TECTONIC EVOLUTION OF THE WEST FLORIDA BASIN,

EASTERN GULF OF MEXICO

by

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ABSTRACT

Basement geometry of the Eastern Gulf of Mexico developed following the breakup of Pangea and the opening of the Gulf of Mexico in Late Triassic time. Nine 2-D pre-stack depth migrated seismic profiles and a structural restoration provide insight into the evolution and development of the southern West Florida Basin, located west of the Florida Escarpment in the Eastern Gulf of Mexico. Seismic reflection profiles reveal basement structures probably developed following a combination of Late Triassic extension and extension and subsequent oceanic crust emplacement in Middle Jurassic time. During Late Triassic rifting, the West Florida Basin developed as a rift graben; however, the graben was later dissected during the Middle Jurassic drift episode. Absence of faulting, syn-rift deposition and sagging in the Lower Cretaceous seismic section indicates that extension and rotation of the Yucatán block must have stopped prior to Cretaceous time. After extension terminated and the Gulf of Mexico reached its modern day configuration, subsidence from lithospheric cooling and sediment loading dominated throughout Cretaceous time. A structural restoration confirms that following Late Triassic rifting, basement topography remains relatively elevated to the south in the West Florida Basin. Subsequent extension and subsidence further dissected the basement allowing for the deposition of Middle and Late Jurassic syn-rift and Cretaceous post-rift sediments.

Because of the lack of well control in the West Florida Basin, seismic packages are correlated northward to the northern margin of the West Florida Basin and slope, the Tampa

Embayment, and the Apalachicola Basin and southward to the Straits of Florida and Yucatán. Seismic interpretations reveal two syn-rift packages, Triassic-Jurassic (TJ) and Jurassic-Cretaceous (JK), and one post rift package, Early Cretaceous (EK), were deposited prior to the Mid-Cretaceous Sequence Boundary, a basin-wide unconformity that marks the termination of subsidence related to lithospheric cooling. These seismic packages are the southern equivalents of stratigraphy in the northeastern Gulf of Mexico, and may include the petroliferous Norphlet and Smackover Formations. Oceanic or 'proto-oceanic' crust in a transitional zone between oceanic and continental crust is interpreted in central West Florida Basin, where there is little brittle faulting and a change in seismic character of basement. This interpretation is further validated by bright basinward shallowing reflectors within the basement that may represent a Moho/detachment that facilitated extension and oceanic crust emplacement.

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1. INTRODUCTION

The Gulf of Mexico (GoM) has been a target for oil and natural gas exploration for close to a century. As a result, large amounts of geological and geophysical data have been collected and interpreted to determine its hydrocarbon potential; yet, the Mesozoic tectonic development of the GoM remains unresolved. The western and central GoM regions, where a majority of exploration is conducted, are not conducive for studying the Triassic and Jurassic tectonic history because thick packages of sediments and complicated salt tectonics prevent quality imaging of the rift related structures. The Eastern Gulf of Mexico (EGoM) has relatively thin overlying sediments and little to no salt tectonics, creating an ideal setting to study rift geometries developed during the opening of the GoM (Figure 1). However, the EGoM remains relatively understudied. Uneconomic production in the 1970's within the EGoM resulted in a lack of enthusiasm for data collection and exploration along the Florida Gulf coast (Dempsey, 2003). This lack of enthusiasm, in addition to a current drilling moratorium in the EGoM, stagnated efforts to determine the tectonic and sedimentary evolution.

Successful onshore production of the Norphlet and Smackover Formations, primary Mesozoic reservoir and source rocks, respectively, has renewed industry interest in the rocks of offshore Alabama, Mississippi, and Florida. The Norphlet and Smackover Formations are present in the northern EGoM (Addy and Buffler, 1984; Dobson and Buffler, 1997; Mancini et al., 2001), spurring new geophysical and geological data collection to resolve the lateral extent of the potential reservoir and source rocks (MacRae, 1994; Dobson and Buffler, 1997; Wilson,

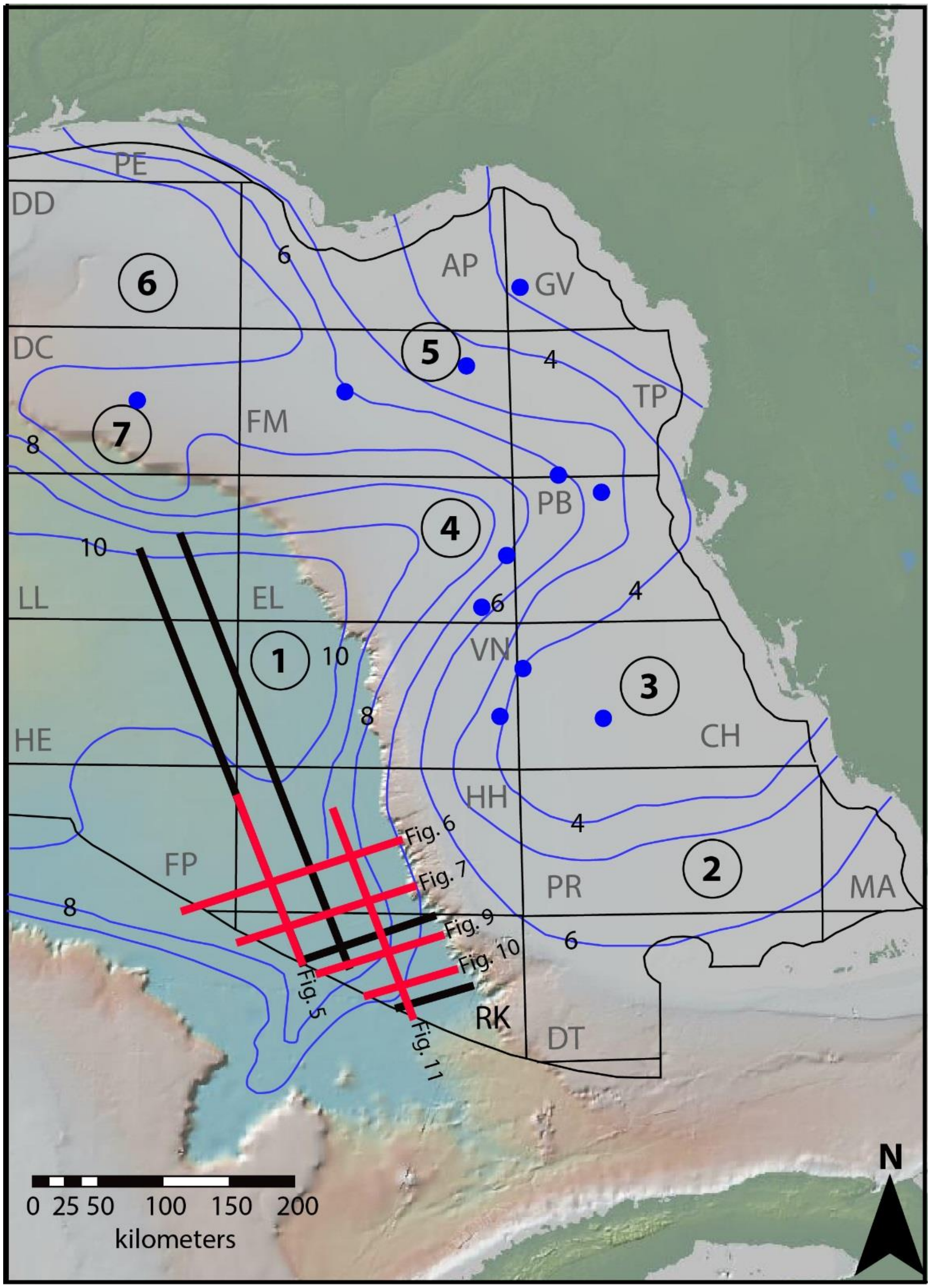


Figure 1. Basement contour map showing locations of major rift related structures in the EGoM that are discussed in text: 1) West Florida Basin; 2) South Florida Basin; 3) Sarasota Arch; 4) Tampa Embayment; 5) Middle Ground Arch; 6) DeSoto Canyon Salt Basin; 7) Southern Platform. Thick black lines are seismic reflection profiles used in this study with figure locations marked. Depth to basement (in blue) is in kilometers from Sawyer et al. (1991). Thin black lines denote protraction areas in the EGoM. Blue dots indicate well locations.

2011) as well as sediment provenance and pathways that aid in the determination of paleotopography of basement rocks following rifting (Hunt, 2012; Lovell, 2013). Because rift related features are more easily imaged in the EGoM, a variety of tectonic models concerning the early evolution of the EGoM have been proposed without much agreement (i.e., Klitgord et al., 1984; Pindell, 1985; Marton and Buffler, 1994; MacRae and Watkins, 1996; Pindell and Kennan, 2001; Kneller and Johnson, 2011; Wilson, 2011).

The geometry of basement and rift related features in the central and southern EGoM remains largely unresolved and are generally excluded in the development of tectonic models because of inadequate data coverage. Deep southern EGoM (i.e. the Straits of Florida and Yucatán, north of Cuba) basement structures were reviewed by Schlager et al. (1984) and Marton (1995) and incorporated in a tectonic model created by Marton and Buffler (1994). However, a complete analysis of the EGoM basement is necessary to confirm the validity of the tectonic models. The basement geometry in the West Florida Basin can contribute to research regarding NW-SE extension during Late Triassic rifting of Pangea and NE-SW extension and oceanic crust emplacement (?) during Middle Jurassic 'drift' of the Yucatán continental block (Klitgord et al., 1984; Pindell, 1985; Buffler and Sawyer, 1985; Salvador, 1987, 1991).

This study focuses on the structural and sedimentological evolution of the West Florida Basin located in the central and southern EGoM (Figure 1). Using interpretations from 2-D post-stack depth migrated seismic reflection data (PSDM) and research in adjacent regions, I infer the relative ages of rift related stratigraphy and structures. Lack of well data prevents definitive determination of the ages of seismic packages; thus, I present preliminary interpretations regarding the depositional setting, age, and lithology of stratigraphy. I use these interpretations to refine the timing of the development of rift related basement features. In addition, I structurally restore a PSDM seismic reflection profile and remove the effects of sedimentation, compaction, and subsidence related to sediment loading and thermal cooling from extension to visualize basin development through time.

The West Florida Basin is located west of the Florida Escarpment in the deep water of the central and southern EGoM. Previous studies regarding the stratigraphy in the region are from Phair (1984) in the southwestern Straits of Florida and Lord (1986) and DeBalko (1991) in the West Florida Basin. Data coverage includes over 2000 km of seismic reflection profiles that lie within the Rankin, Howell Hook, Florida Plain, Henderson, Vernon Basin, and Lloyd Ridge protraction areas (Figure 1).

2. GEOLOGIC SETTING

2.1 Tectonic Setting

The supercontinent Pangea, an amalgamation of Laurentia and Gondwana, formed in Late Permian time following the closure of the Iapetus Ocean (Salvador, 1987). In the wake of a period of tectonic quiescence in Early to Middle Triassic time, the opening of the GoM began in Late Triassic time as western Pangea rifted apart, separating the North American plate from the South American and African plates (Klitgord et al., 1984; Pindell, 1985, Salvador, 1987). Extension is recorded in a rift system and rift related igneous rocks that extend along the east coast of North America from Canada to northwestern South America (Pindell, 1985; Buffler and Sawyer, 1985; Salvador, 1987; Bartok, 1993). The closing and reopening of Pangea may have controlled the structural architecture and rift trends in the GoM (Pindell, 1985; Salvador, 1991; Sawyer et al., 1991; MacRae, 1994; Bartok 1993; Marton and Buffler, 1993).

In the EGoM, Late Triassic rifting and extension is observed in a series of NE-SW trending paleo-highs and paleo-lows (Figure 1) that developed along the present day Gulf coast of Florida (Klitgord et al., 1984; Buffler and Sawyer, 1985; Sawyer et al., 1991). The geometry of these basement grabens and half grabens suggests maximum extension to the NW-SE (Buffler and Sawyer, 1985; Salvador, 1987; MacRae and Watkins, 1996; Pindell and Kennan, 2001; Wilson, 2011). These paleo-lows created accommodation space for the deposition of Early Mesozoic syn-rift rocks that are of interest to oil companies. Though the large scale plate motions in which Pangea opened have been determined, small scale motions and mechanisms that led to the opening of the EGoM, including transform faults, rotation, or pure extensional stress, during Late Triassic time remain unresolved. Many researchers postulate extension in the EGoM occurred along regional NW-SE trending transform faults located to the north and/or south of the EGoM paleo-highs and paleo-lows (Klitgord et al., 1984; Marton and Buffler, 1994; MacRae and Watkins, 1996; Pindell and Kennan, 2001), while others refute the existence of such transform faults (Wilson, 2011; Kneller and Johnson, 2011). Tectonic models proposed to explain Triassic extension are further discussed later in the chapter. The first generation of extension involved in the formation of the GoM ended in Early or Middle Jurassic time (Salvador, 1991; Marton and Buffler, 1994; MacRae and Watkins, 1996; Pindell and Kennan, 2001).

A second generation of extension occurred in a NE-SW direction and began in Middle Jurassic (Callovian) time following widespread deposition of Callovian aged salt in the central Gulf region (Pindell, 1985; Salvador, 1987; Bird et al., 2005), though some models suggest salt deposition continued during extension (Marton and Buffler, 1994). Tectonic movement during this time incorporates the counterclockwise rotation of the Yucatán continental block from its paleogeographic position near the modern day coasts of Texas and Louisiana to its present day location at the southern margin of the GoM (Pindell, 1985; Buffler and Sawyer, 1985; Marton and Buffler, 1994; Pindell and Kennan, 2001; Bird et al., 2005; Kneller and Johnson, 2011). Rotation of the Yucatán plate during the Middle Jurassic drift phase is inferred to have moved along a large transform fault in eastern Mexico (Pindell, 1985; Buffler and Sawyer, 1985; Salvador, 1987, Bird et al., 2005). In the EGoM, extension resulting from the rotation of the Yucatán block exhibits NW-SE striking rift related features as a result of NE-SW directed maximum extension (Phair, 1984; Pindell et al., 2006; Wilson, 2011). Rotation and extension during the second generation of tectonic movement lasted until Late Jurassic (Kimmeridgian) time (Kneller and Johnson, 2011), Early Cretaceous (Berriasian) time (Klitgord et al., 1984; Pindell, 1985; Marton and Buffler, 1994; Bird et al., 2005; Wilson, 2011) or continued rifting throughout Cretaceous time (Schlager et al., 1984).

