NO TRIASSIC STRUCTURAL CONTROL OF THE DEVELOPMENT OF THE MIDDLE GROUND ARCH, EASTERN GULF OF MEXICO

by

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ABSTRACT

Reconstructing the paleogeography and basement structure of the Eastern Gulf of Mexico before and during deposition of the Upper Jurassic Norphlet, Smackover, and Haynesville Formations is important because these formations have hydrocarbon potential and determining the distribution may help us predict the location of these hydrocarbons. Strictly regulated lease sales and drilling moratoria have minimized exploration, leaving the Triassic and Jurassic kinematic evolution and distribution of the Eastern Gulf of Mexico Upper Jurassic sedimentary rocks poorly understood.

Previous studies suggest that basement topographic highs are horsts and lows are grabens formed during NW-SE directed Triassic extension. This research uses 2-D seismic reflection data to analyze the southern boundary of a basement high, the Middle Ground Arch/Southern Platform, to determine if there is a fault present. The seismic data show an ENE-WSW (055, 45°NW) trending normal fault; however, the downthrown block is on the NW side.Offset stratigraphic units show that the fault was active until Middle Jurassic time. If the Middle Ground Arch/Southern Platform or Tampa Embayment was structurally controlled by a horst and graben system, the fault should be down to the SE to form the Tampa Embayment low and up to the NW to form the Middle Ground Arch/Southern Platform. This normal fault with throw down to the NW and up to the SE suggests that the formation of the Middle Ground Arch/Southern Platform and the Tampa Embayment is not structurally controlled by Triassic extension as a horst and graben system.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The Gulf of Mexico (GoM) offshore is a major production area for oil and gas for the United States (http://www.offshore-mag.com/articles/2016/08/western-gulf-of-mexico-lease-sale-yields-18-million-in-high-bids.html). A wealth of geologic and geophysical data for the northern and western areas of the GoM permit a good understanding of the stratigraphy, structure and geologic evolution. However, in the Eastern Gulf of Mexico (EGoM) exploration is minimal due to strictly regulated lease sales and drilling moratoria initiated in the early 1990's (Bureau of Ocean Energy Management, Regulations and Enforcement, 2010). As a result, basic geologic data as well as the structural evolution of the EGoM remains poorly determined. Due to the lack of data, there is still controversy on the initial geometry of basement rocks and style of break-up and where extension occurred.

Recent successful onshore production of the Norphlet and Smackover Formations has renewed industry interest in exploration in the EGoM offshore (Dempsey, 2003). New well and seismic data collected from the EGoM outside of the drilling moratoria are helping to resolve the extent of the Norphlet, Smackover and Haynseville Formations reservoir rocks, and source rocks in the Smackover Formation. In the Norphlet Formation, detrital zircon provenance as well as dipmeter data have identified Upper Jurassic sediment pathways (Lovell and Weislogel, 2010, Hunt 2013; Lisi, 2013; Weislogel et al., 2015; Hunt et al., 2017). In the offshore near Mobile Bay, the sediment in the Norphlet Formation came from the Appalachian Mountains to the north. In offshore Florida, the sediment in the Norphlet Formation came from the eastern Florida. In both regions, sediment was shed from the topographic basement highs and funneled through basement topographic lows. Previous work suggests that these lows are grabens and the highs are horsts formed during rifting of Gondwana from Laurentia during Triassic time (Klitgord, 1984; Dobson and Buffler, 1991, 1997; MacRae and Watkins, 1996; Pindell and Kennan, 2001). Other studies require multiple transform faults to produce extensional fault bounded basement highs and lows (Dobson and Buffler, 1991, 1997; Marton and Buffler, 1994; MacRae and Watkins, 1996; Pindell and Kennan, 2001). However, Wilson (2011) proposes that the Tampa Embayment, one of the basement lows, was not bounded by a large basement fault and thus, could not be a graben.

The objective of this study is to determine if there is a fault large enough to accommodate a horst and graben system on the south side of the Middle Ground Arch/Southern Platform using seismic reflection data (Figure 1). If there is a fault, this fault should dip to the SE with the basement high, the Middle Ground Arch/Southern Platform, on the NW upthrown block and the basement low, the Tampa Embayment, in the downthrown block. If there is not a fault, then the basement highs and lows must be formed by another mechanism and alternative models must be considered, such as pre-existing lithologic and structural weaknesses and crustal distribution around the EGoM.

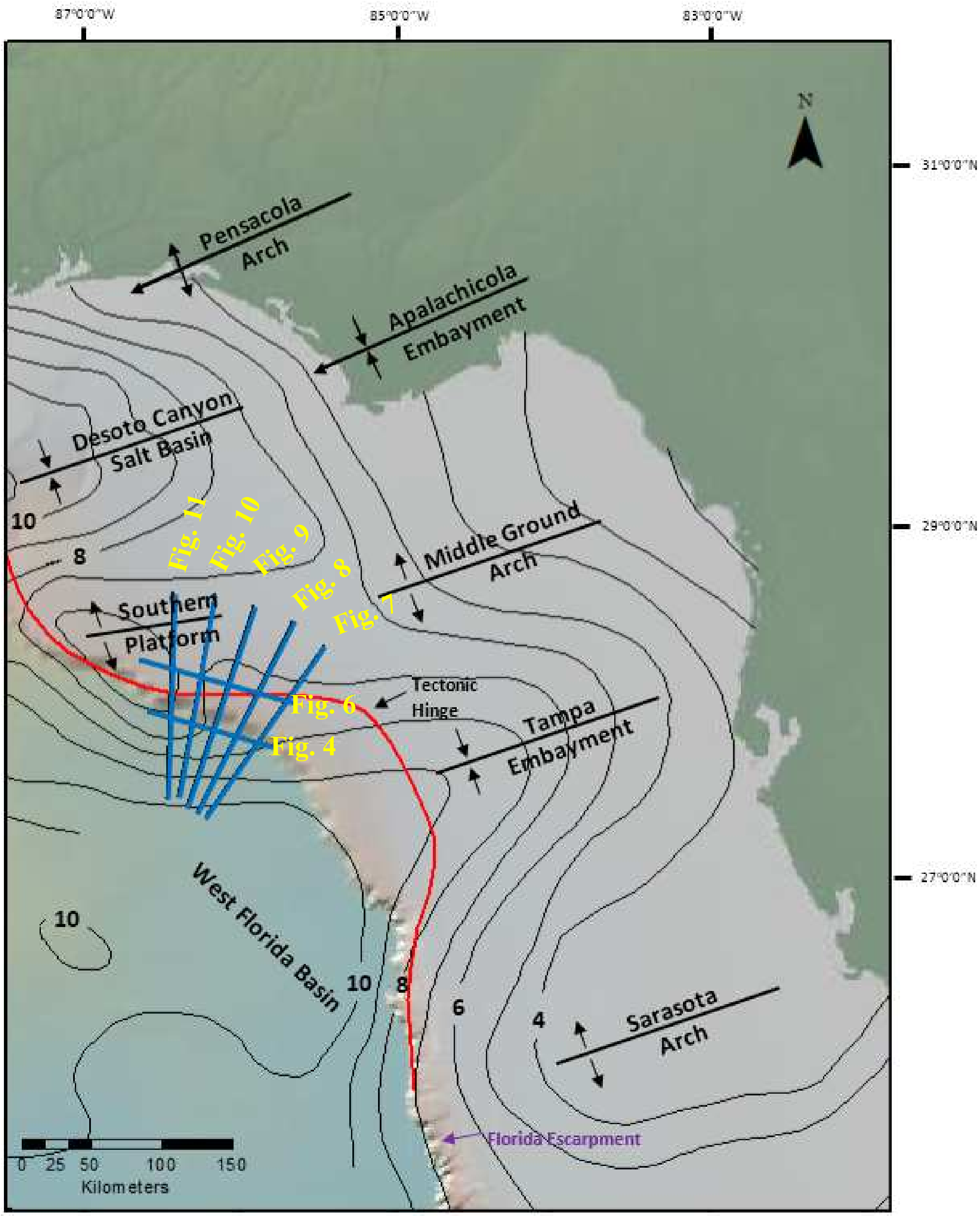


Figure 1: Basement Structure Map. Basement contour map showing locations of paleohighs and paleolows. Black numbers are in kilometers. Blue lines are seismic reflection profiles. Red line represents location of the tectonic hinge (modified from Sawyer et al., 1991; Wilson, 2011; Hunt, 2013).

2. GEOLOGIC SETTING

2.1 Tectonic Background

The supercontinent Pangea formed from the collision of Laurentia and Gondwana with the final suturing occurring in Permian time following closure of the Iapetus Ocean (Salvador, 1987). After Pangea amalgamated, it remained tectonically quiescent until NW-SE directed extension in Late Triassic time, which separated Laurentia, the North American plate, from Gondwana, the African and South American plate (Pindell, 1985; Salvador, 1987). Evidence for Triassic extension is found in extensive networks of fractures, grabens, and half grabens that extend all the way from the Canadian Atlantic offshore into eastern Mexico and northwestern South America (Bartok, 1993). Prior collisional events and major faults involved may have controlled the locus of extension as well as the structural style of these grabens and half grabens (Pindell, 1985; Salvador, 1991; Sawyer, 1991; Bartok, 1993).

A second generation of rifting began in Middle Jurassic time with NE-SW directed extension. During this time, the Yucatan block moved from its initial position from the modern day coast of Texas and Louisiana and rotated in a counterclockwise direction to its present location along the southern margin of the GoM (Pindell, 1985; Buffler and Sawyer, 1985; Salvador, 1991; Marton and Buffler, 1994; Pindell and Kennan, 2001). A transform fault in eastern Mexico may have accommodated the counterclockwise motion of the Yucatan (Pindell, 1985; Buffler and Sawyer, 1985; Salvador, 1987). As the Yucatan rotated, the proto-GOM opened as the continental crust was stretched north of the Yucatan. Influx of seawater into the accommodation space created facilitated the widespread deposition of Callovian aged salt (Salvador, 1987; Marton and Buffler, 1994; Bird, 2005).

In the EGoM, a series of alternating basement highs and lows are present off the western coast of Florida and extend to the northwest into southern Alabama and southeastern Mississippi (Pindell, 1985; Buffler and Sawyer, 1985; Dobson and Buffler, 1997; Salvador, 1991; Pindell and Kennan, 2001; Wilson, 2011). The axes of basement highs and lows trend NE-SW (Figure 1), indicating NW-SE directed extension. Thus, the proposed horst and graben normal faults should also trend NE-SW, indicated these features should be related to the first generation of faulting.

MacRae and Watkins (1996) propose that during the first generation of rifting, the lithosphere broke up into two major segments separated by regional transform faults, the NW-SE trending Florida-Bahamas transform fault to the east and the Pearl River transform fault to the west. In between these two transform faults, rotational normal faults trending in an ENE direction formed in Late Triassic – Early Jurassic time. Oblique-shear extension between these faults led to the development of grabens or half grabens, causing a chain of subbasins like the Tampa Embayment to develop in the EGoM.

Pindell and Kennan (2001) propose a NW-SE trending transform fault that translated a large crustal block, composed of a large portion of modern day Florida and the Bahamas, in a SE direction from its initial position near present day Louisiana and Mississippi to its present day location. As this Bahamas transform fault moved in Late Triassic-Early Jurassic time, a connected section of continental crust on the northwest side of the block was highly extended, developing the observed basement highs and lows. During the sinistral motion of the crustal block, pull-apart basins bounded by normal faults opened to accommodate the extension.

Klitgord (1984) suggests that the basement highs along the shelf margin of the EGoM are large isolated blocks of Paleozoic crustal fragments broken off from the North American plate during the 1st stage of rifting in Late Triassic-Early Jurassic time. The intervening basement lows would be thinned crust in that model. Klitgord (1984) suggests that the NW-SE trending transform fault may have some relationship to the basement blocks, but its function in the development of the basement highs and lows is not defined.

Marton and Buffler (1993) conclude that there were multiple stages of rifting in Late Triassic-Early Jurassic and Middle Jurassic-Late Jurassic times, and suggest a simple shear model for the rifting period that opened the GoM. Based on the rift margin and the extensive accumulation of salt in the northern GoM, they propose an asymmetrical north-south rift geometry starting from the northern Gulf margin to the southern margin, with a southward-dipping detachment that continues underneath the Yucatan margin. Marton and Buffler (1993) conclude that the basement lows, like the Tampa Embayment, were formed in Late Triassic-Early Jurassic time, by reactivating the preexisting structural weakness from the extensive period of rifting that opened the GoM.

