Stratigraphic, Gravimetric, And Radiometric Evidence For The Oligocene Emergence Of The Nascent Lesser Antilles Volcanic Arc Between The Grenada And Tobago Basins, Southeastern Caribbean Sea

By

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DEDICATION

I dedicate this thesis to my loving wife, Carolyn Miller, who provided constant love and support through these past two years of graduate school. I also dedicate this thesis to my son, Gabriel, who was born in September 2020, and for whom I will strive to provide the best life possible. Lastly, I dedicate my thesis to my family and friends for their constant love and support.

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I thank Kurt Rudolph for sharing his extensive knowledge of petroleum geology and basin modeling with me, and I also thank Dr. John Suppe for providing valuable input on the structural interpretations. I thank the research staff and fellow students of the CBTH project at the University of Houston, who have assisted me in many areas of this study. Finally, I thank the many UH professors and friends outside of CBTH who have contributed to my wonderful graduate experience at UH.

ABSTRACT

Using a single, 645-km long, deep-penetration seismic reflection and collinear refraction line, previous workers proposed that the southern segment of the Lesser Antilles volcanic arc (LAVA) migrated 250 km eastward from its extinct Late Cretaceous location along the Aves Ridge to its Oligocene to Recent location that now separates the Grenada Basin (GB) from the Tobago Basin (TB). A second group of previous workers proposed an alternative hypothesis that the Lesser Antilles arc developed above a rifted arc fragment from the Aves remnant arc. In order to test these differing tectonic hypotheses, I integrate an extensive data set from the two basins that include: 9,320 line-km of 2D industry seismic data; a 1,050-km-long 2D gravity model using satellite gravity data; and a compilation of published 22 radiometric ages from the volcanic islands of the southern LAVA. I integrate these three, different data types to better constrain the crustal structure and tectonic events affecting the broad, forearc area of the two basins where the nascent LAVA emerged as a linear ridge during the early Oligocene.

The main results of this thesis include the following: 1) Using the seismic grid, I mapped five, north-south-trending half-grabens within both the Grenada and Tobago Basin; the north-south trend of the half-grabens with both the Grenada and Tobago Basin constrains their east-west opening direction and resolves a long controversy on the basin-opening direction for both basins; 2) Using a tie to previous wells along the Venezuelan margin, I constrained the age of the half-grabens as Middle Eocene; several half-grabens fringe the western end of the Grenada Basin and the western edge of the Tobago Basin and overlie rifted arc crust that is 12-17 km in thickness; the thinned-arc crustal provinces transition into zones of oceanic crust of 4-8 km in thickness that underlie the deepest areas of both basins; 3) The oceanic crust in the Grenada Basin is 4-8-km thick as imaged seismically from a reflective Moho as seen on the industry

seismic and as supported by 2D gravity transect across both basins; this narrow 340-300-km-wide strip of oceanic crust is inferred to represent an extensional forearc basin that formed seaward of the Late Cretaceous-Paleocene intraoceanic volcanic arc (Aves Ridge); 4) Heat flow estimates for the two basins are based on measured depths to the gas hydrate horizon, averages taken from global studies of other areas underlain by oceanic crust, and local heat probe measurements in the Grenada Basin; the three methods yield a present-day heat flow range in the Grenada and Tobago Basins of 64 to 58 mW/m2, which is used as a constraint for basin modeling; 5) Onlap of Oligocene to Middle Miocene deep-marine strata against the inverted Eocene sediment and present-day bathymetric ridge of the LAVA as seen on seismic reflection lines constrains the age of intrusion of the nascent LAVA as Oligocene (35–23.5 Ma); the magmatic body of the LAVA penetrated upwards through the Eocene oceanic forearc basin crust that is now exposed in outcrops in the Grenadines; 6) the uplifted and deformed oceanic crust has been biostratigraphically and radiometrically dated as Early Oligocene (34-30 Ma).

Based on the integration of all of this information, I infer the LAVA was established in its new location 250 km east of the Aves remnant arc during Early Oligocene time. The emergence and eastward shift of the LAVA volcanic arc is attributed to seaward (eastward) slab rollback of the Cretaceous age Atlantic oceanic crust. Basin modeling reveals a depth to the gas window at 3.5 km in these 13-8.5-km-thick and underexplored basins.

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southern terminus of the LAVA (Santamaria and Schubert, 1974); 12) Early Cretaceous mid-ocean ridge basalt, metamorphosed sediment, volcanic rocks, Late Cretaceous island arc, and andesite dated along the east-west-trending **Leeward Antilles** (Santamaria and Schubert, 1974; Stephan et al., 1980; Beets et al., 1984); 13) Middle Eocene island arc meta-granite (44-47 Ma) and calcalkaline basaltic andesite (33-38 Ma) dated at **Los Testigos Island** (Santamaria and Schubert, 1974; Ysaccis, 1997); 14) Grenada: Eocene deep marine turbidites and pelagic marl (Speed et al., 1993); 15) Grenadine Plateau: Eocene limestone on pillow basalt likely from a back arc spreading zone (Speed et al., 1993; White et al., 2017); 16) Martinique Island: Oligocene outer arc, and Miocene inner arc (Germa et al., 2011); 17) Tobago: Late Jurassic to Early Cretaceous metamorphosed primitive island arc and oceanic crust overlain by Late Cretaceous island arc volcanics and sediments (Frost and Snoke, 1989); 18) Barbados: Early to Middle Eocene deformed sedimentary rocks, Middle Eocene to Middle Miocene oceanic (Aitken et al., 2009). **C)** The table summarizes the Paleogene radiometric dates of the LAVA, displayed in Figure 2A of this thesis. The table includes information about the island where the sample was collected, the estimated age range, the method utilized, and the source of the data.

Figure 3. Comparison of the geologic and age predictions of three previous tectonic models for the evolution of the Lesser Antilles subduction system. **A)** The simplest model by Bouysse et al. (1988) and reiterated later by Bird et al. (1999) proposes Eocene back-arc basin opening of the Grenada basin that split the crust of the Aves Ridge into two halves: the western half remained as the Aves remnant arc while the eastern half formed the crustal foundation of the Oligocene to Recent Lesser Antilles volcanic arc; the mechanism for the shift in the volcanic arc and formation of the Grenada back-arc basin is attributed to the rollback of the subducted Atlantic oceanic crust. **B)** The more complex model of Aitken et al. (2009) proposes that the present areas of the Grenada and Tobago Basins formed in a forearc setting by Eocene rifting with oceanic crust formation; this Eocene forearc basin was intruded by the Lesser Antilles arc in the Early Miocene that created present-day Grenada and Tobago basins. This model predicts intrusion of the Lesser Antilles arc through oceanic forearc crust and therefore does not predict the existence of a rifted, crustal remnant of the Aves Ridge beneath the active, Lesser Antilles arc; as in A, the mechanism for the shift in the volcanic arc and formation of the Grenada back-arc basin is attributed to the rollback of the subducted Atlantic oceanic crust. A caveat with this model is that it was only proposed to include the southern part of the Lesser Antilles and, therefore, may not apply to the northern Lesser Antilles. **C)** The most recent model by Allen et al. (2019) is also the most complex and involves two shifts in the volcanic arc axis of the Lesser Antilles: the first shift is during the Eocene from the Aves Ridge to the now-extinct, Outer Arc of the Lesser Antilles that has been dated as 24.1 to 37.9 Ma; this model proposes that the Outer Arc in the southern Lesser Antilles corresponds to the Tobago-Barbados ridge which some previous workers consider as a partially sedimentary ridge (Gomez, 2018); the second shift proposed by Allen et al. (2019) occurred during the Eocene when the volcanic axis shifted from the Outer Arc to the Inner Arc. This model proposes that these shifts affected the entire length of

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LAVA ridge as it collided with the northern margin of South America. The previous study by Ysaccis (1997) shows that the intensity of inversion increases in the southward direction and is the inferred expression of the collision between this part of the Great Arc of the Caribbean underlying the Leeward Antilles and the continental margin of northern South America. Source of geophysical data courtesy of MCG AS.

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Figure 14. A) Location map of the 120-km-long regional, post-stack-depth migrated (PSDM), 2-D MCG AS line across the eastern edge of the LAVA and the Tobago Basin as shown as the thick red line; thick, yellow lines are other regional lines in the MCG AS grid. **B)** The 120-km-long PSDM 2-D seismic line showing the structure of the southern Tobago basin. The box shows

the zoomed area in C; **C)** Zoomed area of the contact zone between the uplifted Eocene section with areas of stratigraphic downlap shown with red arrows and areas of stratigraphic onlap shown with yellow arrows. The period of onlap begins during the Early Oligocene and continues up to the Middle Miocene as the older Eocene units are upturned and onlapped by pre-Middle Miocene units. The first occurrence of downlap is observed starting in the Oligocene and is interpreted as the eastward movement of the depocenter as the Eocene section was uplifted. The uplift of the LAVA is interpreted as the combined effect of its collision with the northern margin of South America during the Middle Miocene and the initiation of LAVA during the Early Oligocene known from radiometric dating of the oldest subduction-related volcanic units. Source of geophysical data courtesy of MCG AS.

Figure 15. A) Location map of the 400-km-long regional, post-stack-depth migrated (PSDM), 2-D MCG AS line across the Aves Ridge, Grenada Basin, LAVA, and Tobago Basin shown as the thick red line; thick, yellow lines are other regional lines in the MCG AS grid. **B)** Interpreted basement and overlying sedimentary units based on well ties between the Venezuelan industry wells and the Tobago Basin. Eocene sedimentary rocks are thickest along the flanks of the LAVA and show the most upward curvature along the uplifted flanks of the LAVA ridge. The Eocene sedimentary rocks are thickest along the LAVA flanks and uplifted by the intrusion of the nascent volcanic arc through the sedimentary rocks of the forearc basin. The Grenada Basin shows a thicker Eocene section (4.5-5.5 km) than the Tobago Basin (4-4.5 km), but the Tobago Basin shows a thicker Oligocene to Recent section (5-8.5 km) than the Grenada Basin (4-5.5 km). **C)** The Grenada and Tobago Basins have been restored to their Late Eocene appearance prior to the Oligocene emergence of the Lesser Antilles. The results show a thickness variation of 0.2 – 0.6 km between the Late Eocene and Middle Eocene sedimentary units within the Grenada and Tobago Basins. The difference in Eocene thickness between the basins is caused by sediment input from the southwest direction during the Eocene that caused the Grenada Basin to receive increased sedimentation. The post-Eocene sediment thickness variation is caused by the emergence of the LAVA during the Oligocene that separated the Grenada and Tobago Basins. As the Caribbean plate migrated eastward, the Tobago basin receives increased sedimentation from South America and the Maracaibo delta (Aitken et al., 2009; Xie et al., 2010). Source of geophysical data courtesy of MCG AS.

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C) The 12-km-long PSDM 2-D seismic line to the northeast in the TB provides a second example of a dense concentration of gas hydrate marked by a stronger bottom-simulating reflector above the zone of normal faulting. Source of geophysical data courtesy of MCG AS.

Figure 17. Plot of three heat flow values from the Grenada and Tobago Basins used to infer the age of the underlying oceanic crust in the deepest, central part of both basins. Hasterok et al. (2013) compiled heat flow from areas of oceanic crust to construct a curve relating heat flow and age of oceanic crust. If we assume the age of the oceanic crust in both basins is late Eocene and post-dates the age of the Middle Eocene half-grabens in both basins, present-day heat flow based on the Hasterok et al. (2013) graph would be 70-75 m/W/m^2. Manga et al. (2012) used heat flow probe measurements from the central Grenada basin 160-200 km north of the study area (location is shown in Figure 4) to estimate a heat flow range of 55-65m/W/m^{2,} which would predict an oceanic crust age of Eocene (50 Ma) to late Cretaceous (90 Ma). The third method for estimating heat flow measured the depth of the hydrates in both basins and is based on deeper hydrates reflecting lower heat flow and shallower hydrates reflecting higher heat flow (Hodgson et al., 2014, Wang et al., 2017). This method yielded a heat flow of 58-64 m/W/m^2 in both basins, which according to the Hasterok et al. (2013) curve, would yield an age for the oceanic crust of Eocene (50 Ma) to late Cretaceous (85 Ma).

Figure 18. The two 1-D basin models for the Grenada Basin use an estimated heat flow (parts A and B) and a constant heat flow (parts C and D) to examine the impact of heat flow on the basin models. **A)** The burial plot with the transformation ratio shows that the early Middle Eocene matured very rapidly due to the high heat flow associated with oceanic crust formation. The Late Eocene to Middle Oligocene potential source rocks have reached at least 80 percent transformation. **B)** The transformation ratio diagram for the high heat flow model reveals that the Late Eocene source rock began maturation during the emergence of the LAVA, and the Middle Oligocene source rock began maturation during the period of (Early Miocene) transpressional folding and faulting. **C)** The early Middle Eocene and Late Eocene source rocks now mature at a much later time due to the lower constant heat flow. **D)** The lower heat flow also causes the early Middle Eocene and Late Eocene to mature significantly later times during the Middle Eocene and Late Miocene, respectively.

Figure 19. The two sets of 1-D basin models for the Tobago basin use an estimated heat flow (part A and B) and a constant heat flow (part C and D) to examine the impact of heat flow on the basin models. **A)** The burial plot with the transformation ratio shows a lower sedimentation rate during the Eocene than the Grenada Basin and an increased sedimentation rate starting in the Oligocene. **B)** The transformation ratio diagram indicates that the sediments deposited before the middle Early Miocene have become mature. **C)** Using the lower constant heat flow, the source

rocks mature at a much later time. **D)** The transformation ratio diagram modeled with the reduced heat flow indicates that the majority of the source rocks are mature during the Miocene.

Figure 20. A) Paleogeographic map of northern South America modified from Xie et al. (2010) showing the evolution of the deltaic systems of the Maracaibo and Orinoco Rivers. From the Late Paleocene to the Early to Middle Miocene, the Maracaibo deltaic system contributed clastic sedimentary rocks into southern Caribbean basins until the Maracaibo system became blocked by the uplift of the northern Andes. Once the northern Andes were formed, the Maracaibo system was redirected eastward to contribute to the east-flowing Orinoco system that included four smaller deltaic systems south of the Grenada and Tobago Basins. **B)** Isopach maps are modified from Escalona and Mann (2011) and show that the Grenada Basin and Tobago Basins have similar thicknesses during the Neogene as compared to adjacent basins.

Figure 21. A) Location map of two post-stack-depth migrated (PSDM) 2-D MCG AS lines within the Grenada and Tobago Basins shown as red lines. **B)** Proposed gas or oil chimneys emanating from the crest of an Early to Middle Miocene transpressional fold structure located along the eastern edge of the Grenada Basin. The white circle notes the location of stacked amplitude anomalies near the base of the seismic chimney. **C)** The polarity reversal marks the possible location of a hydrocarbon water contact that connects with an updip, stratigraphic pinch out. **D)** Zoom of the polarity reversal observed in C that marks the possible location of a hydrocarbon and water contact point. Source of seismic lines courtesy of MCG AS.

Figure 22. Critical moment chart summarizing the inferred hydrocarbon system elements of the Grenada and Tobago Basins. The critical moment occurred during the Oligocene when the Middle Eocene source rock became mature and traps associated with the emergence of the LAVA begin to form. The transpressional folding within the Grenada Basin formed large, anticlinal traps during the Middle Miocene. The submarine channel system observed within both basins provides reservoir sand units and provides stratigraphic traps during the Middle to Late Miocene.

CHAPTER 1: INTRODUCTION TO THIS THESIS

1.1 History and development of this thesis

Growing up in Sugar Land, Texas, much of my time was spent outdoors. This interest in the outdoors and the environment led me to join the Boy Scouts of America (BSA) as I entered the seventh grade in 2006. Field trips with my Boy Scout troop during my high school years culminated in my Eagle Scout status and stimulated my interest in geosciences and environmental studies.

I completed a Bachelor of Science (BS) degree in May 2017 with a dual major in geophysics and geology from the Department of Earth and Atmospheric Sciences of the University of Houston (UH). During my time as a UH junior and senior, I worked in the Allied Geophysical Laboratory (AGL) under the supervision of Dr. Robert Stewart and served as his teaching assistant (TA) at the UH geophysics field camp in May 2016.

In January 2017, I traveled with Dr. Bob Wiley, a UH adjunct professor in geophysics, and three other UH undergraduates to Belize to use seismic and resistivity methods for drilling water wells for rural villages. This work was financially supported by a non-profit organization called Living Waters, which drills water wells in developing countries like Belize to provide a clean source of drinking water to those who lack reliable or safe water sources.

Upon graduation from UH in May 2017, I began a career as an environmental scientist for an environmental company based in Houston, Texas. My two years of environmental work included work ranging from logging soil cores to leading remediation projects at contaminated sites and overseeing the personnel safety of the team. This experience was my first team-based, career experience where specialists work together to understand the local soil geology and how different contaminants can harm the environment.

I was accepted as a candidate for a Master of Science program in Geophysics at the University of Houston in the fall semester of 2018. During my first year, I took the Basin Analysis for Petroleum Exploration class in the fall semester and competed on the UH Imperial Barrel Award (IBA) team in the spring semester, which won the 2019 world IBA championship. Both courses were taught and led by Dr. Paul Mann, a professor and principal investigator of the Conjugate Basins, Tectonics, and Hydrocarbons (CBTH) consortium at the University of Houston.

Upon joining CBTH as an MS student at the start of my second year, I began working with a seismic reflection data set provided to the CBTH project for the southeastern Caribbean Sea, which was not possible for me to continue because Spectrum Geo had merged with TGS in the May of 2019 and the Spectrum data became restricted. While beginning to work with the Spectrum Geo data, I started a review of published literature on the formation of the Tobago-Barbados Ridge (TBR) and the Barbados accretionary prism.

Dr. Mann had met with representatives of MultiClient Geophysical AS (MCG AS) at the 2019 AAPG ACE meeting and discussed using their seismic data for student research projects. After examining what data would be available to use in August 2019, Dr. Mann and I agreed that the seismic reflection data set from MGC for the southeastern Caribbean would make a comprehensive MS thesis study as the data set extended further west and covered areas of the Lesser Antilles volcanic arc and the flanking basins of the Grenada and Tobago Basins.

MCG provided me with 2-D PSTM and PSDM seismic data, and I began my MS thesis research on the Grenada and Tobago Basins in the southeastern Caribbean in August 2019. The seismic data provided by MCG AS was acquired in 2018. In addition to interpreting the seismic reflection data from MCG, this MS thesis integrates additional geologic, gravimetric, and radiometric results to test three different tectonic models for the southern Lesser Antilles volcanic arc.