2.2 Distribution of Crust in GoM

The distribution of crust following extension consists of faulted, attenuated continental, or ‘transitional’, crust possibly surrounding oceanic crust in the central GoM (Figure 1; Buffler and Sawyer, 1985; Sawyer et al., 1991; Dobson and Buffler, 1991). Crustal attenuation is a result of lithospheric extension and thinning during both episodes of extension. Landward on all sides of central GoM, the degree of extension decreases and crust transitions from oceanic (?) crust in the central GoM to highly attenuated, thin transitional crust to less attenuated, thick transitional crust. In the EGoM, transitional crust underlies basins that contain Mesozoic source and reservoir rocks (Buffler and Sawyer, 1985; Sawyer et al., 1991). From north to south, the EGoM basins are the Apalachicola/DeSoto Canyon Salt Basin, the Tampa Embayment, the South Florida Basin, and the West Florida Basin to the west, which may be the deep water extension of the Tampa Embayment (Figure 1; Buffler and Sawyer, 1985; Lord, 1986; Dobson and Buffler, 1997; Wilson, 2011). The transition from thin transitional crust to the thick transitional crust underneath the EGoM basins is interpreted to occur at a tectonic hinge zone, which is roughly defined in some areas of the EGoM by the Florida Escarpment (Buffler and Sawyer, 1985; Corso et al., 1989; Sawyer et al., 1991; DeBalko, 1991; MacRae and Watkins, 1996; Kneller and

Johnson, 2011), though not in the Tampa Embayment (Wilson, 2011). Basinward of the Florida Escarpment, or the hinge zone, areas of thin transitional crust experienced greater amounts of subsidence and therefore received thicker deposits of Mesozoic sediments (Buffler and Sawyer, 1985).

Oceanic crust emplacement may have occurred during the drift episode in late Middle Jurassic time, contemporaneous with the rotation of the Yucatán continental block (Buffler and Sawyer, 1985; Salvador, 1987; Sawyer et al, 1991; Marton and Buffler 1994; Bird et al., 2005). However, the presence and distribution of oceanic crust is still controversial and to determine the presence of oceanic crust more adequate coverage of seismic refraction data is necessary (Ross, et al., 2011). The emplacement of oceanic crust is proposed as a consequence of the rotation of Yucatán block in various tectonic models (Buffler and Sawyer, 1985; Salvador, 1991; Hall and Najmuddin, 1994; Marton and Buffler, 1994; Pindell and Kennan, 2001; Bird et al., 2005; Kneller and Johnson, 2011). Evidence used to support the presence of oceanic crust includes the large salt free region in the central gulf flanked to the north and south by large salt provinces that are interpreted to have been separated during oceanic crust emplacement; gravity and magnetic anomalies along the Florida and Yucatán carbonate margin; and crustal velocities and thicknesses from refraction data (Klitgord et al., 1984; Buffler and Sawyer, 1985; Marton and Buffler, 1994). The seismic profiles in this study cover the region of proposed oceanic crust emplacement and bordering thin transitional crust (Buffler and Sawyer, 1985; Marton and Buffler, 1994; Hall and Najmuddin, 1994; Bird et al., 2005).

2.3 Tectonic Models

Existing interpretations regarding basement geometry and seismic stratigraphy in basins in northern and southern EGoM are from Phair (1984), Lord (1986), DeBalko (1991), Dobson (1991), Marton (1995), Dobson and Buffler (1997), and Wilson (2011). Prevailing tectonic models for the Late Triassic rift phase during the opening of the GoM include sinistral SE transform motion of a continental block composing the southern tip of Florida and the Bahamas, the Florida continental block (Pindell, 1985; Klitgord et al., 1984; Marton and Buffler, 1994; MacRae and Watkins, 1996; Pindell and Kennan, 2001). These models are challenged by models that do not contain large transform faulting due to the lack of strike-slip related structures in the EGoM (i.e. Wilson, 2011; Kneller and Johnson, 2011). Kneller and Johnson (2011) argue that the Florida continental block underwent counterclockwise rotation rather than transform motion. The incorporation of movement of the Florida continental block, similar to those models suggesting transform motion, addresses the issue of continental overlap of Florida and Africa in restorations attempts of conjugate margins of Pangea to Triassic pre-rift positions. Wilson (2011) hypothesizes that Late Triassic rifting is a result of purely extensional stress, which can still account for NW-SE extension observed in the EGoM, but does not address issues that may arise during restoration attempts, such as continental overlap of Florida and Africa. Another possible solution may incorporate the movement of an Euler pole from the west to the east during the 2 generations of extension.

MacRae and Watkins (1996) use seismic reflection data and well interpretation in Desoto Canyon Salt Basin to postulate that development of the basement lows in the EGoM (Figure 1) occurred as a result of oblique-shear extension within two laterally extensive NW-SE transfer faults. The southernmost fault roughly corresponds with the Florida Escarpment in the EGoM. Klitgord et al. (1984) suggest Triassic rifting occurred within similar extensional corridors separated by fracture zones and hinge zones. They suggest that the paleo-highs that surround the EGoM basins (Figure 1) developed as isolated horst blocks following extension in the EGoM.

Marton and Buffler (1994) propose sinistral movement along a single transform fault that moved the Florida continental block from its paleo location between the Yucatán block and northwestern Florida to its present location as southern tip of Florida. Similarly, a tectonic model by Pindell (1985) and subsequent revisions (e.g., Pindell and Kennan, 2001) postulate movement along a single transform fault that transferred the Florida continental block from central GoM to south EGoM in Late Triassic time. Additionally, they suggest the transform fault trends across the location of the Tampa Embayment, creating a pull apart basin (Pindell and Kennan, 2001). The location of this transform boundary corresponds with the transition between thin transitional and thick transitional continental crust, which roughly coincides with the location of the Florida Escarpment (Pindell, 1985). Recent tectonic models agree on the counterclockwise rotation of the Yucatán continental block in Middle Jurassic time (Pindell, 1985; Buffler and Sawyer, 1985; Salvador, 1991; Marton and Buffler, 1994; MacRae and Watkins, 1996; Pindell and Kennan, 2001; Bird et al., 2005; Kneller and Johnson, 2011; Wilson, 2011).

2.4 Stratigraphy

Extension and subsidence in EGoM created paleo-lows in Paleozoic and older basement rocks and accommodation space for the deposition of syn- and post-rift rocks (Buffler and Sawyer, 1985; Sawyer et al., 1991; Dobson and Buffler, 1991). Syn-rift rocks in northern EGoM are the Late Triassic to Middle Jurassic rocks of the Eagle Mills Formation, Werner Anhydrite and Louann Salt, sandstone and carbonate rocks of the Norphlet and Smackover Formations, respectively, and the sandstone, shale, and shallow and deep marine carbonate rocks of the Haynesville Formation and the Cotton Valley Group (Dobson and Buffer, 1997) (Figure 2).

Geologic data from wells drilled in the basins in the north EGoM, including onshore Alabama and Mississippi, support the presence of Mesozoic rocks in depocenters (Dobson and Buffler, 1997; Mancini et al., 2001). Lack of geologic data for lower Mesozoic rocks in and near the West Florida Basin prevents absolute determination of the lithology and the formation names. Instead, we divide the units into discernable seismic packages and then, from nearby studies, make assumptions as to what rocks are present in the seismic packages. Seismic interpretations of rock units by Dobson and Buffler (1997) in the Apalachicola Basin and Tampa Embayment, Wilson (2011) in the Tampa Embayment, and Lord (1986) and DeBalko (1991) in the northern margin of the West Florida Basin and slope, allow for the tentative establishment of ages of packages (Figure 2). The Middle Cretaceous sequence boundary (MCSB) is present through most of GoM as either an unconformity or as the top of a sequence boundary and is prominent throughout the southeastern GoM (Schlager et al., 1984; Phair, 1984; Lord, 1986; Buffler et al., 1991; DeBalko, 1991). Thus, rocks beneath this seismic horizon must be older.

2.5 Previous Seismic Studies

Dobson and Buffler (1991, 1997) use well logs and seismic reflection data to interpret stratigraphy and define basement structures within the Tampa Embayment and Apalachicola

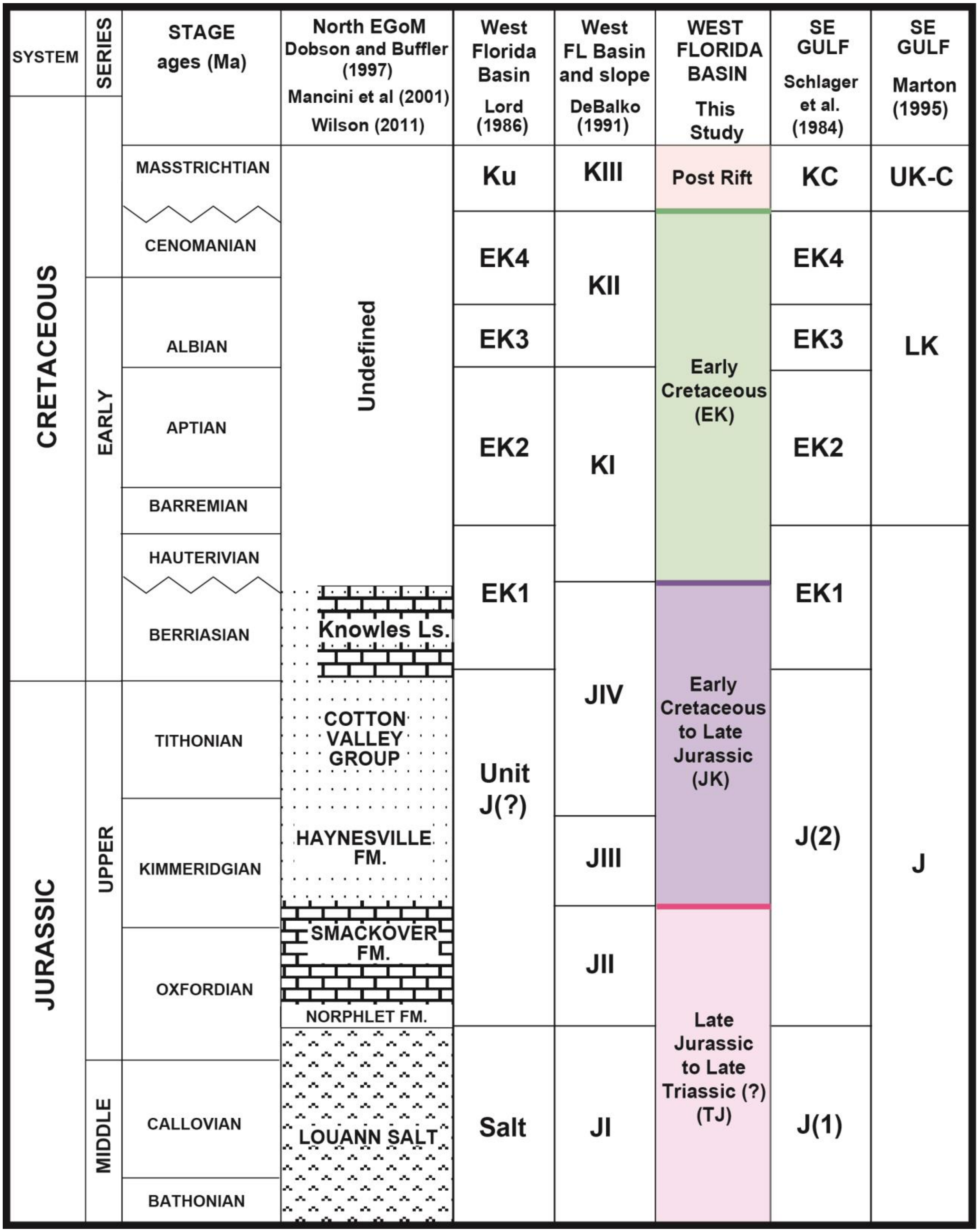


Figure 2. Stratigraphic column comparison from interpretations from respective study areas. Columns are seismic packages from nearby basins as compared to the seismic stratigraphy from this study in West Florida Basin (Modified from Dobson and Buffler, 1997).

Basin. Similar to Dobson and Buffler (1997), Wilson (2011) uses PSDM seismic reflection profiles along with geologic data from wells in the northeastern GoM to define Mesozoic stratigraphy in the Tampa Embayment (Figure 2). Well data from within the Apalachicola Basin confirms the presence of less than 1 km of the petroliferous Mesozoic stratigraphy. Using seismic data, these seismic horizons were correlated and extended to nearby EGoM basins. This process allows for the definition of the stratigraphy within the Tampa Embayment and the southward extent of the Norphlet and Smackover Formations to be defined (Dobson and Buffler, 1997; Wilson, 2011).

Lord (1986) defines eight pre-Cenomanian seismic packages within the West Florida Basin using seismic reflection profiles, gravity and magnetic geophysical data, and geologic data from wells. His interpretations extend seismic packages into the West Florida Basin from interpretations in the deep southeastern GoM by Schlager et al. (1984) (Figure 2). Over the northern margin of the West Florida Basin and the nearby Florida Escarpment, DeBalko (1991) defines four Jurassic sequences and three Cretaceous sequences (Figure 2). These sequences were identified in seismic reflection interpretations and correlated with other studies in EGoM. Within the West Florida Basin, Lord (1986) and DeBalko (1991) define a thin salt unit in the northern margin of that pinches out to the south. ‘Unit J’ from Lord (1986), interpreted to compose the Norphlet, Smackover, Haynesville Formations and Cotton Valley Group equivalents (Figure 2), ranges in thickness from 0.5 km in the center of the basin to 2 km to the northeast and the southeast. The inability of Lord (1986) to further divide ‘Unit J’ prevented the better definition of the ages of faults present within the basin and thus, the timing of tectonic movement. DeBalko (1991) further divides ‘Unit J’ into JII – JIV, but his study area only encompasses the northern margin of the West Florida Basin and does not address structural formation of the basin. Within both studies, the overlying Cretaceous sections are well defined via the use of well data from basins in the north EGoM. The reflection characters of these resolved seismic packages help to better define seismic packages in this study.

North of Cuba and in the Yucatán and Florida Straits, various studies identify Jurassic and Cretaceous rocks above the rifted basement (Schlager et al., 1984; Phair, 1984; Marton and Buffler, 1994; Marton, 1995). These studies rely on seismic data for the interpretation of the Jurassic units; however, well logs were available for the interpretation and identification of the Cretaceous and younger packages. In the deep southeastern EGoM, Schlager et al. (1984) and Marton and Buffler (1999) interpret older Jurassic units were deposited in a continental setting. Following Middle Jurassic extension a deepening marine setting dominated. Well log data confirm the deposition of deep water carbonate rock during Cretaceous time.

3. DATA AND METHODS

3.1 Dataset

Data include nine 2-D pre-stack Kirchoff depth migrated (PSDM) seismic reflection profiles collected and processed by Spectrum as part of their Big Wave Phase 2 survey. Most of seismic coverage lies in the southern corner of the West Florida Basin. Interpretations were made on three WNW-ESE trending strike lines that extend from the northern to southern periphery of the West Florida Basin, and six ENE-WSW trending dip lines that are basinward of the Florida Escarpment over the deep waters of the Florida Plain (Figure 1). Landward of the Florida Escarpment, seismic imaging of the Mesozoic stratigraphy and basement geometry in the South Florida Basin is poor as a result of the thick carbonate shelf and overlying sediments. Thus, landward reaching seismic coverage is not interpreted.

Sparse well control exists in the southeastern territorial waters off the Gulf coast of Florida, which prevents an absolute age determination of the seismic stratigraphy within the West Florida Basin. However, relative ages of stratigraphy are determined by correlating seismic interpretations with studies from nearby regions that incorporate geologic data from wells (Phair, 1984; Schlager et al., 1984; Lord, 1986; DeBalko and Buffler, 1992; Marton, 1995; Dobson and Buffler, 1997; Wilson, 2011). In addition to tentative age determination of stratigraphic packages in the West Florida Basin, a correlation aids in bracketing the ages of tectonic activity in Mesozoic time in the absence of geologic data by assigning timing to faults present.