Wilson (2011) found no evidence for faulting on the sides of the Tampa Embayment, a topographic basement low, and suggests the basin was thermally controlled, which allowed for more sediment accommodation in the center of the basin than on the flanks. Wilson (2011) concludes that rifting occurred in two stages, one that occurred during Late Triassic – Early Jurassic NW-SE motion which allowed for the development of the Tampa Embayment, and the second in a NE-SW motion that occurred in Jurassic time, that allowed some faults to continue into the Lower Cretaceous rocks.

2.2 Stratigraphy

Basement in the EGoM is defined as any pre-rift rock below the Louann Salt. Basement in the EGoM can be sedimentary, metamorphic or igneous rocks with varying Paleozoic ages (Bartok, 1993; Buffler and Sawyer, 1985). Late Triassic extension created accommodation space, which allowed the Eagle Mills Formation to be deposited. The Eagle Mills Formation consists of nonmarine redbeds and volcanic rocks (Tew, 1991) found in onshore and offshore grabens (Klitgord, 1984; Tew 1991; Hunter, 2014). Disconformably overlying the Eagle Mills Formation are the Callovian aged evaporites of the Werner Formation and the Louann Salt (Figure 2; see section 2.3) (Tew, 1991). These deposits represent initial marine transgression into the GoM due to sporadic spilling of Pacific Ocean seawater into the Gulf that led to shallow saline lakes and development of salt deposits (Salvador, 1991; Tew, 1991).

In Middle to Late Jurassic time, the Norphlet Formation was deposited on top of the evaporites (Tew, 1991; Hunt, 2013). The Norphlet Formation is found both onshore and offshore, and consists of sporadic black shale, eolian sandstone, conglomerate, and siltstone (Mancini, 1985; Tew, 1991; Hunt, 2013; 2016). The eolian sandstone of the Norphlet Formation is an important reservoir in both the onshore and offshore. The Smackover Formation, a carbonate rock deposited during a marine transgression, is on top of the Norphlet Formation,

(Figure 2) (Salvador, 1991; Mancini, 1985; Tew, 1991). The Smackover Formation is an important source rock and reservoir rock in the EGoM (e.g., Mancini, 1985).

The Haynesville Formation (Figure 2) was deposited on top of the Smackover Formation, and is composed of anhydrite, shale, and sandstone. The Haynesville Formation is another important reservoir rock in the EGoM (Mancini et al., 2001). During the deposition of the Haynesville Formation, sea levels continued to rise and began submerging the basement highs, such as the Middle Ground Arch/Southern Platform, in the EGoM (Dobson and Buffler, 1997; Wilson, 2011; Hunt, 2013; Hunt, 2017). The Cotton Valley Group was deposited in Late Jurassic - Early Cretaceous time. This group consists of sandstone and shale and marks continued marine transgression (Dobson and Buffler, 1997; Mancini et al., 2001). Salvador (1987) suggests that around this time there was a connection between the GoM and the Atlantic Ocean.

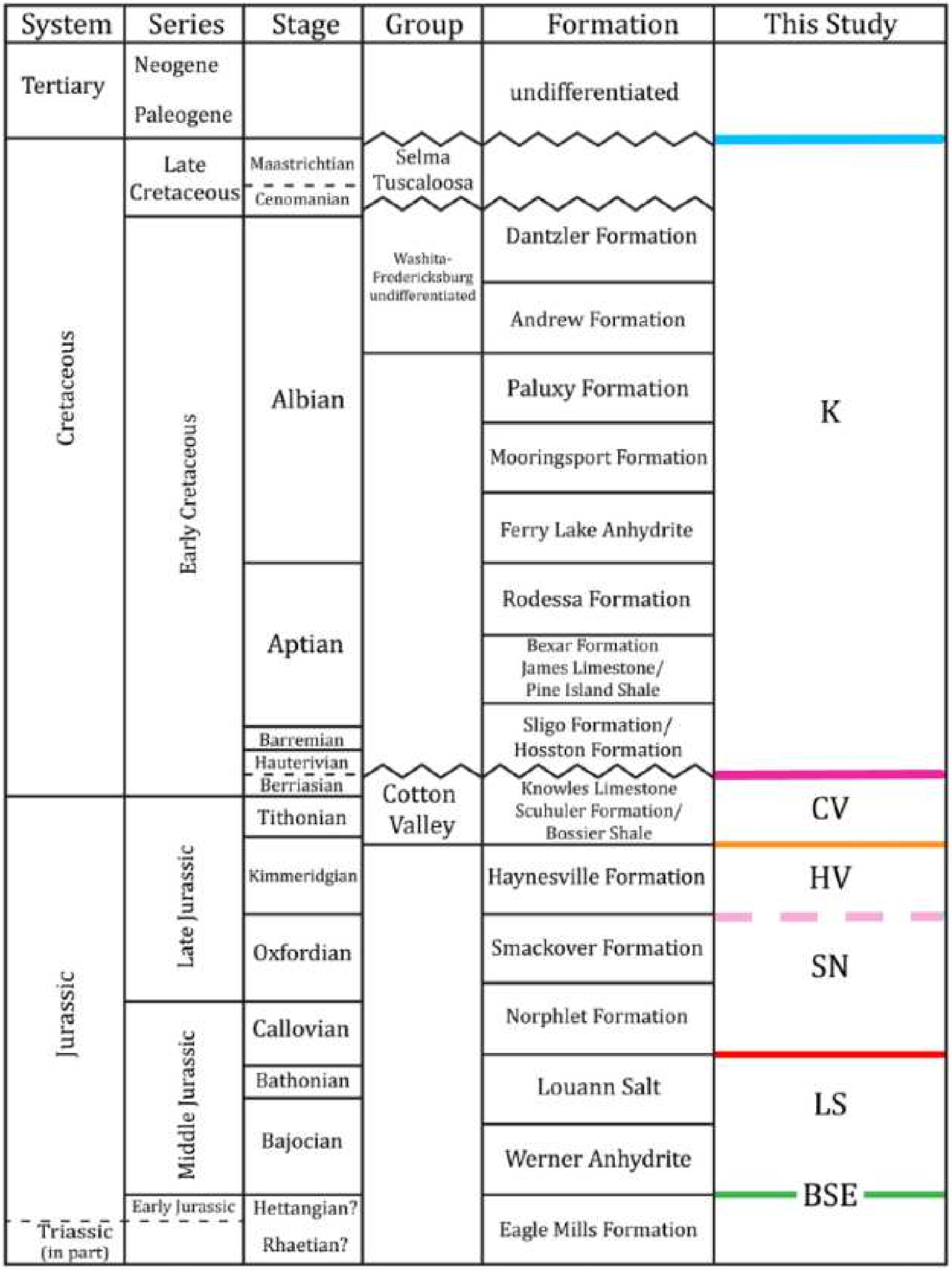


Figure 2: Stratigraphic Column for EGoM (modified from Mancini et al., 2001). Colors in the right hand column correspond to interpreted seismic units.

3. METHODS

Seven 2-D depth migrated seismic reflection lines were collected and processed by Spectrum as part of their Big Wave Phase 1 and 4 surveys. The seismic coverage lies off the western coast of Florida, south of the Apalachicola Basin and across the southern boundary of the Middle Ground Arch/Southern Platform and the Tampa Embayment. The seismic reflection lines include five dip lines that trend broadly in a north-south direction and two strike lines that trend in a roughly east-west direction (Figure 1).

The only well in the nearby area that penetrated Jurassic sedimentary rock was Desoto Canyon (DC) 512. The location of this well is close to the furthest west seismic line in Figure 1, and will be shown later in this thesis. As a result of the poor well coverage, the velocities of the rock units are not well known. These data were processed by Spectrum to enhance the shallower Tertiary units; thus, seismic packages near the basement are prone to velocity problems. Interpreted seismic packages include top of basement (BSE), Louann Salt (LS) Norphlet/Smackover (NS), Haynesville (HV), Cotton Valley (CV), and the top of the Cretaceous (K). I describe how these formations were picked in the next chapter.

In Petrel, I created a 3-D model to visually describe the structures in the seismic data. To create this model, I opened up the seismic profiles into a 3-D window and used the fault interpreter to draw the major normal fault structure in a 3-D interpretation.

4. INTERPRETATIONS

4.1 Basement/Pre-Salt

Top of basement (BSE, base of salt equivalent) is defined by the change in seismic reflectors from more continuous, organized, higher amplitude reflectors above to lower amplitude, chaotic, and incoherent reflectors below (Marton and Buffler, 1999). Below the BSE, west of the Florida Escarpment, a half graben is bounded on the east by a NE-SW normal fault (Figures 3 & 4). The sedimentary rock thins toward the west and fans toward the east, indicating the east boundary fault was active synchronous with the deposition of the sediments. Within the western part of the half graben, there are small accommodating normal faults that strike NE-SW on the seismic reflection dip and strike lines (Figures 4 & 5). Figure 5a (from seismic line 11) shows one of the accommodating faults while Figure 5b (from seismic line 7) shows the bounding normal fault. The reflectors within the half graben are Late Triassic redbeds and volcanic rock based on wells GV 707 and FL State 224-A2, which penetrated the Eagle Mills Formation. It is possible that some of these reflects maybe Paleozoic rocks. Reflectors in the half graben are continuous reflectors similar to the onlapping Jurassic syn-rift sedimentary rock above, instead of chaotic reflectors in the basement rock. The Jurassic sedimentary rocks fan towards the east, toward the bounding normal faultof the half graben, as is expected in synorogenic sedimentary rock. Figure 4 shows a normal fault extending from 14 km up to 7 km in the basement on the east side of the seismic line, ~`7 km of displacement. The N-S extent of the half graben is unclear due to poor seismic processing north of the Florida Escarpment. Figure 5 is a strike line located ~30 km north of Figure 4 on the carbonate shelf. Figure 6 does not show this Triassic graben in the basement, which suggests that the half graben did not extend that far northeast and must terminate south of Figure 6.

Tectonic hinge zones represent different subsidence rates where subsidence was greater on one side and less on the other, and coincides with a extension from continental crust to thinner crust (Buffler and Sawyer, 1985; Corso and Austin, 1995). The identification of the tectonic hinge in this area was from a gradual increasing basinward dip with the continuation of subsidence as explained by Dobson and Buffler (1997). NNE of the Florida Escarpment in Figures 7, 8, 9, 10 and 11, there are reflections in the basement rock with a southward dip. In Figure 7, the reflections are nearly horizontal about 4 km to the NNE of the escarpment and begin to dip southward where the tectonic hinge is located. In Figures 7, 8, 9, 10 and 11, north of the Florida Escarpment, the tectonic hinge is present and there is a subtle change in dip in the basement right next to the tectonic hinge. The change in dip, where the tectonic hinge is located, could be where the crust starts becoming thinner due to extension (Dobson, 1990; Sawyer et al., 1991).

In Figure 7, on the south side of the seismic line outlined in blue is the normal fault that is also in Figure 4. On Figure 7, the fault dips to the NW. The same fault is on Figure 8 dipping 45° NW. The fault is not shown on the other seismic lines (Figures 9, 10, and 11) because the fault is located further south of the remaining seismic lines. Thus, the southwest extent of the half-graben is unknown. The blue curved line in Figures 6, 7, and 8 represents the base of the Triassic sedimentary rock fanning toward the bounding normal fault. Figures 10 and 11 have smaller synthetic normal faults different from the bounding normal fault, these smaller normal faults are found on the western end of Figure 4. Triassic sedimentary rock also fans from that half graben in a SE direction from Figures 10 and 11.

