and well data (Fig. 2.4) to make six 700-1400-km-long, regional dip transects and one 1800-km-long strike transect (Fig. 2.5).

These transects improve geophysical constraints on:

1) The underlying crustal types upon which the Bahamas carbonate platform developed (i.e., continental, oceanic, or oceanic plateau origins) and the structure of this basement and how that affects platform morphology. I have also included transect A across southern Georgia to central Florida, and a discussion of how these relate to a study in the well-studied Carolina trough area of South Carolina where more seismic refraction and reflection data are available on the deep crustal structure than are present in the Bahamas area (Hutchinson *et al., 1982*); one unresolved question is whether this northern area formed as a volcanic passive margin related to the mantle plume and CAMP activity in the Bahamas area or whether this northern area formed independently of CAMP; 2) the tectonic significance of the total sedimentary thickness overlying crystalline basement and how it varies across the platform and along the passive margin of eastern Florida; and 3) whether previously proposed, diachronous hotspot activity in the Bahamas is consistent with its observed crustal structure, subsidence history, and plate history known from surrounding magnetic anomalies in oceanic crust or whether the Bahamas formed as a volcanic passive margin as proposed for the Carolina Trough to the north.

2.3 Data and methodology used in this chapter

Value of potential fields data

The fundamental parameter controlling the range of gravity values seen in the Decade of North American Geology (DNAG) gravity dataset (1992) is rock density. On Earth, these values can range from 1–4 g/cm^3. Because continental, oceanic, and plateau basalts all have different rock densities, gravity can be used as a tool to distinguish crustal types, even in areas where basement is deeply buried or covered by thick, carbonate rocks as in the Bahamas. Gravity can also be used to map local areas of rocks with anomalous densities such as salt and anhydrite that are also present along the Cuban thrust margin (Walles *et al.,* 1993).

Earlier gravity studies of the Bahamas platform, including Uchupi (1971), relied on widely-spaced, marine gravity data collected on academic research cruises. In contrast, the DNAG Bouguer-corrected, free-air gravity data compiled by Hittleman *et al.* (1994) were collected at a much denser spacing of about 6 km than that collected by ship-based gravity surveys (Fig. 2.2). The Bouguer correction removes the density contrast of the air-land boundary by adding density to the air. Thus, no horizontal density variations are created by topography. Historically the value of 2.67 g/cm^3 has been used. Typically data offshore are delivered as free-air which is dominated by topography. Free-air offshore and Bouguer onshore is modeled because the water bottom density contrast is small enough to be modeled and because our stations are not overlying topography as they are onshore. The grid of gravity tracks has complete coverage of the Bahamas region and therefore lacks the large data gaps commonly present in marine gravity data.

The fundamental parameter of magnetic data is susceptibility. Magnetic susceptibility can vary by 4 to 5 orders of magnitude depending on rock types. One limitation of magnetic data is that susceptibility can vary even within a single rock type, making it difficult to use magnetic surveys to map different crustal types at depth. Unlike gravity, magnetic data is a useful tool to map depth to the basement below the Bahamas. The magnetic dataset used is the National Geophysical Data Center's (NGDC) Geophysical Data System (GEODAS) ship-based magnetic survey (2001) (Fig. 2.3).

Cross correlation of the gravity and magnetic data can be used to constrain the structure and geometry of the basement underlying the Bahamas and in turn can be used to test the three hypotheses of underlying crustal type shown in Figure 2.1. These comparisons are facilitated using Geosoft's Oasis Montaj gravity-magnetic interpretation software and are tied to compiled refraction stations from the Gulf of Mexico, Bahamas, Central Atlantic, and northern Puerto Rico (Fig. 2.4).

Long wavelength gravity lows (< ~80 km in width) commonly coincide with structural sags in the top of the basement surface. If these gravity lows correspond with long wavelength magnetic anomalies (i.e. deep basement sources), then a deep basement trough is indicated. However, if the gravity low corresponds to short wavelength magnetic anomalies, then there are two

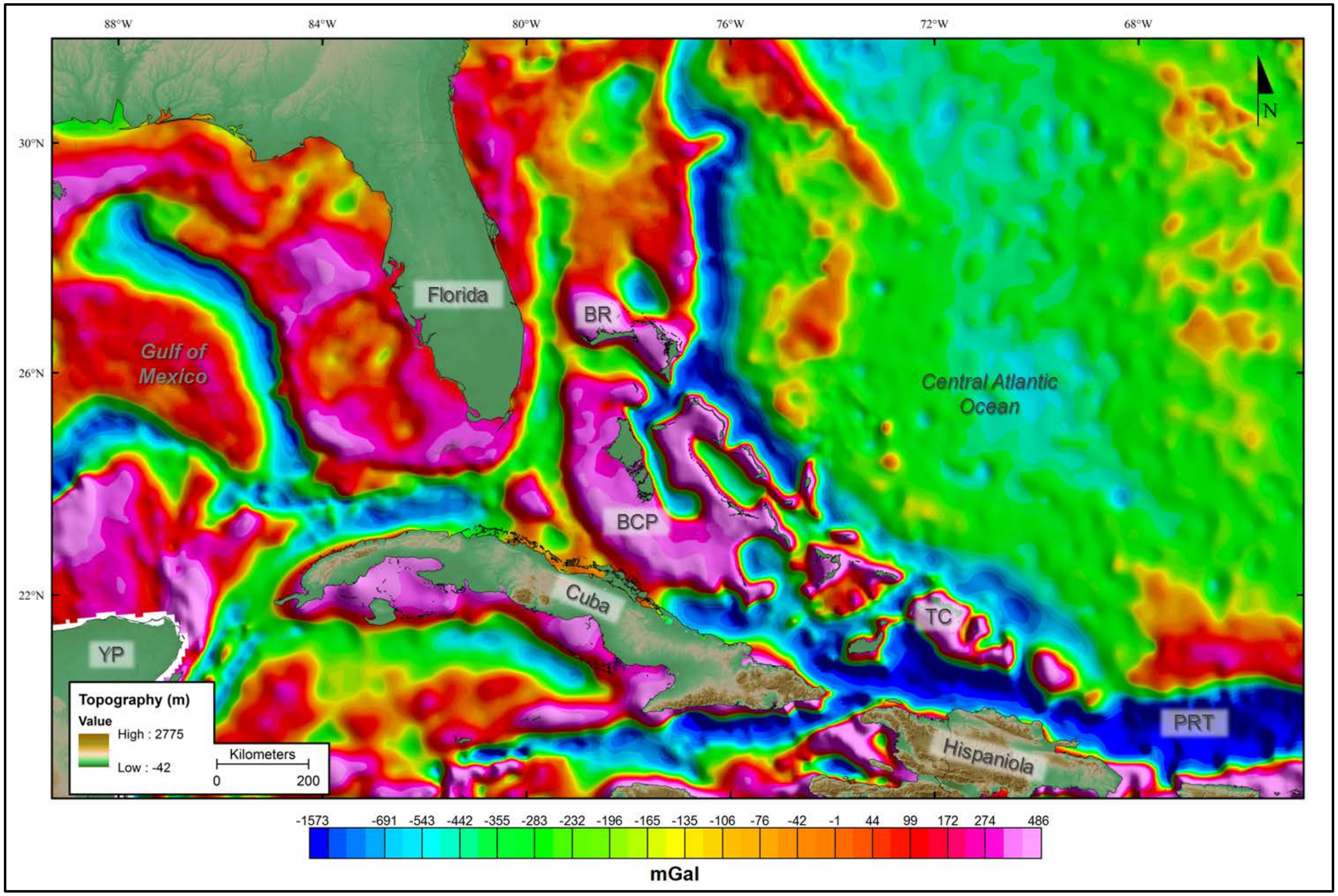


Figure 2.2 Map of onshore topography and free-air-corrected offshore Decade of North American Geology (DNAG) gravity data (1994) used in this study. All gravity shown in this compilation are ship-based. Gravity data shown was used to create transects A-G. BR = Blake Ridge; BCP = Bahamas carbonate platform; TC = Turks and Caicos; PRT = Puerto Rico Trench; YP = Yucatan Peninsula.

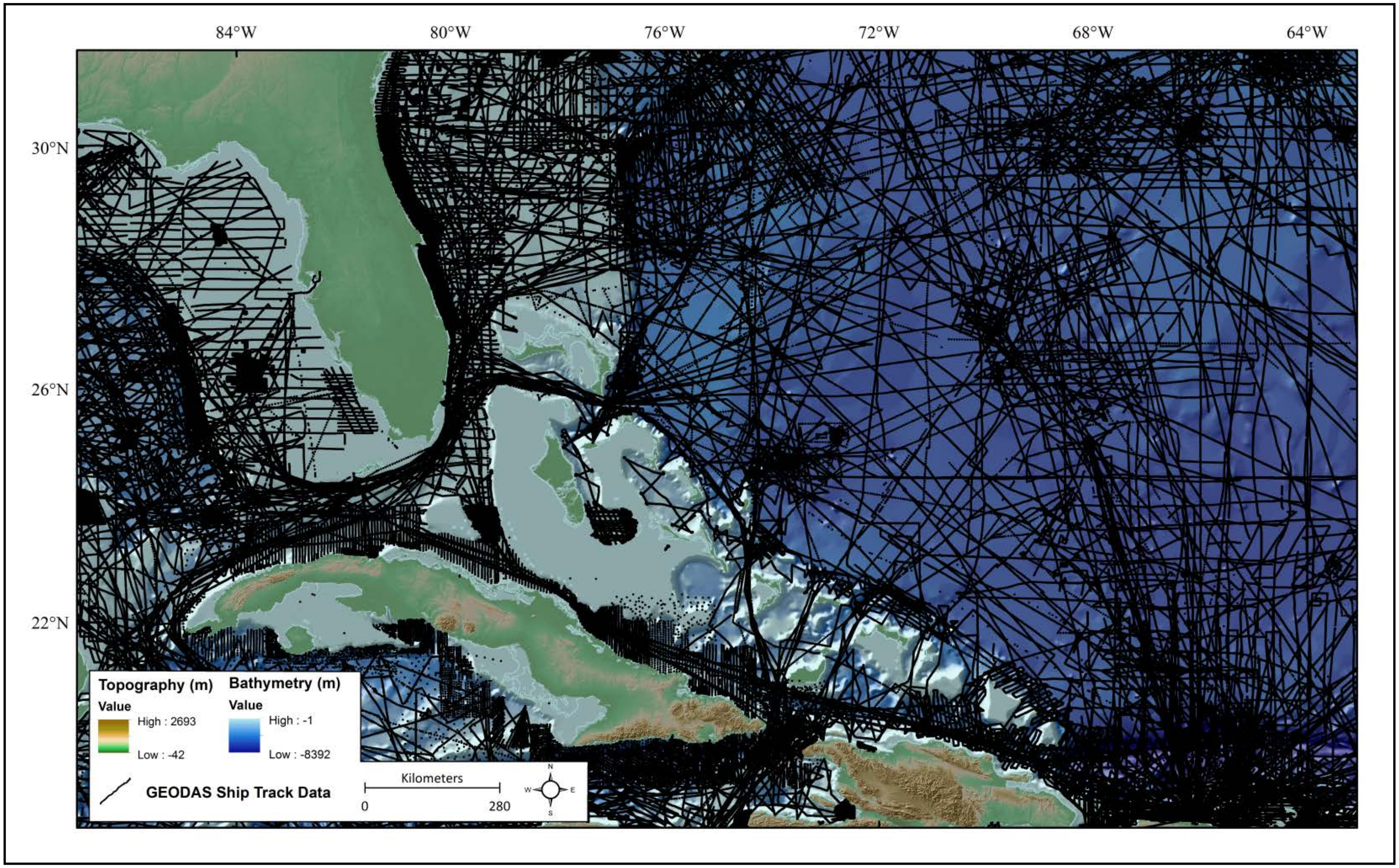


Figure 2.3 Map of the Geophysical Data System (GEODAS) ship-based magnetic dataset (NGDC) used in this study. Black lines represent individual ship tracks from which the magnetic database was compiled.