Previous studies have been completed in the southeastern Caribbean by previous CBTH students that included Trevor Aitken (Aitken MS, 2009; Aitken et al., 2011), Shenelle Gomez (Gomez, 2018; Gomez et al., 2018, PhD; Gomez et al., in press), and Tricia Alvarez (Alvarez et al., 2014, PhD; Alvarez et al., in press). These studies by previous CBTH students focused on the evolution and formation of the major tectonic features from the Tobago-Barbados Ridge and Barbados accretionary prism and the subducting oceanic crust of the Atlantic plate with less emphasis on the stratigraphy, structure, and tectonic origins of the Tobago and Barbados Basins.

Through the generosity of MCG AS, the seismic data over the Grenada and Tobago Basins has allowed me to conduct an in-depth study of the formation of the Grenada and Tobago Basins in relation to the Lesser Antilles volcanic arc (LAVA). Aitken et al. (2009) proposed the LAVA ridge intruded through a preexisting Paleogene forearc basin during the Early Miocene. This thesis provides additional evidence for the Middle Eocene age of the preexisting forearc basin and the Oligocene intrusion of the LAVA based on detailed seismic mapping constrained by wells and seismic data in Venezuela along with 2-D gravity modeling. This thesis also improves the stratigraphic age constraints on units within the Grenada and Tobago Basins by correlations of the new seismic grid to wells in the adjacent area of offshore Venezuela.

During my time as an MS student with the CBTH group at UH, I have presented a total of 13 oral and poster presentations at four conferences and nine in-house or virtual visits with oil company sponsors of the CBTH project. I have a final virtual presentation planned for the 2020 American Geophysical Union online conference in December of 2020.

Conference or industry visit	**Title of presentation**	**Date of presentation**
CBTH Annual Sponsors Meeting, UH, Houston, Texas	Structural and stratigraphic evolution of the Grenada and Tobago Basins, Southeastern Caribbean Sea **(Talk)**	September 27, 2019
UH-HGS Sheriff Lecture and Student Poster Session, Houston, Texas	Stratigraphic and radiometric evidence for the Oligocene emergence of the southern Lesser Antilles Volcanic Arc between the Grenada and Tobago Basins **(Poster)**	November 11, 2019
American Geophysical Union (AGU) – Fall Meeting, San Francisco, California	Did the Grenada and Tobago Basins Originate as a Single Forearc Basin that was Sub-Divided by the Intrusion of the Lesser Antilles Volcanic Arc? **(Poster)**	December 11, 2019
CBTH on-site visit with Equinor, Stavanger, Norway	Progress report: Grenada and Tobago basins, southeastern Caribbean Sea **(Talk)**	March 11, 2020
CBTH online visit with ExxonMobil, The Woodlands, Texas	Progress report: Grenada and Tobago basins, southeastern Caribbean Sea **(Talk)**	March 20, 2020
CBTH online visit with Petrobras, Rio de Janeiro, Brazil	Progress report: Grenada and Tobago basins, southeastern Caribbean Sea **(Talk)**	April 1, 2020
CBTH online visit with Total, Pau France and Houston, Texas	Progress report: Grenada and Tobago basins, southeastern Caribbean Sea **(Talk)**	April 9, 2020
CBTH online visit with Shell, Houston, Texas	Progress report: Grenada and Tobago basins, southeastern Caribbean Sea **(Talk)**	April 29, 2020
American Association of Petroleum Geologists (AAPG) Southeast Caribbean and Guiana Basins Virtual Conference	Stratigraphic and radiometric evidence for the Oligocene emergence of the southern Lesser Antilles Volcanic Arc	September 18, 2020

	between the Grenada and Tobago Basins **(Talk)**	
CBTH Annual Sponsors Virtual Meeting	Stratigraphic and radiometric evidence for the Oligocene emergence of the southern Lesser Antilles Volcanic Arc between the Grenada and Tobago Basins **(Talk)**	September 25, 2020
American Association of Petroleum Geologists (AAPG) Annual ACE Virtual Convention and Exhibition	Structure, stratigraphy, and recent hydrocarbon indicators in the Grenada and Tobago basins, southeastern Caribbean Sea **(Poster)**	October 29 – November 1, 2020
UH-HGS Sheriff Lecture and Student Poster Session	Structure, stratigraphy, and recent hydrocarbon indicators in the Grenada and Tobago basins, southeastern Caribbean Sea **(Poster)**	November 9, 2020
American Geophysical Union (AGU) Fall Virtual Meeting	Stratigraphic and radiometric evidence for the Oligocene emergence of the southern Lesser Antilles Volcanic Arc between the Grenada and Tobago Basins **(Poster)**	December 15, 2020

CHAPTER 2: STRATIGRAPHIC, GRAVIMETRIC, AND RADIOMETRIC EVIDENCE FOR THE OLIGOCENE EMERGENCE OF THE NASCENT LESSER ANTILLES VOLCANIC ARC BETWEEN THE GRENADA AND TOBAGO BASINS, SOUTHEASTERN CARIBBEAN SEA

2.1 Introduction

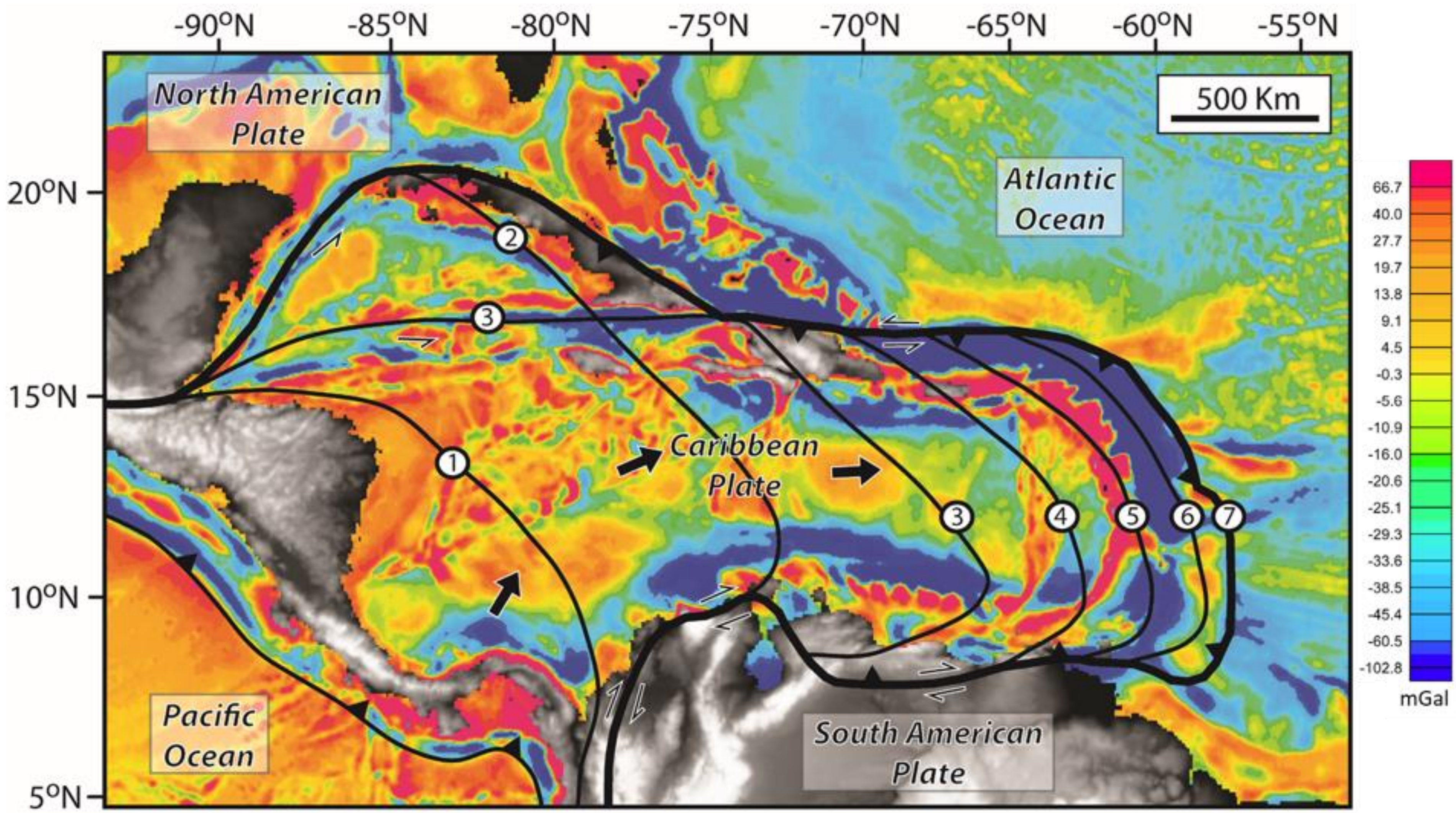
2.1.1 Regional setting of the Grenada and Tobago Basins

Tectonic history of the Caribbean plate. The Caribbean plate formed during the Late Cretaceous in the area of the present-day eastern Pacific Ocean and migrated northeastward and eastward into the Proto-Caribbean oceanic area that formed following the Mesozoic separation of the North and South American plates (Burke, 1988; Escalona and Mann, 2011). The leading edge of the Caribbean plate is defined by the northeast and east-facing Great Arc of the Caribbean, an intra-oceanic arc that formed during the Early Cretaceous (Burke, 1988). The Caribbean Large Igneous Province (CLIP) formed as a broad zone of magmatism above a mantle plume in the late Cretaceous and adjacent to and west of the Great Arc. These two crustal provinces, the Great Arc and the CLIP, coalesced by the end of the Cretaceous to make up most of the present-day Caribbean plate (Fig. 1).

Most segments of the west-to-east moving Great Arc of the Caribbean collided with the passive margins of North and South America during the Late Cretaceous to Recent eastward displacement of the Caribbean plate with the exception of the Lesser Antilles subduction system along the eastern margin of the plate, which continues to actively subduct oceanic crust of the Atlantic Ocean and produce a north-south-trending line of active arc volcanoes (Maury et al., 1990). As known from geodetic studies, the Caribbean Plate is presently moving about 20 mm per year in an eastward direction relative to a fixed South American and North American Plate (Perez et al., 2001; Weber et al., 2001).

This thesis focuses on the tectonic origin and sedimentary history of the Grenada and Tobago Basins that formed within this still-active Lesser Antilles subduction system (Fig. 1). Most previous workers agree that these two basins which flank the west and east margins of the elongate and north—south-trending, active volcanic ridge of the Lesser Antilles arc formed during the Paleogene within an east-west extensional setting that has been related to a period of rollback of the westward-dipping, Atlantic slab (Bouysse, 1988; Aitken, 2011; Allen, 2019). Slab rollback and intra-arc extension commonly occurs when the subducting plate angle steepens and causes the subducting plate to descend quickly with the hinge line, or inflection point in the subducting slab, to move away from the subduction zone (Chase, 1978; Uyeda and Kanamori, 1979).

Figure 1. Free-air gravity map from Sandwell et al. (2014) and modified from Escalona and Mann (2011) showing the west-to-east motion of the Caribbean plate relative to the much larger North and South American plates. The solid black lines represent the inferred locations of the Great Arc of the Caribbean that formed the leading edge of the Caribbean plate at these times: 1) Late Cretaceous (~80 Ma); 2) Middle Paleocene (~60 Ma); 3) Middle Eocene (~44 Ma); 4) Middle Oligocene (~30 Ma); 5) Middle Miocene (~14 Ma); 6) Pliocene (~5 Ma); and 7) Recent. The Lesser Antilles volcanic arc in the eastern Caribbean is the only uncollided segment of the Great Arc that remains as a presently-active volcanic arc.


-90ºN
-85ºN
-80ºN
-75ºN
-70ºN
-65ºN
-60ºN
-55ºN
20ºN
15ºN
10ºN
5ºN
North American Plate
500 Km
Atlantic Ocean
Caribbean Plate
Pacific Ocean
South American Plate
66.7
40.0
27.7
19.7
13.8
9.1
4.5
-0.3
-5.6
-10.9
-16.0
-20.6
-25.1
-29.3
-33.6
-38.5
-45.4
-60.5
-102.8
mGal

Ages of parallel ridges of the Lesser Antilles subduction system. The Lesser Antilles subduction system consists of several parallel ridges that are 20 to 70 km wide and extend for distances of 740 to 800 km. As the crystalline basement is near the surface, these ridges form prominent gravity highs (Fig. 2). Previous workers have radiometrically and biostratigraphically dated samples from either outcrops on the islands or from dredge hauls along submarine scarps that form the edges of the ridges. The locations, age ranges, dating methods, and the references for radiometric ages used for this study are summarized in Figure 2C.

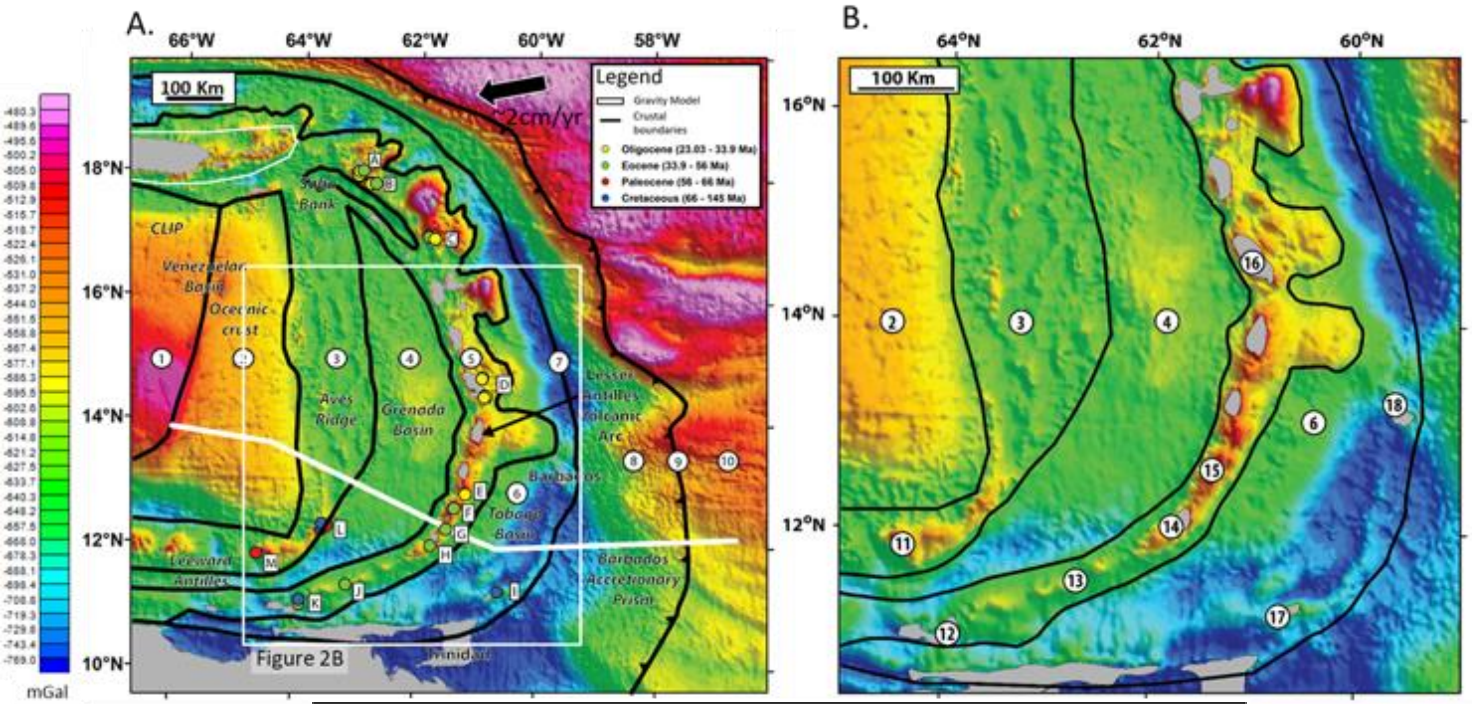
The westernmost ridge of the Lesser Antilles is the Aves Ridge (AR), which is largely a shallow submarine feature whose period of arc-related magmatism is known to have occurred from the Late Cretaceous to Early Paleocene (89-65 Ma) (Fox et al., 1971; Santamaria and Schubert, 1974; Neil et al., 2011) (Fig. 2A).

The Lesser Antilles Volcanic Arc (LAVA) is located east of the Aves Ridge and transitions from a single, southern ridge that bifurcates into two ridges in the north: an inactive arc called the Outer Arc or “Limestone Caribbees” and an active arc called the Inner Arc (Maury et al., 1990) (Fig. 2A). Age dates for both the single southern branch of the LAVA and the two northern branches range from earliest Oligocene to Middle Eocene (Christman, 1953; Nagle et al., 1975; Briden et al., 1979; Speed and Walker, 1991; Speed et al., 1993; Germa et al., 2011; Rojas-Argramone et al., 2017; White et al., 2017).

Ages for the northern branched LAVA include Early Oligocene to Middle Eocene (24.1 to 37.9 Ma) for the Outer Arc (Christman, 1953; Nagle et al., 1975; Briden et al., 1979; Speed and Walker, 1991; Speed et al., 1993; Germa et al., 2011; White et al., 2017) and of Late

Miocene to Pleistocene (5.14 to 0.126 Ma) for the Inner Arc (Germa et al., 2011). The hiatus and westward shift of volcanism have been attributed by McCann and Sykes (1984) to shallow subduction of high-standing, Central Atlantic fracture zones that shallowed the dip of the subducted slab and caused the volcanic axis to move 50 km to the west and southwest (Fig. 2A).