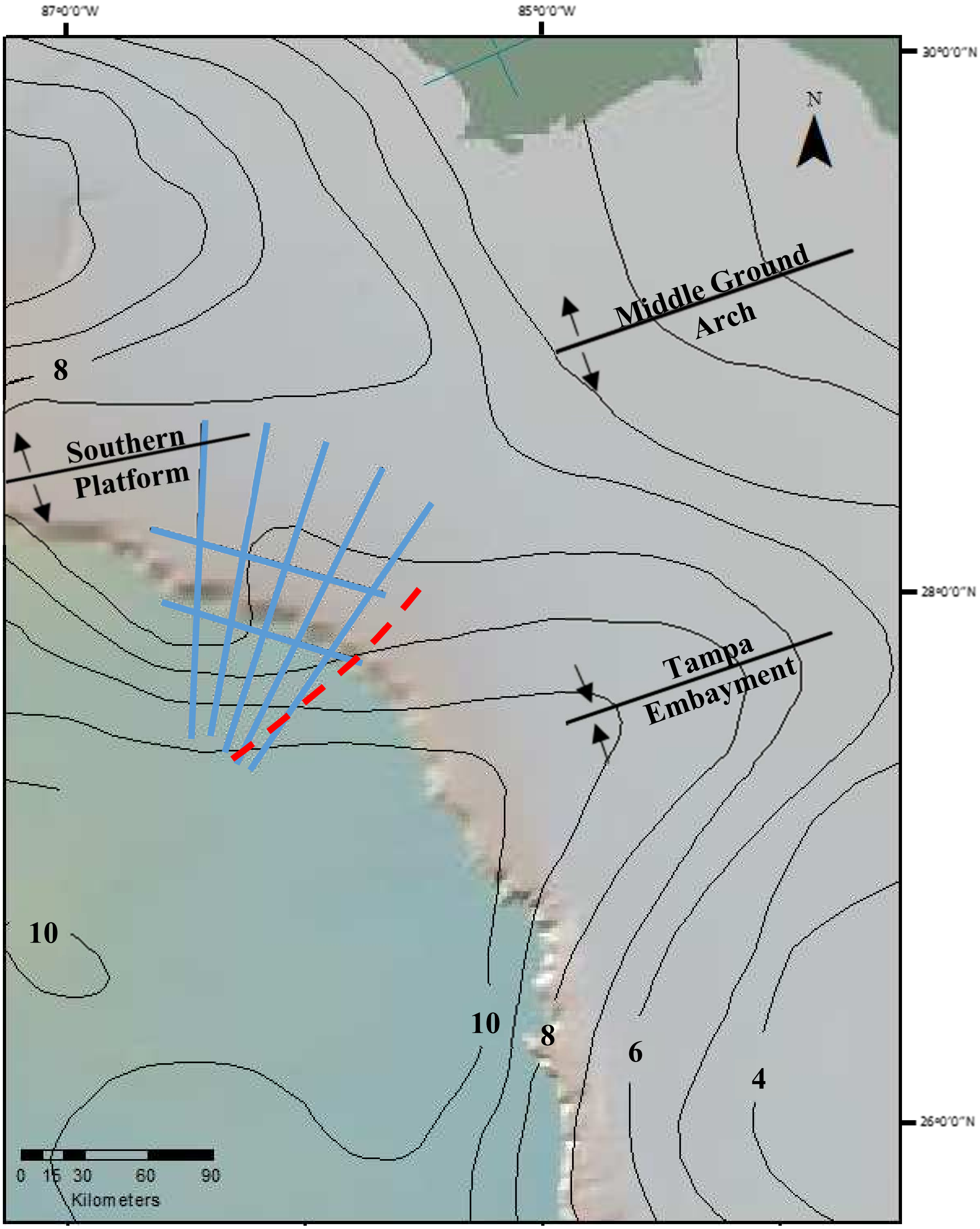


Figure 3: Map of projected normal fault in the Southern Platform. With proposed normal fault and its extent. Black contours represent the basement surface in kilometers.

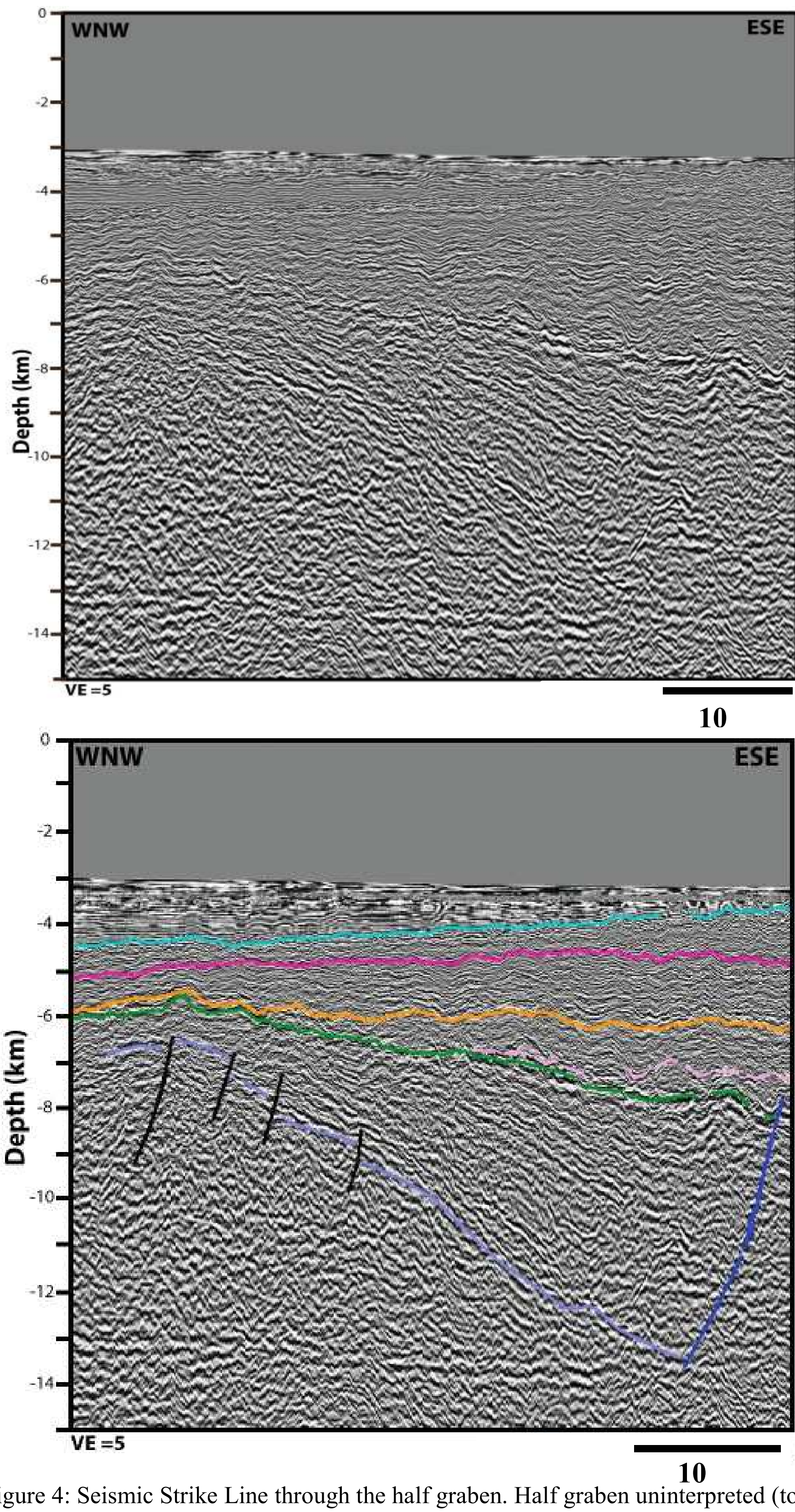


Figure 4: Seismic Strike Line through the half graben. Half graben uninterpreted (top) and interpreted (bottom). Basement fault opened a half graben that was filled with Triassic sediments and was active until Early Jurassic time. Horizons defined in Figure 2. Dark blue

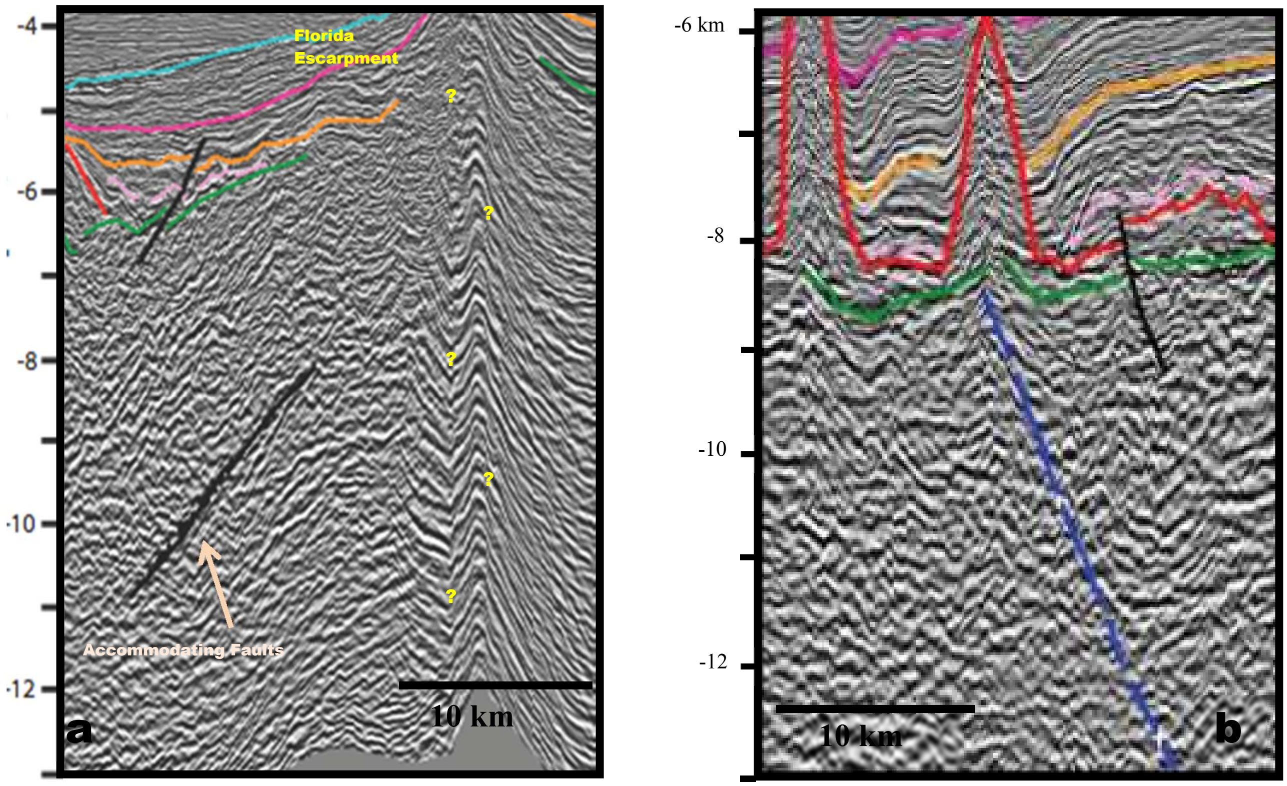


Figure 5: Enlargement of Important Seismic Sections. a) Image from Figure 11 showing the accommodating fault from the half graben, looking on dip line b) anther image taken from Figure 7 showing the normal fault on Figure 7 on dip line