3.2 Seismic Interpretation

Interpreted Mesozoic seismic packages include the Late Triassic to Late Jurassic (Oxfordian) [TJ] and Late Jurassic – earliest Cretaceous (Kimmeridgian - Berriasian) [JK] syn-rift packages and the Early Cretaceous (Valanginian - mid-Cenomanian) [EK] post-rift package (Figure 2). The base of the oldest seismic package, TJ, lies directly on top of basement rocks. Basement is defined as the earliest Triassic rift related rock (pre-Callovian salt), pre-rift Paleozoic rocks, if present, and older rocks, including crystalline continental crust, oceanic crust, and igneous rocks associated with rifting (Salvador, 1987). The top of the interpreted Mesozoic seismic stratigraphy, also the top of the EK package, is a prominent and laterally extensive reflector, the MCSB, and marks an unconformity that separates Mesozoic rocks deposited as the basin developed from younger passive margin sediments deposited in Cenozoic time.

4. SEISMIC DATA AND INTERPRETATION IN THE WEST FLORIDA BASIN

4.1 Basement

The top of the basement is the boundary that marks the change in seismic characteristics of more continuous, organized, higher amplitude reflectors of syn- and post-rift Mesozoic sediments from the lower amplitude, chaotic, and incoherent character of the basement rocks underneath (Marton and Buffler, 1999). The seismic surface separating pre-rift Paleozoic and earliest syn-rift sedimentary and igneous rocks from the top of the basement surface is often difficult to differentiate and so is not distinguished from basement on the tops of rift blocks (Marton, 1995; Wilson, 2011); thus, their presence remains undetermined in the study area. Younger rocks of TJ and JK seismic packages occasionally exhibit fanning on the sides of faulted basement blocks indicating deposition during extension (Figure 3a). In the northwest, younger sediments onlap the basement rocks (Figure 3b).

On the southern margin of West Florida Basin, basement is faulted from extension, with NE-SW trending normal faults bounding uplifted and downthrown basement blocks within thinned transitional continental crust (Buffler and Sawyer, 1985). Figure 4 is a basement map of the West Florida Basin that shows the present day basement depths of the West Florida Basin to demonstrate changes in crust distribution and basement configuration post-Mesozoic extension. The northern and southern margins of the basin consist of alternating basement highs (shallow depths) and lows as a result of normal faulting. Fault interpretations represent apparent dips along the profiles (Figures 5, 6, 7, 9, 10, and 11). These faults are difficult to follow more than 4 to 6 km below basement surface, due to lack of seismic quality with depth. Offset of faults can range several kilometers (Figure 4). Larger faults may have developed as reactivations of faults that developed during the first generation of extension. Interpretations of the basement by Wilson (2011) from the northern margin, outside of the study area, of the West Florida Basin are included in Figure 4.

Extension created basement fault blocks in which syn- and post-rift sediments were deposited. Topography and thicknesses of seismic packages deposited during and following extension indicate that higher degrees of extension and subsidence occurred along the northern and central margins of the West Florida Basin. In the northern margin of West Florida Basin, present day basement is at 10-12 km depth, while the southern margin remains shallower at 7-8 km depth (Figure 4). In the central part of the basin, topography averages about 10 km depth. The higher topography of continental crust to the southeast represents the southern flank of the West Florida Basin. Throughout the basin, additional subsidence following extension created accommodation space for post-rift sediments.

The seismic character of the basement to the south is high amplitude and chaotic (Figure 3c); however, the seismic character of the basement towards the northwest appears more internally planar with a hummocky surface (Figure 3b). In addition, in the northwest of the West Florida Basin, brittle faults are mostly absent (Figures 5a, 6a, and 7a). The variation in seismic character of the basement and the decrease in brittle faults possibly indicate a change in crust type. Internal basement reflectors that are stratified and planar (Figures 5a, 6a, and 7a) to the northwest may indicate oceanic crust (Lord, 1986) or ‘proto-oceanic’ crust in a transition zone

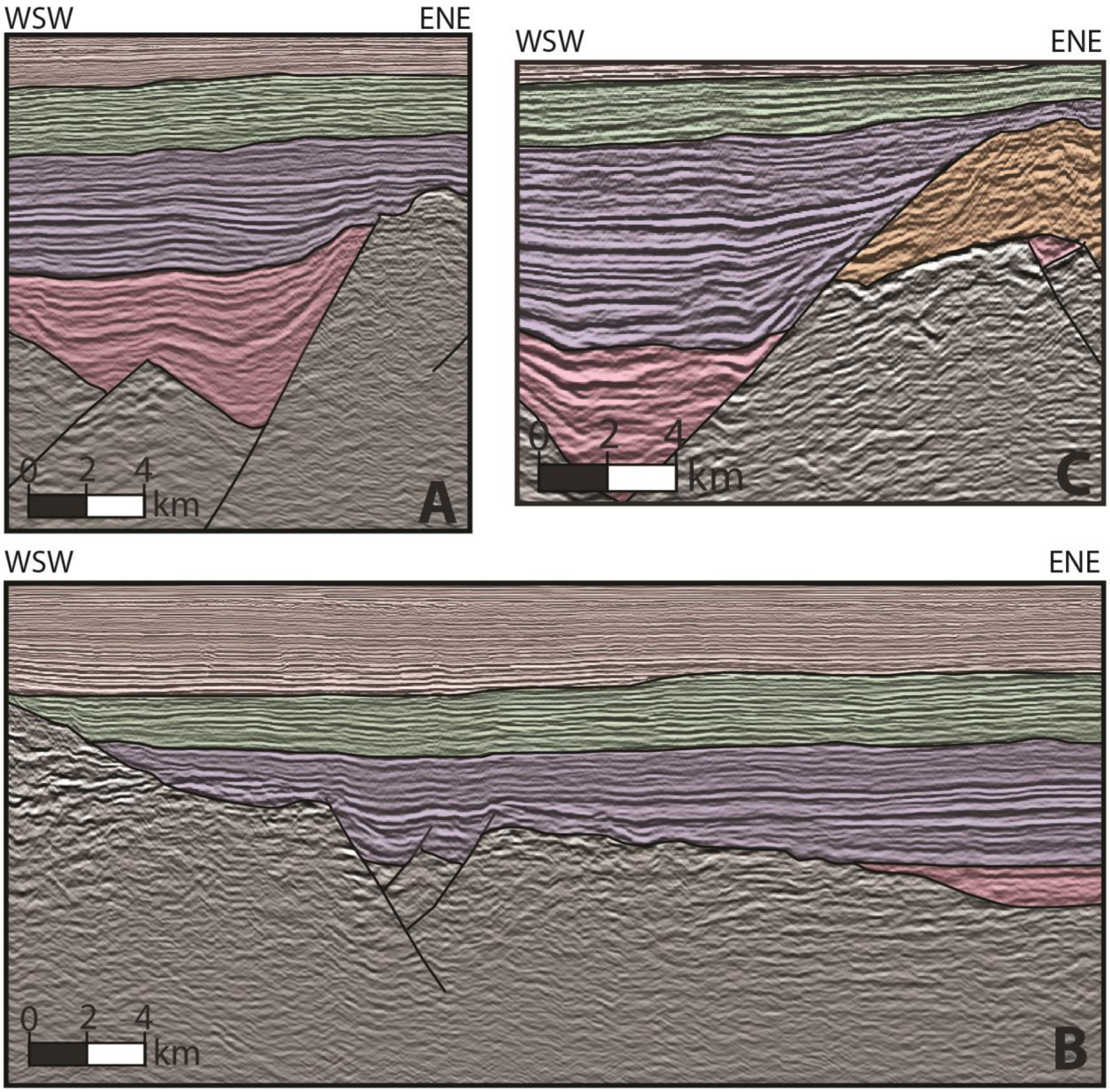


Figure 3. Seismic stratigraphic relationships. A) Fanning of syn-rift (pink and purple) packages onto the fault plane and parallel to subparallel seismic character of seismic packages; B) Basement onlapping seismic packages during subsidence and marine transgression; C) Carbonate buildups (orange) on a high standing fault block. Younger seismic packages drape over these buildups.

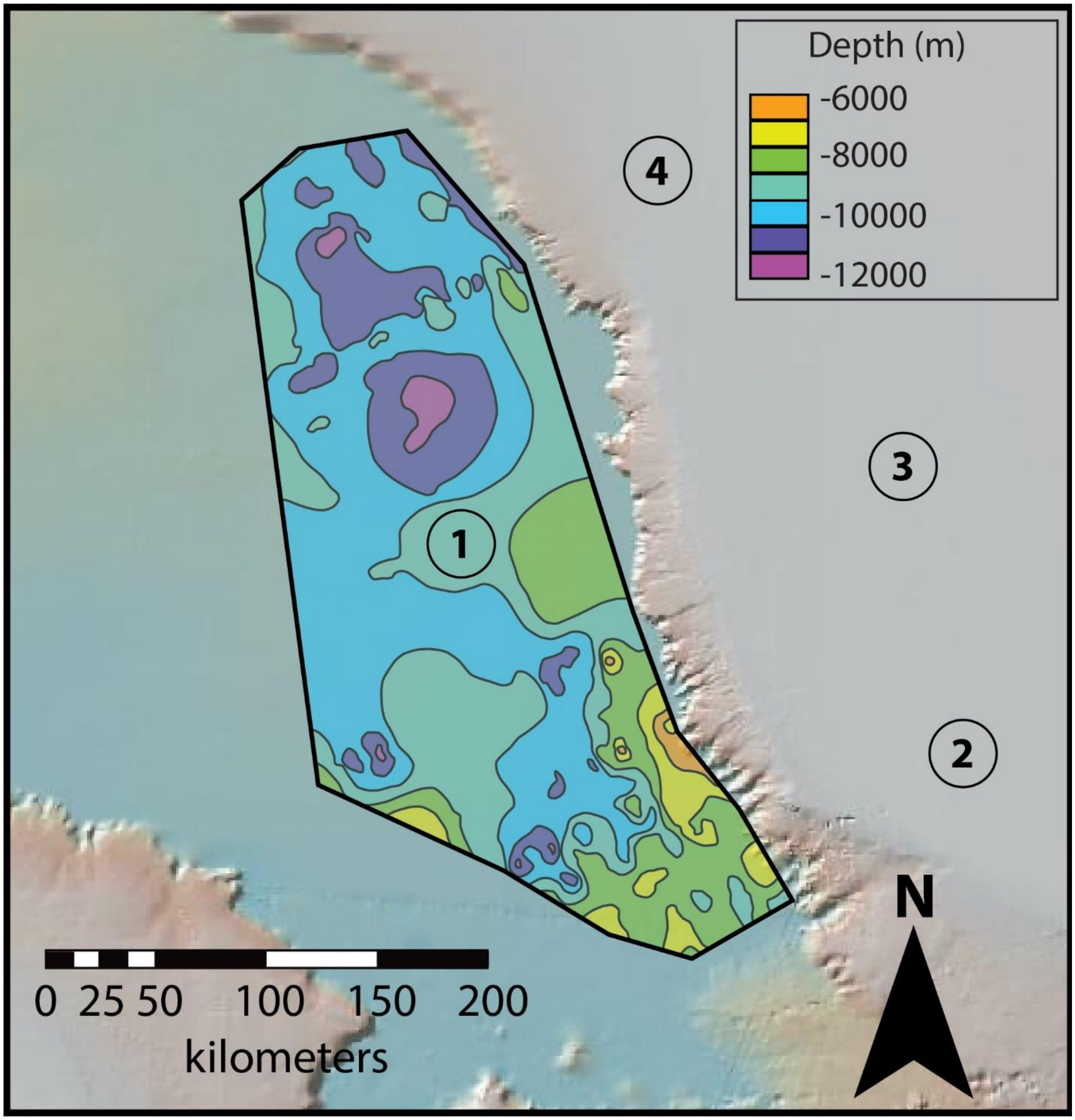


Figure 4. Basement topography map based on seismic reflection interpretations from study area in the West Florida Basin and the Tampa Embayment (Wilson, 2011). 1) West Florida Basin; 2) South Florida Basin; 3) Sarasota Arch; 4) Tampa Embayment. Basement to the north and south of the West Florida Basin consists of brittle, normal faulted continental crust surrounding a central region of oceanic crust.

between continental and oceanic crust domains (Turner and Wilson, 2009; Péron- Pinvidic and Manatschal, 2009), while crust to the east and south that appears chaotic and has a lower amplitude is extended continental crust (Figures 6b, 7b, 9b, 10b, and 11b). To the northwest, basement consists of internally planar reflections bounded by normal faults (Figures 6a and 7a), and has a similar seismic character to proto-oceanic crust in the Ascension Fracture Zone, West Africa (Turner and Wilson, 2009). Figure 8 shows where ocean/proto-ocean seismic reflections (Figures 5a, 6a, and 7a) from the West Florida Basin overlaps with the region where other studies interpret the presence of oceanic crust (Buffler and Sawyer, 1985; Marton and Buffler, 1994; Hall and Najmuddin, 1994; Bird et al., 2005). These studies use seismic refraction, magnetic, and gravity data to map the distribution of oceanic crust in the GoM.