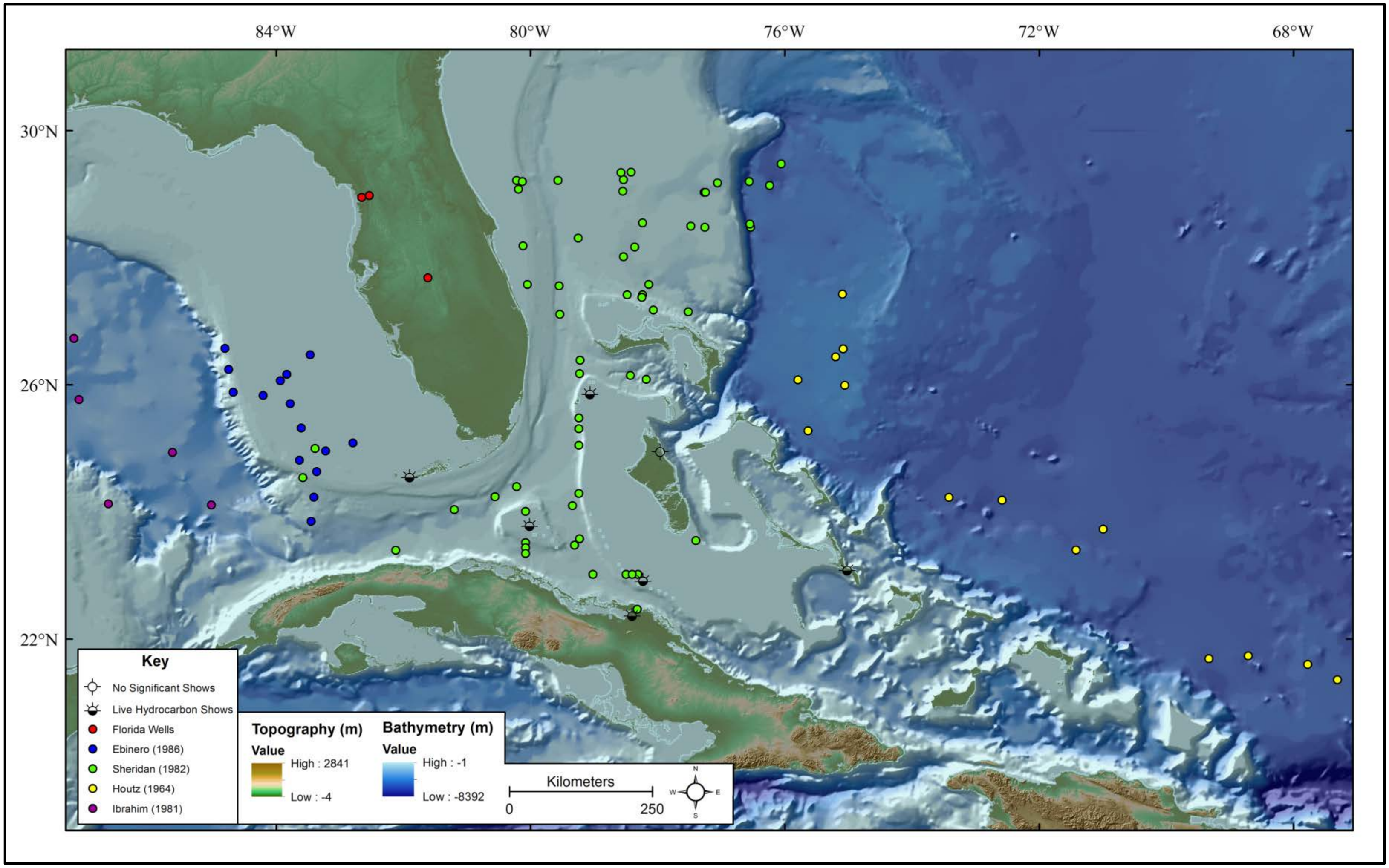


Figure 2.4 Map showing locations of well and refraction data used in this study; Hydrocarbon shows indicated.

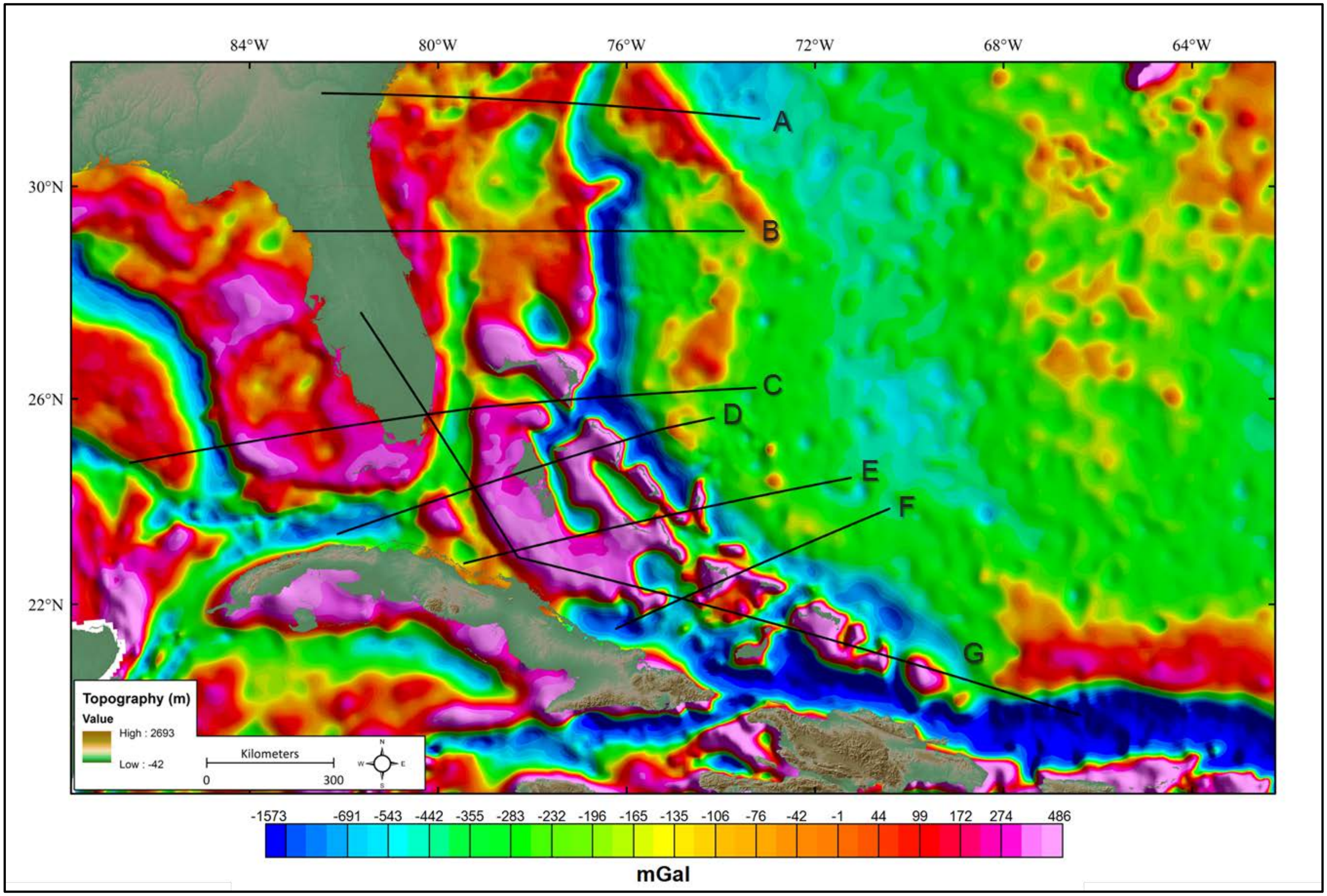


Figure 2.5 Decade of North American Geology (DNAG) gravity map showing the modeled transect locations for the six strike transects (Lines A-F) and the 1750km-long dip transect (Line G).

possibilities: 1) the gravity low is reflecting a continental root or basement arch; or 2) there is a deep basin present containing shallow volcanic flows. Short wavelength gravity anomalies coinciding with short wavelength magnetic anomalies can indicate shallow basement that can be verified with refraction data. Werner depth to magnetic source calculations can be used to distinguish between multiple, thinned crustal blocks or a continuous thick crust. If edge solutions can be resolved, the block model is supported. However, if there are no edge effects from the test, a more continuous crustal model is likely. These calculations provide clusters of solutions that can be interpreted as basement. Basement “picks” are made in the center of these clusters and then are gridded to provide a magnetic depth-to-basement map which is then tied to gravity the modeled gravity transects (Fig. 2.5).

Seismic refraction and well data

Numerous published refraction studies have been conducted in the Bahamas region and were compiled for this study (Figure 2.4). These refraction studies provide layer velocities, thicknesses, and depths to various crustal and mantle boundaries in two-dimensions. These velocities are then compared to a Nafe-Drake (1971) curve to determine the corresponding density of that layer. Typical layer velocities for sedimentary, basement, lower crust, and mantle are 1.8-5.5 km/s, ~6 km/s, 7 km/s, 8 km/s, respectively.

Well data in the area are not useful because few wells - with the exception of the deep Great Isaac-1 well (Meyerhoff and Hatten, 1974) – penetrate deeply enough through the Bahamas carbonate platform to provide any geologic information on the underlying crystalline crust, or at least volcaniclastic sedimentary rocks very near the top basement contact. The Great Isaac-1 well did penetrate to a total depth (TD) of 5,440 m (17,847 ft) into Jurassic volcaniclastic beds (Jacobs, 1977). Deep wells from Florida and Bahamas wells have been compiled and posted on gravity cross sections where they intersect for shallower sedimentary layers and density ties (Fig. 2.4).

2.4 Gravity transects through the Bahamas carbonate platform

Gravity modeling layer parameters

In Geosoft's Oasis Montaj, six dip transects (A-F, Fig. 2.5) were constructed across key parts of the region and Bahamas carbonate platform ranging in dip length from 800 to 1600 km. One strike line (G, Fig. 2.5) along the length of the Bahamas was added to tie the six dip lines.

Gravity modeling consists of defining layer thicknesses based on a certain layer's density and its corresponding gravity signature. This study used six different layer densities to depict the subsurface structure of the region on transects selected from a basemap (Fig. 2.5) and imported to Geosoft's GM-SYS modeling module. The upper mantle was given a value of 3.2 g/cm^3. A two-layer crustal structure is assumed in which a homogeneous upper crust overlies a homogeneous lower crust. The lower crust was assigned a value of 2.9 g/cm^3, while assigned upper crustal values ranged from 2.7 g/cm^3 for continental crust, and 2.8 g/cm^3 for large igneous province/seamount crust.

At the top of the crust, three sedimentary layer values were used to define density contrasts through depth. We used interval velocity-density relationships only for the sedimentary section. These values were 2.5, 2.4, and 2.3 g/cm^3. A value of 2.5 g/cm3 for this region and in this study is considered to be a representative density for the indurated limestone/dolostone and interbedded evaporitic rocks of the Bahamas, and were inferred from interval velocity-density relationships (Ludwig et al., 1971). The upper, less dense sediment layers include shallower, draping sediments, including submarine fans and limestone slides. Water is assigned a value of 1.03 g/cm^3, while the background density used in the models was consistently assumed to be 2.67 g/cm^3.

I assumed a depth between 32 - 34 km for the Mohorovičić discontinuity (Moho) depth beneath southeastern North America's continental crust (Mullins and Lynts, 1977). Layers are added to the model beginning with the Moho, or upper mantle, and upward to the surface**.** Refraction station and well data provide inputs for particular layers of velocity changes, or interpreted layer changes that are of interest for the study. Tables of refraction layer depths and associated velocity changes are found in studies across the Bahamas, Gulf of Mexico, and central Atlantic Ocean (Houtz and Ewing, 1964; Sheridan *et al.*, 1966; Ibrahim *et al.*, 1981; Ebinero *et al.*, 1986) and are then used in association with the Nafe-Drake curve (Ludwig *et al.,* 1971) to define a crustal density to that particular layer depth and thickness. Refraction data provide the main constraints on gravity modeling in the Bahamas as refraction provides the deepest penetrating and most accurate source of crustal layering.

2.5 Observations from gravity modeling

Southeastern North America (Gravity transect A)

Gravity transects A and B were selected to test the crustal structure of the volcanic passive margin origin for the eastern margin of North America (Fig. 2.6). Hutchinson *et al.,* (1982) modeled and described the area of the Carolina trough crossed on gravity transect A as a thinned “rift stage” crust lying in between the normal continental crust of North America and the normal oceanic crust of the central Atlantic Ocean. Transect A shows this same type, but larger area, of intervening crust as the nearby area of rifted crust described by Hutchinson *et al.* This crustal type is modeled here to have a density of 2.8 g/cm^3 with a thickness closer to 10 km (Fig. 2.6A). Sediment densities increase with depth to a maximum value of 2.5 g/cm^3.

Southeastern North America (Gravity transect B)

Transect B reveals this same intervening rifted crust as seen in Transect A with a similar thickness of about 10 km (Fig. 2.6B). The character of the gravity signal shows a strong peak followed by a trough that is a typical signature for rifted continent-transitional-oceanic crustal boundaries (Hutchinson *et al.,* 1988). This area of inferred thickened volcanic crust projects towards the Bahamas carbonate platform and is modeled in the next set of transects (C-F) traversing the Bahamas carbonate platform (Fig. 2.7). The presence of this type of crust over a large area is consistent with the interpretation of Hutchinson *et al.* (1982) that this area formed as a volcanic passive margin during the early rift stage of Mesozoic opening.

Bahamas carbonate platform (Gravity transect C)

Gravity transect C starts in the Gulf of Mexico (GOM), trends through the southern Florida peninsula, across the northern Great Bahama Bank (GBB), across the southern Blake Plateau, and into the central Atlantic Ocean (Fig. 2.6C). Layers on transect C are tied to available refraction studies and exploration wells (Fig. 2.4) as well as to the long dip line (Transect G). Sediment thickness for the Bahamas is modeled here to be about 6-7 km in thickness and consistent with sparse deep well information. The Great Isaac-1 well hit TD in Jurassic age volcaniclastic material at or near the upper crust.