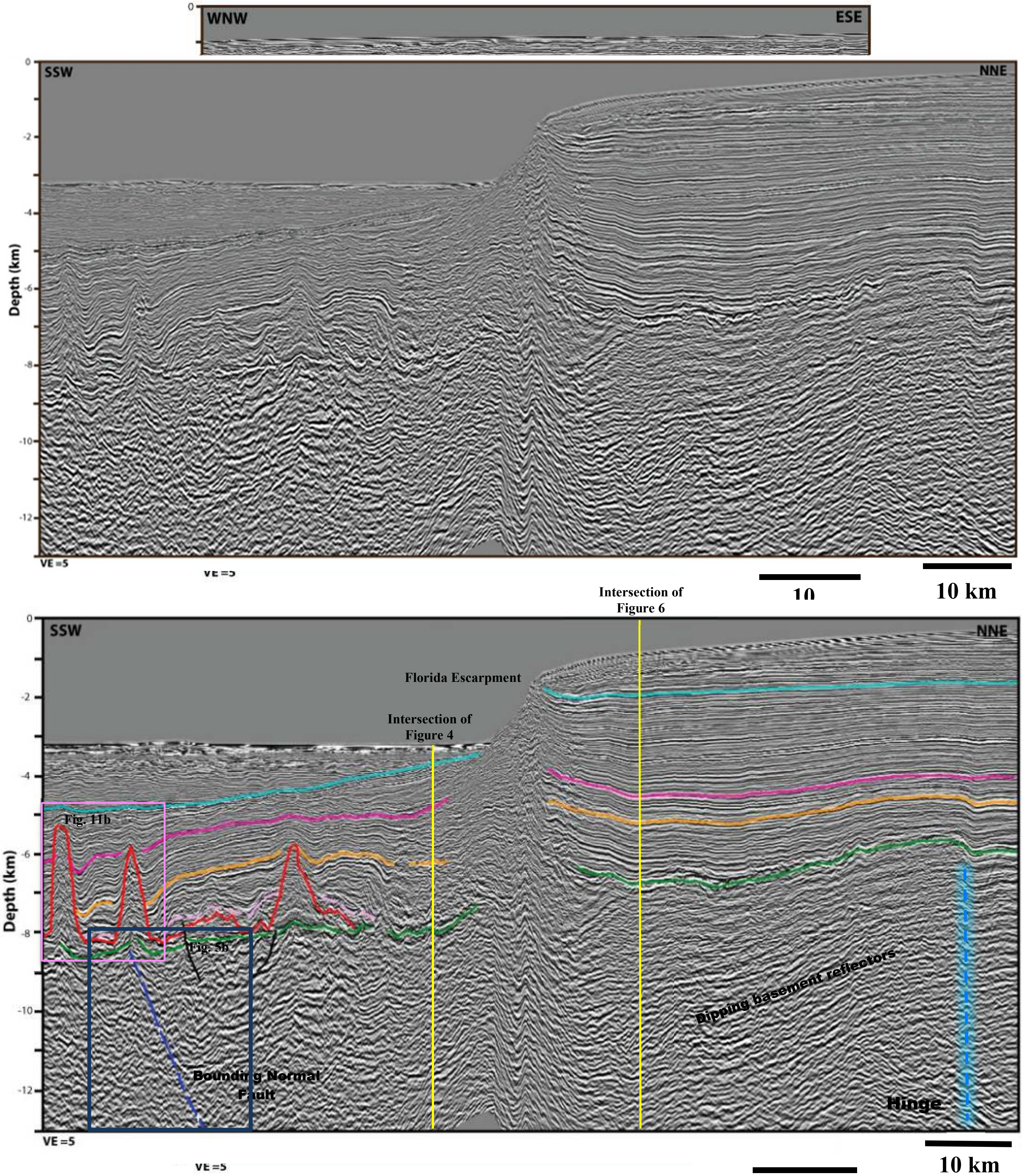
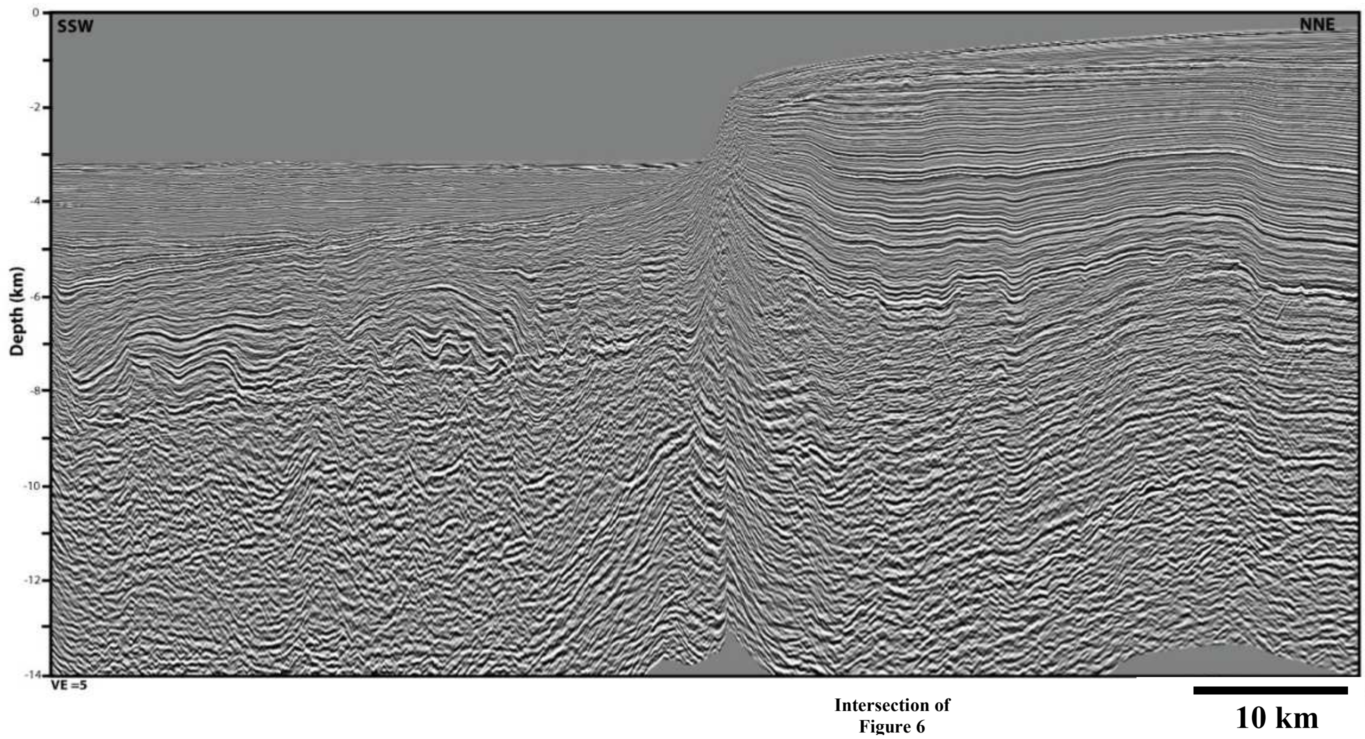


Figure 7: Seismic Dip Line through the Southern Platform. Uninterpreted (top) and interpreted (bottom). Location of line is shown in Figure 1 and colored horizons are shown in Figure 2. The vertical blue line located within the basement near the right side of the seismic line represents the tectonic hinge.

Figure 6: Seismic Strike Line through the Southern Platform. Uninterpreted (top) and interpreted (bottom). Colored horizons defined in Figure 2. No evidence of the Triassic graben is present on this seismic line, which is located 25 km to the south.



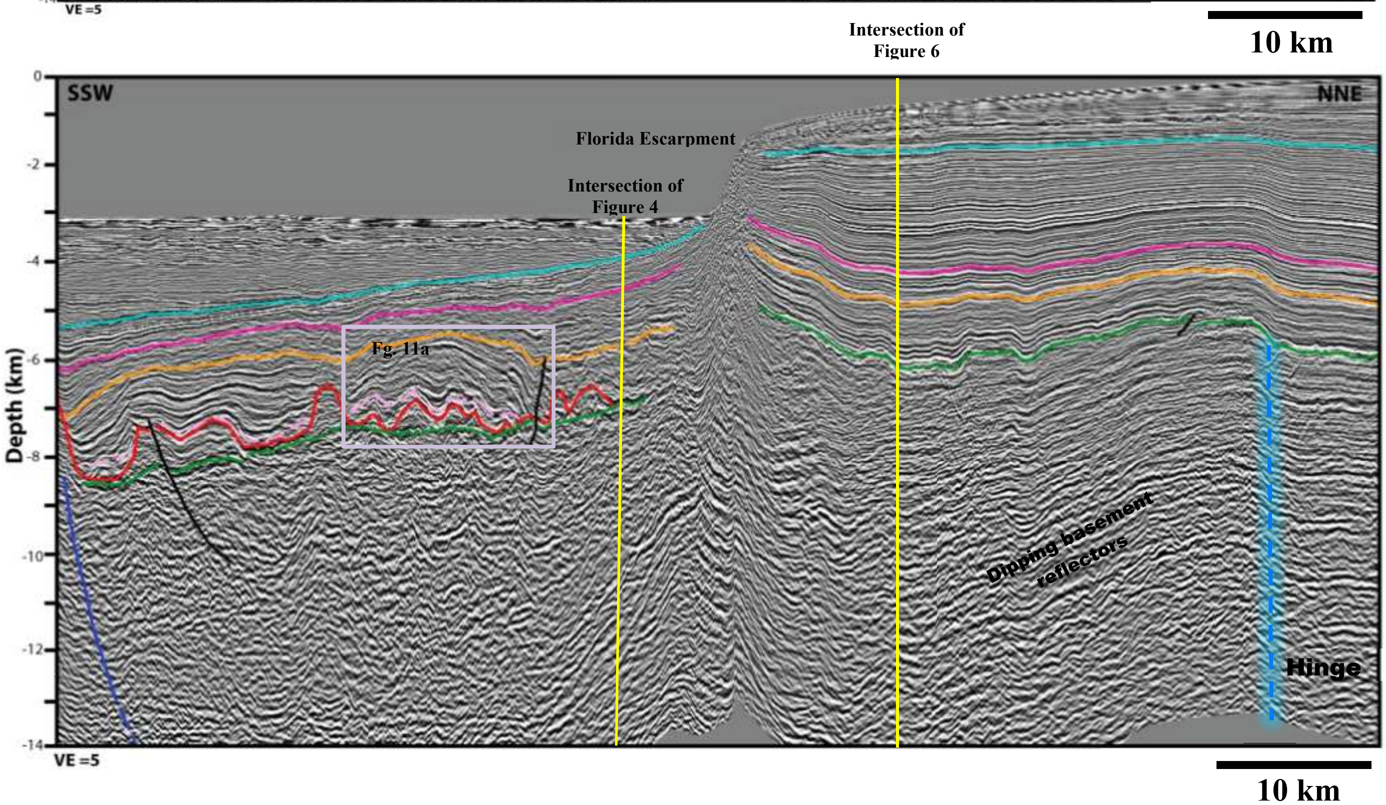


Figure 8: Seismic Dip Line through the Southern Platform. Uninterpreted (top) and interpreted (bottom). Location of line is shown in Figure 1 and colored horizons are shown in Figure 2. The vertical blue line located within the basement near the right side of the seismic line represents the tectonic hinge.

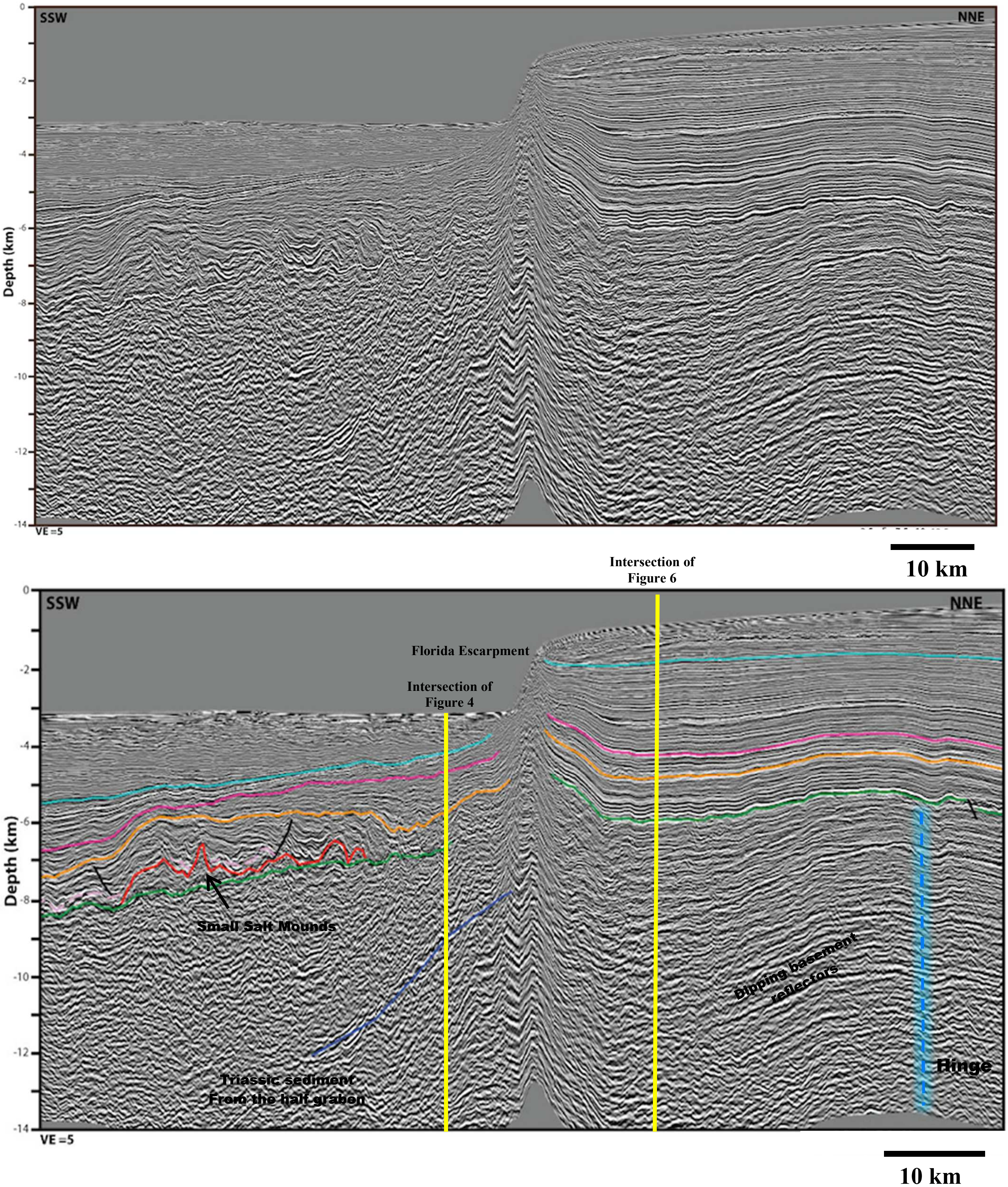


Figure 9: Seismic Dip Line through the Southern Platform. Uninterpreted (top) and interpreted (bottom). Location of line is shown in Figure 1 and colored horizons are shown in Figure 2. The vertical blue line located within the basement near the right side of the seismic line represents the tectonic hinge.