The change in seismic character of the basement, the absence of brittle faults, and the Moho or mid-crustal detachment may suggest the presence of oceanic/proto-oceanic crust within the GoM (Figures 5a, 6a, 7a, and 11a). This bright Moho/detachment reflector shallows basinward, beginning at about 19 km depth in the east and shallowing to 14 km depth in the west. Here, attenuated continental crust thins from 12 km to about 5 km thick oceanic crust. Basinward, shallowing of the Moho is documented by Sawyer et al. (1991) using seismic refraction data. Seismic reflection surveys off the coast of West Africa, northern Australia, and the West Iberian margin have imaged a similar reflector beneath a transition zone between oceanic and continental crust, that represents a mid-crustal (or deeper) detachment facilitating extension along which oceanic crust emplacement can occur (Rosendahl et al., 1991; Hoffmann and Reston, 1992; Péron-Pinvidic and Manatschal, 2009). Driscoll and Karner (1998) infer the presence of a detachment to resolve the thermal-subsidence over regions with little brittle faulting. Depth dependent stretching of the lithosphere can explain the amount of extension

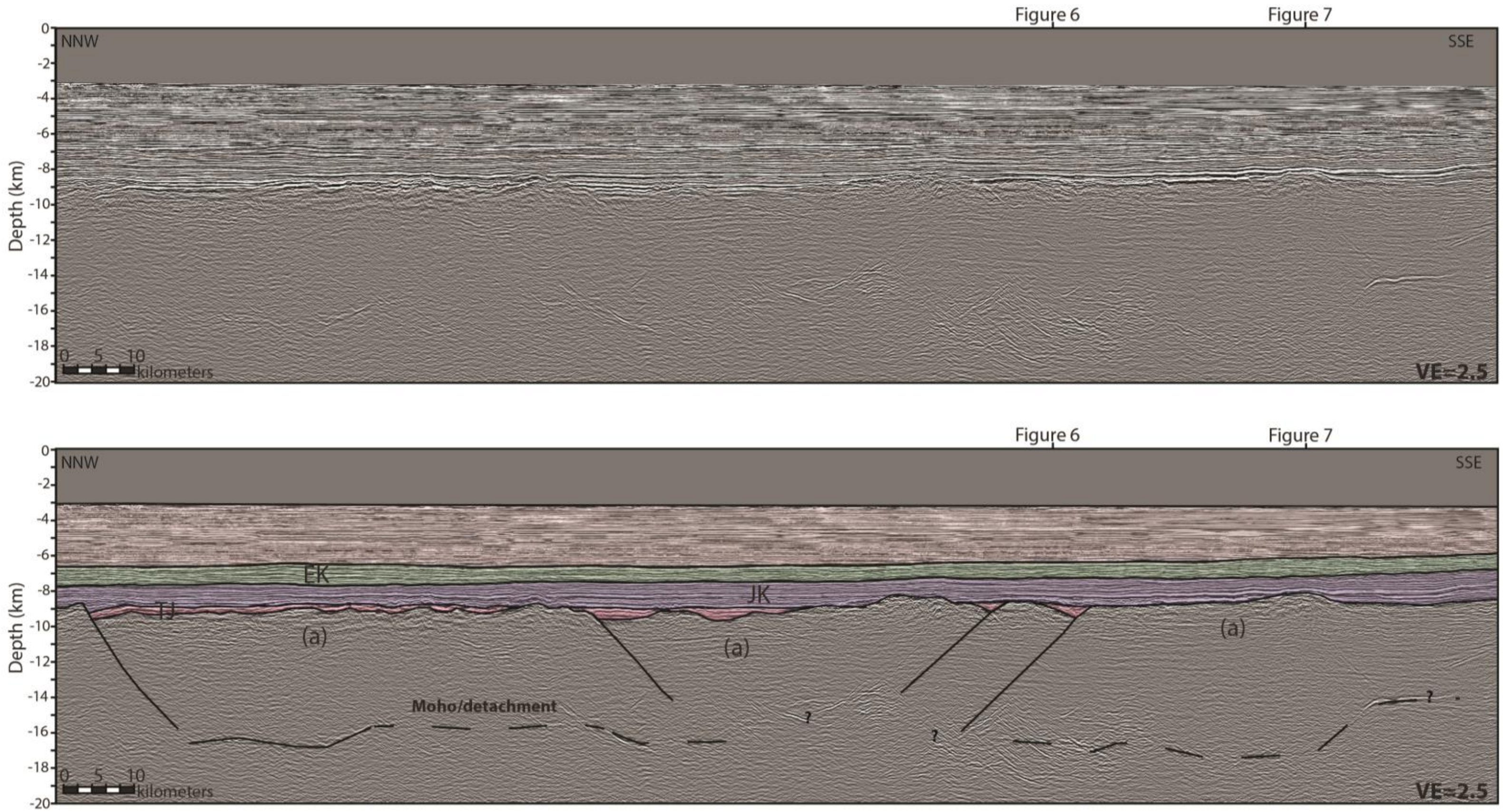


Figure 5. Strike Line. Crust (a) appears more linear and is overall devoid of brittle faults. Moho/detachment surface is present along the entire profile beneath an approximate depth of 16 km. This interpretation is used to infer that crust (a) may be oceanic/proto oceanic crust. TJ is thin or absent along the profile. JK and EK are widely distributed and are generally not influenced by basement topography.

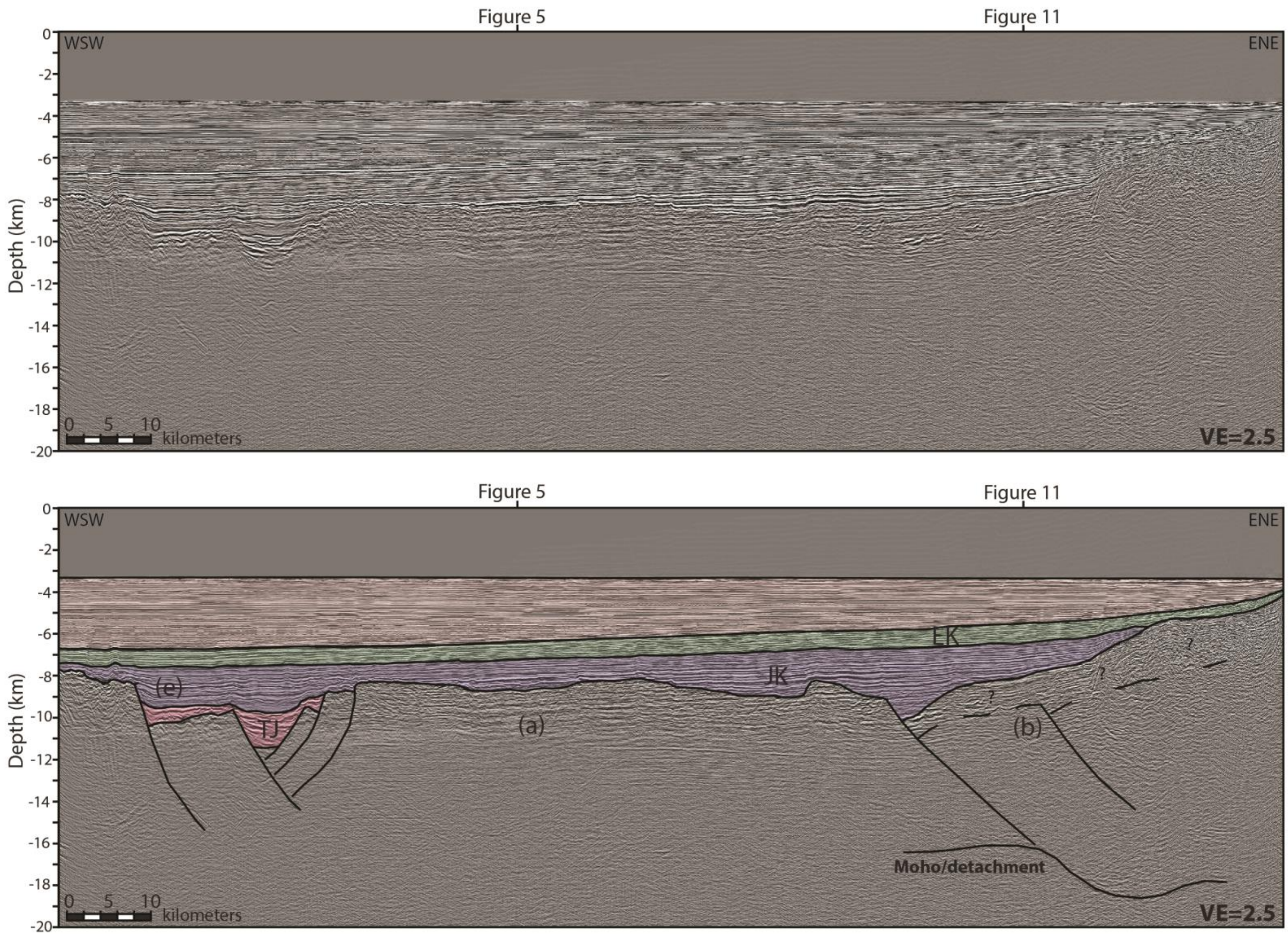
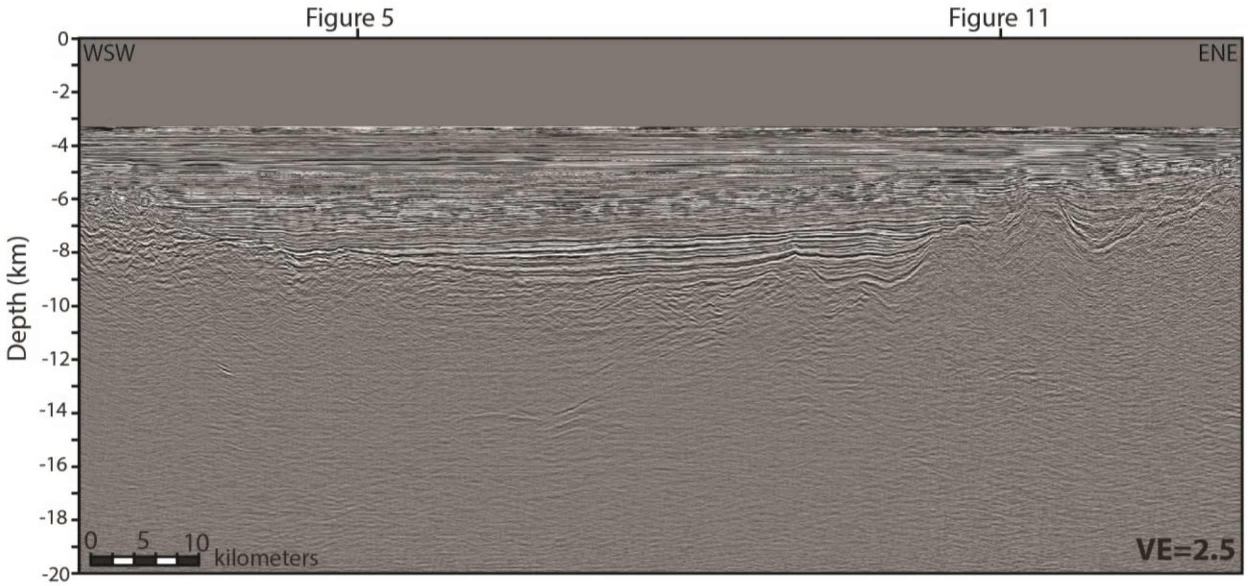


Figure 6. Dip Line. The oceanic/ proto oceanic crust (a) appears more linear, while the continental crust (b) has a chaotic seismic character. Moho/detachment reflector shallows basinward. TJ distribution is highly controlled by basement topography. JK and TJ exhibit fanning (e) off basement structures due to syn-rift sedimentation.



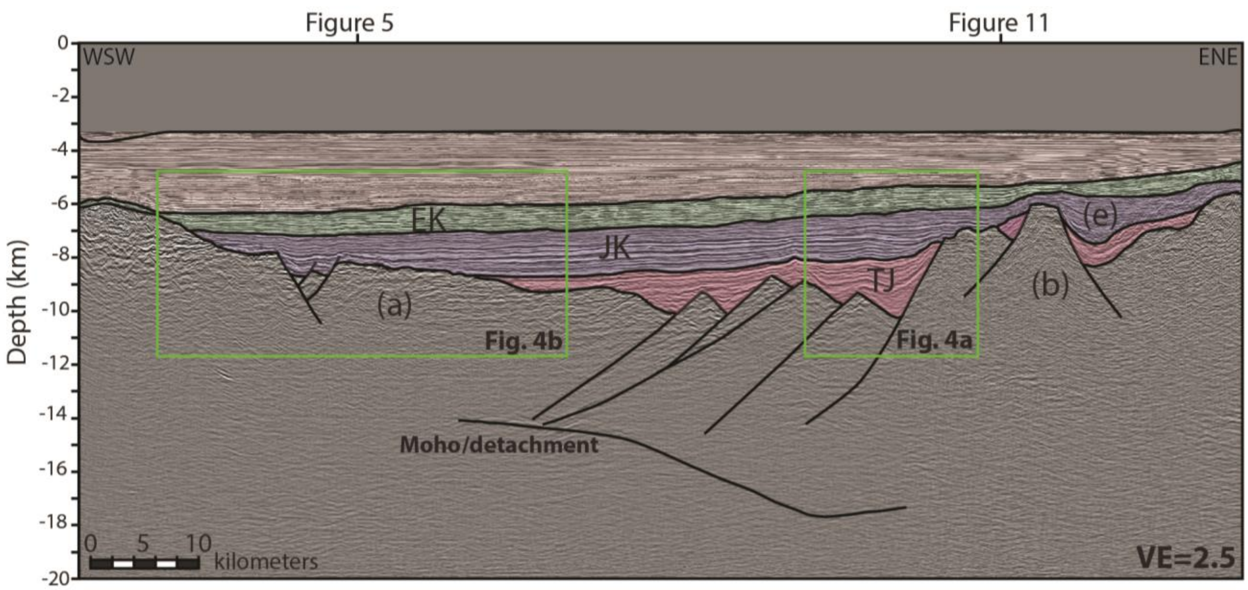


Figure 7. Dip Line. The oceanic/proto oceanic crust (a) lies to the west, while extended continental crust (b) lies to the east towards the Florida Escarpment. A Moho/detachment reflector shallows basinward. TJ has a wider distribution around basement lows and exhibits fanning from basement highs. True dips of normal faults are not represented within this profile, and thus the direction of maximum extension cannot be determined.

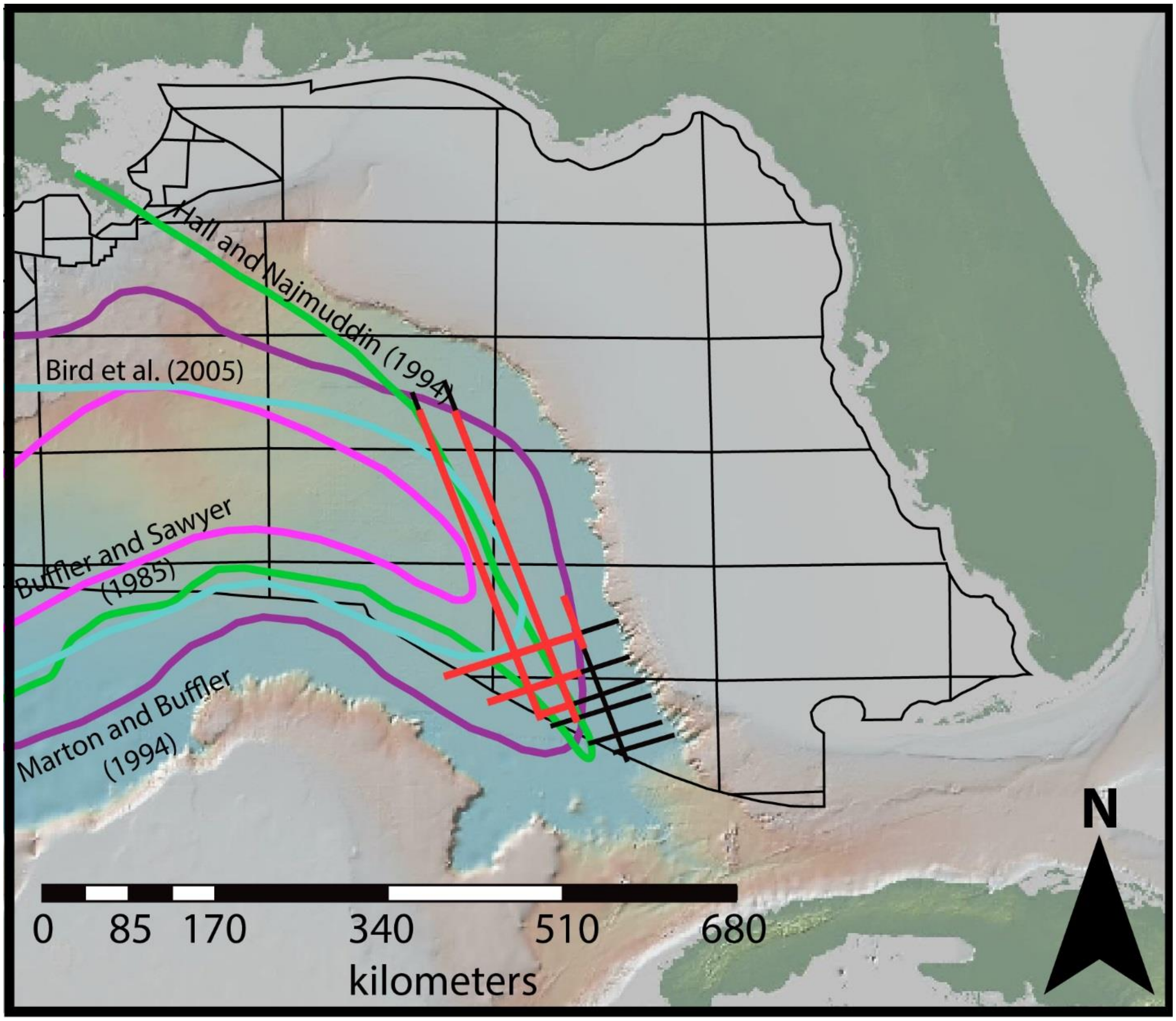


Figure 8. Seismic interpretation of oceanic crust from this study (in red) compared to previous studies interpretations of the occurrence of oceanic crust. Interpreted oceanic crust occurs in light blue over the seismic profiles used in the study area. Pink: Buffler and Sawyer, 1985; Light Blue: Bird et al., 2005; Green: Hall and Najmuddin, 1994; Purple: Marton and Buffler, 1994 (Modified from Bird et al., 2005).

necessary to accommodate oceanic crust emplacement in the GoM due to the scarcity of brittle faulting present in the upper crust in the West Florida Basin (Davis and Kusznir, 2004; Weinberg et al., 2007). This Moho/detachment reflector also exists below the Tampa Embayment and the northern West Florida Basin margin within the EGoM (Wilson, 2011; Pindell et al., 2011).