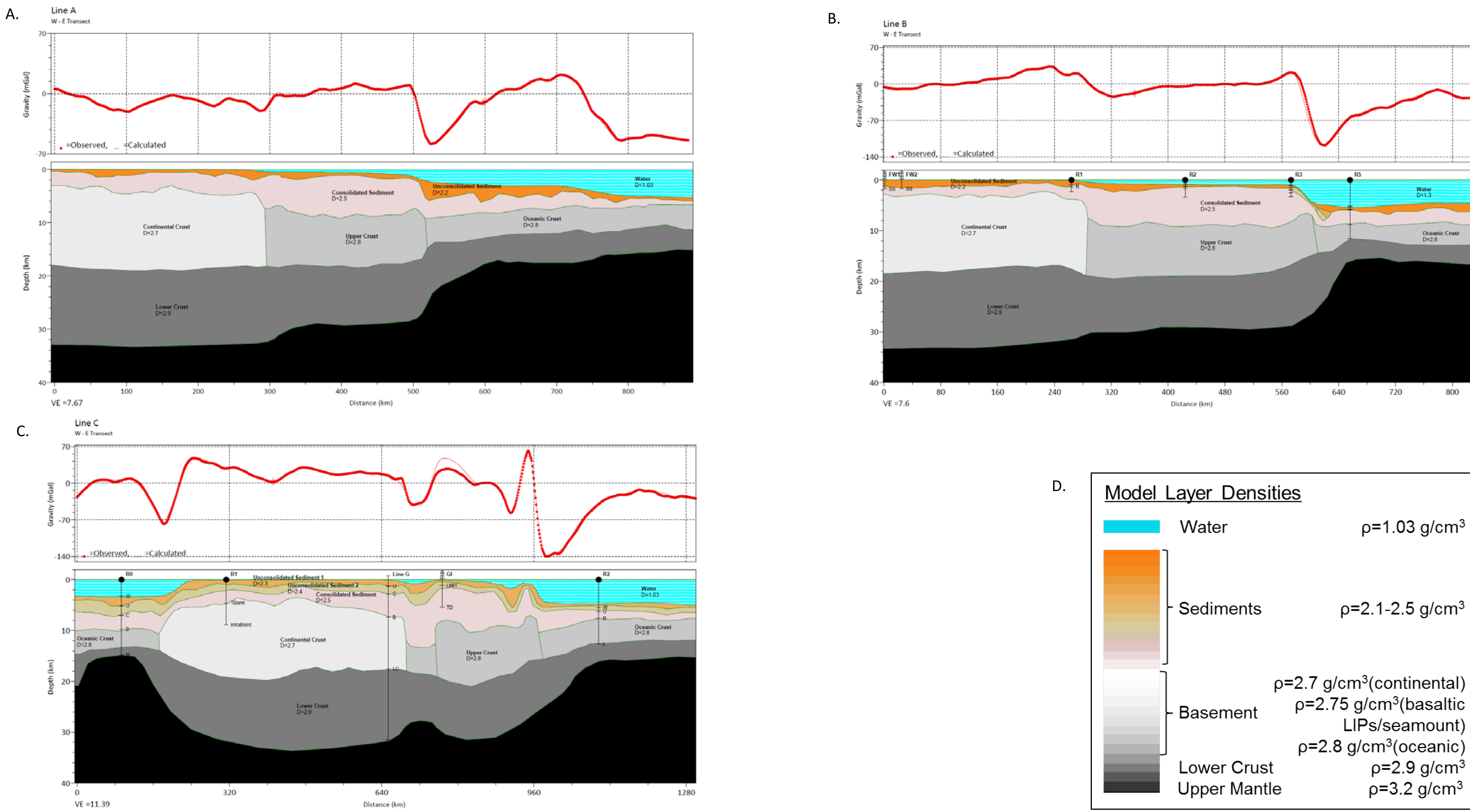


Figure 2.6 (A) East-west-striking transect (~900 km) through southeastern North America (Georgia) to the central Atlantic Ocean. The upper crust is interpreted with an oceanic crustal density (2.8 g/cm3) that was thickened with volcanics during the Late Triassic-Early Jurassic CAMP volcanic event. (B) East-west-striking transect (~860 km) through southeastern North America (northern Florida) to the central Atlantic Ocean. The upper crust is interpreted as a oceanic crustal density (2.8 g/cm3) formed during the CAMP event. FW1 = Florida Well #7 (1965, Personal communication, Dale Bird, 2013), FW2 = Florida Well #9 (1965, Personal communication, Dale Bird, 2013), R1, R2, R3, and R4 (Sheridan, *et al.*,1982). (C) East-west-striking transect (~1300 km) through eastern Gulf of Mexico (GoM), southeastern North America (southern Florida), across the northern Great Bahama Bank, southern Blake Plateau, and to the central Atlantic Ocean. The upper crust is interpreted as a oceanic crustal density (2.8 g/cm3) formed during the CAMP event. GI = Great Isaac-1 Well; R0 = Ibrahim *et al.* (1981); R1 = Ebinero *et al.* (1986); and R2 = Houtz and Ewing (1964). W = Water bottom, U = Unconsolidated Sediment, C = Consolidated Sediment, B = Basement, LC = Lower Crust, M = Moho. (D) Layer density inputs for gravity models.

The nature of the crust is modeled as a thickened basaltic basement of oceanic crustal density (2.8 g/cm^3) with a changing character. The Moho and the nature of the upper mantle appear to be quite variable across transect C. A shallow Moho below the GOM deepens to 34 km under the thick continental crust of North America as well as beneath thick crust of the Bahamas platform.

Northern Bahamas carbonate platform (Gravity transect D)

The east-west-striking transect D begins in the Straits of Florida near the GOM, extends across Cay Sal bank and over the Santaren Channel, across the central Great Bahama Bank (GBB), across the Tongue of the Ocean (TOO), and across Eleuthera Island and into the Atlantic Ocean (Fig. 2.7A). Layers were tied to refraction studies where available (Fig. 2.4) and also tied to Line G for layer coherency. Along-strike extrapolation of basement and Moho depths are assumed for the model. From west to east, the upper crustal thickness increases to ~11 km and decreases to 4 km between the upper crustal blocks, and back to ~6 km in the Atlantic oceanic crust. These upper crustal blocks are interpreted as transitional seamount/LIP blocks related to magmatism during Jurassic rifting.

Northern Bahamas carbonate platform (Gravity transect E)

Line E traverses through the central Great Bahama Bank (GBB), Great

Exuma and San Salvador Islands, and continuing offshore to the central Atlantic Ocean (Fig. 2.7B). Layers were tied to refraction studies at the eastern edge of the transect and tied to transect G for layer coherency. Along-strike extrapolation of basement and Moho depths are assumed for most of the model. From west to east, the upper crustal thickness increases to ~11 km and decreases to 4 km between the upper crustal blocks, and back to ~6 km in the Atlantic oceanic crust. These upper crustal blocks are interpreted as transitional seamount/large igneous province blocks formed by rifting and magmatism in the Jurassic.

Southern Bahamas Carbonate Platform (Gravity transect F)

Line F is a west-east-striking transect through the Cuba-Bahamas maritime border, across the Crooked Islands, and continuing offshore to the central Atlantic Ocean (Fig. 2.7C). Layers were tied to refraction stations at the eastern end of the transect down to the Moho at ~12 km and tied to Line G for layer coherency. Along-strike extrapolation of basement and Moho depths are assumed for the model. From west to east, the upper crustal thickness increases to ~8 km and decreases to 4 km between the upper crustal blocks, and back to ~5 km in the Atlantic oceanic crust. These upper crustal blocks are interpreted as transitional seamount/LIP blocks related to magmatism in the Jurassic. These blocks are thinner than the northwest interpreted as waning of the volcanic output. Sedimentary cover for transect F is less than previous lines and is also

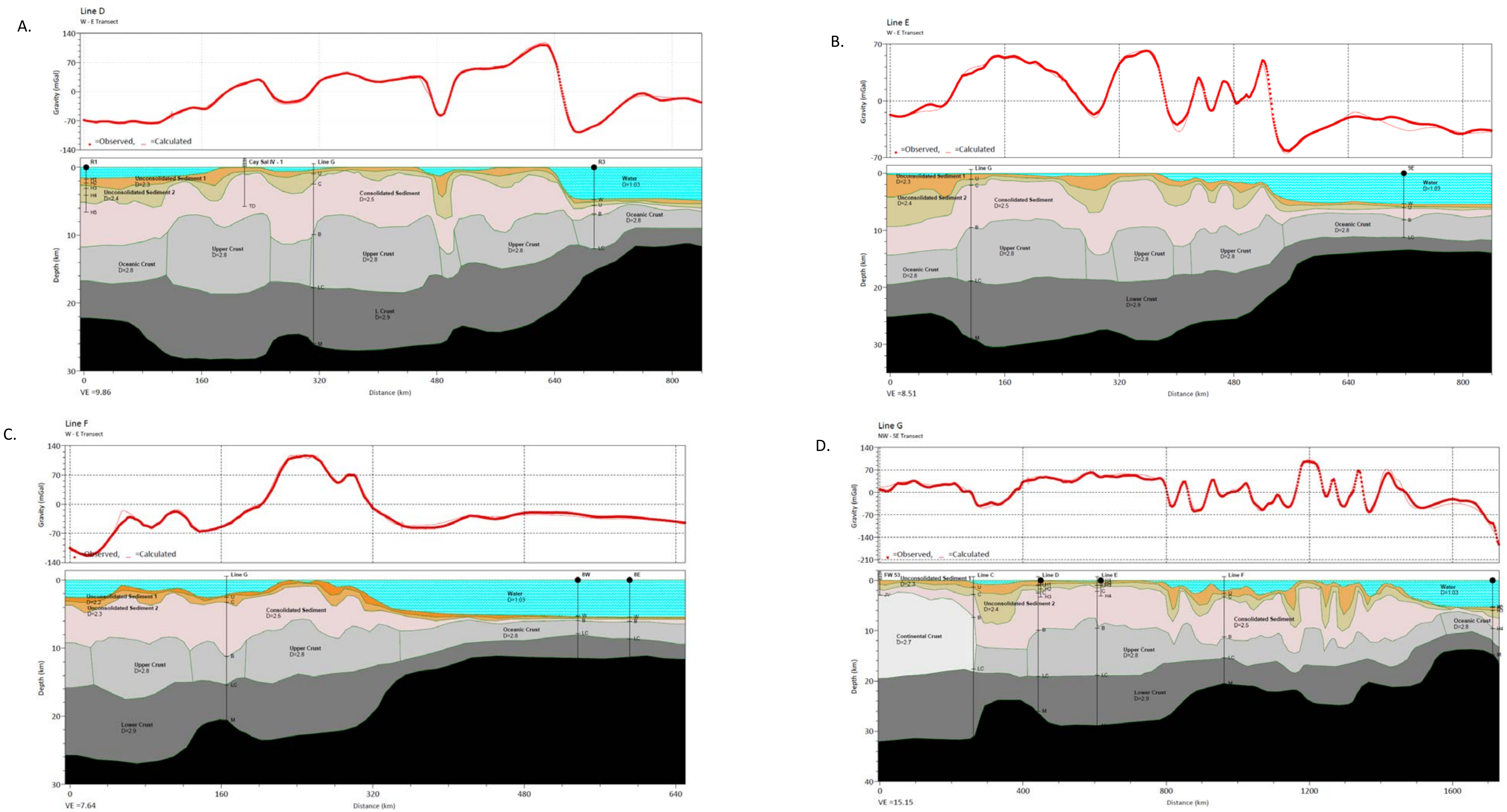


Figure 2.7 (A) West - East striking transect line D (~840 km) through eastern Gulf of Mexico (GoM), Straits of Florida (SoF), Cay Sal, across the central Great Bahama Bank, Tongue of the Ocean (TOO), Eleuthera Island, and continuing offshore to the central Atlantic Ocean. The upper crust is interpreted as a oceanic crustal density (2.8 g/cm3) formed during the CAMP event. CS = Cay Sal IV Well, R1 = Sheridan, *et al.*,1982; R3 = Houtz and Ewing (1964). (B) West - East striking transect line E (840 km) through the central GBB, Great Exuma and San Salvador Islands, and continuing offshore to the central Atlantic Ocean. The upper crust is interpreted as a oceanic crustal density (2.8 g/cm3) formed during the CAMP event. 9E = Houtz and Ewing (1964). (C) West - East striking transect line F (650km) through the Cuba-Bahamas maritime border, across the Crooked Islands, and continuing offshore to the central Atlantic Ocean. The upper crust is interpreted as a oceanic crustal density (2.8 g/cm3) formed during the CAMP event. 8W, 8E = Houtz and Ewing (1964). (D) NW - SE striking transect line G (1750 km) starting in the southern Florida peninsula, across the GBB, and out to the southeastern Bahamas, Turks and Caicos and in the Puerto Rico Trench. The upper crust is interpreted as a oceanic crustal density (2.8 g/cm3) formed during the CAMP event.Black dots represent refraction stations = Sheridan, *et al.,* 1982; FW 53 = Florida Well 53 (1969, Personal communication, Dale Bird, 2013). SS = Sandstone, W = Water bottom, U = Unconsolidated Sediment, C = Consolidated Sediment, B = Basement, LC = Lower Crust, M = Moho.

marked by a shallower Moho beneath the southeastern Bahamas and Turks and Caicos (~24 km).

Strike line through the Bahamas carbonate platform (Transect G)

Line G is a strike transect that starts in the southern Florida peninsula, across the GBB, and out to the southeastern Bahamas, Turks and Caicos, and the area of the Puerto Rico Trench (Fig. 2.7D). Layers were tied to refraction studies where available (Fig. 2.4) and tied to all the previous lines for layer coherency. Also, Florida well #53 reached a total depth at 2895 m (9493 ft) in Jurassic volcanics on the Florida peninsula (Personal Communication, Dale Bird). Along-dip extrapolation of basement and Moho depths are assumed for the model.

From northwest to southeast, the upper crustal thickness increases to ~18 km below Florida, and decreases to 4 km in the Straits of Florida, and back to ~10 km beneath the Bahaman islands with a variable character and back to ~4 km beneath the Puerto Rico Trench. These upper crustal blocks are interpreted as transitional seamount/LIP blocks related to magmatism in the Jurassic. The Moho shallows northwest to southeast, from 32 km to ~14 km.

Depth-to-Moho

After completing the gravity models, the Moho horizon was exported on all seven transects and gridded to provide a depth-to-Moho map for the region (Figure 2.8). The Moho shallows significantly from northwest to southeast in as the crust thins and eventually deepens beneath the Puerto Rico Trench (Figure 2.8).

Location of crustal boundaries and sediment thickness map

The water bottom and basement horizons were exported from each model and then subtracted to provide a map of the crustal blocks associated with the thicker portions of the basement crustal bodies (Figure 2.9A) as well as a total sedimentary thickness map for the Bahamas from the gravity modeling (Figure 2.9B). The crustal boundaries map show a LIP stage crustal section between the continental crust of North America and the normal oceanic crust of the central Atlantic Ocean.