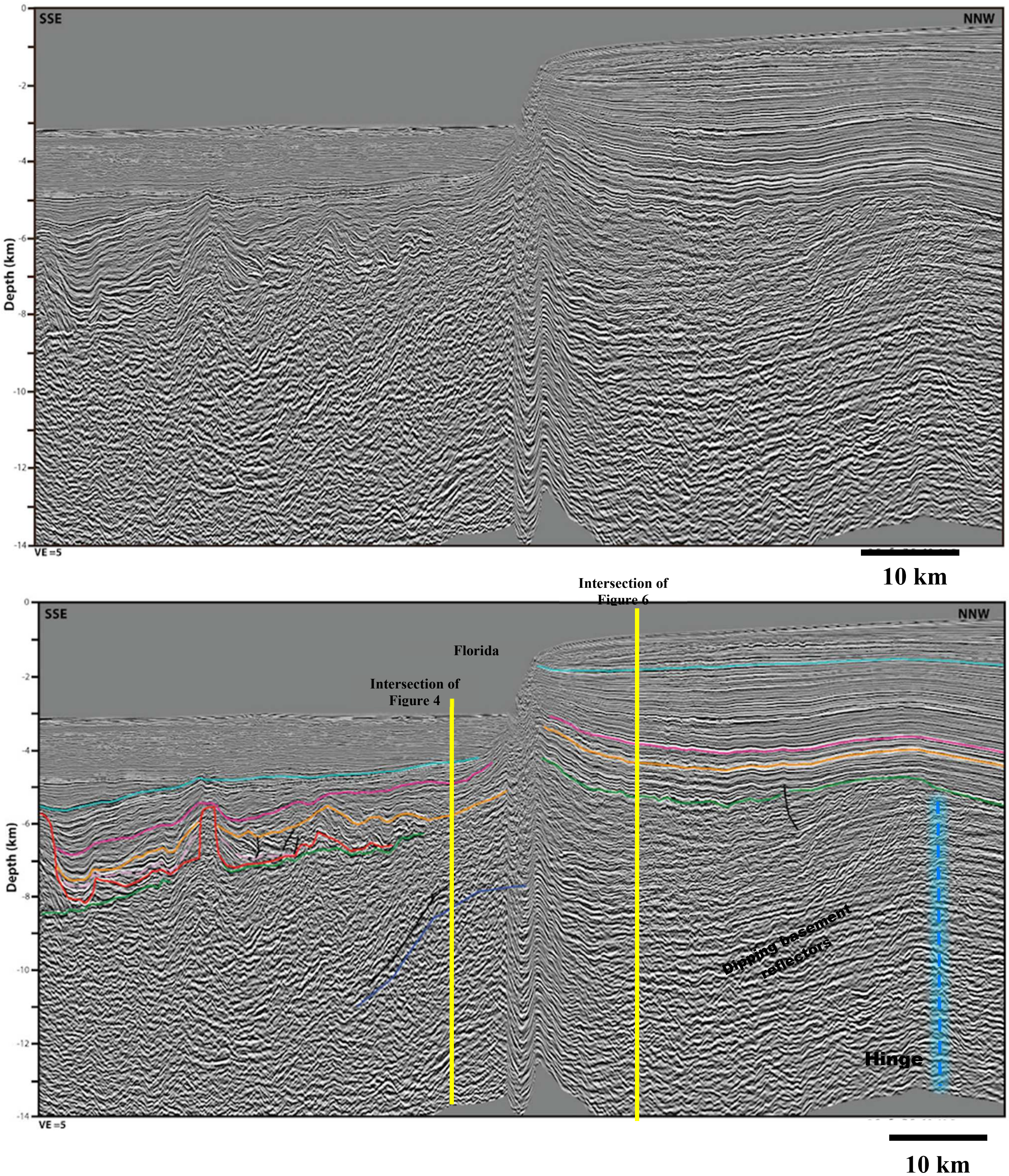


Figure 10: Seismic Dip Line through the Southern Platform. Uninterpreted (top) and interpreted (bottom). Location of line is shown in Figure 1 and colored horizons are shown in Figure 2. The vertical blue line located within the basement near the right side of the seismic line represents the tectonic hinge.

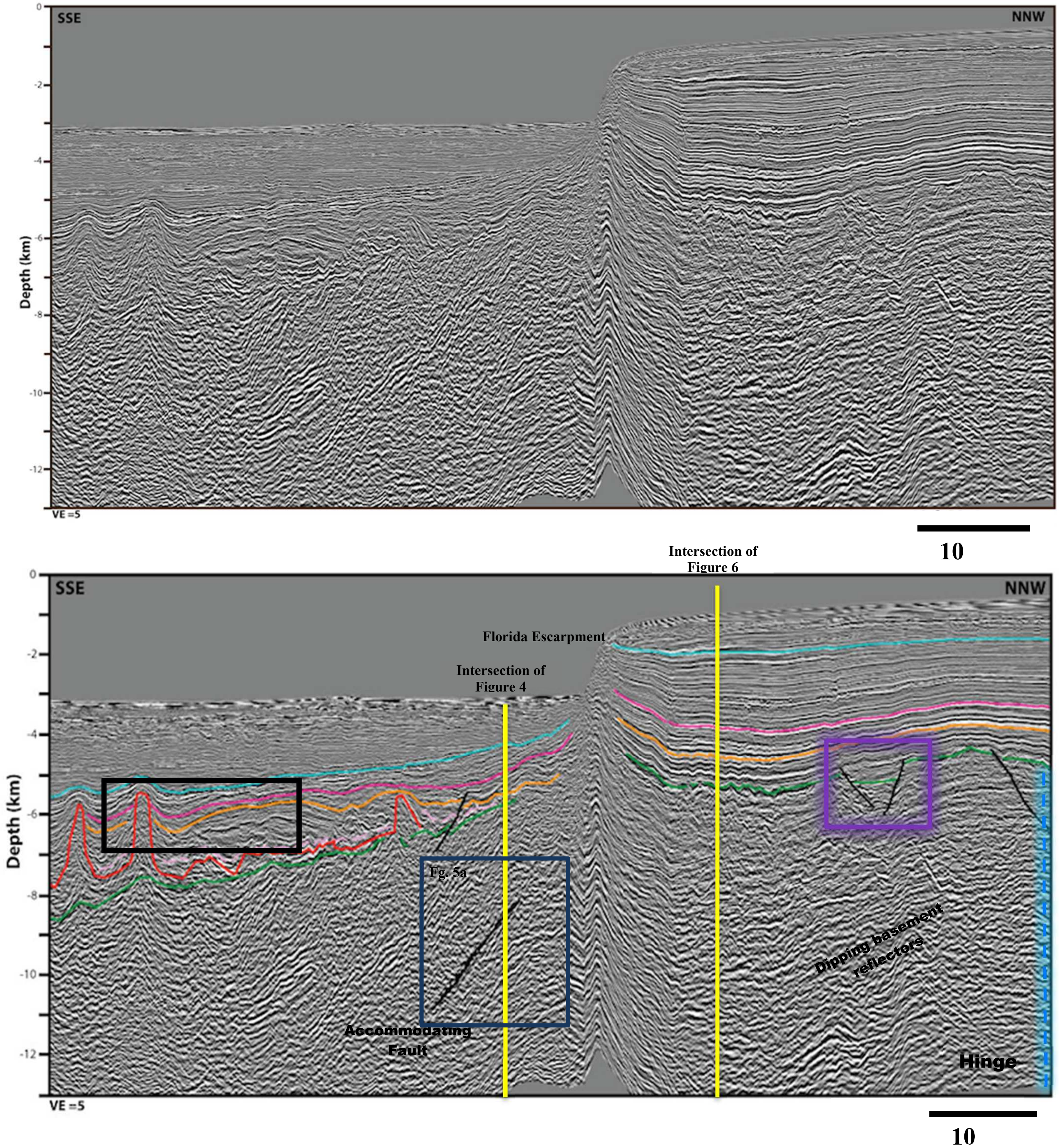


Figure 11: Seismic Dip Line through the Southern Platform. Uninterpreted (top) and interpreted (bottom). Location of line is shown in Figure 1 and colored horizons are shown in Figure 2. The vertical blue line located within the basement on the right side of the seismic line represents the tectonic hinge. Purple box highlights the fault controlled valley that could have acted as a potential sediment transport pathway from off of the shelf.

4.2 Salt and Salt Structures

In Middle Jurassic time, sporadic spilling of Pacific seawater created a shallow inland sea (Salvador, 1987, 1991; Dobson and Buffler, 1997). Evaporation of hypersaline water led to the deposition of the Werner Formation and Louann Salt (Haq et al., 1987; Salvador, 1987, 1991; Dobson and Buffler, 1997). Based on the present location of salt in the Gulf of Mexico, the sea most likely went as far east as the Desoto Canyon Salt Basin and was bounded to the south by the Sarasota Arch (Marton and Buffler, 1999).

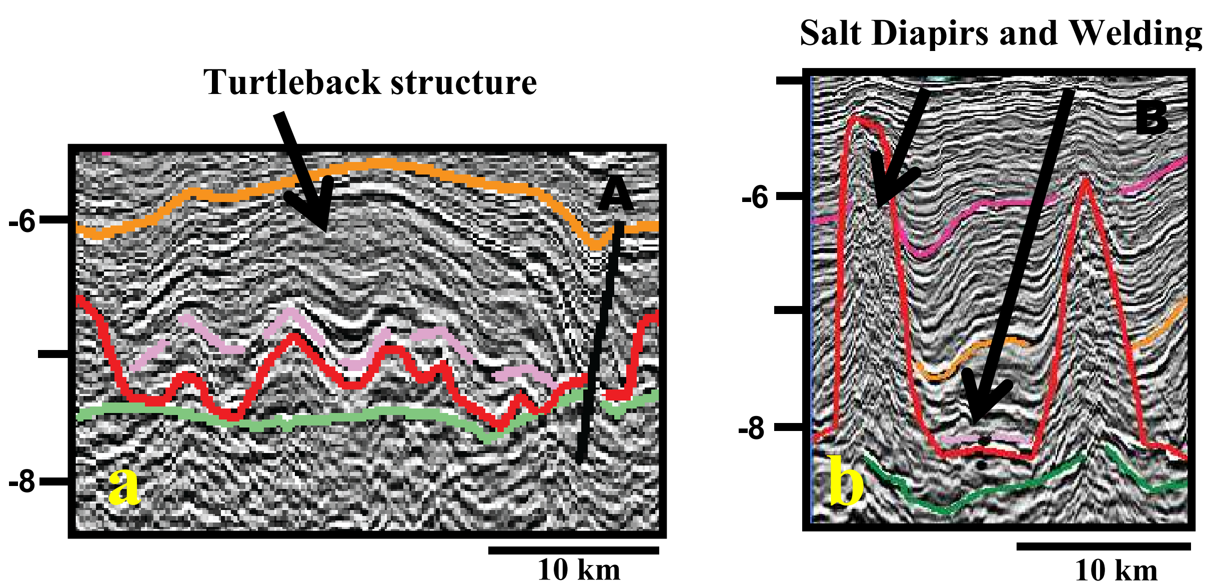


Figure 12: Interpreted Salt Structures in the Southern Platform. Enlarged images of seismic sections from Figures 7 & 8. The figures show salt structures, and post-salt sedimentary rock. Horizons are the same as in Figure 2.