4.2 Late Triassic (?) – Late Jurassic (Oxfordian) – TJ

Late Triassic (?) – Late Jurassic (TJ) is the first syn-rift seismic package above the basement and seismic interpretation indicates this package was deposited throughout both generations of extension in Late Triassic and Middle Jurassic time. Based on correlations with seismic studies in the north EGoM (Dobson and Buffler, 1997; Wilson, 2011), basal TJ sediments appear to be the same age or older than Callovian aged salt correlating with the first generation of extension, while the top of the TJ package corresponds with Norphlet and Smackover Formations deposited during the second generation of extension. Convergent fanning reflections of sediment deposited in depocenters adjacent to basement fault blocks represent deposition of TJ during both phases of extension (Figure 3a). Faulting within the TJ unit (Figure 10c) indicates Middle Jurassic faulting of the older TJ sediments deposited following Late Triassic rifting. However, this interpretation is subject to reinterpretation if the ages of the units correlate differently as more data become available. Reflectors composing TJ are bright and have a high amplitude. Where TJ is not divergent and fanning due to deposition during faulting, in the north TJ is primarily parallel to sub-parallel (Figures 7 and 11), while in the south TJ is more chaotic and deformed (Figures 9 and 10).

To the south, TJ (Figures 9 and 10) is less than 0.5 km thick, in the center of the basin (Figures 6, 7, and 11), TJ is more than 1 km thick. In the south, higher basement topography controlled the deposition of TJ, as indicated by thin or absent sediments. Here, TJ is confined to depocenters surrounding uplifted basement fault blocks (Figure 12). In the center of the basin, TJ has a wider distribution and did not experience the same degree of influence of basement topography. To the northwest, the absence of the TJ basal sections may be a result of oceanic crust emplacement. Upper TJ, however, is not confined by rifted basement geometry and so is more widespread over basement (Figure 5). Basal TJ sediments were deposited prior to the emplacement of oceanic crust (in Callovian time), while upper TJ deposited during the second generation of extension as indicated by onlapping of TJ sediments onto the interpreted oceanic/proto-oceanic crust (Figure 3a).

The age of TJ is determined based on correlations with interpretations on seismic reflection profiles in the Tampa Embayment (Wilson, 2011), the West Florida Basin (Lord, 1986; DeBalko and Buffler, 1992), and the southeastern GoM (Schlager et al., 1984; Marton, 1995). Based on these correlations, TJ is interpreted to be Late Triassic (?) to Late Jurassic (Oxfordian) in age (Figure 2). Onlap and draping of the younger JK and EK packages help refine their age. Deposition of basal TJ in basins surrounding fault blocks in the south was likely nonmarine (Salvador, 1987; Marton, 1995). Additional extension in Middle Jurassic time and subsequent subsidence and marine transgression created a shallow marine setting, so upper TJ is interpreted as shallow marine (Schlager et al., 1984; Lord, 1986). The upper part of this package is similar in age to the petroliferous Norphlet Formation and possibly the Smackover Formation of the northern EGoM though it is not always directly correlatable because of basement topography. The top of TJ is a high amplitude reflector that is mostly conformable with the overlying package, JK. The boundary may represent further marine transgression or increase in sedimentation possibly due to the connection of the GoM with the Atlantic Ocean.

4.3 Carbonate Buildups

Carbonate buildups occur on the tops of high standing fault blocks. The internal seismic character of these buildups consists of low amplitude, chaotic reflections (Figure 3c). This character is similar to the seismic character of the marine unit of the Late Jurassic syn-rift sequence that caps basement highs in the southeastern GoM and are interpreted to be carbonate platforms or buildups with a possible central reef core (Marton and Buffler, 1999). Younger sediments (Late Jurassic and Early Cretaceous packages) commonly exhibit onlap and drape over the tops of the carbonate buildups (Figure 3c) due to differential compaction of sediments and carbonate buildups (Marton and Buffler, 1999). Alternatively, draping of sediments may be shedding of rubble from the tops of carbonate buildups. These may have formed as isolated buildups on topographic highs or as a larger continuous platform that later underwent extension and faulting, separating a once continuous feature. These buildups were deposited in a shallow marine environment following the initial marine transgression into the GoM during Oxfordian time (Figures 9d, 10d and 11d) and are abundant towards the south (Figure 13). Carbonate buildups and platforms have also been mapped below the Florida Escarpment (Dobson and Buffler, 1997; Wilson, 2011) and elsewhere in the southeastern GoM atop high standing fault blocks (Marton and Buffler, 1999).

An alternative interpretation for these disorganized seismic reflectors could be the presence of buildup of igneous material from rift related volcanism. Velocity pull ups and

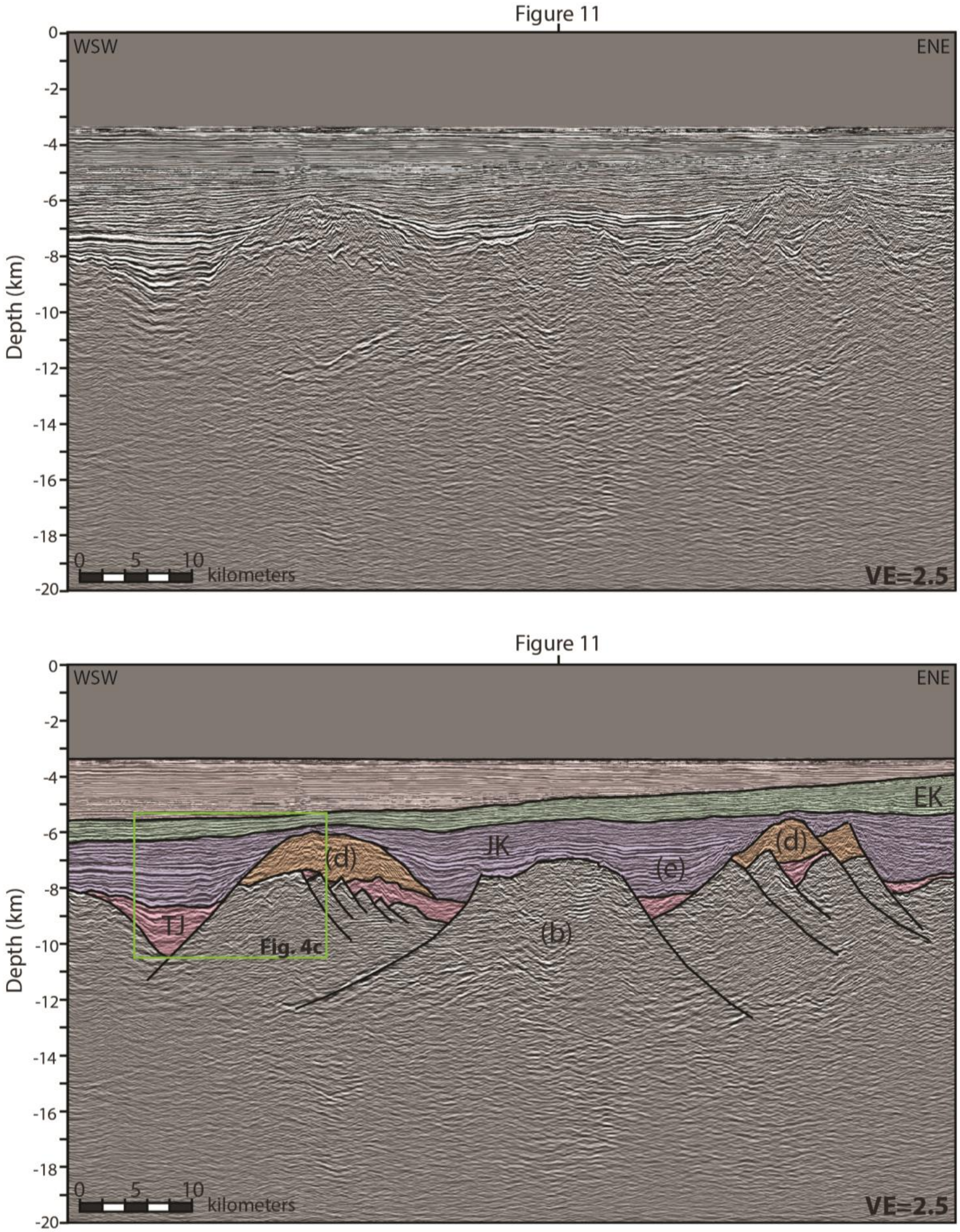


Figure 9. Dip line. The crust (b) is extended continental crust. Basement highs are capped with carbonate buildups (d) while TJ fills basement lows. JK is distributed along the profile, though basement topography controls package thickness.

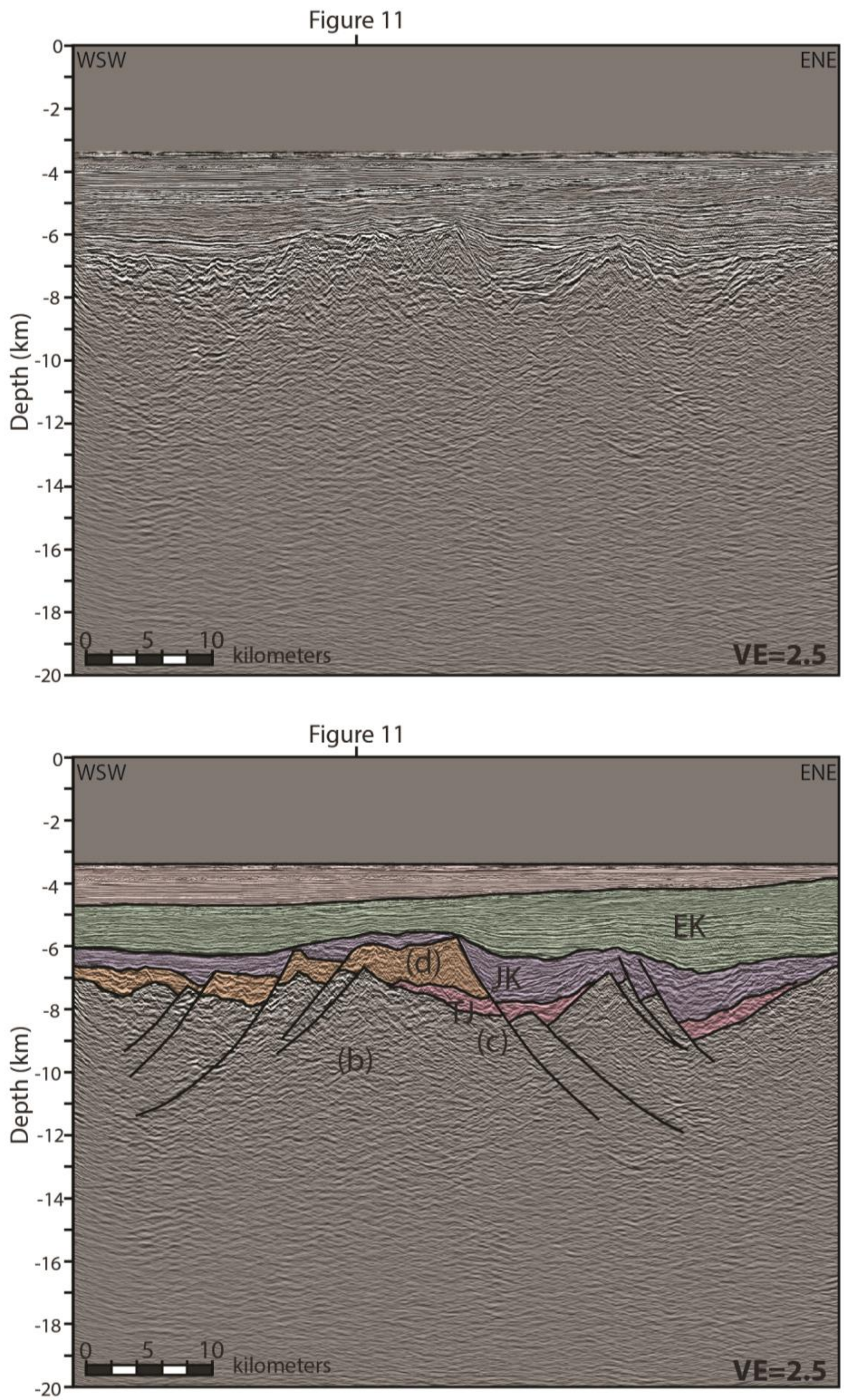


Figure 10. Dip line. TJ is mostly thin or absent along the profile. JK is thin over basement highs and carbonate buildups (d). TJ and JK exhibit draping over carbonate buildups due to sediments shedding or differential compaction. The basement is extended continental crust (b).