Figure 2. A) Bouguer gravity map from marine satellite data from Sandwell et al. (2014) and modified from Aitken et al. (2009) showing the Lesser Antilles subduction system with its major tectonic and crustal features: 1) **Caribbean Large Igneous Province** (CLIP) underlying the deepwater Venezuelan basin (Edgar et al., 1971; Holcombe et al., 1977; Diebold and Driscoll 1999); 2) area of normal thickness oceanic crust underlying eastern deepwater area of the **eastern Venezuelan Basin**; 3) the **Aves Ridge** remnant arc of Late Cretaceous-Paleocene age; 4) **Grenada basin** formed by extension during the Early to Late Eocene; 5) **Lesser Antilles volcanic arc** of early Oligocene to Recent age; 6) **Tobago basin** formed by extension during the Early to Late Eocene; 7) **Lesser Antilles lithospheric trace** where oceanic crust of the Atlantic Ocean underthrusts the leading edge of the Caribbean plate; 8) **Barbados accretionary prism** formed by subduction-accretion along the front of the LAVA; 9) Deformation front of the **Barbados accretionary prism**; and 10) Subducting, Mesozoic oceanic crust of the **Central Atlantic Ocean**. Radiometric ages of magmatic rocks are color-coded to show the oldest dates reported from dated magmatic rocks of the LAVA that outcrop on islands and are keyed to their sources in Figure 2C. Radiometric ages from outcrops on islands of the LAVA range from Eocene (green dots) to Oligocene (yellow dots). The Aves Ridge, the remnant arc of the LAVA, is dated from dredged magmatic rocks from the Late Cretaceous (blue dots) to Paleocene (red dots). The northern region outlined in white forms the collided, eastern end of the Greater Arc of the Caribbean (GAC) with an age range of magmatic rocks from Cretaceous to early Paleogene. **B)** Bouguer gravity map created from Sandwell et al. (2014) free-air gravity data shows locations of geologic structures that are well understood and dated: 2) area of normal thickness Cretaceous oceanic crust underlying eastern area of the Venezuelan Basin; this oceanic crust has not been dated but assumed to be Late Jurassic-Early Cretaceous in age; 3) Cretaceous to Early Paleocene andesite, granite, and extinct magmatic arc forming the **Aves Ridge** remnant arc (Fox and Heezen, 1985; Boynton et al., 1979); 4) Eocene sedimentary rocks of the **Grenada basin** uplifted during the Oligocene, Eocene stratigraphy onlapped by Oligocene sediments, and westward migration of the depocenter (described in this thesis); 6) Tobago Basin: Middle to Late Eocene sediment uplifted during the Oligocene, Eocene stratigraphy onlapped by Oligocene sediments, eastward migration of the depocenter starting in the Oligocene, and well control within Venezuela suggests the oldest unit in the Tobago forearc basin is Middle Eocene (described in this thesis); 11) Early Paleogene island arc dated at **Blanquilla Island** at the southern terminus of the LAVA (Santamaria and Schubert, 1974); 12) Early Cretaceous mid-ocean ridge basalt, metamorphosed sediment, volcanic rocks, Late Cretaceous island arc, and andesite dated along the east-west-trending **Leeward Antilles** (Santamaria and Schubert, 1974; Stephan et al., 1980; Beets et al., 1984); 13) Middle Eocene island arc meta-granite (44-47 Ma) and calcalkaline basaltic andesite (33-38 Ma) dated at **Los Testigos Island** (Santamaria and Schubert, 1974; Ysaccis, 1997); 14) Grenada: Eocene deep marine turbidites and pelagic marl (Speed et al., 1993); 15) Grenadine Plateau: Eocene limestone on pillow basalt likely from a back arc spreading zone (Speed et al., 1993; White et al., 2017); 16) Martinique Island: Oligocene outer arc, and Miocene inner arc (Germa et al., 2011); 17) Tobago: Late Jurassic to Early Cretaceous metamorphosed primitive island arc and oceanic crust overlain by Late Cretaceous island arc volcanics and sediments (Frost and Snoke, 1989); 18) Barbados: Early to Middle Eocene deformed sedimentary rocks, Middle Eocene to Middle Miocene oceanic (Aitken et al., 2009). **C)** The table summarizes the Paleogene radiometric dates of the LAVA, displayed in Figure 2A of this thesis. The table includes information about the island where the sample was collected, the estimated age range, the method utilized, and the source of the data.



C.

Island	Identifier	Age (Ma)	Method	Reference
St. Martin	A	28.4 - 32.0	K - Ar	Briden et al. 1979
		30 - 36.5	K - Ar	Nagle et al. 1975
		Late Eocene	biostratigraphy	Christman, 1953
St. Barthelemy	B	26.5 +/- 0.8	K - Ar	Briden et al. 1979
		23.5 - 35.0	K - Ar	Nagle et al. 1975
		Middle Eocene	biostratigraphy	Christman, 1953
Antigua	C	Middle Eocene	K - Ar	Weiss, 1994
		24.0 - 38.5	K - Ar	Nagle et al. 1975
Martinique	D	24.1 - 24.8	K - Ar	Germa et al. 2011
Mustique	E	19.2 - 25.2	K - Ar	Speed et al. 1993
Mayreau	F	37.9 +/- 0.2	Ar - Ar	White et al. 2017
		Middle Eocene	Major and trace element analysis	Speed and Walker, 1991
Carriacou	G	34 +/- 0.6	Major and trace element analysis	Rojas-Argramone et al. 2017
Grenada	H	37.9 +/- 0.2	Ar - Ar	White et al. 2017
Tobago	I	128.66	U - Pb	Neill et al. 2012
Los Testigos	J	44 +/- 5.4	K - Ar	Vence 2008
Margarita	K	44.0 - 47.0	K - Ar	Santamaria and Schubert 1974
		52.1 - 92.4	Ar - Ar	Vence 2008
Aves Ridge	L	75.9 +/- 0.7	Zircon	Neil et al. 2011
		65.0	K - Ar	Santamaria and Schubert 1974
		78.0 - 89.0	K - Ar	Fox et al. 1971
La Blanquilla	M	75.5 +/- 0.9	Zircon	Wright and Wyld 2011

2.1.2 Previous work on the southeastern Caribbean formation history and objectives of this study

Previous studies of the southeastern Caribbean using gravity, seismic reflection and refraction, and magnetic data have resulted in three different models to explain the formation of the southern, single segment of the LAVA and its symmetrically-flanking Grenada and Tobago Basins (Fig. 3). The first LAVA model proposed by Bouysse (1988) and elaborated by Bird et al. (1999) proposed that the Aves Ridge was split in half due to the east-west extension related to Eocene back-arc opening of the Grenada Basin. The western half remained as the extinct Aves Ridge remnant arc dated as Cretaceous to Late Cretaceous (65 to 89 Ma), and the eastern, rifted half formed the crustal foundation 250 km east of the Aves Ridge for the nascent LAVA dated as Oligocene to Eocene (24.1 to 37.9 Ma) (Fig. 3A). These previous studies made use of gravity, seismic reflection, refraction data, and magnetic data.

Aitken et al. (2009) proposed that Atlantic slab rollback started in the Paleocene and resulted in Paleocene-Eocene rifting that was accompanied by the formation of a north-south strip of oceanic crust, which has been recognized by previous workers using refraction data (Bird et al., 1999; Christeson et al., 2009) (Fig. 3B). The Eocene rifted forearc was proposed to have formed in an extensional forearc basin that was then intruded by the nascent LAVA during the Early Oligocene as the active volcanic line migrated eastward over a distance of 250 km to its current location (Aitken et al., 2009).

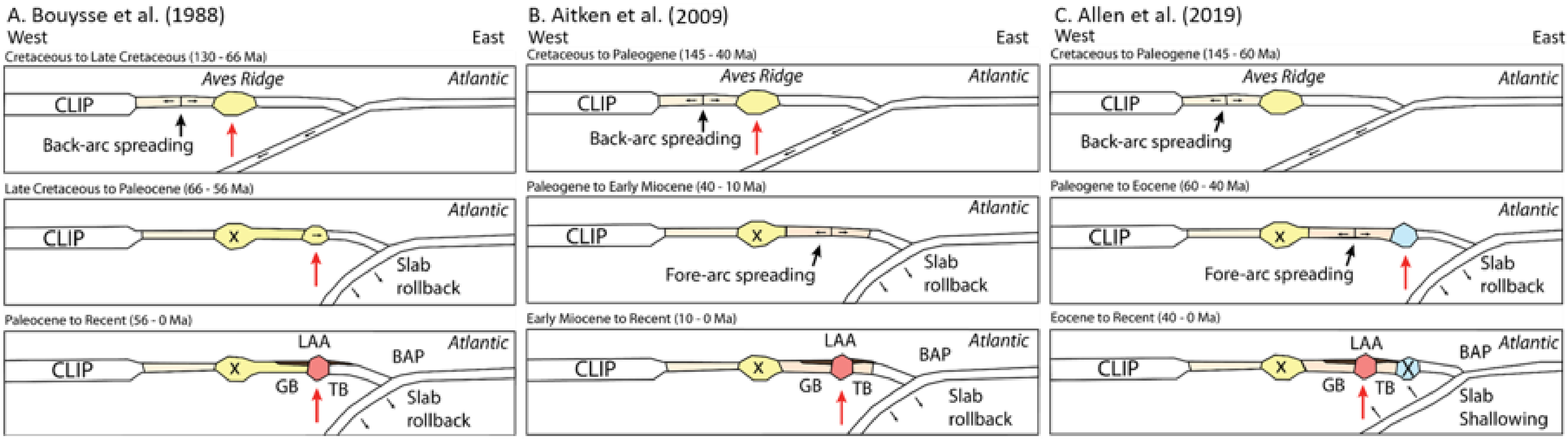
The intrusion and emergence of the Early Miocene LAVA through the forearc oceanic crust separated the single Grenada-Tobago forearc basins into two distinct basins flanking the central volcanic ridge of the LAVA (Aitken et al., 2009) (Fig. 3B). This model does not predict the rifted crustal basement of Aves Ridge beneath the LAVA but instead predicts the diapiric rise of the LAVA through the area of the forearc oceanic crust (Speed and Walker, 1991). The shift in the volcanic axis from the Aves Ridge to the LAVA is attributed to slab rollback of the subducted Atlantic oceanic crust.

Aitken et al. (2011) used seismic data, stratigraphic and radiometric ages, and nearby wells to support this model. It should be noted that Aitken et al. (2009) proposed this model for the southern segment of the LAVA and did not attempt to apply the model to the two branches of the Y-shaped northern LAVA.

The third and most recent model used to describe the formation of the basins is proposed by Allen et al. (2019) (Fig. 3C). The Allen et al. (2019) model predicts two shifts in the volcanic axis of the LAVA. The first shift occurred during the Paleogene forearc spreading from the Aves Ridge to the now extinct outer arc of the LAVA, which has been dated as Oligocene to Eocene (24.1 to 37.9 Ma) (Fig. 2C). The second shift of the LAVA axis is caused by slab shallowing during the Eocene, which resulted in the westward ship of volcanism from the outer arc to the inner arc of the LAVA that is dated as Late Miocene to Pleistocene (5.14 to 0.126 Ma) (Germa et al., 2011).

The Allen et al. (2019) model is similar to the Aitken et al. (2009) model as both predict a single, existing, pre-Eocene forearc basin that became separated by the intrusion of the elongate ridge of the LAVA and produced the flanking basins of the Grenada and Tobago Basins. The Allen et al. (2019) model differs from the Aitken et al. (2009) model by its more complex inclusion of two volcanic axes that change their positions during the Paleogene and Eocene. Their study uses seismic and marine magnetic data as support for the model.

Figure 3. Comparison of the geologic and age predictions of three previous tectonic models for the evolution of the Lesser Antilles subduction system. **A)** The simplest model by Bouysse et al. (1988) and reiterated later by Bird et al. (1999) proposes Eocene back-arc basin opening of the Grenada basin that split the crust of the Aves Ridge into two halves: the western half remained as the Aves remnant arc while the eastern half formed the crustal foundation of the Oligocene to Recent Lesser Antilles volcanic arc; the mechanism for the shift in the volcanic arc and formation of the Grenada back-arc basin is attributed to the rollback of the subducted Atlantic oceanic crust. **B)** The more complex model of Aitken et al. (2009) proposes that the present areas of the Grenada and Tobago Basins formed in a forearc setting by Eocene rifting with oceanic crust formation; this Eocene forearc basin was intruded by the Lesser Antilles arc in the Early Miocene that created present-day Grenada and Tobago basins. This model predicts intrusion of the Lesser Antilles arc through oceanic forearc crust and therefore does not predict the existence of a rifted, crustal remnant of the Aves Ridge beneath the active, Lesser Antilles arc; as in A, the mechanism for the shift in the volcanic arc and formation of the Grenada back-arc basin is attributed to the rollback of the subducted Atlantic oceanic crust. A caveat with this model is that it was only proposed to include the southern part of the Lesser Antilles and, therefore, may not apply to the northern Lesser Antilles. **C)** The most recent model by Allen et al. (2019) is also the most complex and involves two shifts in the volcanic arc axis of the Lesser Antilles: the first shift is during the Eocene from the Aves Ridge to the now-extinct, Outer Arc of the Lesser Antilles that has been dated as 24.1 to 37.9 Ma; this model proposes that the Outer Arc in the southern Lesser Antilles corresponds to the Tobago-Barbados ridge which some previous workers consider as a partially sedimentary ridge (Gomez, 2018); the second shift proposed by Allen et al. (2019) occurred during the Eocene when the volcanic axis shifted from the Outer Arc to the Inner Arc. This model proposes that these shifts affected the entire length of the Lesser Antilles volcanic arc and differs in this aspect from the more local model for the southern LAVA that was proposed by Aitken et al. (2009) and is shown in B.



A. Bouysse et al. (1988)
West
East
Cretaceous to Late Cretaceous (130 - 66 Ma)
Aves Ridge
Atlantic
CLIP
Back-arc spreading
Late Cretaceous to Paleocene (66 - 56 Ma)
Atlantic
CLIP
x
Slab
rollback
Paleocene to Recent (56 - 0 Ma)
LAA
BAP
Atlantic
CLIP
x
GB
TB
Slab
rollback
B. Aitken et al. (2009)
West
East
Cretaceous to Paleogene (145 - 40 Ma)
Aves Ridge
Atlantic
CLIP
Back-arc spreading
Paleogene to Early Miocene (40 - 10 Ma)
Atlantic
CLIP
x
Fore-arc spreading
Slab
rollback
Early Miocene to Recent (10 - 0 Ma)
LAA
BAP
Atlantic
CLIP
x
GB
TB
Slab
rollback
C. Allen et al. (2019)
West
East
Cretaceous to Paleogene (145 - 60 Ma)
Aves Ridge
Atlantic
CLIP
Back-arc spreading
Paleogene to Eocene (60 - 40 Ma)
Atlantic
CLIP
x
Fore-arc spreading
Slab
rollback
Eocene to Recent (40 - 0 Ma)
LAA
BAP
Atlantic
CLIP
x
GB
TB
X
Slab
Shallowing

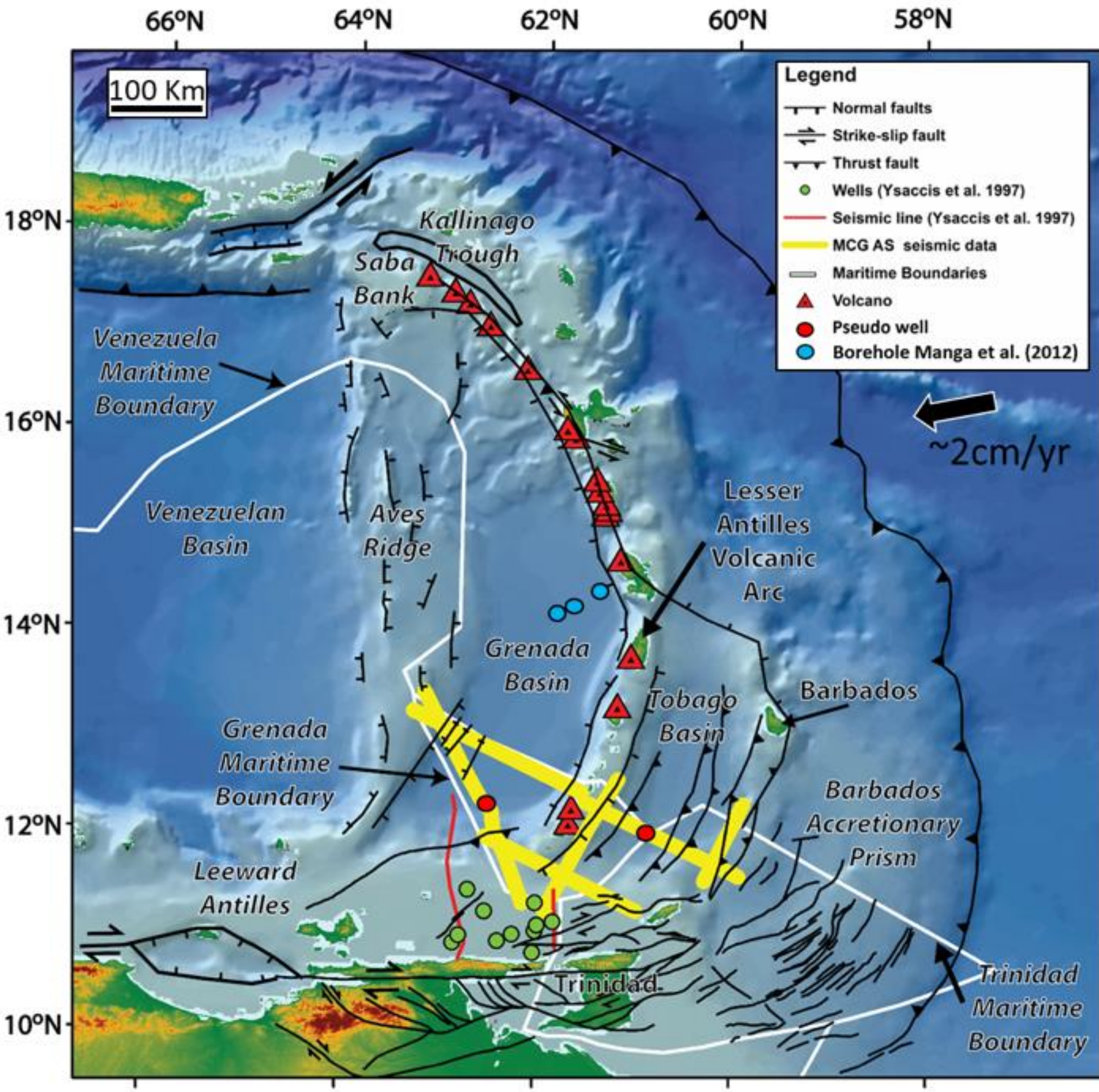
Objectives of this thesis. This thesis aims to gather additional evidence to test these three previous models for the evolution of the LAVA. The goals are accomplished by using the following data: 1) 9,320 line-km of 2D industry seismic data; 2) a 1,050-km-long 2D model using satellite gravity data, and 3) a compilation of 22 radiometric ages from the volcanic islands of the southern LAVA. The last goal of this master's thesis is to conduct basin modeling of the Grenada and Tobago Basin to assess the petroleum potential of these underexplored frontier basins.