Salt is present intermittently to the south and west of the Middle Ground Arch/Southern Platform and west of the Florida Escarpment as diapirs, rollers, turtlebacks and welds, which are found adjacent to small salt structures (Figure 12). When comparing these salt structures to structures found in the northern GoM, they are smaller in magnitude by 100's of meters (MacRae and Watkins, 1993). West of the Florida Escarpment, salt has high amplitude reflectors with internal reflectors that are chaotic and discontinuous, while no salt is identified north of the Florida Escarpment. Mobilization of salt occurred during Jurassic time when the Haynesville Formation was being deposited, as evidence by the post-salt growth found in the Haynesville Formation **(**Figures 7, 8, 9, 10, & 11). In Figures 7 and 11, there are salt diapirs that ascended through the Haynesville Formation and into the Cotton Valley Formation. Salt diapirs form as a result of the overburden and pressure, and salt moves basinward as a result of thermal subsidence and down-slope gravity gliding (Rowan et al., 1999). These salt diapirs started moving and forming around the time of the deposition of the Haynesville Formation (Dobson and Buffler, 1997; Wilson, 2011). In Figures 8 and 9, there are salt mounds, which form before salt diapirs. In all seismic lines, the salt looks like it pinches out up-dip close to the Florida Escarpment; however, the data are too poor in quality around the Florida Escarpment to determine with accuracy.

Salt deposits around the Middle Ground Arch/Southern Platform are about 100 m thick but can have an average thickness of 1000 m where there are salt diapirs (Figures 9 & 10). Where salt is absent, the salt may be there but just below the resolution of the seismic data. On average, the salt found southward and around the Southern Platform is about 500 m thick, similar to the salt found near the Tampa Embayment (Marton and Buffler, 1997; Wilson, 2011; Hunter 2013), whereas salt deposited in the Apalachicola Basin was 700-900 m thick (MacRae and Watkins, 1993). Marton and Buffler (1997) suggest that the salt is thinner around the Southern Platform area due to younger rifting towards the south in the EGoM that kept the region just at or a little bit above sea level when the salt was being deposited. Hudec et al. (2013) also suggest that the salt is thinner due to delayed onset of seafloor spreading, which allowed the salt to thin and stretch before oceanic crust formed. Hudec et al. (2013) also propose that sea floor spreading did not occur until Middle to Late Jurassic time and during postsalt crustal stretching, and sea floor spreading the salt began to stretch and widen to fill the widening basin.

4.3 Norphlet/Smackover Formations

The Norphlet and Smackover Formations were the first sedimentary rocks to be deposited post-salt. The two formations are combined into one undifferentiated unit (NS) because it is difficult to distinguish the units individually on the seismic data. Combined, the formations are less than half a kilometer thick. Top NS is marked by a continuous high amplitude peak. NS thins and pinches northward towards the Florida Escarpment, and is absent over the crest of the Southern Platform/Middle Ground Arch (Figure 11), unlike in the paleolows where salt is easier to identify in the Desoto Canyon Salt Basin, Apalachicola Basin and the Tampa Embayment (Marton and Buffler, 1997). NS is relatively thin, about 200 m or less. In Figures 7, 8 and 11, NS is disrupted by salt, and the NS reflector becomes difficult to follow south towards the Tampa Embayment. In Figures 9 and 10, there are no salt structures. In Figure 8, NS is deformed by a turtle back structure.

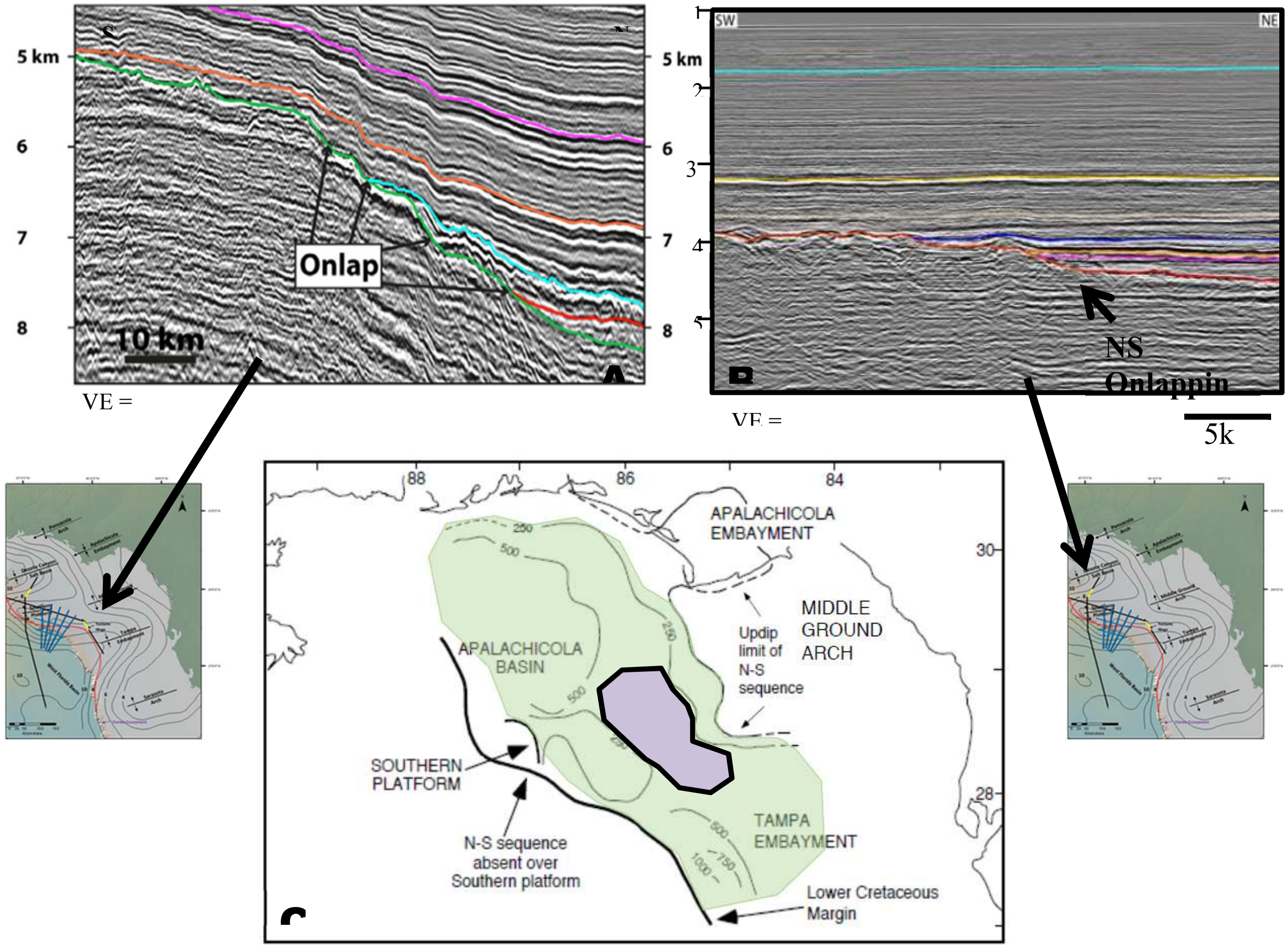


Figure 13: Enlargement of Important Seismic Sections and Cartoon of NS. Norphlet/Smackover is shaded in green a) Seismic profile showing NS onlapping onto the Southern Platform (Wilson, 2011), b) Seismic profile showing NS onlapping onto the Middle Ground Arch (Hunt, 2013), c) Extent of the NS, in green, on the platform, with the purple representing the small valley between the Middle Ground Arch and the Southern Platform (modified from Dobson and Buffler, 1997). Black contours are an isopach map of NS in meters with an interval of 250m.

In many studies, the Southern Platform/Middle Ground Arch is used synonymously. More accurately, the Southern Platform is an isolated high to the west and the Middle Ground Arch is an isolated high to the east (see Figure 1). Between the Southern Platform and the Middle Ground Arch, there is a NW-SE trending valley, less than 100 km wide and 150 km long, where NS is present (Figure 13c, the purple valley) (Dobson and Buffler, 1997). The Norphlet and Smackover Formations onlap onto the Southern Platform and Middle Ground Arch (Figures 13a & 13b). Because of this valley, NS can be correlated from the Apalachicola Basin in the north to the Tampa Embayment in the south (Dobson and Buffler, 1997). NS is not present over the top of the Southern Platform and Middle Ground Arch because NS is eroded (Dobson and Buffler, 1997) or was never deposited. The valley could have transported eroded sediment from the basement highs into the Tampa Embayment and thus, could have been a source for Norphlet siliciclastic sedimentary rock in the Tampa Embayment (Wilson, 2011).

4.4 Haynesville/Cotton Valley Formations

The Haynesville Formation (HV) was deposited as marine transgression occurred in the Gulf of Mexico. HV is present both south and north of the Florida Escarpment. HV thickness is a little less than 1000 m toward the south and thins and pinches out northward toward the Florida Escarpment but is found on the shelf (Figures 7, 8, 9, 10 & 11). In Figure 7, HV is cut by multiple salt structures. Just south of the Florida Escarpment, HV has a thickness of about 250 m and southward towards the basin, the growth faults and the salt diapirs that formed during deposition cause the unit to thicken basinward. In Figure 8, HV thickens southward from the Florida Escarpment and contains turtleback structures and smaller salt structures. Figure 9 is similar to Figure 8 in that there are no salt diapirs but HV contains smaller salt structures. Figure

10 also shows the affect of salt on HV with a salt diapir in the middle of the seismic line south of the Florida Escarpment.

HV on Figure 11 is disrupted by two salt diapirs south of the Florida Escarpment and the initial stages of a salt diaper near the Florida Escarpment. Between the salt structure near the Florida Escarpment and the salt diapirs in the middle, HV is deformed by salt and has small salt features. In Figure 11, a salt block was detached from the mother salt and caused a shallower HV depth by 200 m than the surrounding HV. Southward of the Florida Escarpment, HV is about 100 m or less. It is possible that this line contains a detached salt body but lacks the chaotic reflectors normally exhibited by salt. To the south, salt thickens to 500 m until the two salt diapirs are encountered.

HV thickens southward possibly due to tilting of the tectonic hinge slope by less than 1° (Brun and Fort, 2011). The tilting of the tectonic hinge might have resulted from extension causing fault reactivation, which could cause the tectonic hinge to tilt slightly in addition to the continental crust thinning from extension as well (Brun and Fort, 2011; Godo et al., 2011). This tilting could have created greater accommodation space south of the shelf resulting in a thicker HV deposit. In Figure 4, HV thickens to the ESE into the Tampa Embayment, which is a basement low and allows for greater accommodation space. In Figure 6, HV also thickens southward into the Tampa Embayment.

Figure 11 shows a fault controlled valley in the basement, outlined in the purple box. A similar graben on the Middle Ground Arch is a potential sediment transport pathway that funneled sediment off of the arch and into the Tampa Embayment (Hunt, 2013; Hunt et al., 2017). The fault controlled valley in Figure 11 could also be a sediment transport pathway to the Tampa Embayment.

With the deposition of the Cotton Valley Formation (CV), the sedimentary rock changes from clastic to carbonate dominated deposition. During Late Jurassic to Early Cretaceous time, a marine seaway between the Proto-Caribbean and the GoM is proposed to explain the change in lithology (Haq et al., 1987). CV has higher amplitude and shorter wavelength reflections than HV. CV has a more consistent thickness of about 500 m throughout the seismic data, unlike HV that thickens toward the south. In Figure 11, CV has an estimated thickness of 250 m possibly due a possible salt structure. In Figures 7, 8, 9 and 10, CV remains relatively unaffected by the salt except for the salt diapirs that formed in Figures 7 and 10.