2.6 Interpretation of magnetic data from the Bahamas carbonate platform

Werner solutions

Werner magnetic source depth estimation is an automated profile-based technique that solves a system of over-determined linear equations to calculate

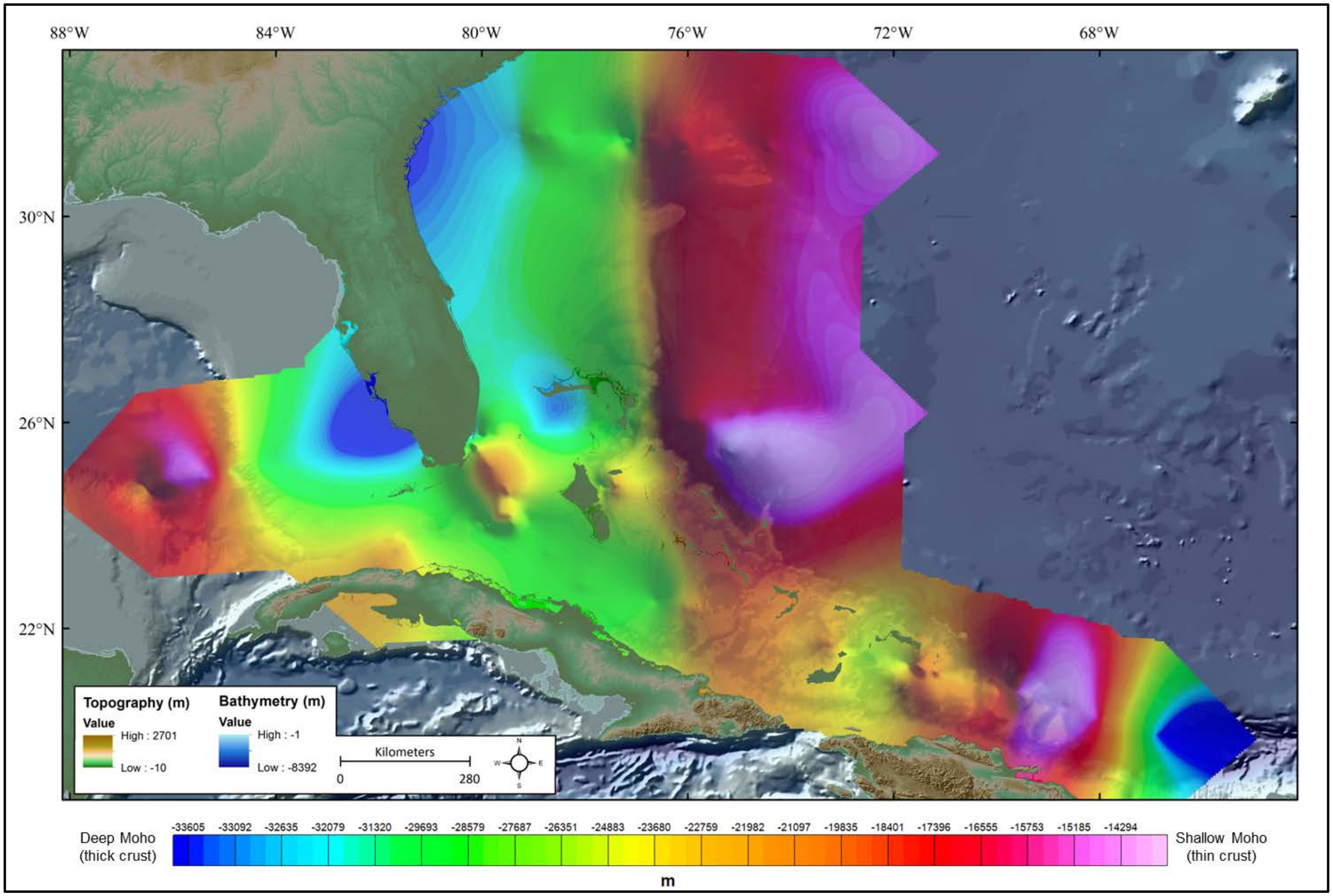


Figure 2.8 Depth to base of crust (Moho) based on gravity models shown in Figures 2.7-2.8. A deep Moho (cold colors) indicates areas of thick continental crust as seen beneath Florida while a shallow Moho (hot colors) indicates areas of thinner rifted continental, oceanic plateau, or normal oceanic crust as seen beneath and around the Bahamas carbonate platform.

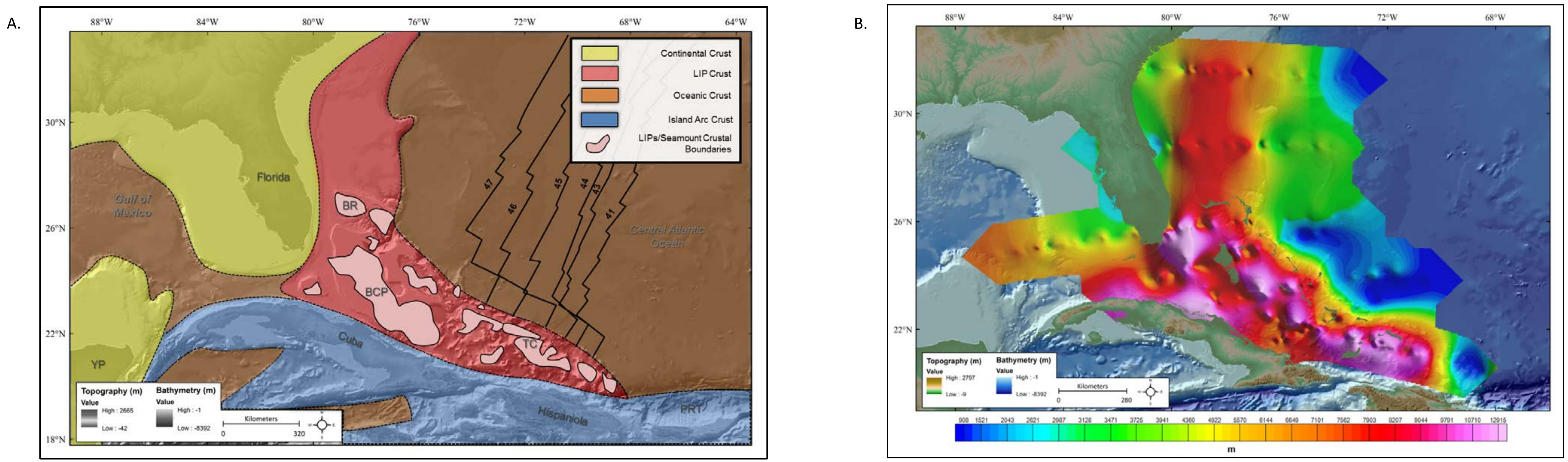


Figure 2.9 (A) Crustal types of the eastern Gulf of Mexico, Florida, Atlantic margin of the southeastern USA and the Bahamas area based on the gravity and magnetic models in Figures 2.7, 2.8 and 2.10. Crustal provinces in the Yucatan basin are from Rosencrantz (1990), in the Cayman trough from Leroy et al. (1996) and in the Gulf of Mexico from Bird et al. (2005). Offshore western Florida COB shown in yellow, long-dashed line. Large igneous plateau crust of the Bahamas and the southeastern North America is shown with a red dashed line. The large igneous plateua to oceanic crust boundary between the eastern North America, Bahamas and the Central Atlantic is shown in orange small dashes. World magnetic isochrons (black lines); BR = Blake Ridge; BCP = Bahamas carbonate platform; TC = Turks and Caicos; PRT = Puerto Rico trench; YP = Yucatan Peninsula. (B) Sediment thickness grid from gravity modeling showing the difference in sediment thickness of the LIP crust versus the continental crust beneath southeastern North America and oceanic crust of the Atlantic Ocean.

magnetic source position (x and z), dip and magnetic susceptibility. It calculates edge solutions from the horizontal gradient of the total field profile, and dike solutions from the total field profile. In practice many solutions are calculated and a source location is picked by examination of the solution distribution with the help of constraining data such as well depths or results from seismic refraction experiments.

Test Werner profiles were generated over seismic refraction control several times while changing the program parameters. These changes also altered the pattern of depth solutions such that they can be "tuned" to be consistent with nearby refraction control (Fig. 2.4).

Depth-to-basement picks

The patterns of depth solutions were analyzed for each magnetic profile and final depth locations are shown in Figure 2.11. 296 final depths picks were selected from forty-five straight-lined profiles from the GEODAS ship-track data and entered into a database (Fig. 2.10). Figures 2.10 A-D show four examples of the output of the magnetic modeling. Color was added to the profiles to demonstrate the different sections of the profile where blue is the water column, yellow is a sedimentary layer, and orange hatched areas are the difference between the world basement and our basement selections. The world basement was derived by subtracting the World Sedimentary Thickness grid (http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html) from the TerrainBase topography grid (Personal communication, Dale Bird, 2013).

The picks were then gridded to create a depth-to-magnetic basement map (Figure 2.12). The two independent studies using gravity and magnetics werethen combined to provide a tie, or correlation, between the two separate studies.

2.7 Discussion

Relationship of the CAMP plume to the tectonic origin of the Bahamas basement

Studies of the early history of the central Atlantic Ocean basin show a vast tholeiitic flood basalt province that was active over 10 million km^2 of central Pangea, starting in the Triassic about at 201 Ma during continental rifting, and before the initiation of new ocean crust (Hames *et al.,* 2002). This LIP is known as the Central Atlantic Magmatic Province, or CAMP (Marzoli *et al.,* 1999), and it's thought to have evolved into the mid-ocean rift production of Atlantic Ocean crust, starting in the Early Jurassic and continuing into the present (McHone, 2006). This event is also marked by a mass extinction typically associated with the volcanism produced from rift-related CAMP volcanoes (Whiteside *et al.*, 2007).

After the initial split of Pangea, little igneous activity occurred within the central Atlantic Ocean during the next 70 Ma, outside of ocean-ridge volcanism

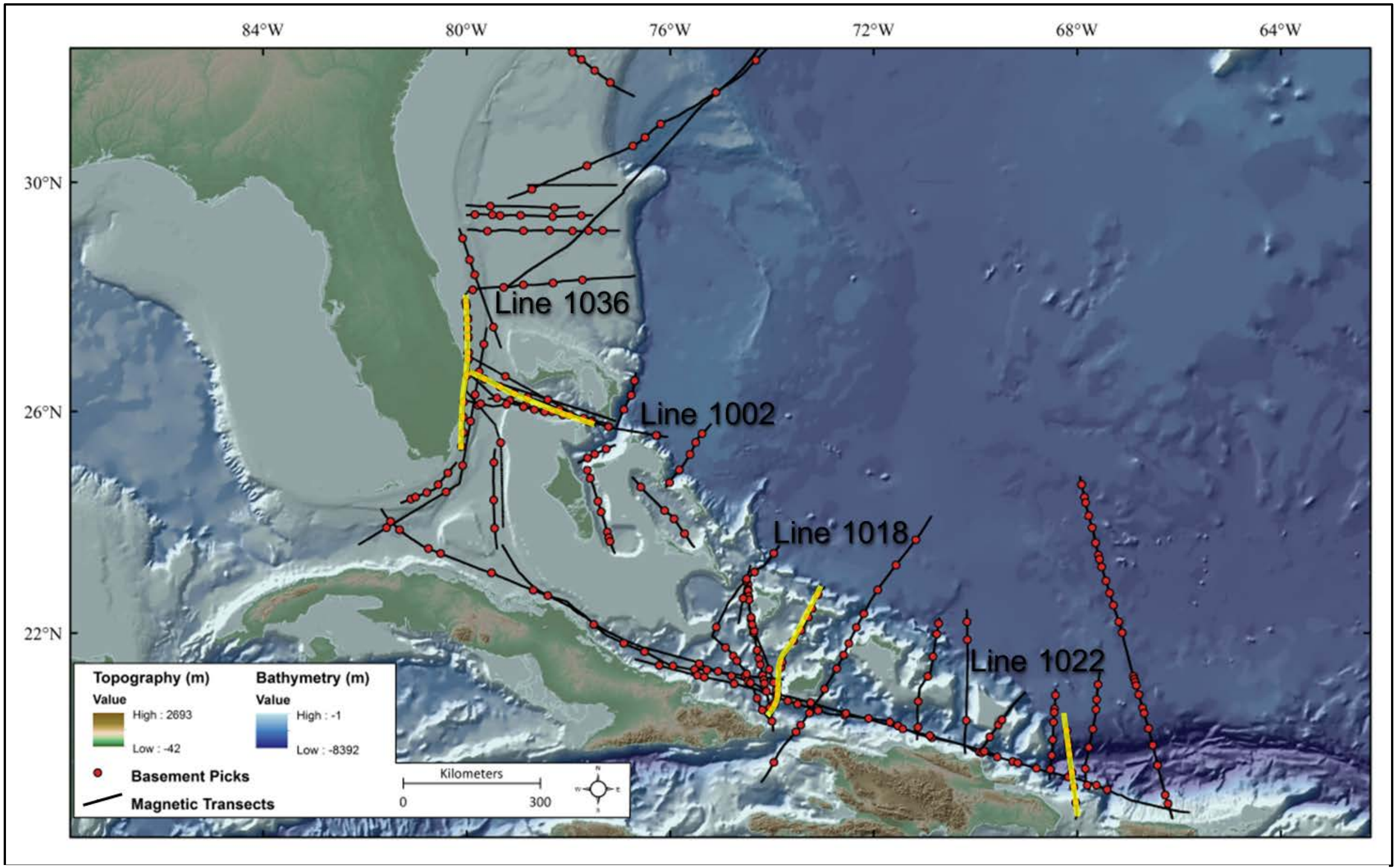


Figure 2.10 Map of Geophysical Data Systems (GEODAS) magnetic transects (black lines) used to create 45 magnetic transects used to calculate Werner solutions for constraining 296 basement picks shown on map as red dots. Yellow lines indicate magnetic transects shown in Figures 2.11 (A-D).