2.2 Data and methods used in this thesis

Seismic reflection data. The seismic data provided by MultiClient Geophysical AS (MCG AS) includes 9,320-km of 2-D PSDM industry seismic data that extends in 400 km in the dip direction from the Aves Ridge to the Tobago-Barbados Ridge (Fig. 4). The seismic data is recorded to a depth of 18 seconds two-way time (TWT) and has been depth converted to approximately 30 km. The majority of the lines (87%) are located within the Tobago Basin and fewer lines (13%) located in the Grenada Basin to the west (Fig. 4). The line spacing for the seismic lines within the Grenada Basin and northern Tobago Basin is approximately 20 km. The seismic line spacing for the southern Tobago Basin is about 8 km.

Additional seismic lines from the Venezuelan maritime zone south of the study area were integrated from Ysaccis (1997) to provide additional stratigraphic constraints on the ages of units with the Grenada and Tobago Basins as no deep well data was available. The study by Ysaccis (1997) contains 11 wells tied to a grid of seismic data within the Venezuelan maritime zone. This is the first time seismic lines from the areas of the southern LAVA have been directly tied to wells and seismic lines in the Venezuelan maritime zone. The tie to the previous interpretations by Ysaccis (1997) provides a stratigraphic constraint for the Tobago Basin, with the oldest stratigraphic unit being Middle Eocene. Lines from the Ysaccis (1997) and the MCG AS seismic line did not intersect within the Grenada Basin and had to be jump correlated to provide a stratigraphic constraint. This correlation was based on regional basin scale events, such as the Oligocene emergence of the LAVA causing the Oligocene sediment to onlap the Late Eocene sediment and the Middle Miocene unconformity. Additional interpretation of the Tobago Basin used interpreted seismic lines from Gomez et al. (2018) and Alvarez et al. (2020). In order to map the Moho and basement features, a 5-10 Hz low-pass filter was applied to help increase the signal to noise at depth. The low-pass filter was successful within the Grenada Basin but did not improve the seismic data quality within the Tobago Basin.

Figure 4. Regional tectonic map of the LAVA modified from Gomez et al. (2018) with an emphasis on my study area of southern Grenada and Tobago basins. The white lines show the maritime boundaries of Trinidad and Tobago, Venezuela, and Grenada. The wide, yellow lines are the regional seismic reflection lines kindly provided by MultiClient Geophysical ASA that are shown in this thesis. The thinner red lines are seismic lines compiled from Ysaccis (1997) from the Venezuelan maritime zone along with 11 Venezuelan industry wells shown as green dots. The two red dots are pseudo wells in the Grenada and Tobago Basins that were constructed for this study to construct the basin modeling as no actual wells have been drilled in the deeper water areas of both basins. The blue dots are borehole locations from Manga et al. (2012) used to estimate the thermal gradient of the Grenada basin. Source of geophysical data courtesy of MCG AS.



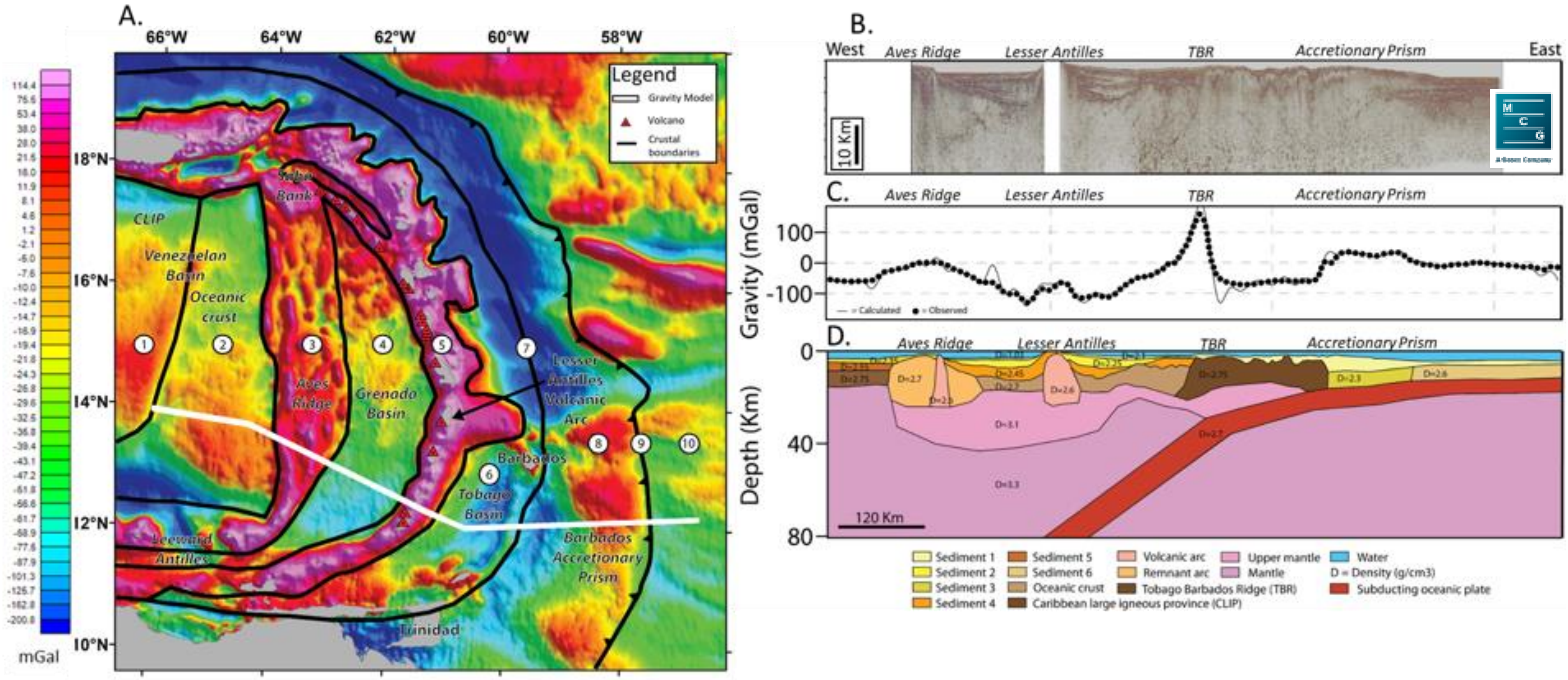
66ºN
64ºN
62ºN
60ºN
58ºN
18ºN
16ºN
14ºN
12ºN
10ºN
100 Km
Legend
Normal faults
Strike-slip fault
Thrust fault
Wells (Ysaccis et al. 1997)
Seismic line (Ysaccis et al. 1997)
MCG AS seismic data
Maritime Boundaries
Volcano
Pseudo well
Borehole Manga et al. (2012)
Kallinago Trough
Saba Bank
Venezuela Maritime Boundary
~2cm/yr
Venezuelan Basin
Aves Ridge
Lesser Antilles Volcanic Arc
Grenada Basin
Tobago Basin
Barbados
Grenada Maritime Boundary
Barbados Accretionary Prism
Leeward Antilles
Trinidad
Trinidad Maritime Boundary

Gravity data. Gravity data used in this study is open-source data compiled from Sandwell et al. (2014). The free-air data was used to create: 1) a free-air gravity map (Fig. 5A); 2) a Bouguer gravity map (Fig. 2A); and 3) a 1,050-km-long 2-D gravity model (Fig. 5A). The different gravity maps and models were created to better identify the different crustal terranes within the Lesser Antilles subduction system and eastern Caribbean Plate (Fig. 2A; Fig. 5A).

The 2-D gravity model was constrained by seismic interpretations, refraction stations located within the Grenada and Tobago Basins, and previously constructed gravity models published by Christensen et al. (2008) and Gomez et al. (2018). The Moho used within the 2-D gravity model was based on interpretations within the Grenada Basin that utilized the Moho depth as observed from a prominent Moho reflector observed on the 2D seismic reflection data set. The Moho was not recognizable from seismic reflection data from the Tobago Basin and was estimated based only on the 2-D gravity model.

A sub-crustal layer of lower density was included on the gravity model and was inferred to correlate to a zone of serpentinized mantle (Toft et al., 1990; Blakely et al., 2005; Tibi et al., 2008) (Fig. 5D). The serpentizined zone has a slightly lower density (3.1 mg/cc) than the deeper mantle (3.3 mg/cc) and reduced the overall error of the model.

Figure 5. A) Free-air gravity map based on satellite data from Sandwell et al. (2014) showing the regional crustal features of the Lesser Antilles subduction system and locating the gravity transect. Key to numbered crustal types shown on the map: **1)** CLIP; **2)** Oceanic crust; **3)** Aves remnant arc; **4)** Grenada Basin; **5)** Lesser Antilles volcanic arc, **6)** Tobago Basin; **7)** Subduction trace; **8)** Accretionary prism **9)** Deformation front; **10)** South American Plate. **B)** Source of geophysical data courtesy of MCG AS. Regional, 940-km-long MCG AS seismic line used to constrain the gravity model is shown by the white line in A. **C)** The calculated and observed gravity measurements are displayed on the graph and have a small averaged root-mean-square error of ~15 mgal. Source of geophysical data courtesy of MCG AS **D)** The cross-section view of the regional gravity model depicts the different crustal terranes and is shown by the white line in part A. As supported by the gravity model, the main crustal types and their thicknesses include normal oceanic crust in the easternmost Venezuelan basin (14-15 km), oceanic crust within the basin (4-8 km), rifted island arc crust (12-17 km), and normal island arc crust (20-24 km).


A.
B.
C.
D.
Legend
Gravity Model
Volcano
Crustal boundaries
mGal
CLIP
Venezuelan Basin
Oceanic crust
Saba Bank
Aves Ridge
Grenada Basin
Lesser Antilles Volcanic Arc
Barbados
Tobago Basin
Barbados Accretionary Prism
Leeward Antilles
Trinidad
West
East
Aves Ridge
Lesser Antilles
TBR
Accretionary Prism
10 Km
Gravity (mGal)
Depth (Km)
120 Km
Sediment 1
Sediment 2
Sediment 3
Sediment 4
Sediment 5
Sediment 6
Oceanic crust
Caribbean large igneous province (CLIP)
Volcanic arc
Remnant arc
Tobago Barbados Ridge (TBR)
Upper mantle
Mantle
Water
D = Density (g/cm3)
Subducting oceanic plate

Basin model for hydrocarbon maturity. There are no available deepwater wells within both the Grenada and Tobago Basins to constrain a basin model for hydrocarbon maturation. To constrain a basin model for the Grenada and Tobago Basins, estimates of paleowater depths from paleoflora and paleofauna were used (Jung, 1971; Speed et al., 1993). Since the LAVA observations only apply to pre-uplift sediments, an additional paleowater depth constraint was provided by decompaction of clinoforms observed within the Tobago Basin.

Gas hydrate heat flow was estimated from the seafloor to the base of the gas hydrates expressed as a bottom simulating reflector (BSR) on the seismic data. The distance from the seafloor to the BSR was compared to a hydrate stability diagram in order to calculate the temperature gradient at the measured depth of the BSR. The last two methods to estimate the heat flow included shallow heat probe measurements within the Grenada Basin from Manga et al. (2012) and a global heat flow estimate from Hasterok (2010) based on the average heat flow variation of oceanic crust of different ages.

Source rock geochemical properties were assumed to be similar to the nearest hydrocarbon discovery of the offshore Dragon field in the Venezuelan maritime zone (Schneider et al., 2012). The source rocks are thought to be type II to type III and younger than Cretaceous. Gas-prone source rocks of the Dragon field are a likely analog to source rocks of the Grenada and Tobago Basins (Schneider et al., 2012).

Lithologic constraints were used from Ysaccis (1997) and his description of wells in the Venezuelan maritime zone and Eocene outcrops on the southern LAVA (Speed and Walker, 1991; Aitken et al., 2009; White et al., 2017). Outcrops were also used to constrain the age and water depth of the Eocene units in both basins.

2.3 Results

2.3.1 Results from 2-D gravity modeling

To understand how the Grenada and Tobago Basins formed, it is important to distinguish the different crustal types and their boundaries. The three crustal types of this region include over thickened, oceanic plateau crust of the Caribbean large igneous province (CLIP), normal-thickness oceanic crust, and rifted and full-thickness island arc crust of the Great Arc of the Caribbean. The free-air gravity map in Figure 5A identifies these three different crustal types and their boundaries based on their characteristic gravity signatures.

The interpretations in Figure 5A are tested by a 1050 km-long, 2-D gravity model (Fig. 5D). The 2-D gravity model has a minimal error of approximately 15, which indicates a close correspondence between the observed and calculated gravity values (Fig. 5C). The crustal types and their thicknesses as seen on the gravity model in Figure 5D include: 1) thickened oceanic crust in the easternmost Venezuelan basin (14-15 km); 2) normal-thickness, oceanic crust within the Grenada and Tobago Basins (4-8 km); 3) rifted island arc crust (12-17 km) that fringes the eastern margin of the Aves Ridge and the western margin of the Tobago-Barbados Ridge; and 4) normal-thickness island arc crust (20-24 km) of the Aves remnant arc and the active volcanic arc of the Lesser Antilles Ridge. The 2-D gravity model results support the existence of normal-thickness oceanic crust beneath the Grenada and Tobago Basins (Fig. 5D). The oceanic crust beneath both basins is supported by the high crustal velocity of about 6.9 km/s (Speed and Walker, 1991; Wadge, 1994; Bird et al., 1999; Christeson et al., 2007).

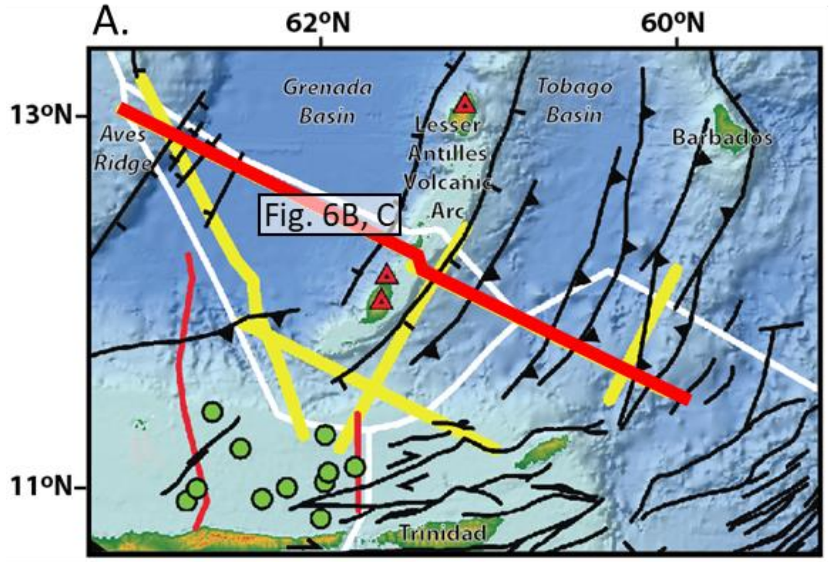
2.3.2 Results from seismic reflection interpretations of the Grenada and Tobago Basins

Regional seismic line. The 400-km-long regional, post-stack-depth migrated (PSDM), 2-D MCG AS seismic line extends from the eastern edge of the Aves ridge in the west to the western edge of the Tobago-Barbados Ridge in the east (Fig. 6A). The thicker areas of the Aves Ridge and LAVA are composed of un-rifted island arc crust that averages 20-24 km in thickness, while the rifted crust of the eastern Aves Ridge varies in thickness from 12-17 km.

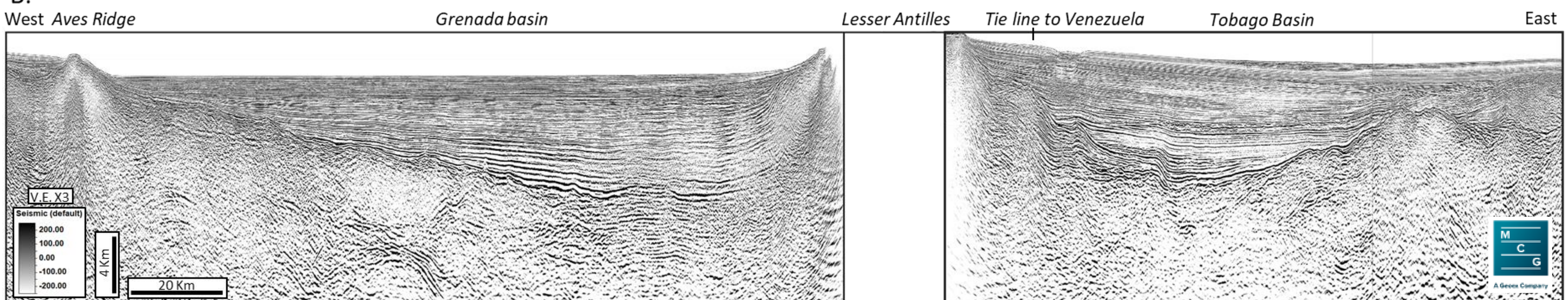
Using the MCG AS seismic grid, my mapping shows that the southern Grenada Basin contains 8.5-12 km of sedimentary rocks, while the Tobago Basin contains 9-13 km of sedimentary rocks (Fig. 6B). These thicknesses generally agree with the 8-12 km sedimentary thicknesses inferred for both basins based on previous reflection and refraction studies (Edgar et al., 1971; Boynton et al., 1979; Speed and Westbrook, 1984). The Eocene sedimentary fill of the Grenada Basin is thicker (4.5-5.5 km) than the Eocene thickness in the Tobago Basin (4-4.5 km), while the Tobago Basin exhibits a thicker Oligocene to Recent section (5-8.5 km) than the Grenada Basin (4-5.5 km). The two basins both exhibit half-grabens along the western parts of both basins that are filled with thicker syn-rift sections of Middle Eocene age (Fig. 6C).

Figure 6. A) Location map of the 400-km-long regional, post-stack-depth migrated (PSDM), 2-D MCG AS seismic line across the Aves Ridge, Grenada Basin, LAVA, and Tobago Basin shown as the thick red line; thick, yellow lines are other regional lines in the MCG AS grid. **B)** The PSDM 2-D seismic line is a composite line composed of two sections across the Grenada (175 km) and Tobago (145 km) basins with a 25-km-wide data gap across the platform area of the LAVA. **C)** Interpreted basement and overlying sedimentary units based on well ties between the Venezuelan industry wells and the Tobago Basin. Eocene sedimentary rock is thickest along the flanks of the LAVA and shows the most upward curvature along the uplifted flanks of the LAVA ridge. The Eocene sediments are uplifted by the volcanic arc's intrusion through the sediments. The Grenada Basin has a thicker Eocene section (4.5-5.5 km) than the Tobago Basin (4-4.5 km), but the Tobago Basin has a thicker Oligocene to Recent section (5-8.5 km) than the Grenada Basin (4-5.5 km). Source of geophysical data courtesy of MCG AS.