4.5 Cretaceous Formation

The Cretaceous and Cenozoic units are separated by the Mid Cretaceous Unconformity (Haq et al., 1987). The unconformity is identified by its prominent reflectors and is found in the deep basins south of the Florida Escarpment; this unconformity is not seen north of the Florida Escarpment (Figures 7, 8, 9, 10 & 11) (Buffler, 1991). This unconformity is caused by either a rapid submergence event or a fall in sea level, which led to a significant amount of erosion (Haq et al., 1987; Dobson and Buffler, 1997).

5. DISCUSSION

5.1 Triassic Extension

The half graben in these seismic data south of Middle Ground Arch/Southern Platform has a NE-SW trend, with an of 050, 45° NW, similar to other Triassic grabens on the East Coast (Figure 14). However, the graben bounding fault has its down thrown block on the northwest side where the Southern Platform is located and its up thrown side to the southeast where the Tampa Embayment is located. Figure 14a is a view of the half graben looking towards the south. From this angle the bounding fault crosses three of the seven seismic lines and then continues southward. In the north, the fault trends toward the northeast and must pass to the east of Figure 7. Figure 14b is a view of the normal fault looking to the northwest with the fault dipping in to the northwest. The fault shown ~7 km of displacement and the width of the half graben is ~40 km.

On Figure 4 a high amplitude reflection can be seen at about 13 km, which looks similar to a reflection found by Wilson (2011). Wilson (2011) found a high amplitude reflection in the Tampa Embayment at around 15 km, which he interprets as the Moho based on the work of Radovich (2011). Radovich (2011) shows a deep dipping seismic reflection dipping at 40 km subsea depth. The high amplitude reflection at roughly 13 km depth in Figure 4 is similar to the one that Radovich (2011) identifies but at a much shallower depth. This reflection could be a detachment that developed in a hyperextended margin (Hoffman and Reston, 1992; Radovich et al., 2011; Wilson, 2011). Dobson and Buffler (1994) suggest that there is an asymmetrical rift that developed in the GOM with a southward dipping detachment and that this would allow a longer rifting duration. However, the most probably cause of this high amplitude reflection line is that it is the result of sideswipe from the nearby Florida Escarpment. Gunther et al. (2006) discusses how large scale features scatters the seismic energy and displaces and disturbs the reflections causing them to appear out-of-plane. This can cause reflection is seismic data where there is in fact nothing present.

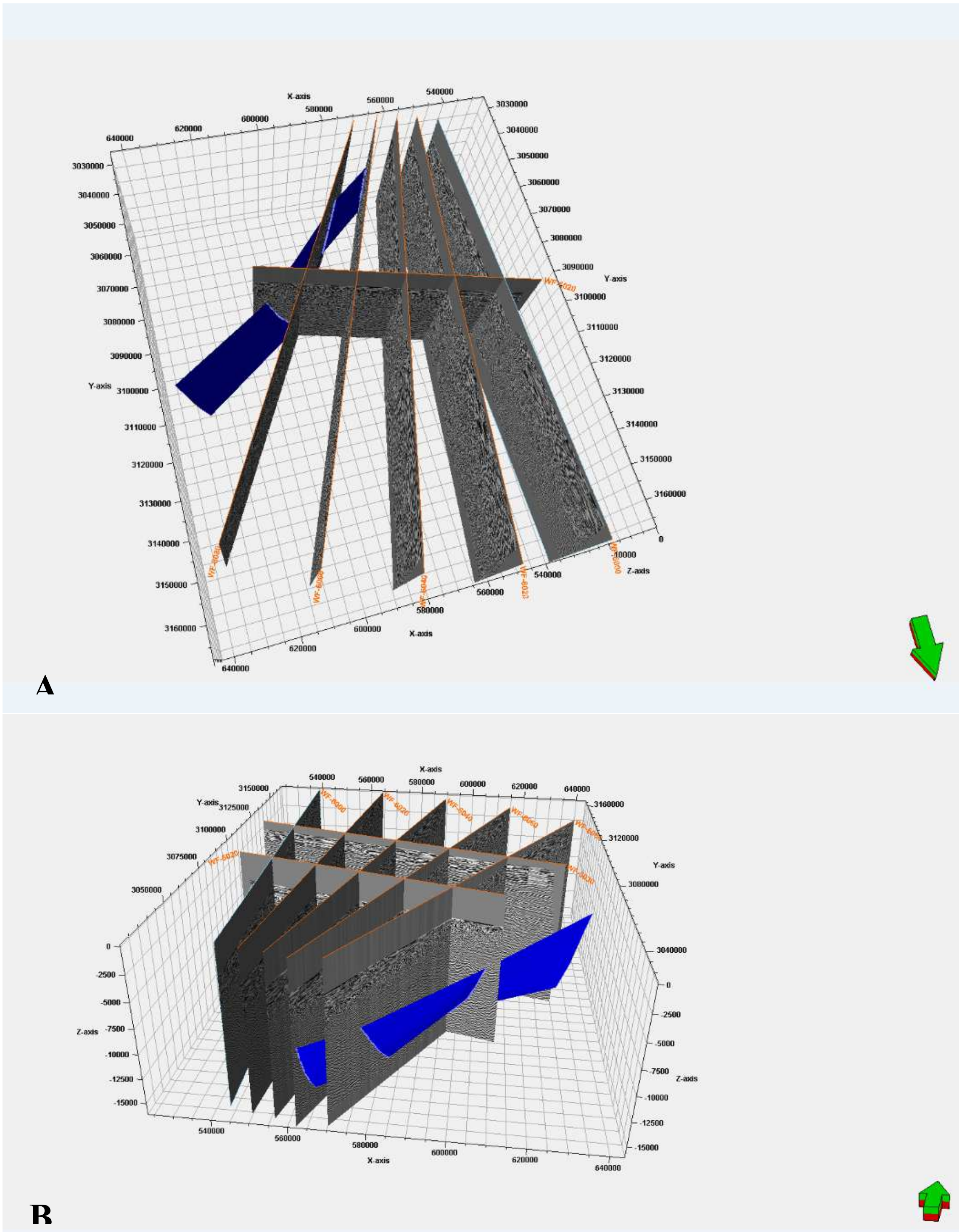


Figure 14: Model for the normal bounding fault. a) Aerial view of the bounding normal fault looking south. Green arrow is the north arrow. The fault crosses three of the seven seismic lines and is just to the east of the strike line on the shelf. b) A view of the bounding normal fault looking northwest. The fault is dipping northwest

5.2 Origin of Basement Paleohighs and Paleolows

5.2.1 Crustal Distribution and Thermal Subsidence

Crustal distribution may determine the location of the basement paleohighs and paleolows. Extended crust consists of attenuated continental crust and transitional crust surrounding oceanic crust in the central GoM (Figure 3) (Buffler and Sawyer, 1985; Sawyer, 1991; Sandwell, 2014). The thinning of the crust due to extension occurs along the tectonic hinge zone in the EGoM (Figure 1) as interpreted by Dobson (1990) and Sawyer et al. (1991). This tectonic hinge zone is also present in the seismic data (blue line in Figures 7, 8, 9, 10 & 11). In the paleolows that are found in the EGoM crust is seen to be thiner, most likely due to greater amounts of subsidence occurred resulting in thicker Mesozoic deposits (i.e., Tampa Embayment and Apalachicola Basin; Buffler and Sawyer, 1985; Sawyer, 1991; MacRae and Watkins, 1996; Wilson, 2011; Gregg, 2014). In the Tampa Embayment and the Apalachicola Basin, the tectonic hinge is further landward than it is in the Southern Platform (Dobson, 1990; Sawyer et al., 1991). Perhaps the hinge placement in the Tampa Embayment and the Apalachicola Basin is the result of more stretching and thinning of the crust due to attenuation.

In the Southern Platform/Middle Ground Arch and Sarasota Arch, the tectonic hinge is close to the Florida Escarpment revealing that these highs are on thicker crust. After rifting and subsidence, the basins would have been stretched to a greater degree than the paleohighs because they are on thin crust. This could have been a factor in the development of the basement paleohighs and paleolows in the EGoM.

5.2.2 Pre-existing lithological weaknesses

Some wells are deep enough to penetrate below the Jurassic sedimentary rock into Paleozoic rock (Figure 15). In the southern part of western Florida near the Sarasota Arch, Shell 3912 and Tenneco 3917 have pre-Ordovician granite (Ball, 1983; Bartok, 1993). GV 707 is close to the Middle Ground Arch, and penetrated Triassic red beds, volcanic rock, and volcaniclastic rocks that were dated at 224 Ma; however, samples towards the base of the well in the Paleozoic basement yielded an age of 576 Ma (Ball, 1983).

Mississippian rhyolites proposed to be from multiple flows overlie Paleozoic sedimentary rocks cut by Jurassic diabase dikes were drilled in Texaco 2523 within the Tampa Embayment (Ball, 1983; Chowns and Williams, 1983). Another well, FM 252, located northeast of the Tampa Embayment, contains Paleozoic siltstone (Ball, 1983; Dobson and Buffler, 1997).

During Triassic time as Pangea rifted, remnants of Gondwana, including the Suwannee Terrane, did not rift away from Laurentia with Africa and South America (Chowns and Williams, 1983). The Suwannee suture delineates Laurentia to the north from remnant Gondwana terranes to the south. The Suwannee Terrane is in the southeastern Mississippi, southern Alabama, southern Georgia, northern and central Florida and west coast of Florida (Thomas et al., 2011; Lisi, 2013). Within the Suwanne terrane, wells indicate the rocks consist of several pre-Middle Jurassic provinces: 1) Late Precambrian to Early Cambrian felsic intrusive and extrusive rocks--the Osceola Granite, and the St. Lucie metamorphic complex that includes dioritic gneiss, amphibolite, and biotite-muscovite schist (Chowns and Williams, 1983; Dallmeyer, 1989), 2) Lower Ordovician quartz arenite and Ordovician to Middle Devonian shale and siltstone (Chowns and Williams, 1983; Arthur, 1988; Dallmeyer, 1989; Lisi, 2013), and 3) Early to Middle Mesozoic hypabyssal and extrusive mafic rocks (Arthur, 1988; Dallmeyer, 1989; Lisi, 2013).

Because the Suwannee terrane was part of Africa, basement rock beneath the West African orogenies should be similar in age and composition. These include the Liberian province, which consists of high grade metamorphic gneiss, and the Eburnean province, that consists of migmatitic gneiss, quartzite and marble (Chowns and Williams, 1983; Dallmeyer, 1989; Culver et al, 1991; Lisi, 2013). Underlying these provinces, granite and metamorphic rock may compose the basement rock in the African craton (Chowns and Williams, 1983; Dallmeyer, 1989).

The Suwannee terrane is the foundation for the future Florida. In Mesozoic time, an arid climate allowed salt to be deposited as well as a shallow warm marine environment that deposited both siliciclastic and carbonate rocks on top of the Suwannee terrane, and continued until Oligocene time (Lane, 1994). In Oligocene time, sea levels dropped and sandstone and shale were deposited (Lane, 1994).

Opdyke (1987) indicates that the basement rocks within the Suwannee terrane across Florida consists of Ordovician through Early Devonian sandstone and shale with fossils of African and South American affinities. In the Florida panhandle, many wells (Shell 3912, Tenneco 3917, Texaco 2523, FL State 224-A No. 2, Texaco 2516, Mobil FL State 224-A No. 1-A, Mobil FL State 224-A No. 1-B, GNV 707) drilled into Paleozoic marine clastic rock (Ordovician sandstone and Silurian-Devonian black shale) and also syn-rift (Triassic) red beds (Klitord, 1984). Off of southwestern Florida, wells were drilled into Pennsylvanian aged glauconitic siltstone (Pequegnat et al., 1971). Wells (Shell 3912, Tenneco 3917, GNV 707, Texaco 2516) near the Sarasota Arch and the Middle Ground Arch drilled into granite and volcanic rock (Ball, 1983; Opdyke, 1987). These data indicate heterogeneities in rock types with different strengths. Contrasting strengths may have led to weaker rocks extending more and thus, subsiding more, which may have created the paleolows, and the stronger rocks not extending, creating the paleohighs. Or alternatively, the stronger rock may have been harder to erode creating paleohighs with the weaker rock may have been easier to erode, creating the paleolows.