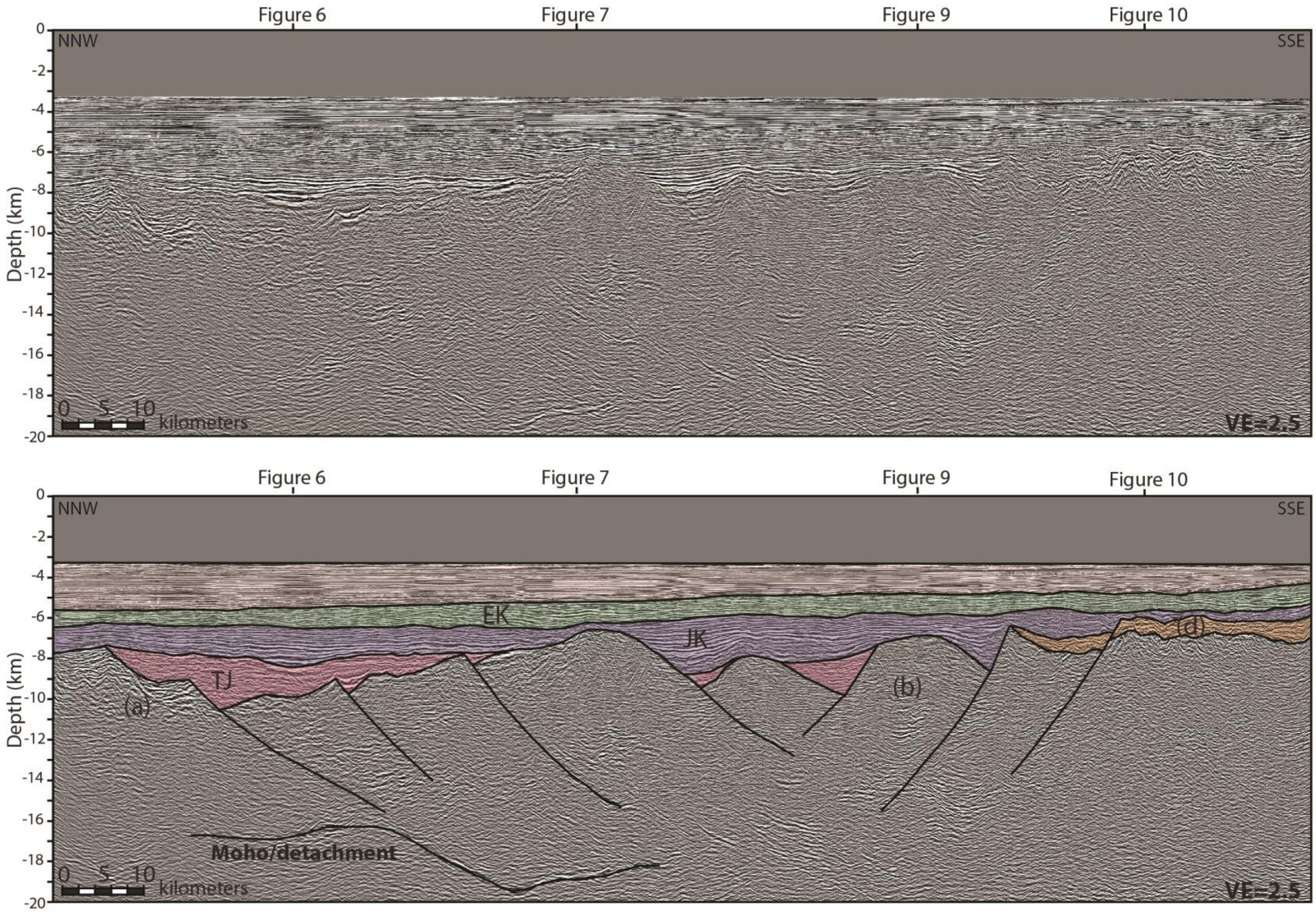


Figure 11. Strike Line. Basement topography increases towards the southeast. Carbonate buildups (d) cap basement highs in the south. TJ is absent in the southeast but present in basement lows to the northwest. A Moho/detachment shallows towards the northwest and crust type changes from continental to oceanic/proto oceanic in the north.

differential compaction can indicate a carbonate buildup or volcanic rocks. Rift associated volcanic rocks occur amongst fault blocks throughout the southeastern GoM, north of Cuba, as indicated by well data (Phair, 1984; Schlager et al., 1984); however, no such volcanic rocks with similar morphology have been interpreted near the study area. Criteria for identification of carbonate rocks in seismic reflection data include the regional setting (marine setting and paleolatitude), the topography upon which the buildup developed (paleo-highs), predominately aggradational with localized thickening, and high angle marginal slope of the buildup (Burgess et al., 2012). Based on these criteria, the buildups are interpreted as carbonate rock. However, further research, including more seismic coverage and well data, will clarify the origin and lithology of these features.

4.4 Late Jurassic and Early Cretaceous (Kimmeridgian-Berriasian) – JK

During Late Jurassic time, a large marine transgression took place, possibly from an already established connection with the Pacific Ocean through central Mexico, combined with thermal subsidence following oceanic crust emplacement (Salvador, 1987; Mancini et al., 2001). However, in Late Jurassic (Kimmeridgian) time, the GoM may have established a connection with the Atlantic Ocean between Florida and Yucatán, resulting in a widespread incursion of marine waters (Schlager et al., 1984; Pindell, 1985; Marton and Buffler, 1994). In the northern EGoM, this incursion resulted in the swamping of the eolian Norphlet Formation and deposition of the carbonate Smackover Formation (e.g. Hunt, 2012). This marine incursion, in combination with thermal subsidence from rifting, resulted in the deposition of the widespread JK package. To the south, the basement fault blocks control the deposition of JK (Figures 9, 10, and 14). To the north, the absence of rift blocks allows JK to have a uniform thickness of about 1 km over the region of oceanic crust (Figures 5, 6, 7, and 14). To the east, JK appears to thin towards the Florida Escarpment, the location of the inferred tectonic hinge (Figure 14).

JK is the youngest syn-rift package deposited during the second generation of extension. However, extension is mostly complete before the deposition of JK, though some faults remain active, possibly as reactivations, throughout the deposition of this package. JK occasionally exhibits fanning adjacent to uplifted fault blocks (Figures 6e, 7e, and 9e). This relationship, however, may be from drape due to differential compaction from deposition over older carbonate buildups and not a result of tectonic movement (Figure 3c). JK is differentiated from the older Jurassic package by a laterally extensive high amplitude reflector, which may represent a change in depositional setting from shallow marine to deeper marine due to the large marine transgression in Kimmeridgian time. The seismic character of JK consists of high amplitude subparallel and continuous reflectors that are indicative of deposition in a marine setting (Phair, 1983).

Towards the north, where oceanic/proto oceanic crust exists, this package is occasionally deposited directly onto the top of the basement (Figure 3a, 5, 6, and 7). Here, JK exhibits onlap onto the flanks of the younger oceanic crust that was undergoing thermal subsidence. This relationship indicates that oceanic crust was deposited during Middle and Late Jurassic time, prior to the deposition of JK. This interpretation is consistent with previous studies regarding salt deposition and the timing of oceanic emplacement in GoM in Middle and Late Jurassic time (Buffler and Sawyer, 1985; Salvador, 1987). Occasionally, JK demonstrates draping over the top of the interpreted carbonate buildups (Figure 3c). This relationship of the younger Jurassic

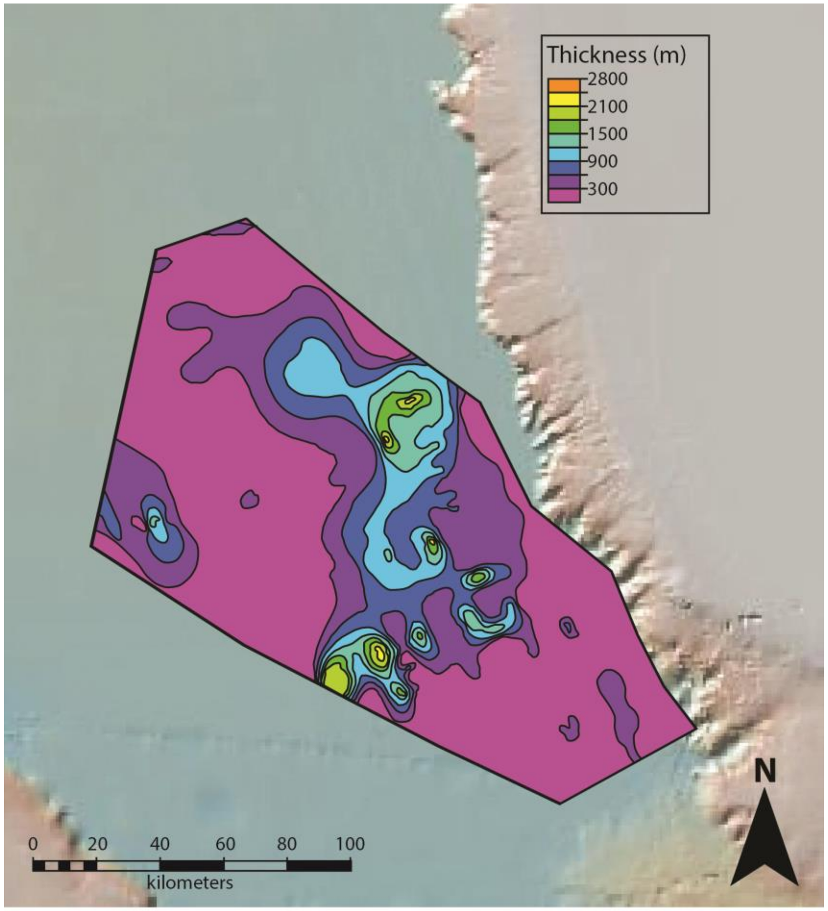


Figure 12. Isochore map for TJ. Distribution is limited to the south by basement topography, while to the northwest TJ is thin over oceanic/proto-oceanic crust.

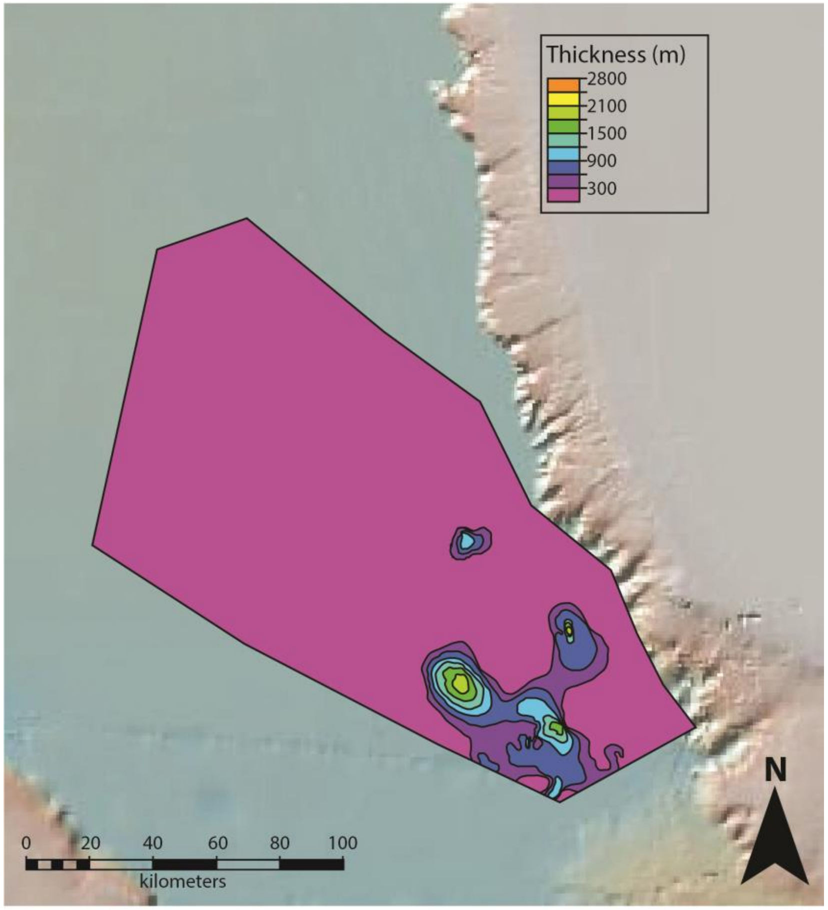


Figure 13. Isochore map for carbonate buildups. Carbonate buildups are present on basement highs towards the southeast.

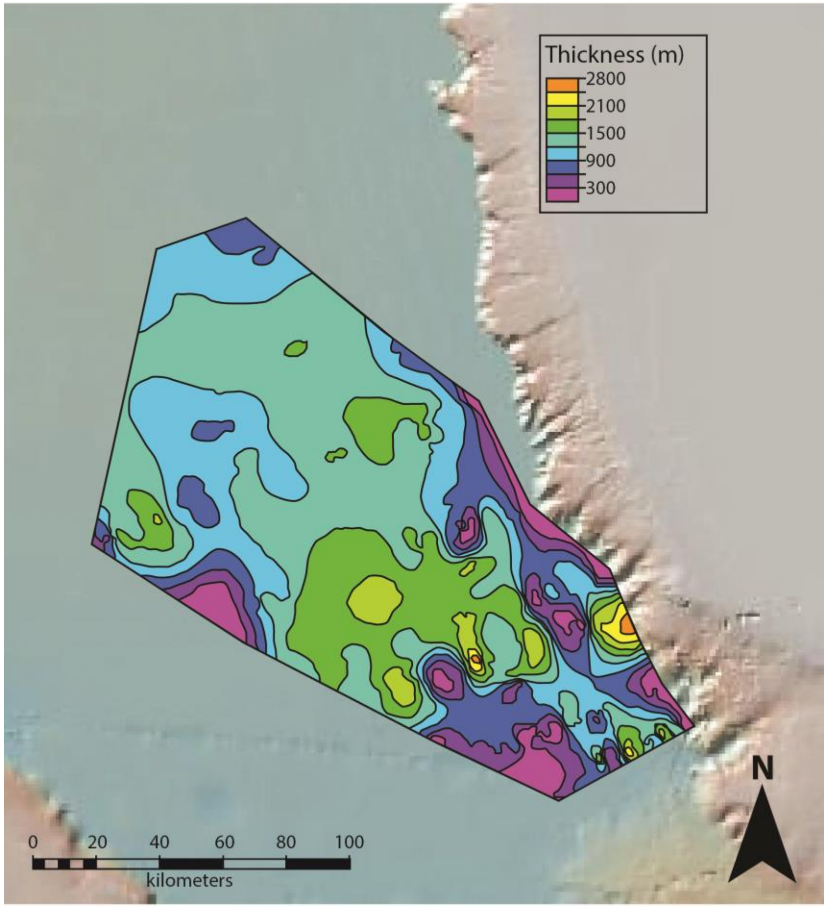


Figure 14. Isochore map for JK. JK thickness varies from north to south depending on basement topography following extension.

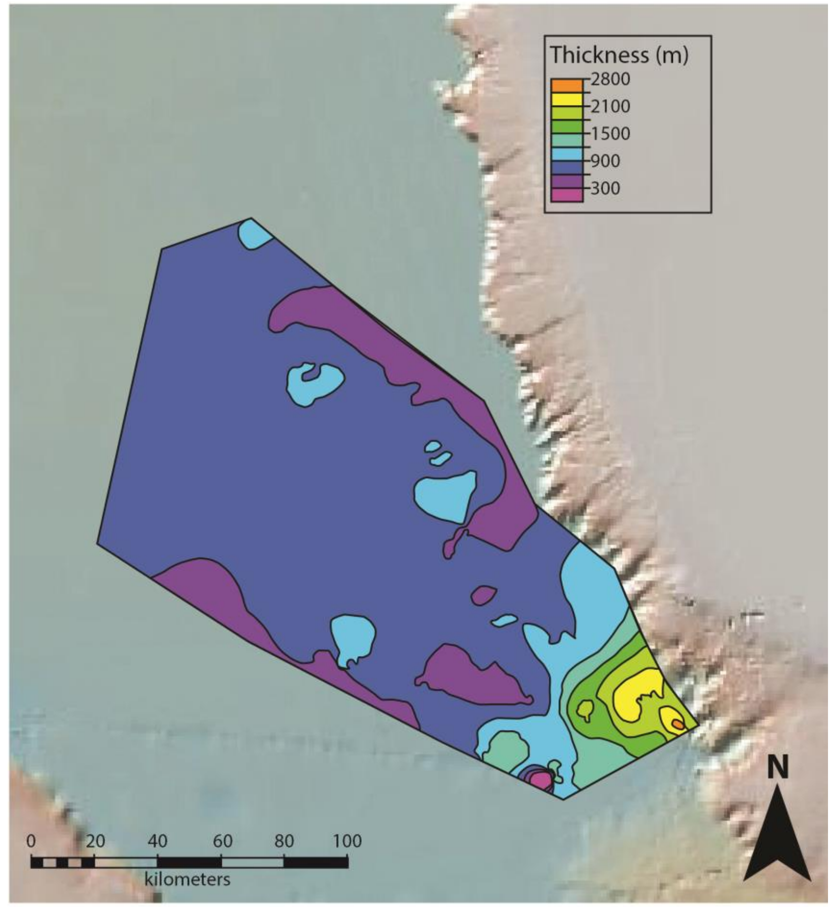


Figure 15. Isochore map for EK. EK has a wider distribution within the study area as sedimentation overcomes basement topography.

package with the carbonate buildups further confirms the interpretation of the age of the carbonate buildups to be older.