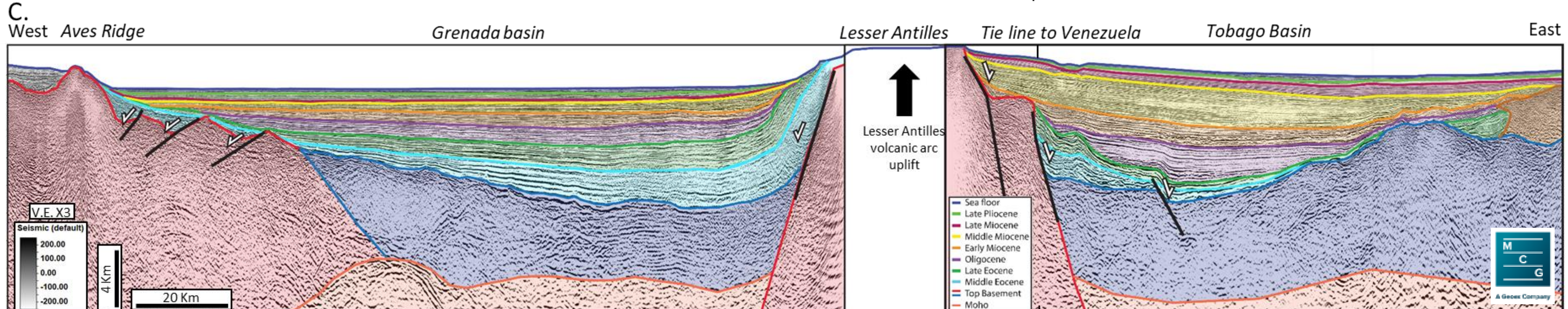
A.


62ºN
60ºN
13ºN
11ºN
Grenada Basin
Tobago Basin
Aves Ridge
Lesser Antilles Volcanic Arc
Barbados
Fig. 6B, C
Trinidad

B.


West Aves Ridge
Grenada basin
Lesser Antilles
Tie line to Venezuela
Tobago Basin
East
V.E. X3
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
4 Km
20 Km
A Geoex Company

C.


West Aves Ridge
Grenada basin
Lesser Antilles
Tie line to Venezuela
Tobago Basin
East
Lesser Antilles volcanic arc uplift
V.E. X3
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
4 Km
20 Km
Sea floor
Late Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
Late Eocene
Middle Eocene
Top Basement
Moho
A Geoex Company

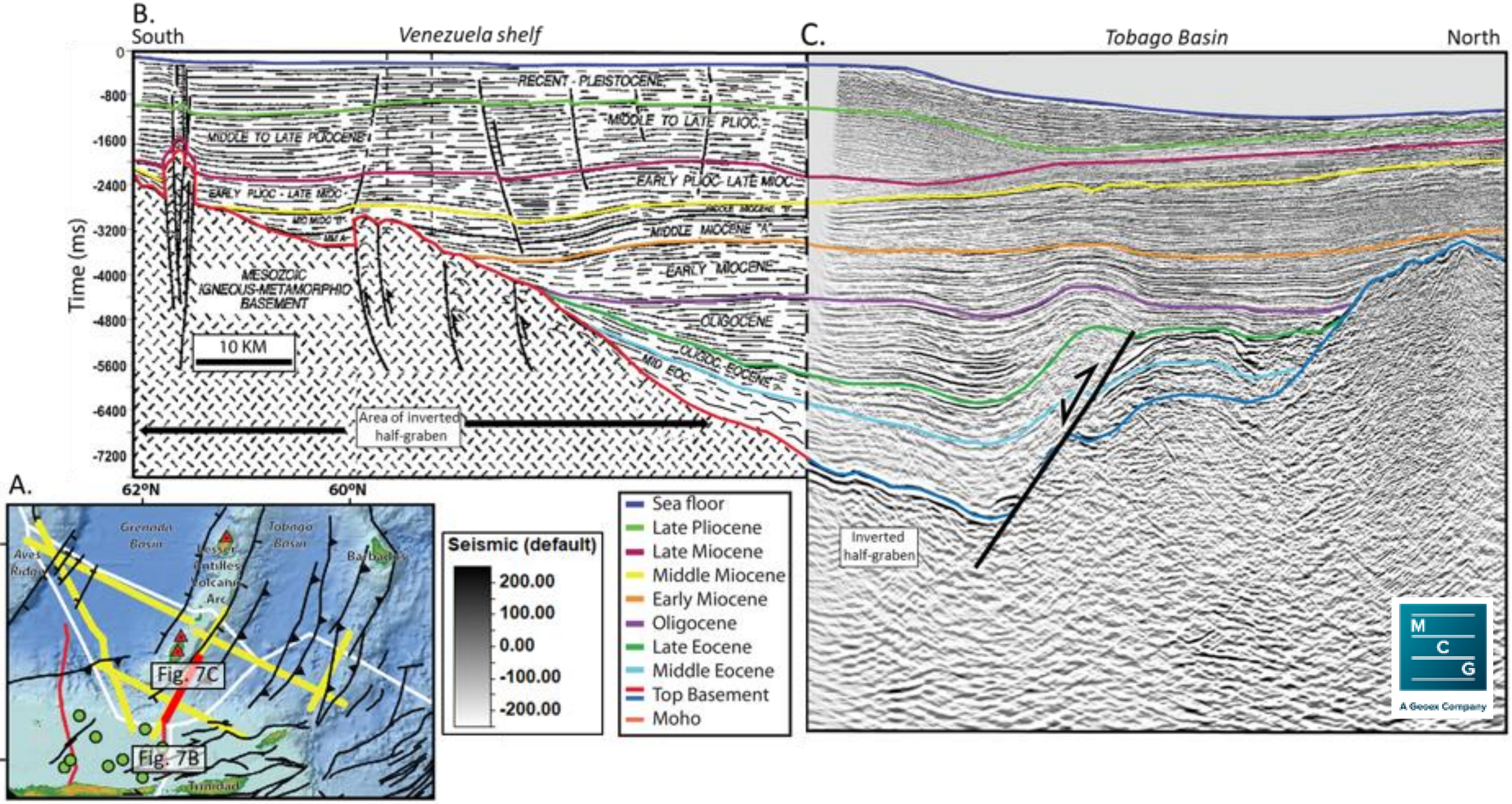
New stratigraphic age constraints for the Grenada and Tobago Basins. In order to improve the stratigraphic age constraints for both basins, which lack well data from their deeper areas, I tied vintage, oil industry seismic reflection lines and 11 wells from the Venezuelan maritime zone (Ysaccis, 1997) with an intersecting seismic line of the MCG AS data set. I made a jump correlation from the Venezuelan margin wells to the southern Grenada Basin because there was a gap between the Ysaccis (1997) grid and the MCG lines in the Grenada Basin (Fig. 7A).

These correlations are the first time wells in the Venezuelan maritime zone have been directly tied to either the Grenada or Tobago Basins. According to this correlation, the oldest sedimentary unit within both the basins is Middle Eocene (Fig. 7B). The interpretations in Figure 7C show 2 seconds TWT (~5 km) of inverted syn-rift Eocene sediments that were folded and uplifted during the interval of Oligocene to Middle Miocene. This Oligocene-Middle Miocene event is an older event than the younger collision between the Caribbean and South American Plates during the Early to Middle Miocene (Escalona and Mann, 2011).

Since the jump tie from the Venezuelan margin to the Grenada Basin was used to connect the seismic grids of Ysaccis (1997) and the MCG AS grids, additional seismic characteristics were used from the Grenada Basin to better constrain the age interpretations for this basin. For example, the prominent Middle Miocene unconformity - that has been described throughout the area (Alvarez, 2014; Alvarez et al., 2020; Gomez, 2018; Gomez et al., 2019) was also observed and correlated with both the Ysaccis (1997) and MCG AS seismic grids. Additionally, the observation of Eocene uplifted sediments in the Grenadine Islands on the elongate ridge of the

LAVA (Speed and Walker, 1991) was used to help define the age of the crystalline basement and its overlying basal sedimentary units in both the Grenada and Tobago Basins.

Figure 7. A) Location map of the 400-km-long regional, post-stack-time migrated (PSTM), 2-D MCG AS line across the Tobago Basin shown as the thick red line; thick, yellow lines are other regional lines in the MCG AS grid. The map shows the location of the 2-D PSTM seismic line as a thick red line that intersects and is tied to the 64-km-long seismic line compiled from the previous study by Ysaccis (1997) of the Venezuelan margin that is shown as the thin red line. The seismic line from Ysaccis (1997) provides a direct constraint for the stratigraphic and age interpretation of the Tobago Basin and an indirect tie to the Grenada Basin. **B.** The Ysaccis (1997) seismic line to the south in the Venezuelan maritime zone is directly tied to the MCG AS line in the TB and the cluster of Venezuelan industry wells that are shown on the map in Figure 4. **C)** The 2-D PSTM seismic line provided by MCG AS shows a 2-second-thick, Eocene half-graben within the Tobago Basin filled with a syn-rift Middle Eocene section and inverted during the Oligocene to the Middle Miocene. The inversion is separate from the collision between the South American and the Great Arc due to the deformation beginning in the Oligocene. Source of geophysical data courtesy of MCG AS.


B.
South
Venezuela shelf
C.
Tobago Basin
North
Time (ms)
RECENT - PLEISTOCENE
MIDDLE TO LATE PLIOCENE
MIDDLE TO LATE PLIOC.
EARLY PLIOC - LATE MIOC
EARLY PLIOC- LATE MIOC
MIDDLE MIOCENE "A"
EARLY MIOCENE
OLIGOCENE
OLIGOC. EOCENE
MID EOC.
MESOZOIC IGNEOUS-METAMORPHIC BASEMENT
10 KM
Area of inverted half-graben
Inverted half-graben
A.
62°N
60°N
13°N
11°N
Grenada Basin
Tobago Basin
Aves Ridge
Lesser Antilles Volcanic Arc
Barbados
Fig. 7C
Fig. 7B
Trinidad
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
Sea floor
Late Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
Late Eocene
Middle Eocene
Top Basement
Moho
A Geoex Company

2.3.3 Patterns of sedimentary infilling from regional structure and isochore maps

The regional structure maps (Fig. 4) and isochore maps (Fig. 8) reveal the present-day structural setting and sedimentary infilling history of the Grenada and Tobago Basins. The structure map shown in Figure 8C indicates that the eastern side of the Tobago Basin is controlled by westward backthrusting related to the formation of the Tobago-Barbados Ridge (Gomez et al., 2018).

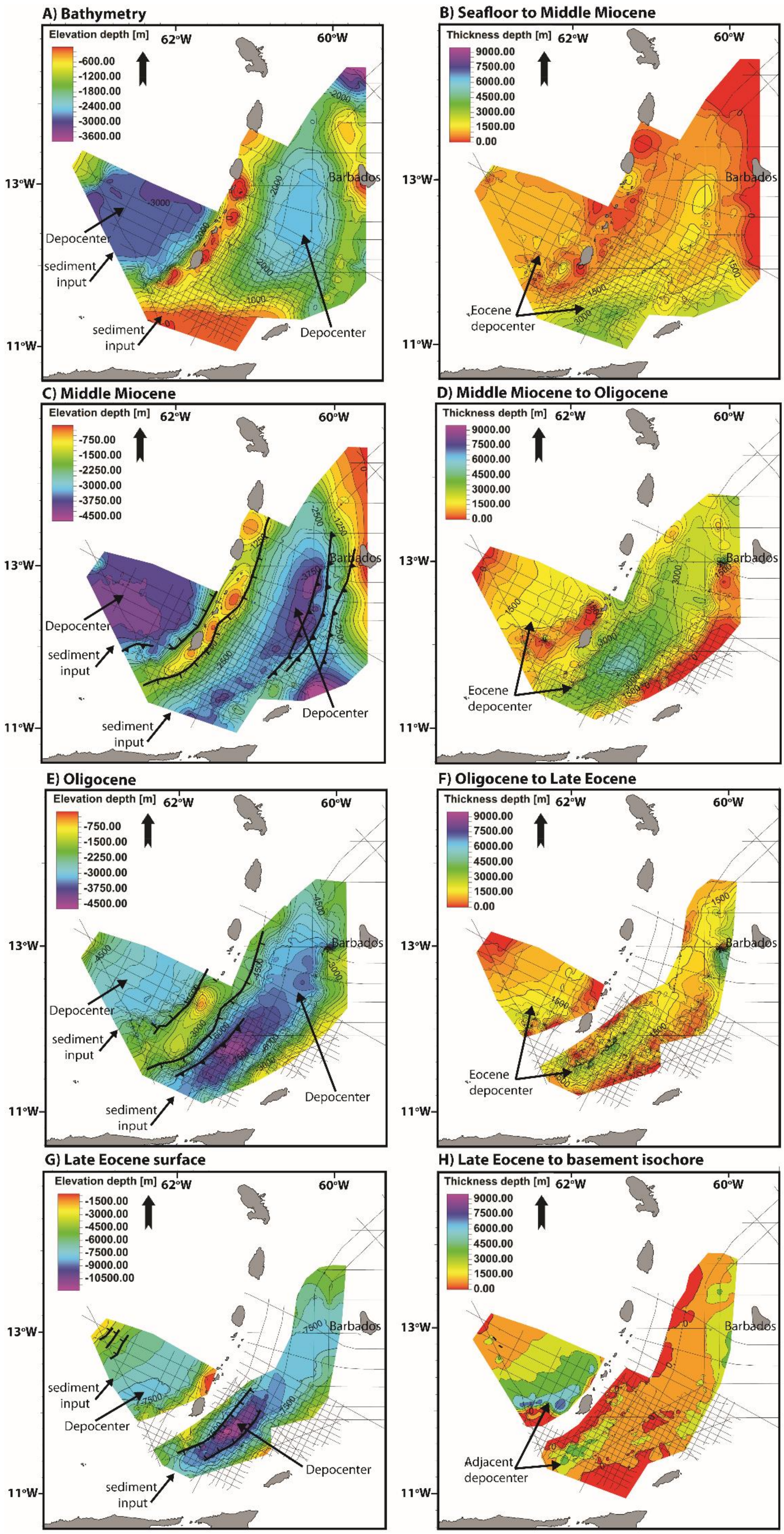
The east-dipping backthrusts and associated westward-verging folds define an "Inner Forearc Deformation Belt" (IFDB) along the western edge of the Tobago-Barbados Ridge, as previously described by Westbrook et al. (1988), Torrini et al. (1989), and Aitken et al. (2009). The deformed sedimentary rocks along the eastern flank of the Tobago Basin (including the chaotically deformed Eocene sedimentary rocks on the island of Barbados) have been uplifted on the north-south-trending and elongate popup block of the Tobago-Barbados Ridge during its formation from Eocene to the present-day (Torrini et al., 1989).

North-south-striking normal faults bound the LAVA with the Eocene sediments uplifted along its flanks due to its emergence during the Oligocene. The western sides of the Grenada and Tobago Basin contain half-grabens filled with Eocene sediments and formed as the result of east-west rifting during the Eocene (Ysaccis, 1997; Bird et al., 1999). The Grenada and Tobago Basins contain approximately 12 km and 13 km of clastic sedimentary rocks, respectively (Fig. 6C). The thicker Tobago Basin is filled to near capacity, while the Grenada Basin is a deeper-water basin (3-2.7 km) with accommodation space that remains to be infilled. The distal position of the Grenada Basin west of the elongate barrier formed by the ridge of the LAVA that isolates the more distal Grenada Basin from the effects of deltaic infilling by the Orinoco Delta as seen for the southeastern margin of the Tobago Basin (Diaz de Gamero, 1996; Xie et al., 2010; Osman et al., 2020; Punnette et al., 2020).

By comparing the regional surface maps and isochore maps, the migration of major depocenters in the Grenada and Tobago Basins can be tracked through time (Fig. 8). The depocenter for both basins in the Eocene was located at the southern ends of both basins adjacent to the LAVA during a time when the basins were located hundreds of kilometers west of their present-day locations and prior to the formation of the LAVA (Fig. 1). Uplifted and steeply-dipping Eocene sedimentary rocks, as seen in Figure 6, are attributed to the emergence of the LAVA during the Oligocene.

The Oligocene uplift of LAVA also relocated the depocenter westward in the Grenada Basin and eastward in the Tobago Basin away from the LAVA ridge (Fig. 8A, C, E, G). These shifts in the depocenters are also observed on the surface maps in Figures 8A, C, E, G, where the deepest portion of each unit progressively migrates away from the LAVA through time. Additionally, the isochore maps (Fig. 8B, D, F, H) reveal that the thickest section is within the Eocene half-grabens, but above the half-grabens, the younger sedimentary rocks of Oligocene to Late Miocene age thicken toward their current depocenters to the northwest in the Grenada Basin and to the northeast in the Tobago Basin.

Figure 8. Comparison of structural maps to thickness maps of the Grenada and Tobago Basins to show the history of infilling of both basins from the Eocene to the present. **A)** The structure map of the seafloor shows that the Grenada basin is deeper (3,000 m) than the Tobago basin (2,200 m) and that the two basins are separated by the shallow ridge of the LAVA; **B)** Total sedimentary thickness map as measured from the sea surface to the top basement of the two basins showing that their thickest areas are 8.5-12 km for the GB and 9-13 km for the TB. The total sedimentary thicknesses are symmetrical and extend 140 km along the southern ends of both basins. The sedimentary thicknesses in both basins diminish in a northward direction. **C)** The structure map of the Middle Miocene surface that is a prominent unconformity that remains uniformly deep in the Grenada basin (4 km). The surface forms a more localized depression (3.5 km) along the western flank of the Tobago-Barbados ridge that records the onset of post-Middle Miocene, westward-directed thrusting of the TBR. **D)** The thickest section of the Middle Miocene to top basement is within the Eocene depocenter, but the sedimentary units are thickening toward the modern-day depocenters through time within the GB and TB as shown by the cooler colors extending northward when comparing B and D; **E)** The Oligocene surface map depicts the beginning of the depocenters shifting away from the LAVA due to emergence of the LAVA that also caused the Eocene sedimentary units to become upturned; **F)** The Oligocene to Late Eocene isochore displays the eastward and northward thickening of the units related to the emergence of the LAVA. **G)** The Late Eocene surface shows that the original depocenter is located at the southern end of the GB and TB and adjacent to the LAVA; **H)** The Late Eocene to top basement isochore shows that the GB has a thicker Eocene unit than the TB and is likely caused by the GB being a deeper basin at that time. Source of geophysical data courtesy of MCG AS.