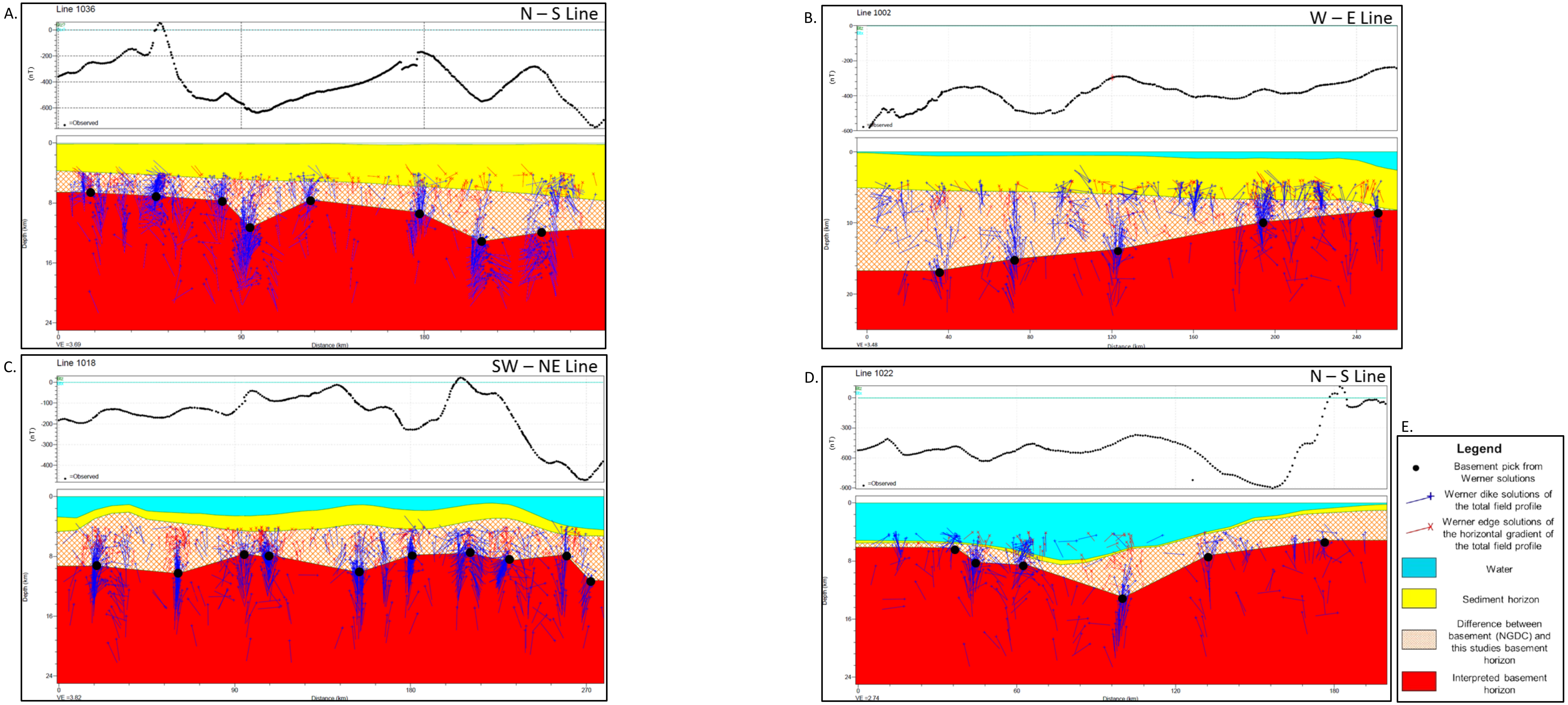


Figure 2.11 **(A)** North-south-striking transect line 1036 along the eastern Florida coast. This transect shows the depth-to-basement deepening southwards towards the Straits of Florida. Solution clusters at the top of basement are found much deeper than the world basement calculated from subtracting the World Sedimentary Thickness grid (http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html) from the TerrainBase topography grid (Personal communication, Dr. Dale Bird, Bird Geophysical) (orange hatched area). Eight top basement picks were taken from this transect (black dots). **(B)** East-west-striking transect line 1002 between the GBB and the Blake Plateau. This transect shows that the top of basement shallows as it goes from the platform in the west to the Atlantic Ocean in the east. Five basement picks were taken from this transect (black dots). **(C)** Southwest-northeast-striking transect line 1018 from offshore Cuba through eastern Bahamas platform. Ten basement picks were taken from this transect (black dots). **(D)** North-south-striking transect line 1022 through the southern Bahamas, Puerto Rico Trench, and Atlantic Ocean. Six basement picks were taken from this transect (black dots). **(E)** Legend for the magnetic depth-to-basement study.

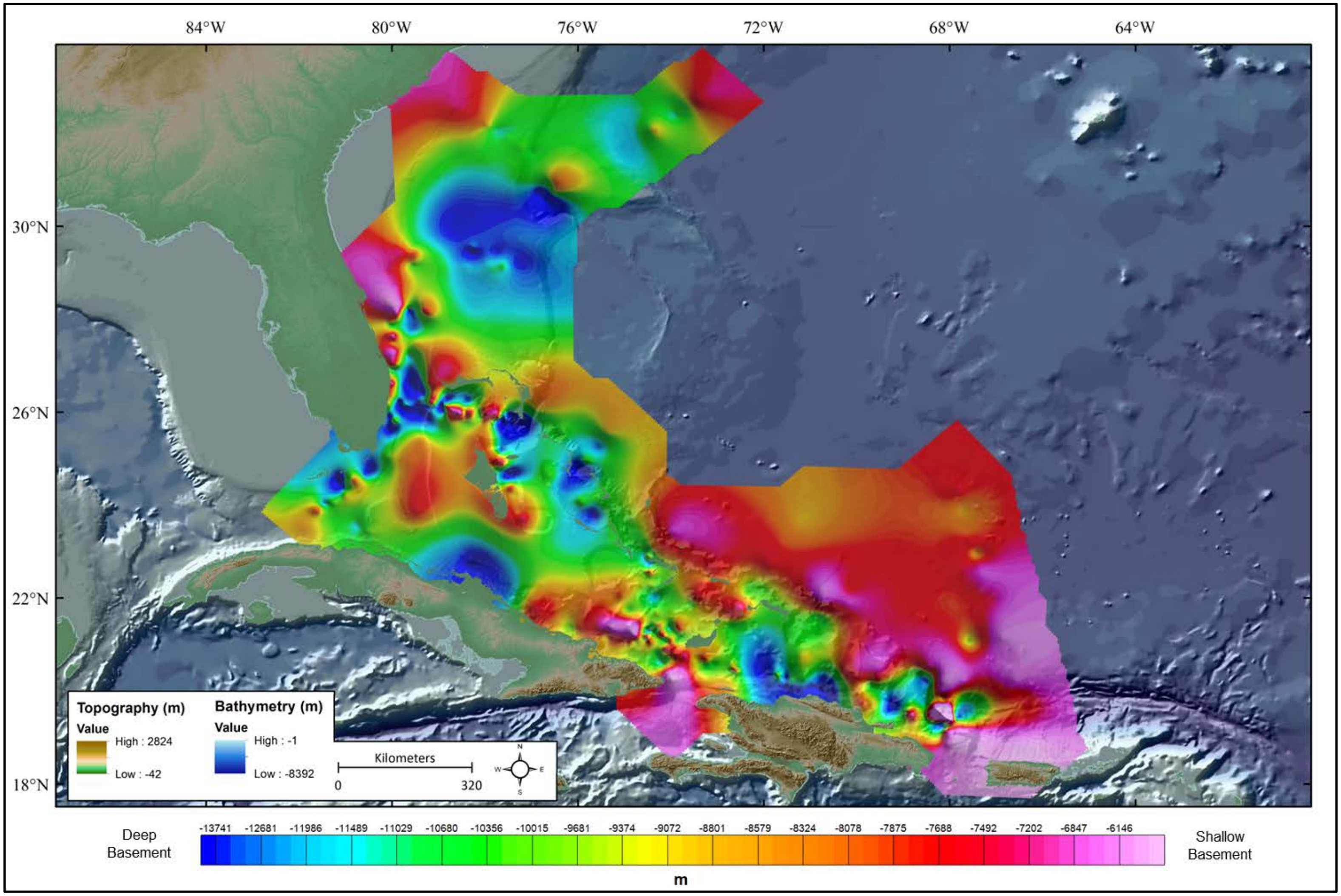


Figure 2.12 Magnetic depth-to-basement map in meters generated from 296 basement picks shown on map in Figure 2.6. The Kriging method was used to grid the picks.

(Marzoli *et al*., 1999). In the Early Cretaceous, numerous alkaline igneous plutonic/volcanic complexes developed in widely separated continental margin regions of eastern North America, Iberia, and western Africa. Later throughout the Cretaceous Period and Cenozoic Era, similar alkaline igneous events have marked many regions of the Atlantic seafloor with more than a hundred seamounts and volcanoes.

In contrast to the brief but enormous pulse of Early Jurassic CAMP magmatism, the Cretaceous and younger continent margin/ocean basin volcanoes were mainly localized events with mainly independent histories of activity (McHone, 2006). Despite the time gap of 70 Ma and the compositional gulf between quartz tholeiites and alkali olivine basalts (McHone, 2006). Some geologists have attempted to connect and explain these different igneous features through a model of a single, deep mantle plume. However, these models do not explain the geographic patterns and petrologic histories of numerous volcanic features in and around the central Atlantic Ocean, which must therefore be products of upper-mantle tectonics and lithospheric rifting (Marzoli, et al., 1999, McHone, 2006).

Analogous to the alkaline and tholeiitic magmatism of the CAMP is the Parana-Etendeca system in northern South America (Hawkesworth *et al.,* 2000). This region also contains the same lithospheric mantle origin for the extrusives as described the CAMP. During rifting of Pangaea, fragments of rifted continental crust were mixed to create a heterogeneous lithospheric mantle reservoir which has previously been interpreted as a purely continental crustal basement (McHone, 2006). However, this study supports the oceanic and volcanic origin of these tholeiitic seamounts upon which carbonate banks of the Bahamas platform continue to grow today.

Using algorithms in ArcGIS, the mantle plume focus point was calculated from the central intersection point dikes and sills dated and identified in North America, Africa, and South America (Fig. 2.13) (McHone, 2003). This plume focus point is within error of multiple other studies (Marzoli *et al.,* 1999; McHone, 2002; Schlische, *et al.,* 2002; Whiteside *et al.,* 2007). This point was then shown in a series of paleogeographic maps created utilizing the PaleoGIS software (red dot on parts A-E in Fig. 2.13).

LIPs and seamounts were outlined from the results of the gravity modeling earlier in this chapter and are also indicated on the reconstructions. Four geologic time period maps (200, 180, 160, 140 Ma) as well as one present-day map are shown in Figure 2.13.

At 200 Ma, rifting in the central Atlantic is occurring and CAMP volcanics are being extruded in close proximity to the present-day Blake Plateau as North American plate moved northwest from a fixed Pangea (Fig. 2.13A). By 180 Ma in Figure 2.13B, the majority of the CAMP volcanics have been extruded and the Bahamas carbonate platform has been growing for ~20 Ma (Fig. 2.13B). From 160 to 140 Ma, smaller seamounts are extruded in the newly formed oceanic crust produced from rifting of Pangea (Figs. 2.13C and D). By 140 Ma, the

Bahamas and Turks and Caicos have been created. The present-day configuration of the Bahamas is shown in Figure 2.13E.

The geometry of the Bahamas LIP area was little affected by the Paleogene collision Cuban segment of the Great Arc of the Caribbean (Saura *et al.,* 2008) since the Bahamas formed a thick and massive crustal edifice. This collision had a much more profound effect on the Great Arc of the Caribbean that changed its azimuth from northeast to due east. Figure 2.14 shows a summary of the potential hot spot track location which was overprinted by extensive carbonate growth since the Jurassic. The Hawaiian hotspot track can be used as a present-day analog for the sequence of events shown in Figure 2.13A-E where mantle plume volcanism pierces through oceanic crust and produces subaerially exposed volcanoes as the plate moves over the plume focus.

2.8 Conclusions

Gravity and magnetic modeling of the Bahamas are interpreted to be created on a thickened large igneous plateau crust with a 6-10-km thick crust that is thicker than normal, 4-6-km thick normal oceanic crust. Despite their thickness differences both LIP and oceanic crustal types are modeled to have the same density (2.8 g/cm^3). My interpretation is that volcanics were emplaced in the rift produced by crustal thinning as the North American plate moved away from Pangea and during the eruption of the CAMP plume.

The topographic expression of the Bahamas is a result of extensive and flourishing carbonate factory and growth since the Late Jurassic. Subsidence and sea level changes have aided in the vast growth of the platform overlying the original volcanic islands. The shape of the platform with a taper to the southeast is consistent with a more voluminous plume head followed by a more narrow and defined hotspot track. The Paleogene collision of the Bahamas platform appears to have little effect on the Bahamas carbonate platform due to its massive thickness. Some folding is present along the southeastern edge of the plateau and the suture with the Great Arc.