JK was deposited in a deepening marine environment. Schlager et al. (1984) interpret this unit to be deep water carbonate rock based on the similar seismic character to established carbonate packages deposited in Early Cretaceous time. However, parallel, high amplitude reflections within JK better correspond with interpretations and well data from the north of the study area that indicate clastic deposition dominated at this time (Dobson and Buffler, 1997; Mancini et al., 2001). JK is the lateral equivalent for the Haynesville and Cotton Valley Formations of the north EGoM, which is correlated from northern seismic interpretations (Dobson and Buffler, 1997; Wilson, 2011), though source provenance may vary. Bright reflectors and a change in reflection character within the JK package may help distinguish the Haynesville from the Cotton Valley equivalent packages in the West Florida Basin. However, a good correlation to distinguish these units cannot be established as JK thins to the north and west and are undifferentiated to the south (Schlager et al., 1984), so this package is lumped together as one. The age of JK is interpreted to be Late Jurassic (Kimmeridgian and Tithonian) to Early Cretaceous (Berriasian) in age.

4.5 Early Cretaceous (Valanginian – Mid-Cenomanian) – EK

EK is a widespread post-rift sequence deposited following the rift and drift episodes that formed the GoM in Triassic and Jurassic time. By Early Cretaceous, Yucatán reached its final destination at the southern margin of the GoM (Schlager et al., 1984; Klitgord et al., 1984; Pindell, 1985; Salvador, 1987). This package was deposited following oceanic crust emplacement in the central GoM. No faulting, sagging, or fanning of sediments is interpreted within this package, indicating that brittle extension terminated before Berriasian time in the southeastern GoM, though subsidence from extension and oceanic crust emplacement continued until Cenomanian time (Phair, 1984; Lord, 1986; Marton and Buffler, 1994; Mancini et al., 2001).

This package is distinguished from the JK seismic package below by a distinct change in seismic character from highly continuous, high amplitude reflections of JK to low or moderate amplitude and less continuous reflections in EK. This seismic unconformity, the top Berriasian horizon, is present throughout the EgoM, and Dobson and Buffler (1997) state that this boundary is a result of a drop in sea level and marks a reduction in sedimentation in Cretaceous time (Marton, 1995). EK may have been deposited in a deep water setting during continued thermal subsidence, as indicated by deep water carbonate rock drilled in the southeastern GoM (Schlager et al., 1984; Marton, 1995). The rocks that compose EK are likely similar to the carbonate rocks that are present north of Cuba. Sediment sources for younger EK rocks are likely coming from the Florida continental block (Schlager et al., 1984).

The top of EK is a laterally extensive unconformity that is mapped throughout the EGoM, known as the mid Cretaceous sequence boundary (MCSB) or mid Cretaceous unconformity (MCU), and is interpreted to be a result of a mid-Cenomanian drop in sea level (Buffler, 1991). This regression, along with decreased sediment input and large amounts of erosion, led to a depositional hiatus from Cenomanian to Maastritchian time (Schlager et al., 1984; Buffler, 1991). The MCSB surface is easily identifiable by onlap of upper Cretaceous and younger rocks.

5. DEVELOPMENT OF THE WEST FLORIDA BASIN

5.1 Late Triassic (?) Rifting and Middle Jurassic Drift

The West Florida Basin developed following the two generations of extension that formed the GoM in Mesozoic time. During the Late Triassic (?) to Middle Jurassic NW-SE directed rift phase, crustal attenuation is interpreted in the north EGoM creating the NE-SW trending Tampa Embayment and the Apalachicola and DeSoto Canyon Salt Basins (Buffler and Sawyer, 1985; Salvador, 1987; Sawyer et al., 1991; Dobson and Buffler, 1991). Marton and Buffler (1994) suggest that extension in the southeastern GoM, following Late Triassic (?) rifting, is nominal and rifting probably took place in a continental setting (Lord, 1986; Salvador, 1987). The absence of a widespread TJ package towards the south and the control basement topography had on its distribution indicates a higher paleotopographic surface following the first generation of extension (Figure 12). The 1.5-2 km deposits of TJ sediments present in depocenters around fault blocks may have been deposited in a continental setting and sourced locally from erosion from the uplifted basement blocks. In addition, the absence of salt in the southern EGoM may be attributed to higher basement topography due to reduced amounts of extension. Higher topography probably prevented the bodies of water that developed the thick salt deposits in northern and central GoM from reaching the southern margin of the West Florida Basin and the location of the modern day Straits of Florida and Yucatán (Marton, 1995). Salvador (1987) interprets that the deep southeastern GoM remained emergent until

Kimmeridgian time, when the Atlantic Ocean established a connection with the GoM. The southern margin of the West Florida Basin may have been a part of this emergent landmass until Oxfordian (or later?) time when the second generation of extension, the drifting of the Yucatán block and oceanic crust emplacement, further dissected and subsided the once emergent continental crust.

Lesser amounts of extension in the southern West Florida Basin could result from the tectonic model proposed by MacRae and Watkins (1996), which proposes that extension within corridors (Figure 16) is responsible for the formation of the Triassic grabens in the EGoM (Figure 1). Similarly, Klitgord et al. (1984) suggest that extensional corridors occur within several regional fracture zones. The southern West Florida Basin lies to the west of the corridor in which the other EGoM Triassic grabens formed (Figure 16) (Klitgord et al., 1984; MacRae and Watkins, 1996) and so the corridor in which the West Florida Basin formed may have experienced lesser amounts of extension. The Yucatán block, possibly located within the same corridor or one adjacent to the West Florida Basin, experienced some translation in the GoM during Triassic rifting (Marton and Buffler, 1994; Kneller and Johnson, 2011), producing large amounts of extension north of the Yucatán block, but not south of the block.

Motion of the Florida continental block along a transform fault still allows for the interpretations by Lord (1986) and Wilson (2011) that the northern West Florida Basin is the basinward extension of the Tampa Embayment. Transform motion, in the model proposed by Pindell and Kennan (2001), steps over the location of the Tampa Embayment (Figure 16) and continues to the southeast along the northern flank of the Florida continental block, rather than the southern flank. If the Tampa Embayment formed as a pull apart basin following translation of the continental block, the northern margin of the West Florida Basin could still be considered part of the pull apart basin. The proximity of the southern West Florida Basin to the final rift position of the Florida continental block could explain the reduced amount of extension. To the south, the southern margin of West Florida Basin is basinward of the Florida continental block. The model proposed by Kneller and Johnson (2011) states that as the Florida continental block rotated counterclockwise away from the Yucatán block in the central GoM, extension amounts may be reduced in regions closer to the final position of the rifted block, which includes the West Florida Basin.

All models, except for Kneller and Johnson (2011), contradict interpretations by Wilson (2011) that no transform faults are present along the Florida Escarpment/hinge zone in the Tampa Embayment. If transform motion within the EGoM is absent or occurs to the north of the Triassic grabens as in the model by Marton and Buffler (1994) and Pindell and Kennan (2001) (Figure 16), the region to the west of the Florida Escarpment may have undergone similar amounts of extension producing deeper water extensions of the Triassic grabens. If the northeastern margin of the West Florida Basin is an offshore extension of the Tampa Embayment (Lord, 1986; Wilson, 2011), then the southern margin of the West Florida basin may be an offshore extension of the Sarasota Arch that was later dissected by Middle Jurassic drift of the Yucatán block. This circumstance would explain the high topography in the southern West Florida Basin following Late Triassic (?) rift phase that would later be dissected during Middle Jurassic time (Figure 4).

Rift directions are difficult to distinguish because of sparse data coverage and continuous rift structures from Late Triassic extension are not easily detected, thus interpreted faults show te apparent dip of the fault planes. Thick TJ deposits in depocenters around fault blocks may be indicative of a long history of deposition during extension beginning in Late Triassic (?) time.

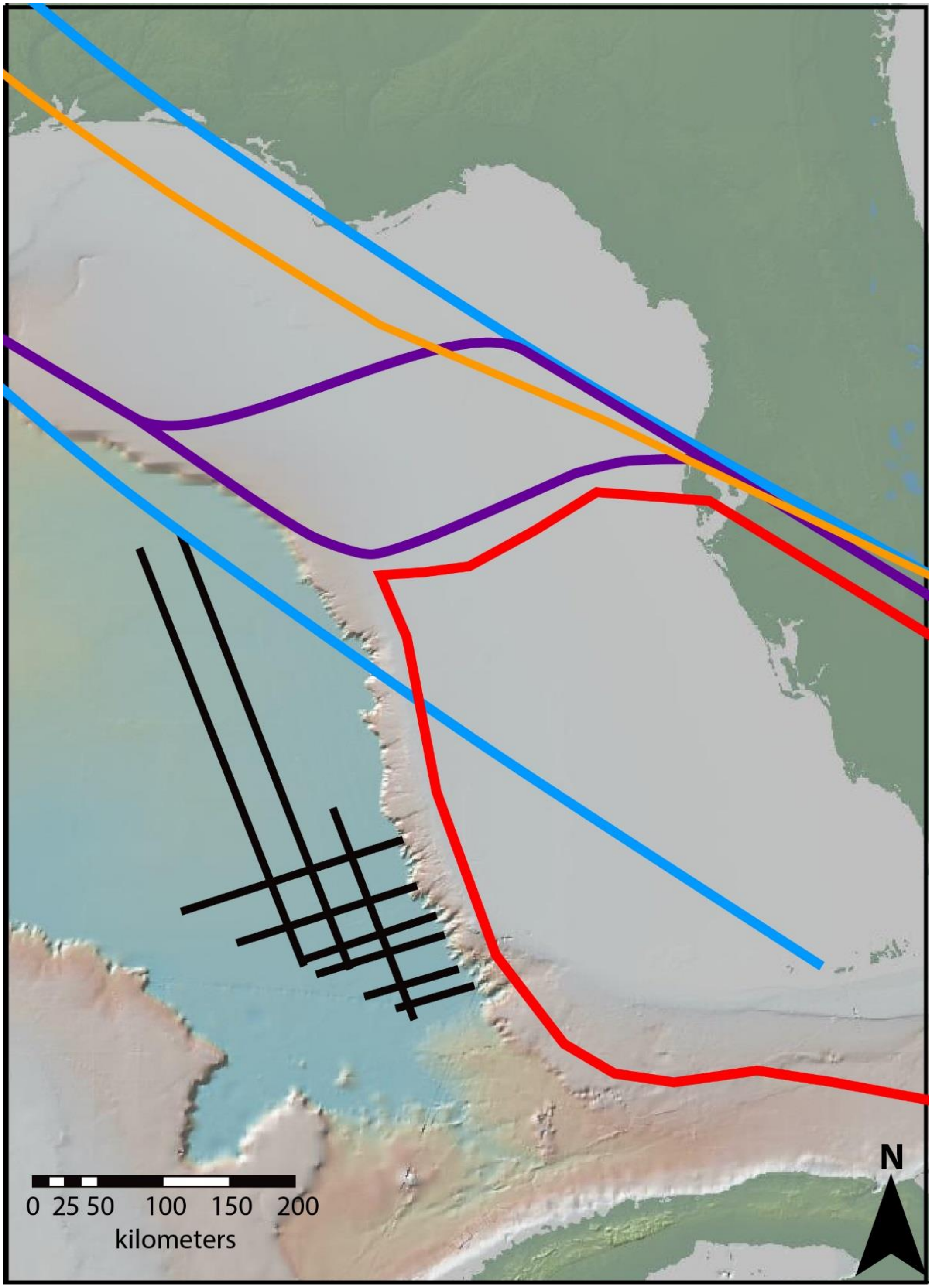


Figure 16. Location of proposed transfer faults during Late Triassic rifting in the EGoM. Orange: Marton and Buffler, 1994; Blue: MacRae and Watkins, 1996; Purple: Pindell and Kennan, 2001. Red indicates the Florida Continental Block by Pindell and Kennan, 2001

Nevertheless, if the West Florida Basin did experience extension during Triassic time, older rift geometries may be obscured by younger rift structures generated during Middle Jurassic extension as the Yucatán continental block rotated out of the central GoM.

5.2 Seismic Stratigraphy

Thickness maps for each of the seismic packages (Figures 12, 14, and 15) demonstrate the influence of the Middle Jurassic extension and subsequent thermal subsidence had on the development of the basin. Immediately following the Middle Jurassic rift episode, uppermost TJ was deposited on the newly emplaced oceanic crust and is relatively thin to the northwest of the West Florida Basin. In the northwest, younger JK sediments onlap basement (Figure 3b, 5, 6 and 7), which is probably a consequence of thermal subsidence combined with marine transgression in the GoM. The thicker TJ deposits in the center of the map coincide with the transition zone between continental crust and oceanic crust. To the south, basement must have remained elevated following extension, preventing widespread deposition of TJ. In addition to surrounding high standing fault blocks, elevated topography to the south of the West Florida Basin (Salvador, 1987) may have served as a source for the thick TJ deposits surrounding the basement fault blocks and in the transition zone between oceanic and continental crust. Sediments may also have come from the east, the Florida continental block, and the west, Yucatán continental block.

Because the age of TJ package cannot be determined, it is difficult to know whether or not they were deposited following both generations of extension or just the second. However, the thickness of TJ within many of the depocenters surrounding fault blocks in the West Florida Basin may indicate a longer period of deposition, beginning with Late Triassic extension.

Basement geometries following Late Triassic (?) rifting may be hidden by subsequent extension. Additionally, overlying stratigraphy and additional faulting may obscure basement rift features from the generation of extension. Alternatively, extension in the southeastern GoM may not have begun until Early or Middle Jurassic time, preventing the generation of pronounced rift geometries as those that are observed to the north. In this instance, the oldest TJ rocks in depocenters around fault blocks may only be Middle or Late Jurassic in age. Seismic interpretations (Figures 6, 7, 9, and 10) indicate that the majority of extension occurred during deposition of TJ, while thermal subsidence continued through the deposition of JK and EK units.