A) Bathymetry
Elevation depth [m]
-600.00
-1200.00
-1800.00
-2400.00
-3000.00
-3600.00
62°W
60°W
13°W
11°W
Barbados
Depocenter
sediment input
sediment input
Depocenter
B) Seafloor to Middle Miocene
Thickness depth [m]
9000.00
7500.00
6000.00
4500.00
3000.00
1500.00
0.00
Eocene depocenter
C) Middle Miocene
Elevation depth [m]
-750.00
-1500.00
-2250.00
-3000.00
-3750.00
-4500.00
D) Middle Miocene to Oligocene
E) Oligocene
F) Oligocene to Late Eocene
G) Late Eocene surface
Elevation depth [m]
-1500.00
-3000.00
-4500.00
-6000.00
-7500.00
-9000.00
-10500.00
H) Late Eocene to basement isochore
Adjacent depocenter

2.3.4 Interpretation of seismic facies from seismic reflection lines

Deepwater sedimentary lithologies and facies within both the Grenada and Tobago Basins remain largely unknown as the result of the lack of deep wells in both basins. My seismic facies classification based on the amplitude, configuration, and continuity within its geologic and stratigraphic framework is shown in Figure 9. The locations of the six seismic facies are shown in Figure 9A and are also identified in the seismic line shown in Figure 10.

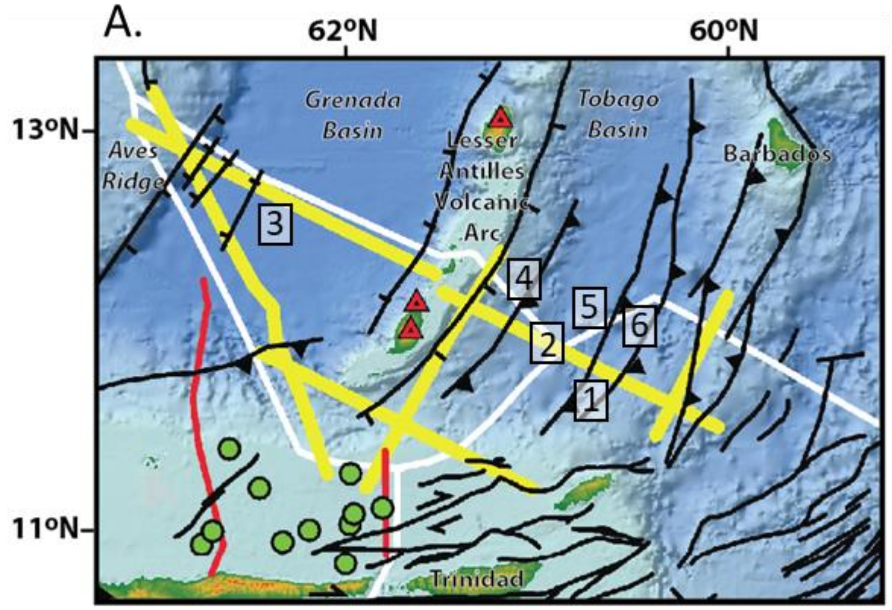
The seismic amplitude provides information on the change in impedance between the stratigraphic units, and reflection continuity provides information for events that are variable at a basin or local scale. The configuration of the amplitudes and continuity provides information on the depositional environment that the sediments were deposited. These classifications were used to identify potential source rocks within the basins with characteristics of transparent seismic expression or very low impedance within a section of medium impedance shale. These facies are mostly observed in moderate to deep water depositional environments. A few of these source rocks are shown in Figure 10 as S-1 through S-4.

Both basins have Miocene, north-flowing channel systems that vary from leveed channels to distal fan complexes. Figure 10 illustrates the leveed channels system (SF-4) on the upper slope on the western side of the Tobago Basin, a confined channel system (SF-5) on the mid-slope, and the distributary fan system (SF-6) within the deepest part of the basin.

Figure 10 shows a facies change from west to east from a proximal distributary fan system (SF-6) to a distal distributary fan system (SF-2), west of the S-4 label. This facies change likely results from the decreasing sand content and increasing fine-grain sediment as it entered the deeper part of the basin where the larger sand grains settle out. Additionally, mass-transport complexes are commonly found along the edges of the LAVA and TBR. Both basins contain large sections of semi-continuous to chaotic reflectors that reflect the presence of a distributary fan complex from the Oligocene to Middle Miocene.

Figure 9. A) The location of the six deepwater seismic facies are defined in the map using the areas of the MCG AS seismic lines. **B)** SF-1 is a proximal, mass-transport complex of Oligocene age from the Tobago Basin commonly found along the edges of the LAVA, TBR, and in areas adjacent to the Venezuelan margin; SF-2 is a distributary fan complex of Middle Miocene age that displays a semi-continuous and chaotic amplitude pattern and is located in the middle to distal portion of a fan complex. SF-3 is a distal fan complex of Late Pliocene age located within the deeper sections of the two basins and shows localized disturbances along smaller channels. SF-4 is a leveed channel system of Middle to Late Miocene age and is commonly located in the proximal setting of the LAVA and South America and is made up of mud with interbedded thin sands. SF-5 is a confined channel complex of Middle to Late Miocene age and is more distal than the leveed channel system. SF-4 is commonly located in the proximal setting of the LAVA and South America. SF-6 is a distributary fan complex of Late Miocene age located in the distal or deeper segments of the GB and TB - but is more proximal and has increased sand content than SF-2. Source of geophysical data courtesy of MCG AS.

A.



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B.

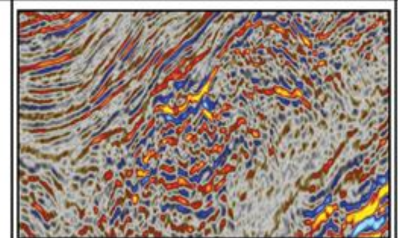
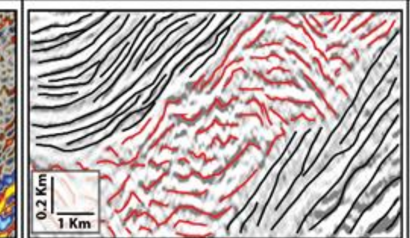
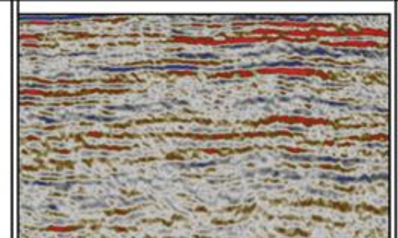
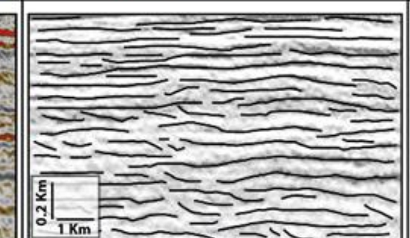
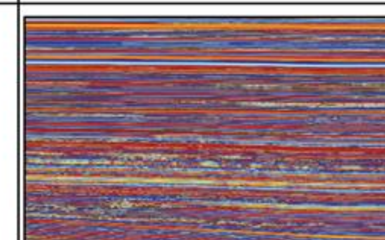
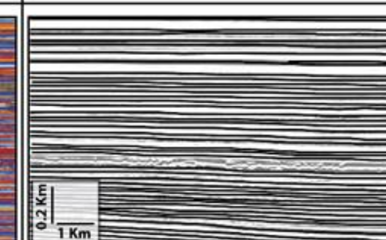
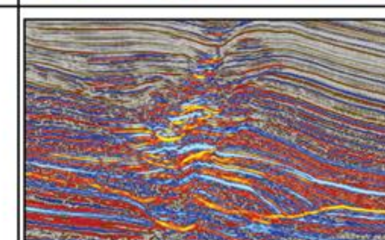
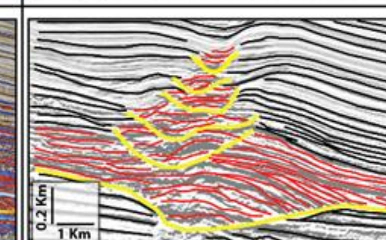
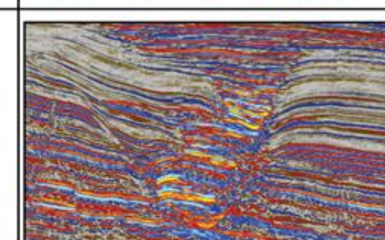
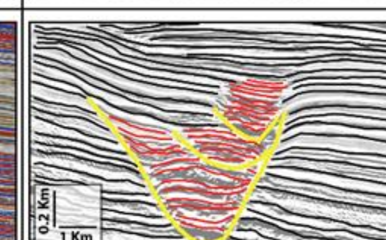
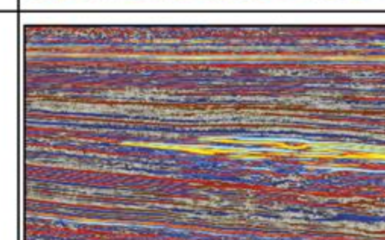
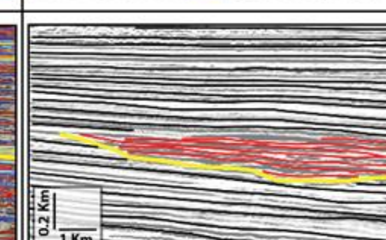
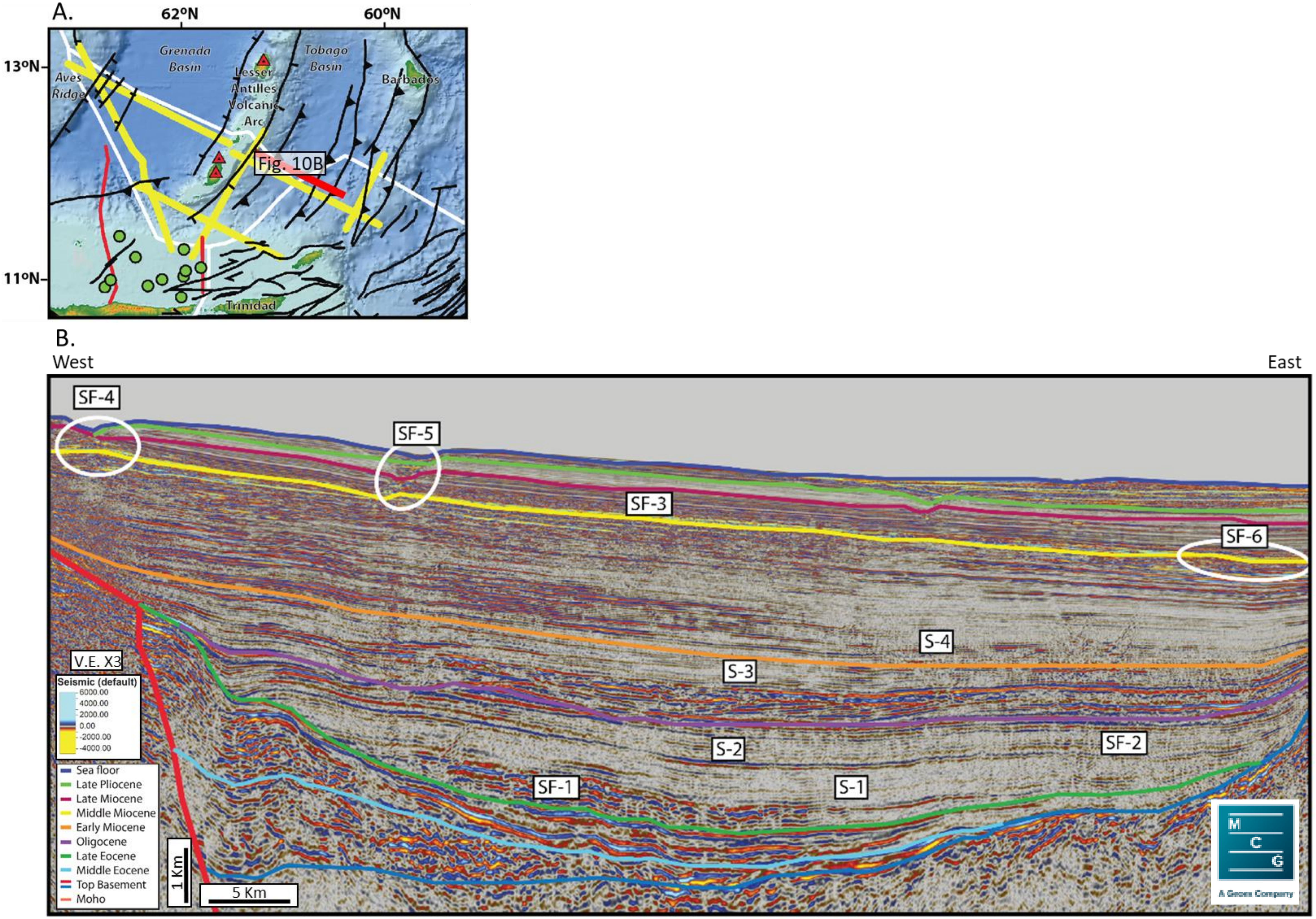
Facies	Seismic example	interpretation/schematic	Seismic character	Occurence
SF-1			Discontinuous and chaotic reflectors with a short reflection length, and is located between two semi-continuous reflectors.	The features are a mass transport complex once located on an unstable slope allowing the sediments to flow into the basin to a stable environment and likely contain sand and volcaniclastic.
SF-2			Semi-continuous to chaotic reflectors with transparent to moderate amplitude reflectors that are semi-parallel to wavy and have a short to medium reflection length.	The feature is likely composed of shale and mudstone with the higher amplitudes caused by sand or volcanoclastics within a distributary fan complex that is more distal than SF-6.
SF-3			The seismic image displays continuous reflectors with high amplitudes that are parallel with a very long reflection length.	The sediments are likely hemipelagic and composed of clay, silt, and/or volcaniclastic sediment. Small channels with increased sand likely caused the localized disturbances.
SF-4			The semi-continuous reflectors have high amplitudes that are semi-continuous within the channel system. The unit above the channel is mostly transparent with continuous reflectors.	The high amplitudes are likely caused by low density turbites composed of volcaniclastic sediment with interbedded sand. The leveed channel system that occurs within the upper slope.
SF-5			Semi-continuous reflectors have low to high amplitudes that are continuous until a channel system interprets them. The highest amplitudes occur within the channels.	The high amplitudes are likely a result of sandstones and volcaniclastic sediment. The confined channel system occurs in the mid-slope.
SF-6			The continuous reflectors have high amplitudes that are semi-continuous and are parallel within the channel system. The units above and below have a medium amplitude and are parallel.	The high amplitudes are likely a result of sandstone and volcaniclastic sediments. The distributary fan complex has a fan-like characteristic and is likely deposited on or near the basin floor.

Figure 10. Location map of the 90-km-long regional, post-stack-time migrated (PSTM), 2-D MCG AS line across the Tobago Basin shown as the thick red line; thick, yellow lines are other regional lines in the MCG AS grid. **B)** The seismic facies outline in Figure 8 have been identified within the seismic line. SF-4 is a leveed channel system located within the upper slope, SF-5 is a channel system located in the middle slope, and SF-6 is a distributary fan system located within the deepest section of the Tobago Basin. A facies change occurs from west to east from a proximal distributary fan system (SF-6) to a distal distributary fan system (SF-2), west of the S-4 label. This facies change is caused by the decreasing sand content and increasing fine-grain sediment as it enters the deeper section of the basin where the larger grains settle out. Some of the source rocks included in the basin model have been identified with a label of S-1 through S-4. Source of geophysical data courtesy of MCG AS.


A.
62ºN
60ºN
13ºN
11ºN
Grenada Basin
Tobago Basin
Aves Ridge
Lesser Antilles Volcanic Arc
Barbados
Fig. 10B
Trinidad
B.
West
East
SF-4
SF-5
SF-3
SF-6
S-4
S-3
S-2
SF-2
SF-1
S-1
V.E. X3
Seismic (default)
6000.00
4000.00
2000.00
0.00
-2000.00
-4000.00
Sea floor
Late Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
Late Eocene
Middle Eocene
Top Basement
Moho
1 Km
5 Km
M
C
G
A Geoex Company

2.3.5 Summary of evidence for the Grenada and Tobago Basins as a single rifted forearc basin

The origin and evolution of the Grenada and Tobago Basins remains controversial, as shown by the three tectonic models summarized in Figure 3. This study summarizes supporting evidence for the tectonic model proposed by Aitken et al. (2009) (Fig. 3B), although I refine the age dating for the main evolutionary stages of this model.

The direction of the Middle Eocene opening in both basins is east-west (Tomblin, 1975; Bouysee, 1988; Bird et al., 1999; Aitken et al., 2009) rather than north-south as proposed by Pindell and Barrett (1990). This study has identified rifts within the western areas of both the Grenada and Tobago Basins that are filled with Middle to Late Eocene sedimentary rocks (Fig. 11; Fig. 12). Bird et al. (1999) suggests that both basins were extended in a west-east direction with the spreading zone trending north to south. In addition, both spreading zones have a slight counter-clockwise rotation as they extend northward. The observed rifts are filled with Middle Eocene and constrain the creation of the oceanic crust within the forearc as post-Middle Eocene and prior to the Early Oligocene emergence of the LAVA (Fig. 11; Fig. 12).

Figure 11. A) Location map of the 270-km-long regional, post-stack-depth migrated (PSDM), 2-D MCG AS line across the Aves Ridge, Grenada Basin, and western edge of the LAVA shown as the thick red line; thick, yellow lines are other regional lines in the MCG AS grid. **B)** The 270-km-long PSDM 2-D seismic line shows the structure of the southern Grenada basin down to the 16-20 km depth of the Moho as seen at the base of the section. **C)** Interpreted basement and overlying sedimentary units based on well ties between the Venezuelan industry wells and the Tobago Basin, as shown in Figure 7. Eocene sedimentary rocks are thickest along the flanks of the western LAVA and are deformed into a large anticline. Three half-grabens of Middle Eocene age are present along the eastern margin of the Aves Ridge, trend to the northeast, and reflect Eocene stretching of the Great Arc of the Caribbean prior to the formation of post-Middle Eocene oceanic crust that underlies the deepest and most thickly sedimented part of the basin. Convergent deformation of Middle Miocene age is observed along the western margin of the LAVA and is inferred to reflect the post-Eocene emplacement and later deformation of the LAVA ridge as it collided with the northern margin of South America. The previous study by Ysaccis (1997) shows that the intensity of inversion increases in the southward direction and is the inferred expression of the collision between this part of the Great Arc of the Caribbean underlying the Leeward Antilles and the continental margin of northern South America. Source of geophysical data courtesy of MCG AS.