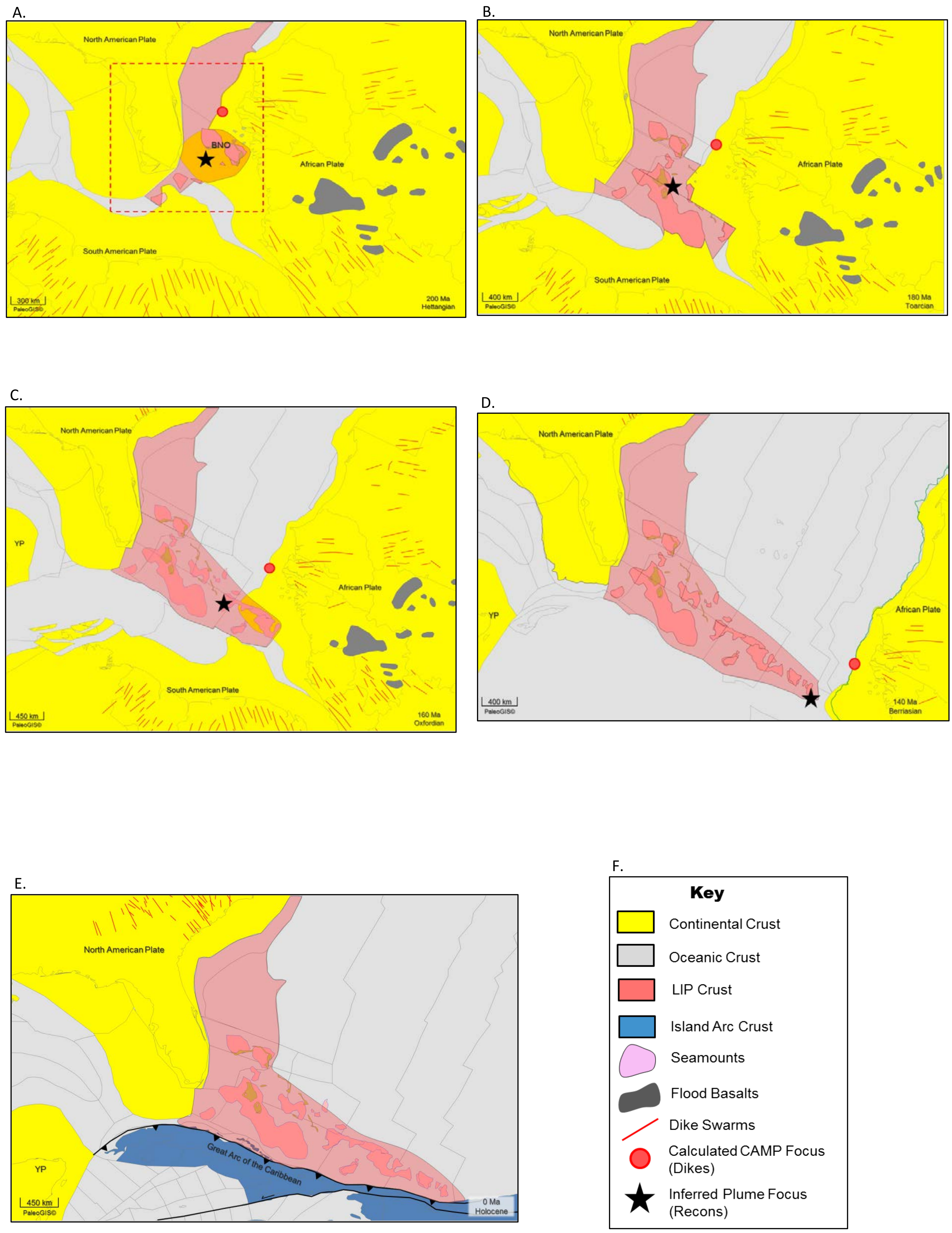


Figure 2.13 **(A)** Paleogeographic map at 200 Ma. Orientations of dike swarms (red lines) related to the CAMP event were used to calculate a plume focus location (red dot). This focus was found to be off the western coast of Senegal, Africa (18°7'45''W, 12°35'15''N). Flood basalts are shown in black. BNO = Blake Nose Overlap. **(B)** Paleogeographic map at 180 Ma. **(C)** Paleogeographic map at 160 Ma. **(D)** Paleogeographic map at 140 Ma. **(E)** Paleogeographic map at 0 Ma. YP = Yucatan Peninsula **(F)** Key for reconstructions.

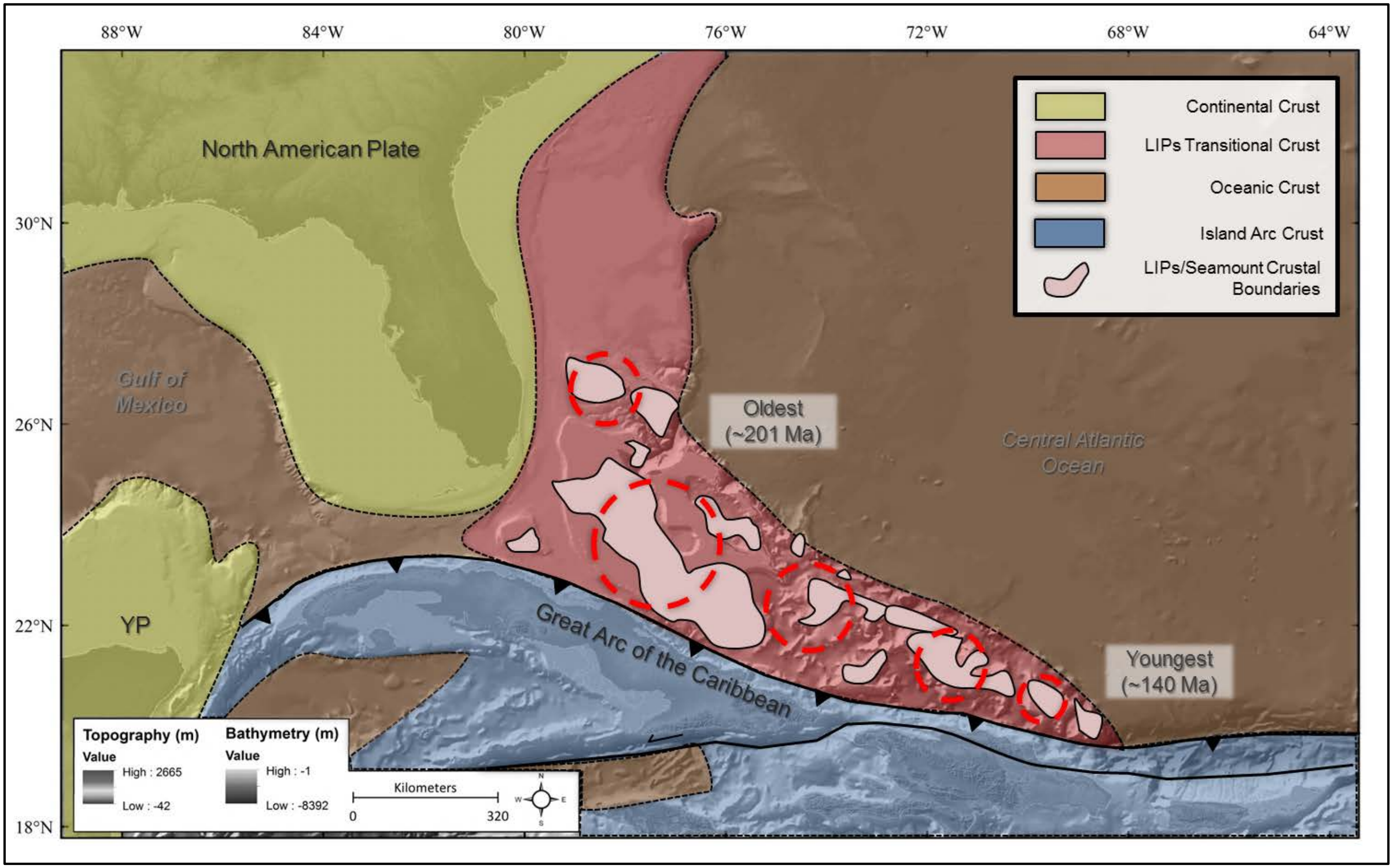


Figure 2.14 Map showing a potential hot spot track location which was covered by extensive carbonate growth beginning in Jurassic time. The earliest hotspot-related volcanics were extruded under the Blake plateau, while the largest volume of volcanism occurred under the Great Bahama Bank and waned as the southeastern Bahamas passed over the hotspot.

Chapter 3

Implications of a new, potential field-derived total sediment thickness map for petroleum exploration of the Bahamas carbonate platform

3.1 Petroleum system of the Bahamas carbonate platform

The Lower Cretaceous and Jurassic rocks of the South Florida and Bahamas lagoonal evaporite basin is characterized by alternating sequences of shallow water carbonates (limestone and dolomite) interbedded with evaporites (anhydrites) (Applin and Applin, 1965; Tator and Hatfield, 1975). The major difference between the Early Cretaceous and the Jurassic is that during the Early Cretaceous, halite and thin clastic sequences were deposited instead of only carbonate lithologies (Jacobs, 1977). The interbedded evaporites formed on a carbonate platform within an interior coastal margin setting and behind a barrier where active reef growth periodically occurred. The eastern Bahamas margin reef/marginal barrier carbonates have since been eroded during the Tertiary to Recent (Meyerhoff and Hatten, 1974). This has also occurred along the western shelf margin of south Florida (Meyerhoff and Hatten, 1974). However, these important Cretaceous-Jurassic barrier type reef/marginal carbonates have been documented within the subsurface and surface within Cuba (Bryant et al., 1969).

Exceptions to this general depositional sequence are present. In the southern interior part of the South Florida Basin thin halite sequences exist within the Lower Cretaceous (Aptian) of the Punta Gorda Formation (Applegate *et al*., 1981). Also, within the central, northern coastal area of Cuba, Middle to Upper Jurassic thick, salt sequences are present (Khudoley, 1967). Three salt diapirs, as delineated by their surface expression and well penetrations, are known to occur on the north coast of Cuba (Meyerhoff and Hatten, 1968). These salt diapirs, located and extruded along major thrust fault planes during the Middle Eocene, are direct evidence for widespread evaporitic depositional environments within the Jurassic.

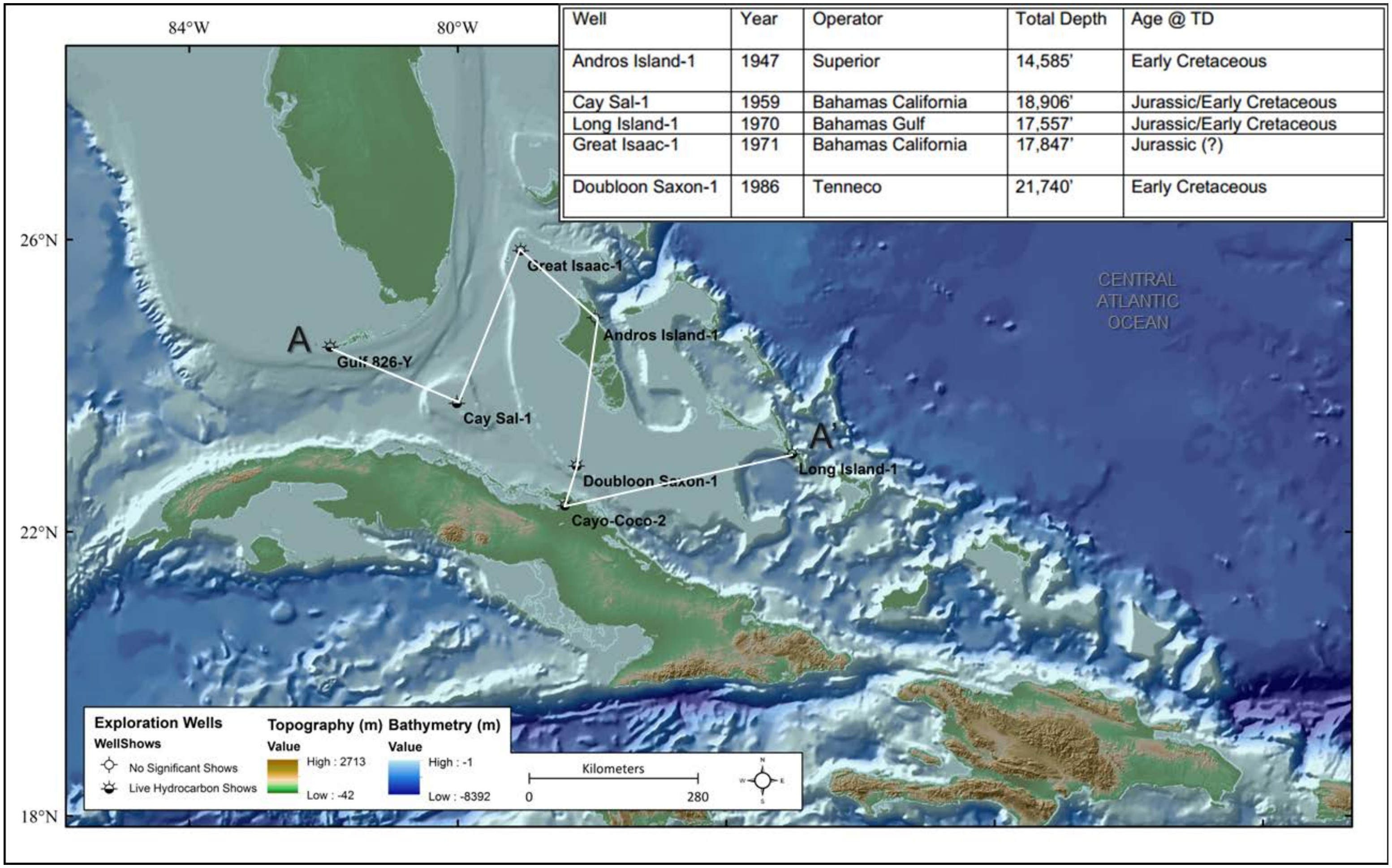
Figure 3.1 shows the location of wells used for the regional lithological and stratigraphic cross-section (Ramirez and Dames, 2011) (Fig. 3.2). This cross-section includes deep wells from Florida, Cuba, and the Bahamas and shows both lithology and stratigraphic age. The Doubloon Saxon well penetrated a 4000 m plus Early Cretaceous (Albian and Aptian) age section (Walles, 1993). This thickness compares with the regionally expected and thinner range of 1800-2400 m. The anomalous thickness at this location is interpreted to represent a stratigraphic repetition caused by a major thrust or reverse fault.

The most significant point derived from the correlation in Figure 3.2 is that within the Doubloon Saxon well the original anhydrite sequences (potential seals) have not been preserved within the upper repetition of the Lower Cretaceous (Albian-Aptian) section. These anhydrites have been deformed along with their hydrocarbon-sealing capability through tectonic and post-tectonic diagenetic alteration (i.e., hydrodynamically induced alteration). In the Bahamas region inboard of this narrow zone of deformation near Cuba, both anhydrites and halites form potential seals that likely still remain intact. Evaporites are important hydrocarbon seals of many giant oil fields in the world such as in the Persian Gulf and Permian basin of Texas (Mann *et al.,* 2001).