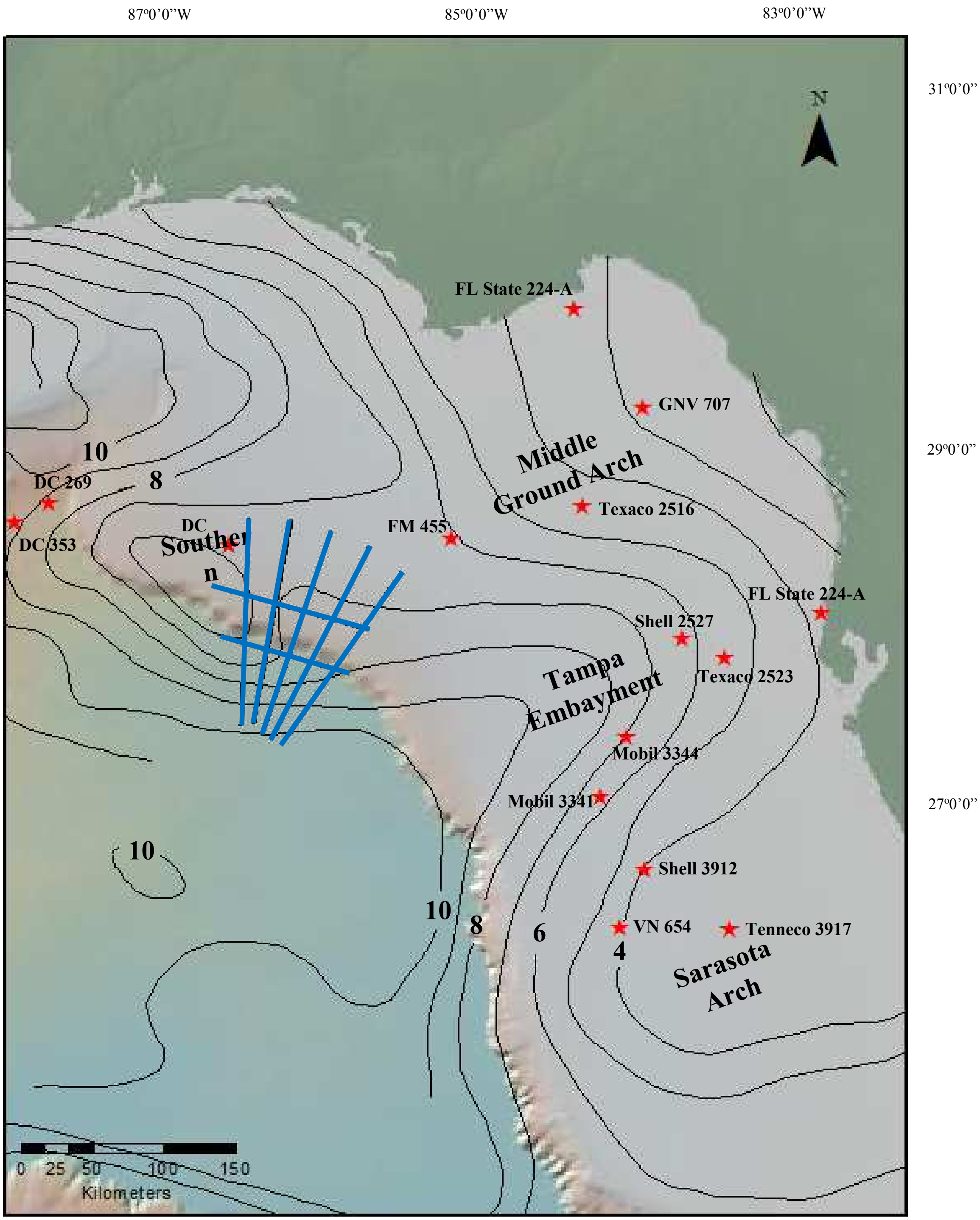


Figure 15: Basement Structure Map with wells. Base map of study area with critical wells and their relation to the paleohighs and paleolows. Red stars show wells locations. Black contour lines are in kilometers

5.2.3 Pre-existing structural weaknesses

Another factor regarding how these basement paleohighs and paleolows formed could be preexisting structural weaknesses from past tectonic events before breakup of Gondwana and Laurentia. Because the Middle Ground Arch and Tampa Embayment are located on what was part of Gondwana, I will focus on the structural and tectonic history of West Africa. At the beginning of the Neoproterozoic, the West African craton was affected by extensional events associated with continental break-up (Ennih and Liegeois, 2008). From 760-660 Ma, the West African craton was subjected to island arc accretion on its northern and eastern sides in the Moroccan Anti-Atlas, the Malian Tilemsi, and Gourma areas (Thomas et al., 2002; Ennih and Liegeois, 2008). During the main Pan-African orogenic phase around 600 Ma, the West African craton was compressed on all boundaries (Hefferan et al., 2000; Ennih and Liegeois, 2001) with the Anti-Atlas in the north, the Trans-Saharan belt in east, the Mauritanides belt in the west and to the south the Rockelides and Bassarides belt (Ennih and Liegeois, 2001). In Late Neoproterozoic to Early Paleozoic time, the western West African craton boundaries were extended and rifted producing sedimentary and volcanic sequences and drifting of some of the peri-Gondwana terranes (Ennih and Liegeois, 2001). These pre-existing structures could have been further defined with the collision of Gondwana and Laurentia during Late Carboniferous to Permian time. Thus, the pre-existing structures that were formed in Late Neoproterozoic through Paleozoic could have helped in the creation of the basement paleohighs and paleolows.

Similar to Wilson (2011), the development of these paleohighs and paleolows could have been from more thinning in the weaker lower crust during the early stages of Jurassic rifting and as a result show very little evidence of brittle extension in the upper crust. When subsidence occurred, these paleolows sagged to a greater extent and accommodated more sediment that would further define it as a paleolows (Wilson, 2011).

5.3 Implications of Interpretations

In the seismic data presented, no evidence for the proposed transform faults exists to support the idea that these basement paleohighs and paleolows formed as a result of the movement on one or more large transform fault(s) with transtensional normal faults between the transform faults. Wilson (2011) did not find evidence within the Tampa Embayment of large transform faults. A half graben was found south of the Southern Platform, trending a 050 direction, with a graben bounding normal fault that dips 45°NW. During Triassic time, NE-SW trending grabens and half grabens were formed and filled with the Eagle Mills Formation (Salvador, 1991; Bartok, 1993). These red beds and associated volcanic rocks were filled in actively subsiding grabens, half grabens or rift basins (Salvador, 1987). The synrift sedimentary rock that filled the half graben is shown on Figure 4 with sedimentary beds that fan toward the graben bounding normal fault. MacRae and Watkins (1996) and Hunter (2014) identify a Triassic half graben underneath Desoto Canyon Salt Basin using seismic data, trending in a NE-SW with fanning and faulted synrift sedimentary rock.

Because of the orientation of the half graben, it cannot be part of the horst and graben system as proposed by MacRae and Watkins (1996) and Pindell and Kennan (2001) (Figure 16). Figure 16 shows where the seismic lines are located in relation to the proposed transform fault as described by MacRae and Watkins (1996) and Pindell and Kennan (2001). No evidence of a transform fault was found in this study or that of Wilson (2011) in the Tampa Embayment. In addition, based on the location of the tectonic hinge on the seismic lines (blue line on Figures 6, 7, 8, 9 & 10), the half graben south of the Southern Platform is located on thinned crust and potentially experienced more crustal stretching.

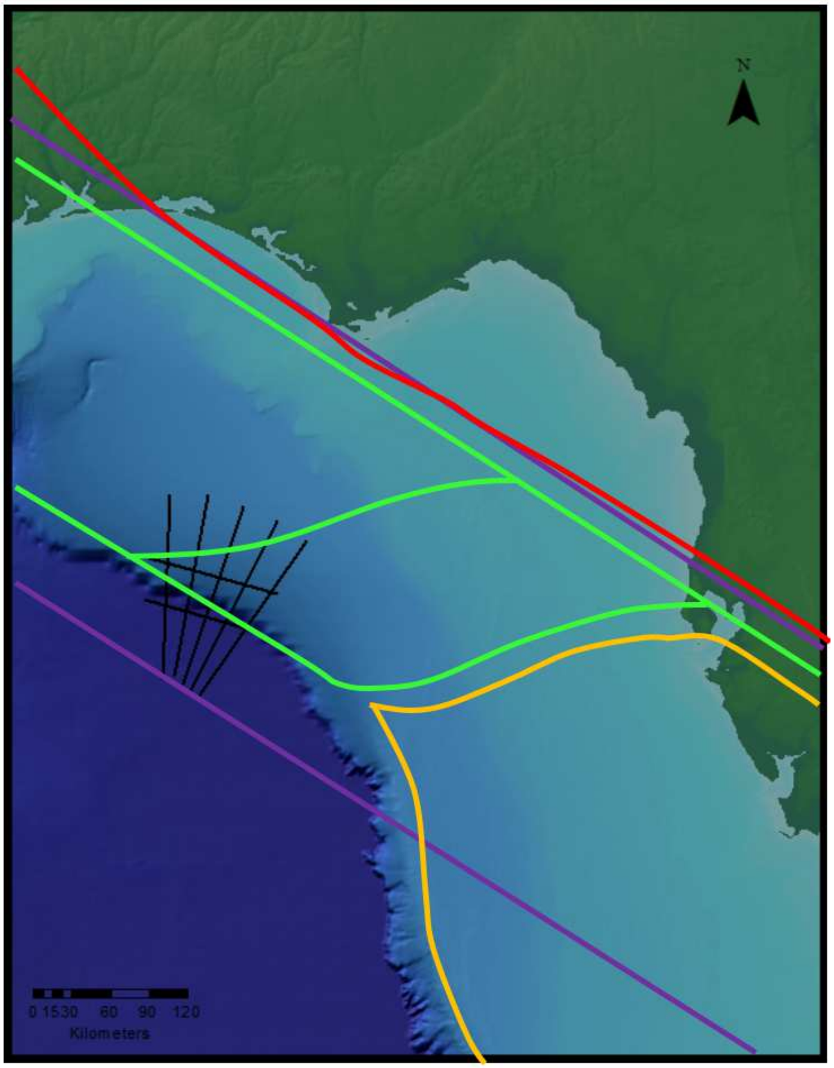


Figure 16: Tectonic Model for NE-SW Triassic rifting. Location of proposed transform faults during Late Triassic rifting in the EGoM. Purple: MacRae and Watkins, (1996); Red: Marton and Buffler, (1994); Green: Pindell and Kennan, (2001). Orange indicates the Florida Continental Block by Pindell and Kennan, (2001) (Modified from Gregg, 2014).

6. CONCLUSIONS

1. Seismic data indicates a half graben located near the Southern Platform filled with Triassic sedimentary rock with a graben bounding normal fault on the east side that has an orientation of 050, 45°NW. The graben bounding fault is down to the northwest and up to the southeast, indicating that the Middle Ground Arch/Southern Platform high is not formed by uplift of this fault. For this fault to help form the basement high, it would need to dip southeast with the upthrown block on the northwest side, and that is not what the seismic data show.
2. Based on the deposition of salt, this graben could have been active until Middle Jurassic time. No evidence exists for a regional transform fault. The half graben south of the Middle Ground Arch/Southern Platform is not a part of the horst and graben system as proposed by MacRae and Watkins (1996) and Pindell and Kennan (2001). However, the half graben did developed during Triassic extension through crustal extension on thin transitional crust.
3. This half graben has a NE-SW trend similar to other grabens and half grabens in the EGoM, suggesting that they developed during NW-SE directed extension.

4. A tectonic hinge exists that marks the transition from thick crust to thin crust roughly 30 km northeast of the Florida Escarpment. South of the tectonic hinge toward the Florida Escarpment, south dipping basement reflectors are the result of tilting caused by the cooling of the crust and allow for more accommodation of the HV unit.
5. Thus, the alternating series of basement highs and basement lows along the Eastern Gulf of Mexico may be the result of pre-existing lithologic differences and preexisting structural weaknesses in conjunction with lithospheric thinning.

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