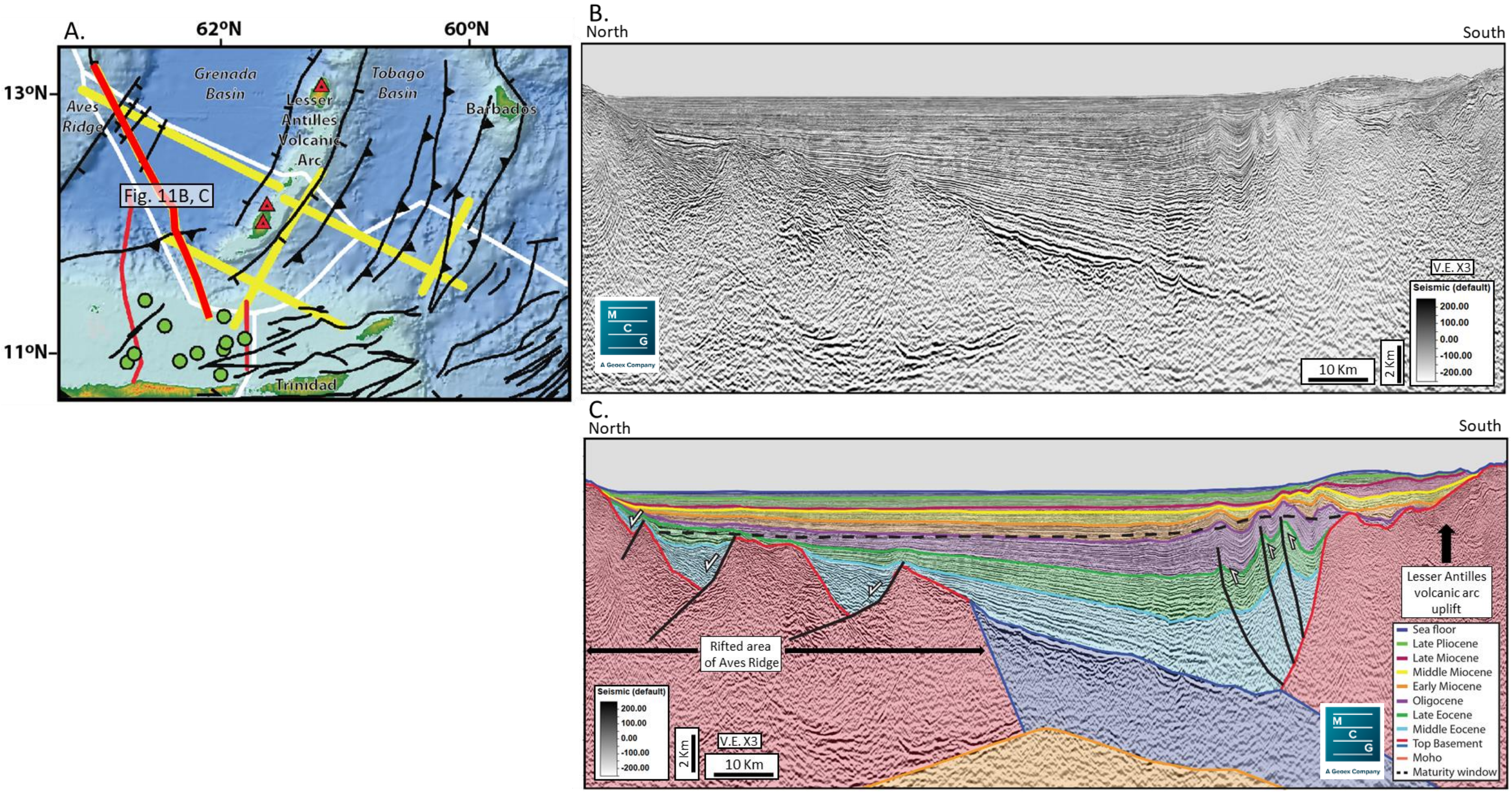
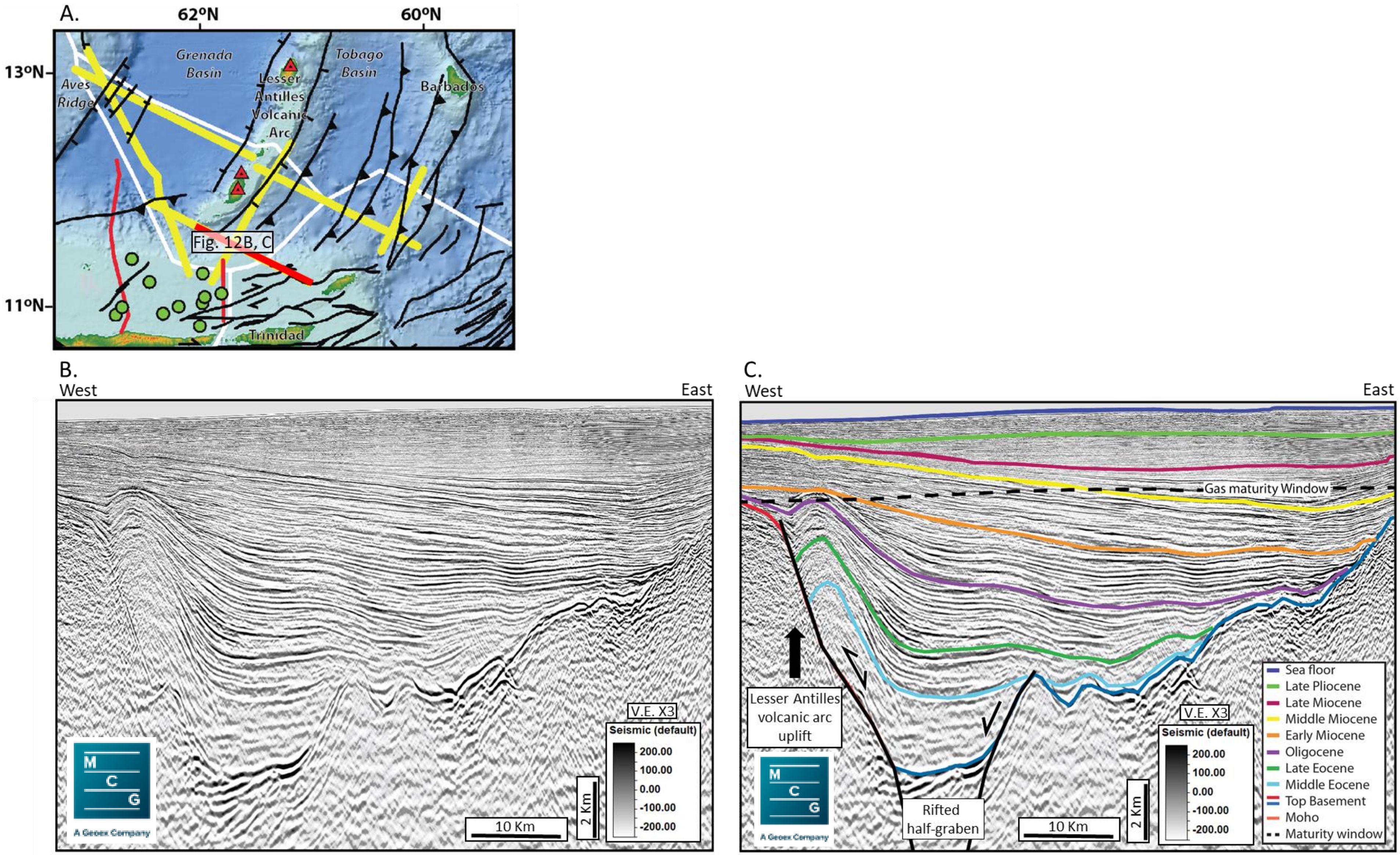

A.
62ºN
60ºN
13ºN
11ºN
Grenada Basin
Tobago Basin
Aves Ridge
Lesser Antilles Volcanic Arc
Barbados
Fig. 11B, C
Trinidad
B.
North
South
V.E. X3
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
10 Km
2 Km
M C G
A Geoex Company
C.
North
South
Lesser Antilles volcanic arc uplift
Rifted area of Aves Ridge
Sea floor
Late Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
Late Eocene
Middle Eocene
Top Basement
Moho
Maturity window
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
2 Km
V.E. X3
10 Km
M C G
A Geoex Company

Figure 12. A) Location map of the 120-km-long regional, post-stack-depth migrated (PSDM), 2-D MCG AS line across the eastern edge of the LAVA ridge and the Tobago Basin as shown as the thick red line; thick, yellow lines are other regional lines in the MCG AS grid. **B)** The 120-km-long PSDM 2-D seismic line showing the structure of the southern Tobago basin down to 16 km depth. **C)** Interpreted basement and overlying sedimentary units based on direct well ties between the Venezuelan industry wells and the Tobago Basin, as shown in Figure 7. Eocene sedimentary rocks are thickest along the flanks of the eastern LAVA and are deformed into an inverted half-graben. This Middle Eocene half-graben trends to the northeast and reflects Middle Eocene stretching of the Great Arc of the Caribbean prior to the formation of post-Middle Eocene oceanic crust that is inferred to underlie the deepest and most thickly sedimented central part of the Tobago Basin. The inversion-related deformation of Oligocene to Middle Miocene age along the eastern margin of the LAVA is inferred to reflect the emergence of the LAVA ridge as it intruded through the GB and TB, uplifting the Eocene sediment, and is onlapped by Oligocene sediments. Source of geophysical data courtesy of MCG AS.


A.
62ºN
60ºN
13ºN
11ºN
Grenada Basin
Tobago Basin
Aves Ridge
Lesser Antilles Volcanic Arc
Barbados
Fig. 12B, C
Trinidad
B.
West
East
V.E. X3
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
2 Km
10 Km
A Geoex Company
C.
West
East
Gas maturity Window
Lesser Antilles volcanic arc uplift
Rifted half-graben
V.E. X3
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
2 Km
10 Km
A Geoex Company
Sea floor
Late Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
Late Eocene
Middle Eocene
Top Basement
Moho
Maturity window

2.3.6 Summary of stratigraphic and radiometric evidence for Oligocene uplift of the nascent LAVA within a rifted forearc basin

The LAVA was interpreted by Bird et al. (1999) as a rifted fragment of the Late Cretaceous-Paleocene volcanic arc of the Aves Ridge. Published radiometric dating from the LAVA has revealed no ages older than early Oligocene and supports the first emergence of the nascent LAVA during this period. A recent study by White et al. (2017) on the island of Grenada resulted in the discovery of uplifted Eocene pillow basalts formed in a back-arc spreading zone. These findings are consistent with the earlier studies of Speed and Larue (1985) and Speed et al. (1991), which biostratigraphically constrained Late Eocene (37.9 Ma) pillow basalts and Late Eocene (37.9 Ma) turbidites on the islands of Mayreau and Grenada, respectively. Speed et al. (1991) also proposed that the pillow basalt is an oceanic crust that was uplifted from the basin floor to its current position, as later reiterated by Aitken et al. (2009).

Germa et al. (2011) conducted a radiometric study of the outer and inner arc on Martinique to place additional constraints on the migration of the transition of volcanism from the Aves Ridge to the LAVA. Germa et al. (2011) concluded that the emergence of LAVA occurred during the Oligocene (24.1-24.8 Ma), and the inner arc of the northern Lesser Antilles formed during the Late Miocene (5.4 Ma).

This study dates the Oligocene emergence of the LAVA using seismic interpretations of uplifted Eocene sedimentary strata along the LAVA that are onlapped by the younger, Oligocene sedimentary rocks within both the Grenada and Tobago Basins (Fig. 12; Fig. 14). The Oligocene unit first onlaps the more steeply-dipping Eocene section, and the onlap continues onto the Middle Miocene with the first occurrence of downlap observed along the LAVA in the Grenada Basin (Fig. 13C). In the Tobago Basin, the depocenter shifted eastward due to the emergence of the elongate ridge of the LAVA (Fig. 14C). The depocenter's migration is supported by the shingled stacking of downlapping reflectors that were previously described in the section on structure and isochore maps (Fig. 14C). The outward movement of the depocenter away from the elongate ridge of the LAVA is caused by the inversion of the Eocene sediments and supports the proposed Early Oligocene emergence of the LAVA.

One weakness of the Aitken et al. (2008) model is that it invokes an originally continuous forearc basin, but the now separated basins show differing thicknesses of the Eocene units in the Grenada Basin (4.8 km) and in the Tobago Basin (4.2 km) (Fig. 15). The difference in Eocene sedimentary thickness is about 0.5-1 km over a distance of 70 km, with a rapid thinning to the east within the Tobago (Fig. 15). The slight thickness variation could be caused by the 70 km distance, and rapid thinning could be caused by the Tobago Basin receiving the distal fringe of deltaic sediments originating from the Proto-Maracaibo delta (Xie et al., 2010). The Tobago Basin would also receive decreased sediment contribution from the Maracaibo deltaic system through time as the Caribbean Plate moved eastward and away from the Maracaibo deltaic system. The LAVA would act as a barrier between the Tobago Basin and Grenada Basin after its emergence during the Early Oligocene. The crystalline basement of the Grenada Basin is also 2 km deeper than the Tobago Basin, giving the Grenada Basin a larger accommodation space for its faster deltaic sedimentation rates during this period (Fig. 15).

Figure 13. A) Location map of the 80-km-long regional, post-stack-depth migrated (PSDM), 2-D MCG AS line across the western edge of the LAVA and the eastern Grenada Basin as shown as the thick red line; thick, yellow lines are other regional lines in the MCG AS grid. **B)** The 80-km-long PSDM 2-D seismic line showing the structure of the southern Grenada basin. The box shows the zoomed area in C; **C)** Zoomed area of the contact zone between the uplifted Eocene section with areas of stratigraphic downlap are shown with red arrows and areas of stratigraphic onlap shown with yellow arrows. The period of onlap begins during the Early Oligocene and continues up to the Middle Miocene. The first occurrence of downlap is observed starting in the Middle Miocene and is interpreted as the progradation of sediments eroded from the uplifted LAVA ridge. The uplift of the LAVA is interpreted as the combined effect of its collision with the northern margin of South America during the Middle Miocene and the initiation of LAVA during the Early Oligocene known from radiometric dating of the oldest subduction-related volcanic units. Source of geophysical data courtesy of MCG AS.

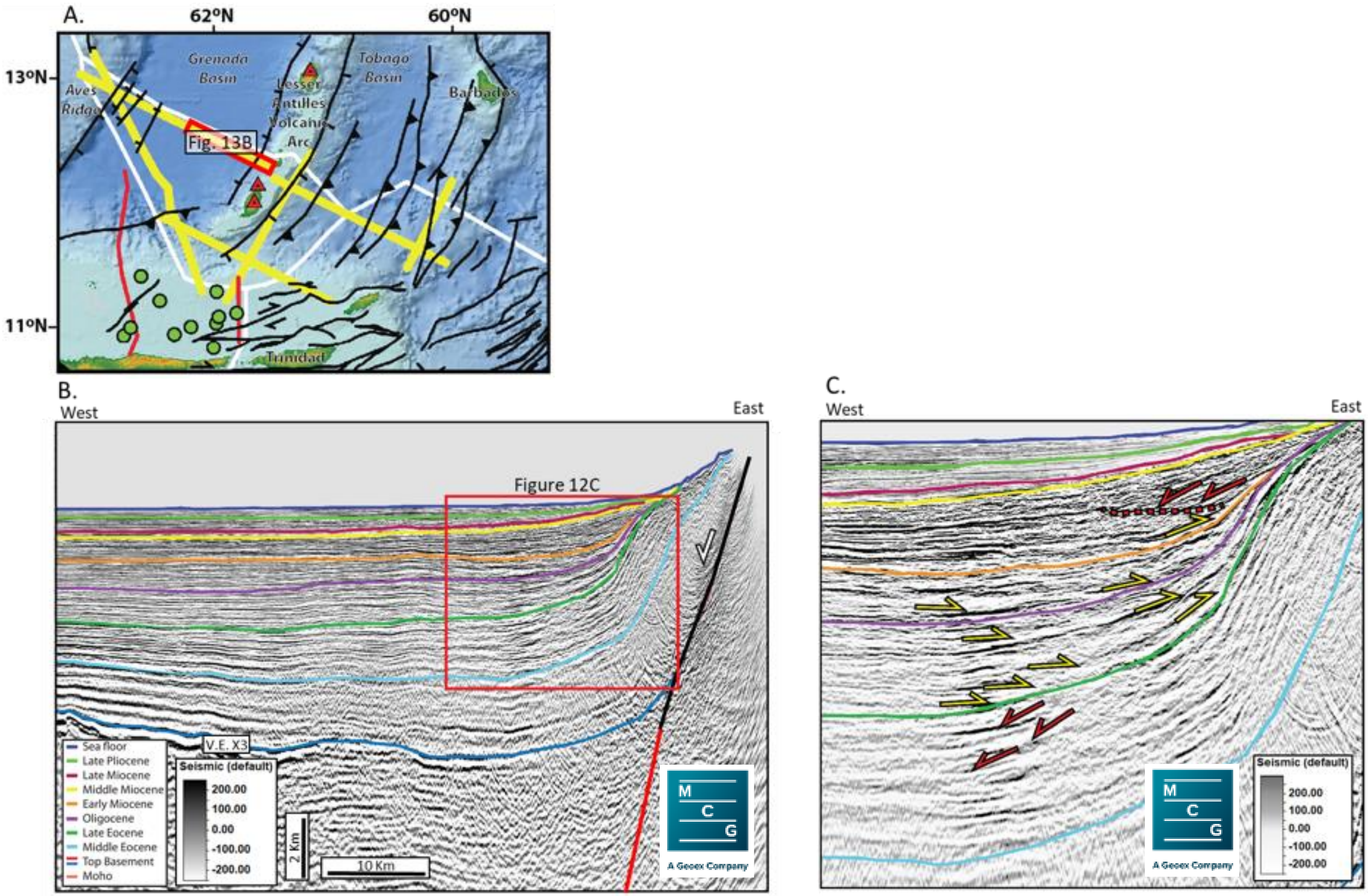

A.
62ºN
60ºN
13ºN
11ºN
Grenada Basin
Tobago Basin
Aves Ridge
Lesser Antilles Volcanic Arc
Barbados
Fig. 13B
Trinidad
B.
West
East
Figure 12C
Sea floor
Late Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
Late Eocene
Middle Eocene
Top Basement
Moho
V.E. X3
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
2 Km
10 Km
M
C
G
A Geoex Company
C.
West
East
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
M
C
G
A Geoex Company

Figure 14. A) Location map of the 120-km-long regional, post-stack-depth migrated (PSDM), 2-D MCG AS line across the eastern edge of the LAVA and the Tobago Basin as shown as the thick red line; thick, yellow lines are other regional lines in the MCG AS grid. **B)** The 120-km-long PSDM 2-D seismic line showing the structure of the southern Tobago basin. The box shows the zoomed area in C; **C)** Zoomed area of the contact zone between the uplifted Eocene section with areas of stratigraphic downlap shown with red arrows and areas of stratigraphic onlap shown with yellow arrows. The period of onlap begins during the Early Oligocene and continues up to the Middle Miocene as the older Eocene units are upturned and onlapped by pre-Middle Miocene units. The first occurrence of downlap is observed starting in the Oligocene and is interpreted as the eastward movement of the depocenter as the Eocene section was uplifted. The uplift of the LAVA is interpreted as the combined effect of its collision with the northern margin of South America during the Middle Miocene and the initiation of LAVA during the Early Oligocene known from radiometric dating of the oldest subduction-related volcanic units. Source of geophysical data courtesy of MCG AS.