Halite (versus anhydrite) is considered to be the best seal type due to its increased ductility and resulting lack of permeability to hydrocarbons. Anhydrite sequences often do not have the superior seal characteristics of halites unless they are found in very thick (>30m) sequences. This is due to their lower ductility in the subsurface compared with halites. In the Doubloon Saxon well, these potential seals (anhydrites and halites) do not occur above 5050 m (Meyerhoff and Hatten, 1974).

Near the Doubloon Saxon well, an alteration of original rock lithology has occurred. It is proposed by Walles (1993) that this alteration is due to hydrodynamically induced alteration that has been focused through time along major faults. The proposed origin for the primary hydrodynamic head is from the deformation derived from the southwest in Cuba, where an island arc to continental margin collision occurred in the Paleogene (Walles, 1993).

Based on regional well control, the Bahamas region is an actively generating hydrocarbon basin (Meyerhoff and Hatten, 1974; Walles, 1993). This is documented on the A to A' regional cross-section (Fig. 3.2). Hydrocarbon shows are plotted with respect to quality. Live hydrocarbon shows can signify either actively migrating or trapped hydrocarbons. The quality of these shows is based on industry show classification standards for well cuttings, sidewall cores and conventional cores. Dead hydrocarbon shows can be indicative of either



Well	Year	Operator	Total Depth	Age @ TD
Andros Island-1	1947	Superior	14,585'	Early Cretaceous
Cay Sal-1	1959	Bahamas California	18,906'	Jurassic/Early Cretaceous
Long Island-1	1970	Bahamas Gulf	17,557'	Jurassic/Early Cretaceous
Great Isaac-1	1971	Bahamas California	17,847'	Jurassic (?)
Doubloon Saxon-1	1986	Tenneco	21,740'	Early Cretaceous

Figure 3.1 Basemap showing exploration wells in the Bahamas region including the Cay Sal-1 and Great Isaac-1 wells used in this chapter for subsidence and thermal modeling. Line A-A' is the line of section for the cross section shown in figure 3.2. Well information for major exploration wells in the Bahamas located in the table inset on the map.

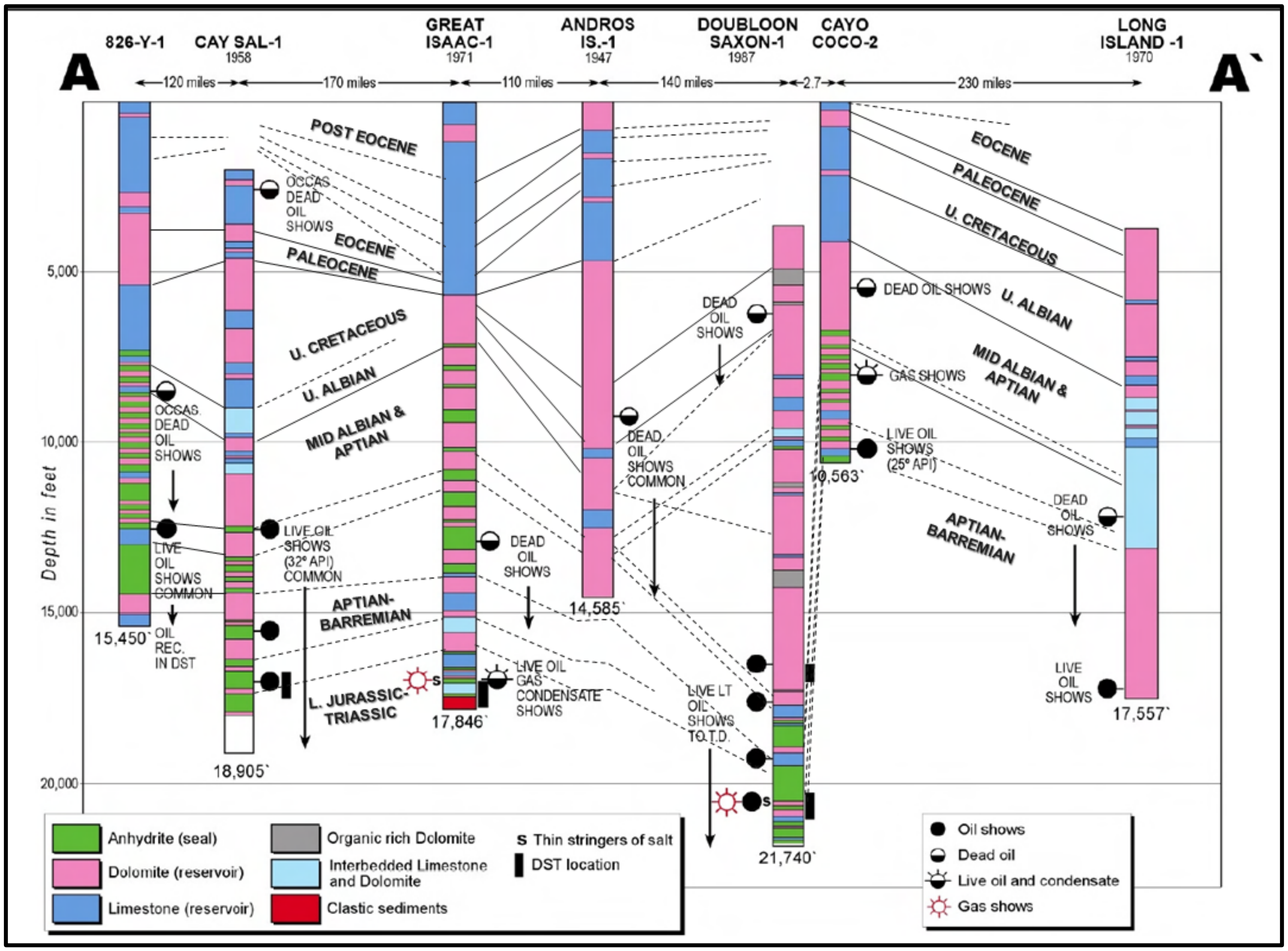


Figure 3.2 Well log cross section through exploration wells in the Bahamas modified from BPC, 2011, and Walles et al., 1993. Multiple oil and gas shows are indicated in most wells although none of these wells has been a commercial success. Anhydrite seals mostly found in deeper sections of the wells and dolomitic limestone reservoirs are widespread throughout the platform. Rocks shown as clastic sediments were reclassified as volcaniclastic beds by Jacobs (1977). Modified from BPC Ramirez and Dames, 2011 and Walles, 1993.

biodegraded or water-flushed hydrocarbons (i.e. tar mats) or immature hydrocarbons (carbonaceous material). Most significantly, dead hydrocarbon shows can signify a loss of seal or trap in a reservoir's past history. Of particular note on the cross-section is the distribution of live hydrocarbon shows versus dead oil shows. Live oil shows appear where evaporite seal sequences occur and dead oil shows typically appear where there is a lack or loss of evaporite seal sequences. The Doubloon Saxon well did exhibit live oil shows, but not until evaporite seal rocks were encountered at depth (5050 m).

Active hydrocarbon leakage in the greater Bahamas region has also been confirmed by the 1985 JOIDES Ocean Drilling Program with shallow, live gas and oil shows being reported (Katz, 1988; Proceedings of the Ocean Drilling Program) north of Grand Bahama Island at ODP Leg 101, site 627 (TD 163 m with BHF in Albian carbonates). Within the same program, Leg 101, site 632 located in Exuma Sound (eastern Bahamas) encountered marginally immature oil within Late Miocene carbonates. Evaluation of multiple source samples taken during ODP Leg 101 found above average to rich quantities of total organic carbon (TOC) percentages to ranging from 0.51-4.06 wt. % (Katz, 1988). Total sulfur content increased with carbon content which is typical of normal marine sediments and are consistent with either aerobic or poikiloaerobic conditions at the sediment/water interface, with sulfate reduction occurring in the subsurface (Katz, 1988). Rock-eval pyrolysis-derived hydrogen and oxygen indices plotted on a van Krevelen diagram show most rocks to contain type II and type III source material (Katz, 1988). Pyrolysis also calculated a transformation ratio (TR) and the temperature at which peak hydrocarbon generation occurs (T_{max}). These values were 0.10 and 435°C, respectively, indicating thermally immature samples that have not yet entered the peak hydrocarbon generation and expulsion phase (Katz, 1988).

A significant analog could be the Sunniland Field Trend in southern Florida (within the Lower Cretaceous Lagoonal Evaporite Basin) where up to 100 million barrels of recoverable oil is reported to occur within the Sunniland Formation limestones, top-sealed by Albian anhydrites, within ten field accumulations (Halley, 1985). In addition to the Sunniland Formation, oil shows have been reported in the deeper Brown Dolomite Formation dolomites, which are also between potentially sealing anhydrites (Lower Aptian) and are considered an important future objective in the offshore portion of the South Florida Basin (Applegate, 1981). As mentioned earlier, the origin of the saline fluids for the proposed alteration of the evaporites (original seal capacity) is dynamically tied to the unique tectonic position of the western margin of the Bahamas (Sheridan et al., 1981; Pindell and Dewey, 1982; Kligord et al., 1984; Ball et al., 1985).

Figure 3.3A illustrates the division of the region into the crustal provinces defined in Chapter 2 and compared to the total sedimentary thickness map based on gravity and magnetic modeling in Chapter 2. These crustal provinces help illustrate that the Bahamas region has had a major tectonic overprint of an island arc to LIP margin collision primarily during the Lower Tertiary (Ball et al., 1985; Masaferro *et al.* 1999; Pindell *et al.,* 2005; Cruz-Orosa *et al.,* 2012a).

Critically, this collision event occurred after the deposition of the Lower Cretaceous evaporites (seal rock) so this event may have caused certain areas of the platform to be uplifted and eroded and lose their critical evaporitic seal for preserving hydrocarbons.

It is because of the lack of a successful exploration campaign in the Bahamas that further subsidence and thermal modeling is necessary to predict the locations of the hydrocarbon-filled reservoirs to increase the chance of future exploration successes.

3.2 Methodology

Two of the deepest penetrating wells in Bahamas exploration history were used to study the subsidence and thermal history of the region to shed light on the potential reason for a lack of significant hydrocarbon discoveries. These models are then compared to a model from the southeastern United States.

The Cay Sal IV-1 well was drilled in 1958-1959 by the Standard Oil Company of California and the Gulf Oil Corporation on Cay Sal, in the northwestern region of the Bahamas (Figure 3.1). At total depth 5,766 m (18,906 ft) the well was in shallow-water carbonates and anhydrites of Early Neocomian or Late Portlandian age (Meyerhoff and Hatten, 1974).

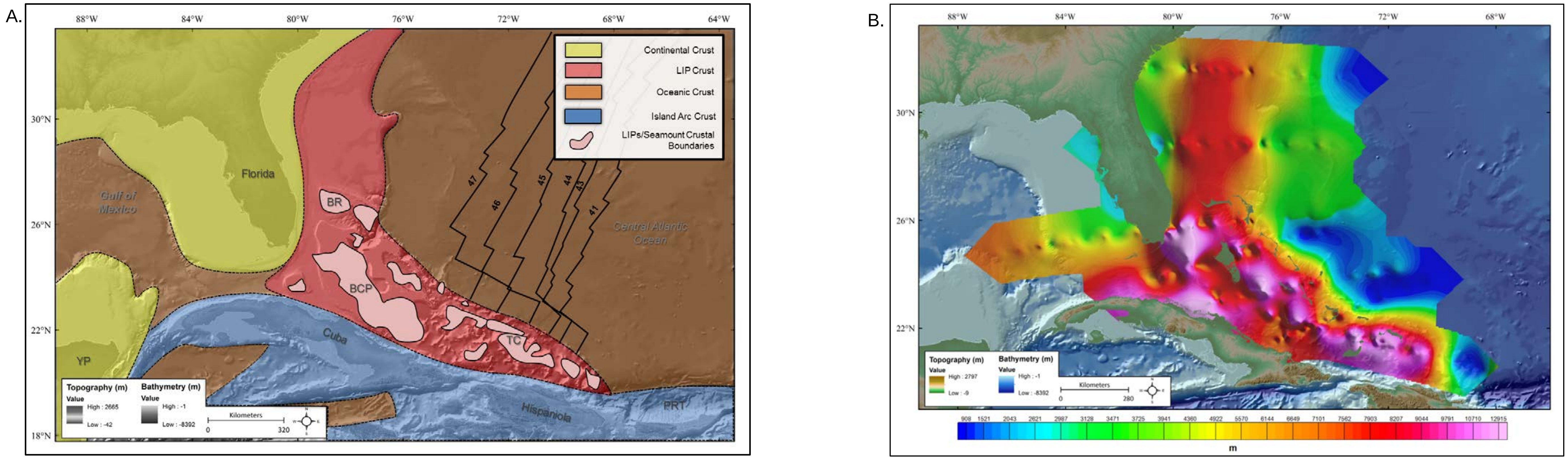


Figure 3.3 **(A)** Summary of crustal types of the eastern Gulf of Mexico, Florida, Atlantic margin of the southeastern USA, and the Bahamas area based on the gravity and magnetic models shown in Figures 2.7, 2.8 and 2.10. Crustal provinces in the Yucatan basin are from Rosencrantz (1990), the Cayman trough are from Leroy et al. (1996) and the Gulf of Mexico are from Bird et al. (2005). Offshore western Florida continent-ocean boundary (COB) is shown in yellow long-dashed line. Large igneous plateau crust of the Bahamas and southeastern North America are shown with a red dashed line. The transitional to oceanic crust boundary between the eastern North America, Bahamas and the Central Atlantic is shown in orange small dashes. World magnetic isochrons from give reference = black lines; BR = Blake Ridge; BCP = Bahamas carbonate platform; TC = Turks and Caicos; PRT = Puerto Rico Trench; YP = Yucatan Peninsula. **(B)** Sediment thickness grid from the gravity modeling showing the difference in sediment thickness of the LIP crust than that of the continental crust beneath North America and oceanic crust of the Atlantic Ocean.