Reactivations of faults are interpreted to occur during the deposition of JK. Though most faulting from extension has terminated by earliest Late Jurassic time, faulting of carbonate buildups and fanning of JK sediments are interpreted along fault planes to the south of the West Florida basin (Figure 9 and 10) indicating additional extension in Late Jurassic time. Extension and oceanic crust emplacement ended by Late Jurassic or Early Cretaceous (Berriasian) time because of the absence of faulting above the JK package.

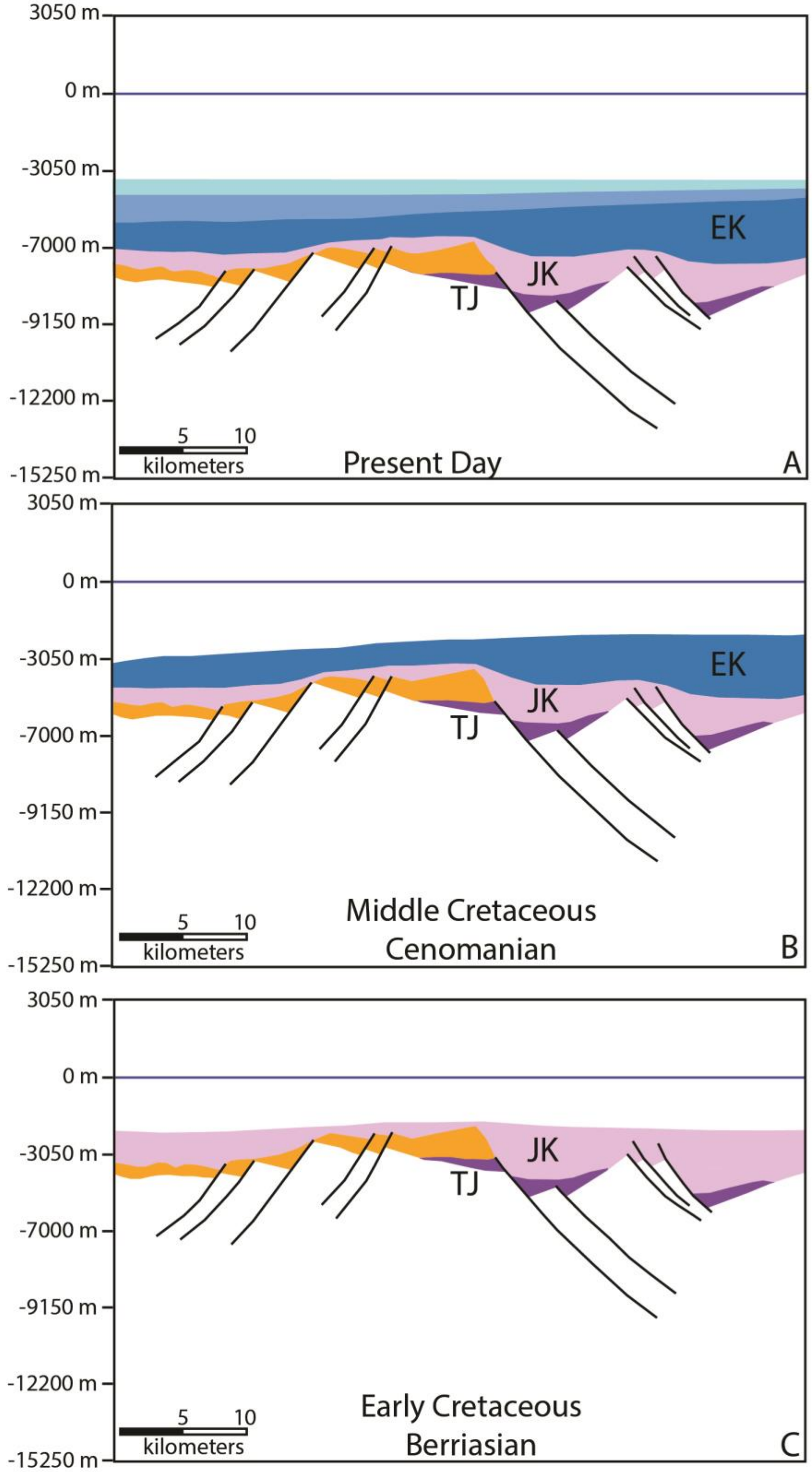
Following Middle Jurassic (Callovian) extension, subsidence following the emplacement of oceanic crust and marine transgression produced a shallow marine setting for the deposition of carbonate buildups. Higher topography towards the south lends itself to development of carbonate rocks in a deepening marine environment (Figure 13). These carbonate buildups were flooded in Late Jurassic (Tithonian) or Early Cretaceous (Berriasian) time, following an extensive marine transgression resulting from the connection of the Atlantic Ocean to the GoM. Continued basement subsidence following oceanic crust emplacement allowed for a thicker JK unit. Regions of subsidence to the northwest of the West Florida Basin can be distinguished from uplifted regions to the south that underwent relatively less extension as determined by basement topography (Figure 3). Basement topography to the southeast also appears to surround a wedge shaped zone of a thicker JK package (Figures 3, 12, and 14). This coincides with the rotation path of the Yucatán block that occurred in Middle Jurassic time (Wilson, 2011). Additionally, the oceanic – continental transition zone is a pronounced depocenter during the deposition of JK.

Thick deposits of the EK package (Figure 15) developed with continued subsidence in Early Cretaceous time. Rift structures from the rotation of Yucatán block are still evident, though not as prominent during its deposition. EK is no longer under the same influenced of basement structures as the TJ and JK packages are. The EK package thickens towards the Florida Escarpment in the southeastern corner of the West Florida basin; however, this may be a result of increased erosion from the nearby Florida carbonate shelf or improper interpretation because of decreased seismic quality or depth migration.

5.3 Seismic Section Restoration

To visualize the development of the West Florida Basin, Figure 17 is a structural restoration following extension beginning in Late Triassic (?) time to present day. By restoring basement to its pre-rift geometry, the restoration demonstrates the effects of subsidence from sediment loading and from the thermal response of the lithosphere to extension and oceanic crust emplacement on basement topography.

2D Move is used to restore Figure 10 in the south West Florida Basin. Beginning with the present day configuration of the basin (Figure 17A), seismic packages were removed (Figures 17B and 17C) and underlying packages decompacted using Sclater and Christie's (1980)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3050 m
0 m
-3050 m
-7000 m
-9150 m
-12200 m
-15250 m
EK
JK
TJ
5
10
kilometers
Middle Cretaceous
Cenomanian
B
3050 m
0 m
-3050 m
-7000 m
-9150 m
-12200 m
-15250 m
JK
TJ
5
10
kilometers
Early Cretaceous
Berriasian
C

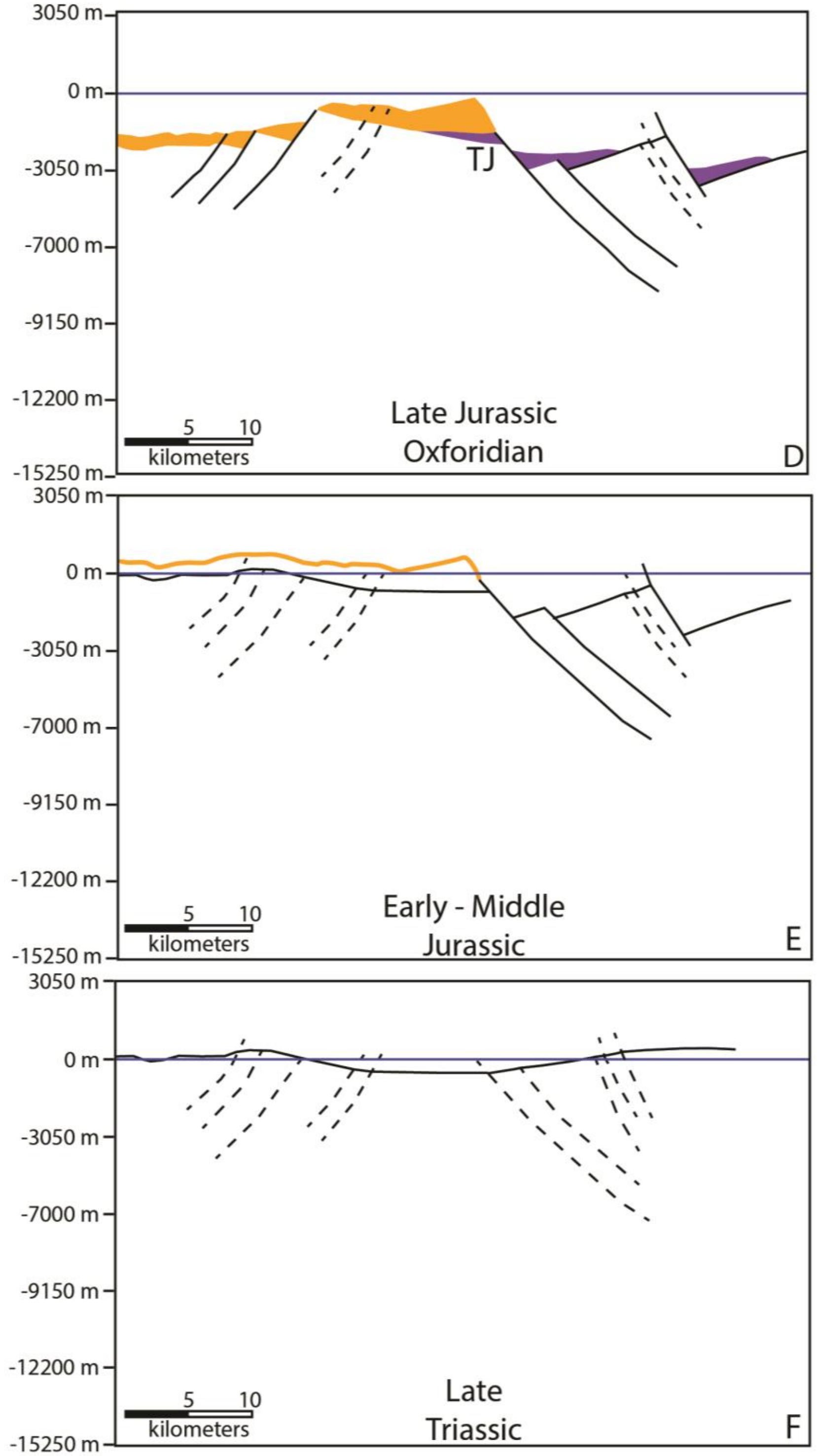

Figure 17. Restoration of Figure 10. A-F are time slices in the evolution of the West Florida Basin. In each frame, the youngest layer is removed and the layers underneath are decompacted. Faults (in black) are restored at the appropriate time intervals. This seismic dip line trends over transitional continental crust in the southeastern GoM. Blue line represents modern day sea level. Dashed lines indicate location of future fault planes. Faults represent apparent dip.

compaction curve. Basement was then restored to its original geometry by restoring normal faults to pre-rift positions (Figures 17D-17F). Depth of the basement shallows as subsidence effects from the Middle Jurassic extension are corrected and decompaction and lithospheric rebound as younger Cenozoic stratigraphy is removed. Flex isostasy is assumed.

The top unit in Figure 17B corresponds with the EK seismic package and possibly the youngest rock package to be largely affected by thermal subsidence (Phair, 1984). Figure 17D shows paleo depth below current sea level after removal of the JK package. Basement highs are at a relatively shallow depth, when carbonate buildups are developed (Figure 17D) given a lower sea level in Mesozoic time (Haq et al., 1987). This confirms interpretations regarding the development of these carbonate buildups on high standing horst blocks in a shallow marine setting. Younger sediments (upper JK and EK) were not under the same influence of basement topography as lower JK and TJ, which were confined to depocenters around these fault blocks. Figures 17E and 17F show movement along normal faults that comprise extension during the first and second generations of extension in Late Triassic (?) to Late Jurassic time. Restoration of basement following Late Triassic rift phase (Figure 17E) demonstrates high standing topography following extension, demonstrating a continental setting during the deposition of basal TJ sediments. Topography in Figure 17F may have had a higher topography, indicating more slip along faults than indicated. The second generation of extension (Figure 17C and 17D) further dissected basement and lowered basement topography. This, in combination with thermal subsidence, created a deepening marine environment.

Restoration of these faults brings basement topography to near present day sea level. Paleotopography may have been higher as effects from thermal subsidence and sediment loading may have not been completely addressed in the reconstruction. However, restoration of this seismic section demonstrates the evolution of continental crust in the southeastern GoM from the original basement geometry in a continental setting to a deep marine setting of highly attenuated continental crust.

The restoration demonstrates that extension terminates by Late Jurassic or Early Cretaceous time (Figure 17C) as suggested in the tectonic models for the formation of the GoM (Klitgord et al, 1984; MacRae and Watkins, 1996; Pindell and Kennan, 2001; Kneller and Johnson, 2011). Faulting within the carbonate buildups (Figure 17C and 17D), deposited on high standing horst blocks in Late Jurassic time, confirms the timing of the proposed models, though it cannot further refine them. Additionally, these faults demonstrate that both the Late Triassic rift phase, prior to the deposition of the TJ package, and Middle Jurassic drift phase led to the development of the West Florida Basin.

6. CONCLUSIONS

A review of three regional post-stack depth migrated seismic reflection strike lines and six dip lines and the development of a structural restoration in the southern margin of the West Florida Basin found that:

1. Seismic stratigraphy indicates deposition during two periods of extension in the West Florida Basin, Late Triassic (?) and Middle Jurassic (TJ and JK) associated syn-rift sedimentation, and one post-rift package (EK) prior to the Mid Cretaceous Sequence Boundary.

2. A structural restoration of basement geometry along a seismic reflection profile indicates that interpretations are possible. The restoration provides validation that interpretations are a potential solution to resolve basement structures developed during extension in Mesozoic time. The restoration indicates that following northwest-southeast Late Triassic (?) extension, basement in the West Florida Basin remained elevated preventing the deposition of salt that is prevalent in the north EGoM. Basement topography is later affected by additional extension and subsidence.

3. Subsequent northeast-southwest directed extension in Middle Jurassic time further dissected basement to produce present day basement configuration. Rift structures in the southern West Florida Basin were primarily influenced and formed during the second generation of extension and resultant thermal subsidence.

4. Mesozoic extension terminated by Late Jurassic or Early Cretaceous (Berriasian) time in the southern West Florida Basin. Although faulting occurs within JK, these may be reactivated faults, and the main episode of extension terminated prior to Cretaceous time.

5. Oceanic or 'proto-oceanic' crust in a transitional zone between continental and oceanic crust may be present from Middle Jurassic rifting as indicated by seismic characteristics of basement, onlap of Late Jurassic sediments due to absence of older Mesozoic sediments, scarcity of normal faults, and a shallow Moho/detachment reflector.

6. Though inferred transform faults are not present in the West Florida Basin, transform faulting during the first generation of extension beginning in Late Triassic (?) time is a viable model to explain the inferred northwest-southeast directed extension in the EGoM. However, because the Late Triassic rift direction is not well defined in the West Florida Basin and specific ages of sediments within the TJ and JK packages cannot be determined, variations on tectonic models regarding Late Triassic (?) northwest-southeast directed extension that do not incorporate transform faulting (i.e. Kneller and Johnson, 2011; Wilson, 2011) and the age that rifting terminated following the second generation of extension may still be applicable.

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