The Great Isaac-1 well was drilled in the northeastern Great Bahama Bank by the Standard Oil Company of California during 1970-1971 to a total depth of 5,443 m (17,847 ft; Meyerhoff and Hatten, 1974). Drilling reports indicate the well encountered Jurassic red beds at a depth of 5,355 m (17,570 ft) that persisted to TD (Jacobs, 1977; Figure 3.2). These volcaniclastic beds at TD of the Great Isaac-1 well are typically associated with the edge of continental crust.

In 1972, Florida well #46 was drilled in central Florida (Personal Communication, Dale Bird). This well was drilled to a depth of 7810 m (25,620 ft) and hit TD in continental crustal granites. Many wells drilled in Florida encountered diabase sills in the Jurassic age Eagle Mills Formation. These sills have been attributed to the volcanic activity of the CAMP plume head in the Jurassic; sills of the same age are found on multiple continents affected by CAMP (Marzoli, 1999). I use this well to test the subsidence rates of continental crust versus that of the volcanic crust modeled in this study beneath the Bahamas. To study the subsidence and thermal history using the two wells, PetroMod 1D modeling software was employed.

3.3 Tectonic setting for subsidence of the Bahamas region from the Mesozoic to the Recent

The Bahamas have experienced a long tectonic history beginning with rifting from the supercontinent Pangea during the Triassic to create the North and Central Atlantic. The Bahamas area restore to a triple junction with the Guinea Nose and Demerara Rise (Chapter 2). Pangea continued to rift like a zipper to the south, creating separation between North America, South America, and Africa. As previously proposed in this paper, seamounts and LIPs pierced the newly formed oceanic creating thicker, denser crust near the surface of this shallow seaway, creating prime environments for a thriving growth of the carbonate banks. The Bahamas were in a passive margin stage up until the collision with Cuba ~60 Mya and continued to ~35 Mya (Mullins *et al*. 1991, Walles, 1993, Saura, 2008).

Figure 3.2 shows the location of the well log cross section for figure 3.3. Well log cross sections show the complexity of correlating beds in the distant exploration wells throughout the region. Thick dolomites and limestone beds have accumulated and kept up with sea level fluctuations. Anhydrites are believed to mark subaerial exposures and are thought to be the main seals in the petroleum system. These limestone-seal sequences dominate the stratigraphy of the Bahamas and document a long history of a thriving carbonate system that remained near sea level in a tropical setting.

Parameters and constraints

In this subsidence modeling, multiple parameters were used as inputs into the modeling software to determine the subsidence and thermal history for the region to determine source rock maturity and the overall chances of success of petroleum exploration in the Bahamas. Along with well logs and lithologies from the Cay Sal IV-1 and Great Isaac-1 wells, the information from the modeling in Chapter 2 is also used to generate the inputs for the modeling in PetroMod. These data are used to determine layer thicknesses, densities, velocities, and rock types. Inputs for the wells came from a compilation of well analyses by Meyerhoff and Hatten (1974), Schlager *et al.* (1988), Furrazola *et al.* (1964, 1968).

Results of subsidence modeling

The 1D PetroMod subsidence modeling shows subsidence on the order of 6 km since the Early Jurassic time (Figures 3.4a and 3.5a). The lack of tectonic subsidence from the Late Triassic/Early Jurassic shows the presence of the CAMP plume uplifting the basement to the surface. Large subsidence occurred during the Early Cretaceous possibly related to the final stages of rifting in the area.

These events affected the two areas of deep wells differently. In the west (Cay Sal-1), a large subsidence event lasts from ~130 Ma to ~100 Ma, while in the northeastern Bahamas (Great Isaac-1), this event only lasts around 10 Mya, from ~130 to 120 Mya. The western region continues to subside at more rapid

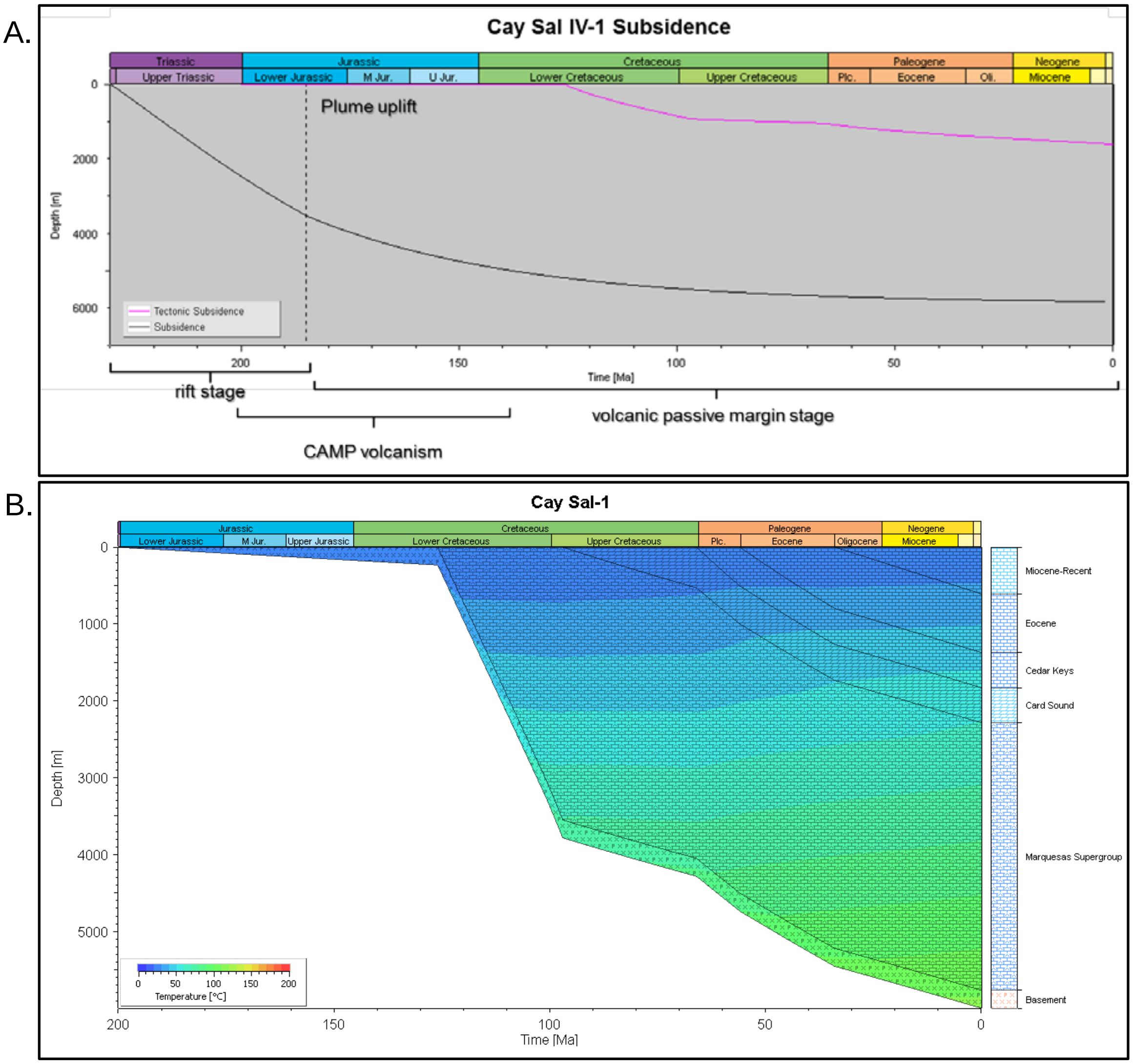


Figure 3.4 **(A)** subsidence history plot of the Cay Sal-1 well. **(B)** Thermal history plot of the Cay Sal-1 well.

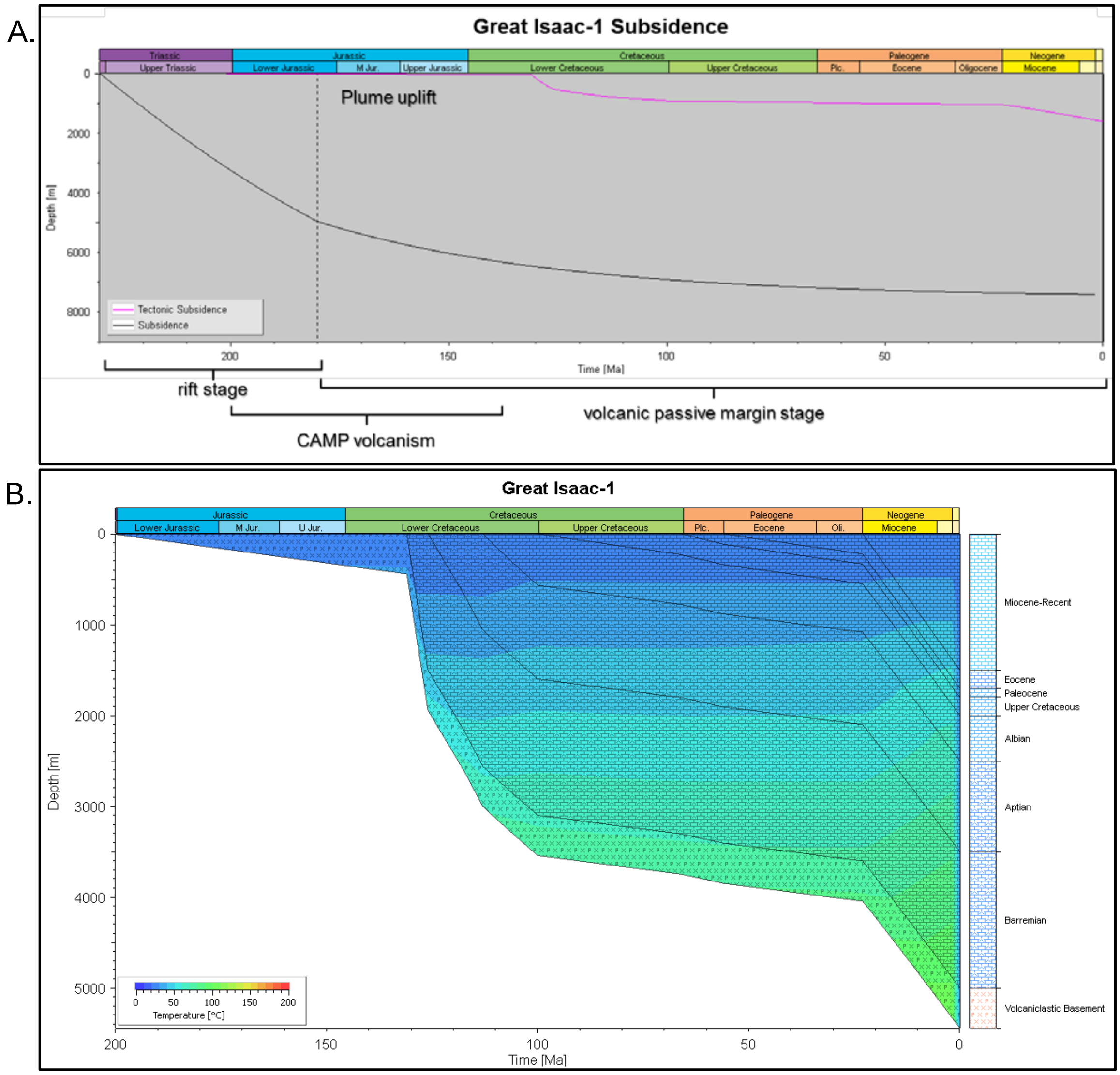


Figure 3.5 **(A)** subsidence history plot of the Great Isaac-1 well. **(B)** Thermal history plot of the Great Isaac-1 well.

rates than that seen on the continental crust proposed in the Florida block to the north. Modeling shows the northern region experienced an enigmatic, rapid subsidence event in the Early Miocene and has continued to recent times. Thermal modeling shows temperatures in the base of the Bahamas carbonate-evaporite basin and thought to contain source rocks of Late Jurassic and Early Cretaceous age to be approximately 120-130°C.

3.4 Conclusions: Implications for future hydrocarbon exploration

The petroleum prospectivity and source rock maturity of the Bahamas may be closely controlled by the basement type (continental, thinned continental, LIP) of the Bahamas and is focused to the northeastern portion of the Bahamas platform. Since the Bahamas have a thick, dense, volcanic intrusive basement it has allowed for much more subsidence than the North American continent just across the Straits of Florida (6 km versus ~2 km) (Sawyer, 1985). The carbonate platform has thrived during sea level fluctuations and subsidence creating a thick carbonate accumulation since the Jurassic.

However, with low heat flow of 40 mW/m^2 allowed through the basement, lower Jurassic source rocks would be present within the oil generation window only since the Eocene for the Cay Sal-1 well and the Miocene for the Great Isaac-1. This could explain the lack of wider spread commercial hydrocarbon accumulations in reservoirs in the few wells drilled on the platform and surrounding areas (Fig. 3.2). Also, seal failures could have released hydrocarbons from reservoirs as a result of the collision with Cuba and other tectonic events that fractured the evaporitic seals, especially in a narrow deformed zone near the Cuban suture zone (Walles, 1993) (Fig. 3.3). Reservoir-seal pairs are found when the platform has thrived and remained stable and undeformed and either: 1) became subaerially-exposed to produce a hard karst or evaporite sequence above the porous limestones; or 2) drowned and became blanketed by a thick shale layer deposited during the middle Cretaceous (Denny et al. 1994). Both events have been found in cores and wells in the Bahamas (Fig. 3.2).

Though deeper drilling may eventually find large oil accumulations with evaporate seals, the expensive and high-risk nature of a drilling program in the Bahamas has left the region unfavorable to current exploration and fiscal conditions. The Bahamas benefits from a fiscal structure that includes no corporate tax and a sliding royalty that could make even the most modest discovery commercial. The farm-in by Statoil provides not just an implied value but also credibility that accompanies the involvement of a major with deep water experience and validation of the opportunity. Any commercial find would be located within 200 miles of the USA, which is the world's largest energy market.

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