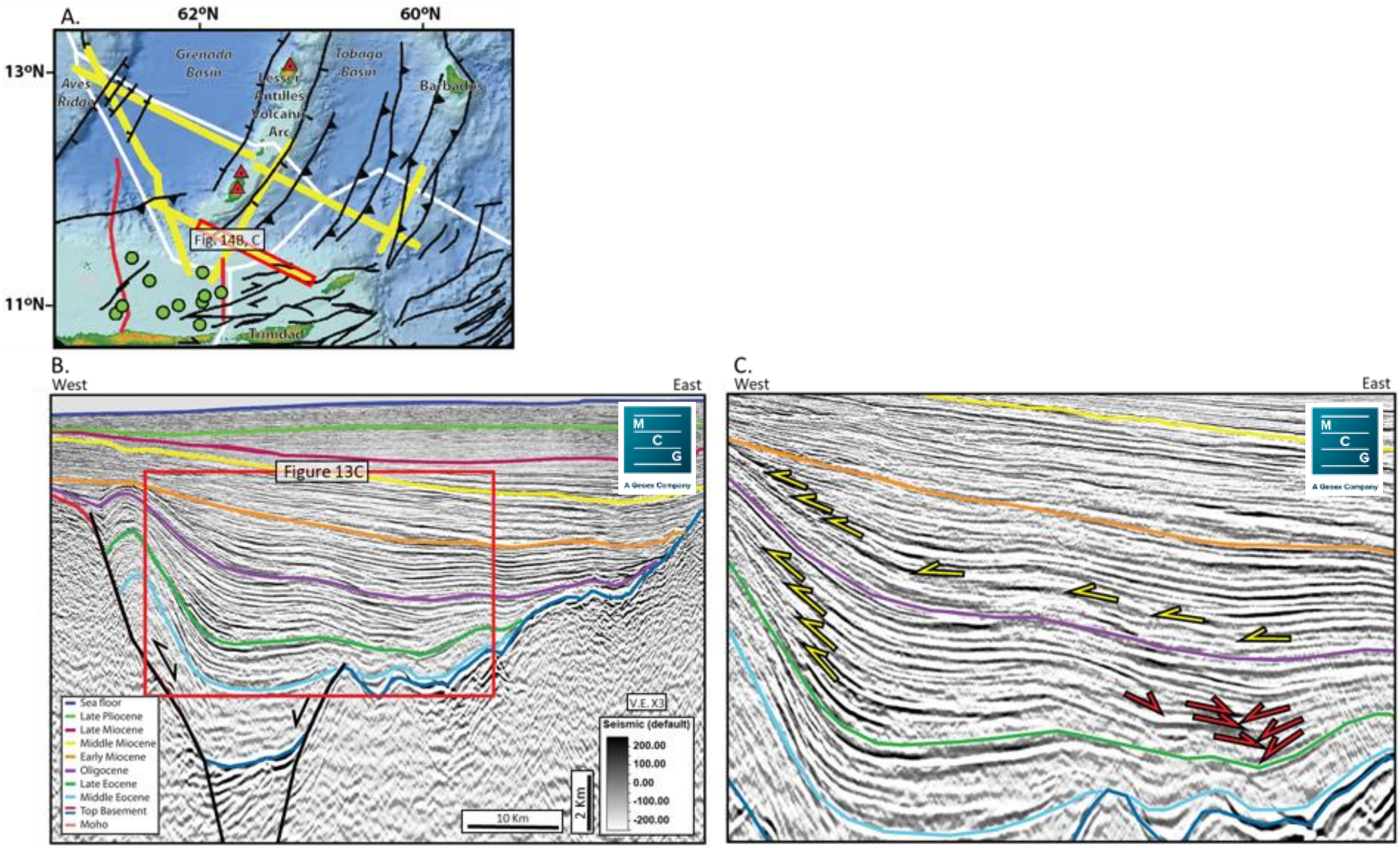
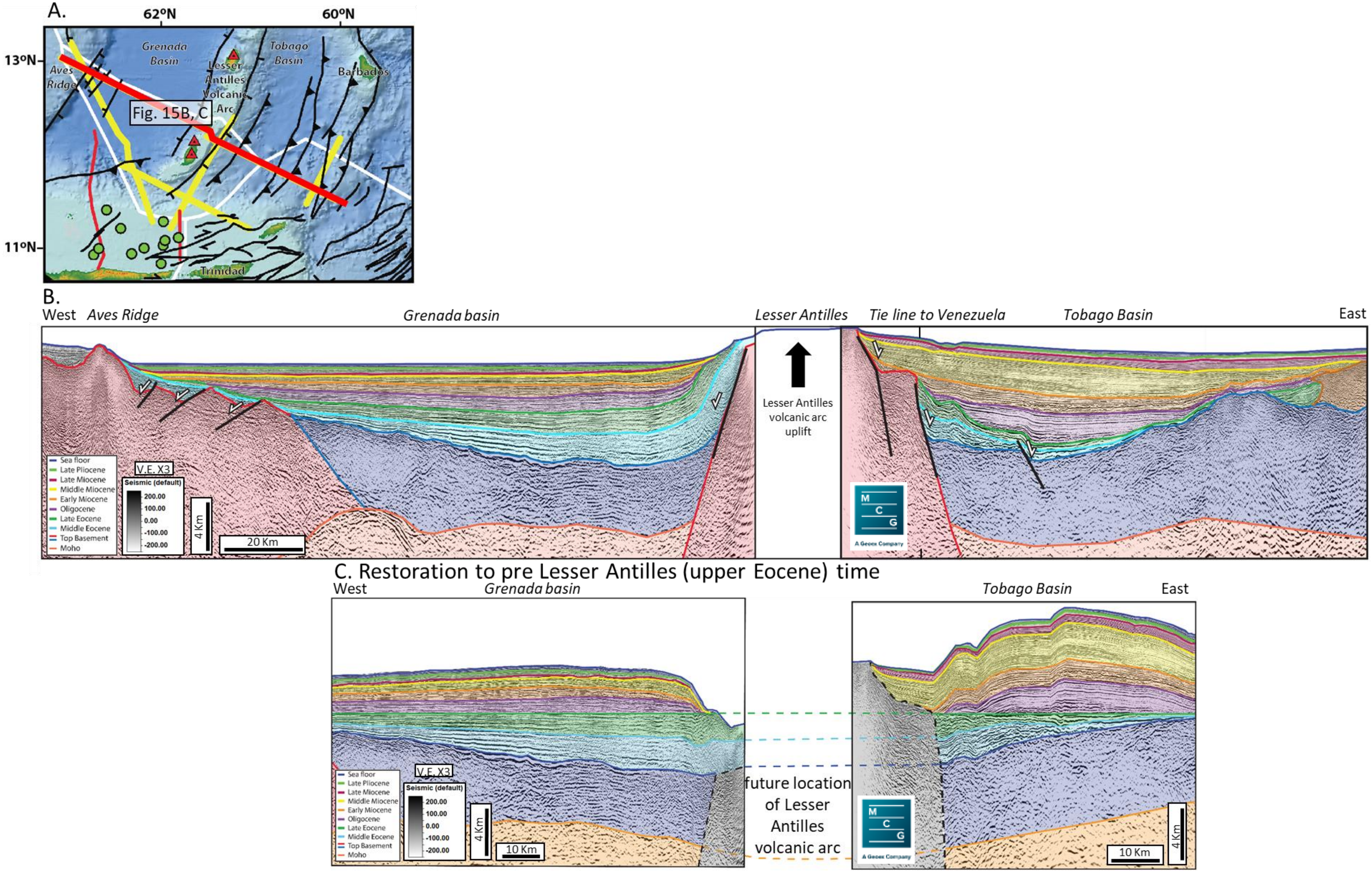

A.
62ºN
60ºN
13ºN
11ºN
Grenada Basin
Tobago Basin
Aves Ridge
Lesser Antilles Volcanic Arc
Barbados
Fig. 14B, C
Trinidad
B.
West
East
Figure 13C
Sea floor
Late Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
Late Eocene
Middle Eocene
Top Basement
Moho
V.E. X3
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
10 Km
2 Km
C.
West
East

Figure 15. A) Location map of the 400-km-long regional, post-stack-depth migrated (PSDM), 2-D MCG AS line across the Aves Ridge, Grenada Basin, LAVA, and Tobago Basin shown as the thick red line; thick, yellow lines are other regional lines in the MCG AS grid. **B)** Interpreted basement and overlying sedimentary units based on well ties between the Venezuelan industry wells and the Tobago Basin. Eocene sedimentary rocks are thickest along the flanks of the LAVA and show the most upward curvature along the uplifted flanks of the LAVA ridge. The Eocene sedimentary rocks are thickest along the LAVA flanks and uplifted by the intrusion of the nascent volcanic arc through the sedimentary rocks of the forearc basin. The Grenada Basin shows a thicker Eocene section (4.5-5.5 km) than the Tobago Basin (4-4.5 km), but the Tobago Basin shows a thicker Oligocene to Recent section (5-8.5 km) than the Grenada Basin (4-5.5 km). **C)** The Grenada and Tobago Basins have been restored to their Late Eocene appearance prior to the Oligocene emergence of the Lesser Antilles. The results show a thickness variation of 0.2 – 0.6 km between the Late Eocene and Middle Eocene sedimentary units within the Grenada and Tobago Basins. The difference in Eocene thickness between the basins is caused by sediment input from the southwest direction during the Eocene that caused the Grenada Basin to receive increased sedimentation. The post-Eocene sediment thickness variation is caused by the emergence of the LAVA during the Oligocene that separated the Grenada and Tobago Basins. As the Caribbean plate migrated eastward, the Tobago basin receives increased sedimentation from South America and the Maracaibo delta (Aitken et al., 2009; Xie et al., 2010). Source of geophysical data courtesy of MCG AS.


A.
62ºN
60ºN
13ºN
11ºN
Grenada Basin
Lesser Antilles Volcanic Arc
Tobago Basin
Barbados
Aves Ridge
Fig. 15B, C
Trinidad
B.
West
Aves Ridge
Grenada basin
Lesser Antilles
Tie line to Venezuela
Tobago Basin
East
Lesser Antilles volcanic arc uplift
Sea floor
Late Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
Late Eocene
Middle Eocene
Top Basement
Moho
V.E. X3
Seismic (default)
200.00
100.00
0.00
-100.00
-200.00
4 Km
20 Km
C. Restoration to pre Lesser Antilles (upper Eocene) time
West
Grenada basin
Tobago Basin
East
future location of Lesser Antilles volcanic arc
10 Km
4 Km

2.3.7 Evidence for Pre-Middle Miocene deformation of the southern margins of the Grenada and Tobago Basins

Transpressional folding that deformed the southern Grenada Basin is related to the oblique collision of the Great Arc of the Caribbean with the passive margin of the northern South American continent (Escalona and Mann, 2011). The collision between the plates occurred during the Early to Middle Miocene (Aitken et al., 2009; Escalona and Mann, 2011; Gomez et al., 2018). Transpressional faults shown in Figure 10 are the result of a thick-skinned basement-involved deformation that involves the entire sedimentary section of both basins.

The Miocene deformation associated with this oblique collision differs from the older, Oligocene deformation of the Tobago Basin that is observed along both sides of that basin. The deformation associated with the Early to Middle Miocene collision is only observed in the southern Grenada Basin and produced large, anticlinal traps. Additionally, the faults have the potential to act as migration pathways for the deeper source rocks.

2.3.8 Applications for petroleum exploration of the Grenada and Tobago Basins

Estimating basinal heat flow. In the absence of deepwater well data available from both basins, three different techniques were used to estimate the heat flow in the Grenada and Tobago Basin. The first method utilized the depths of large, gas hydrate fields located within both basins to calculate a local estimate of heat flow beneath both areas (58-64 $m/W/m^2$) (Fig. 16, Fig. 17) (Hodgson et al., 2014; Wang et al., 2017).

The second source of heat flow estimates is from Manga et al. (2012) based on an east-west transect of shallow-penetrating heat flow probes within the Grenada Basin (55-65$m/W/m^2$) (Fig. 4; Fig. 17).

The third source for heat flow estimates is from Hasterok (2013), who compiled global heat flow averages for different ages of oceanic crust. Using the inferred, post-Middle Eocene age for the oceanic crust of the Grenada and Tobago Basins based on stratigraphic dating of uplifted basalts in the Grenadines (Speed and Walker, 1991), the graph shown in Figure 16 estimates the present-day heat flow of both basins as 70-75 m/W/m^2 (Fig. 17). With increasing age, the error estimate for heat flow increases for Paleocene and older oceanic crusts.

Figure 16. A. Location map of two post-stack-depth migrated (PSDM) 2-D MCG AS lines across two gas hydrate fields shown as green polygons and are marked by a prominent bottom-simulating reflector that is located in the thrust faulted and folded zone that separates the southeastern edge of the Grenada Basin and along the normal-faulted zone of the Tobago-Barbados Ridge; thick, yellow lines are other regional lines in the MCG AS grid. **B)** The 18-km-long PSDM 2-D seismic line to the southwest shows the concentration of gas hydrate above the zone of thrust faulting in the GB. I propose that some of the free gas may be thermogenic due to its proximity to the deeper migration pathways that are provided by the underlying thrust faults; **C)** The 12-km-long PSDM 2-D seismic line to the northeast in the TB provides a second example of a dense concentration of gas hydrate marked by a stronger bottom-simulating reflector above the zone of normal faulting. Source of geophysical data courtesy of MCG AS.

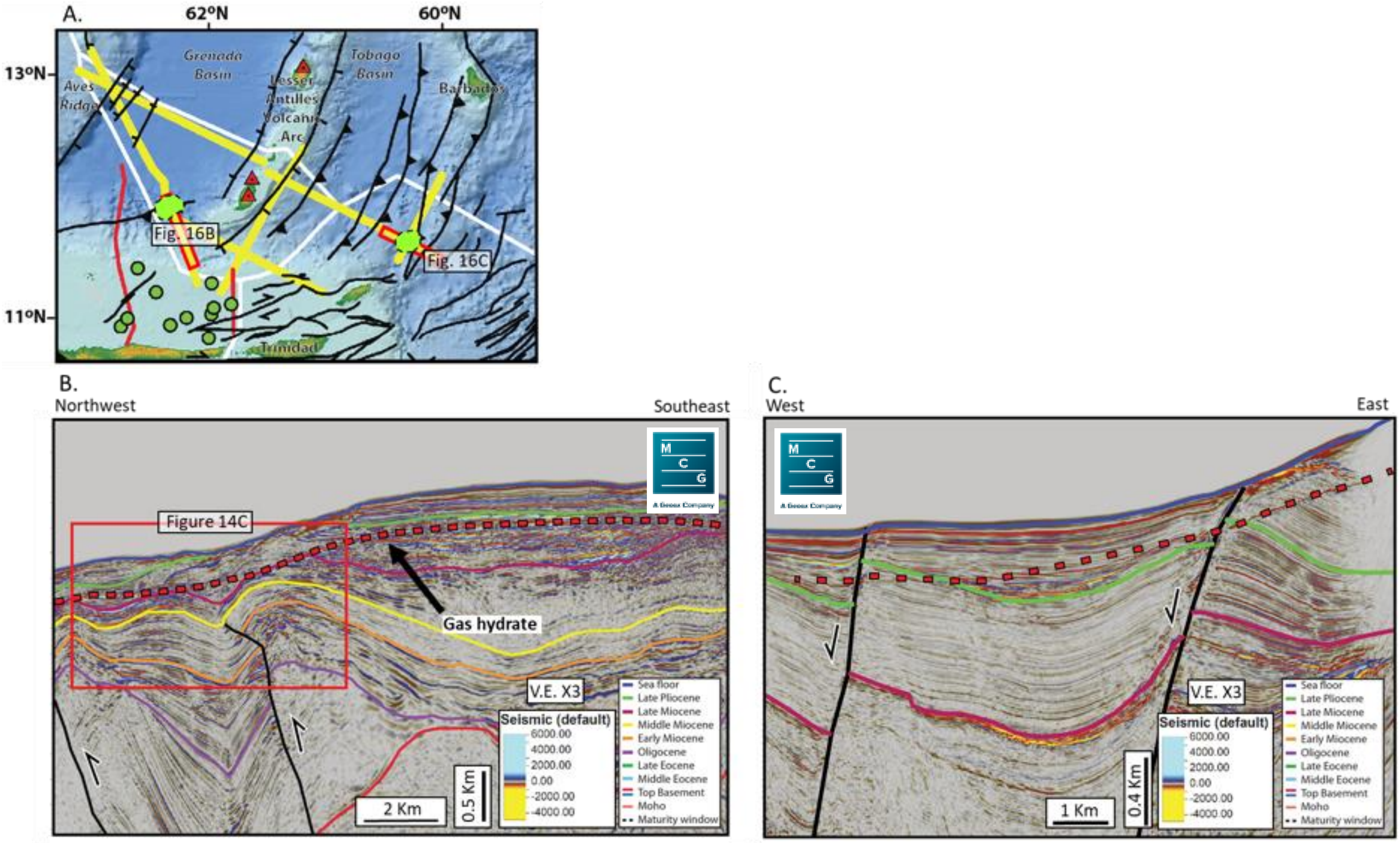
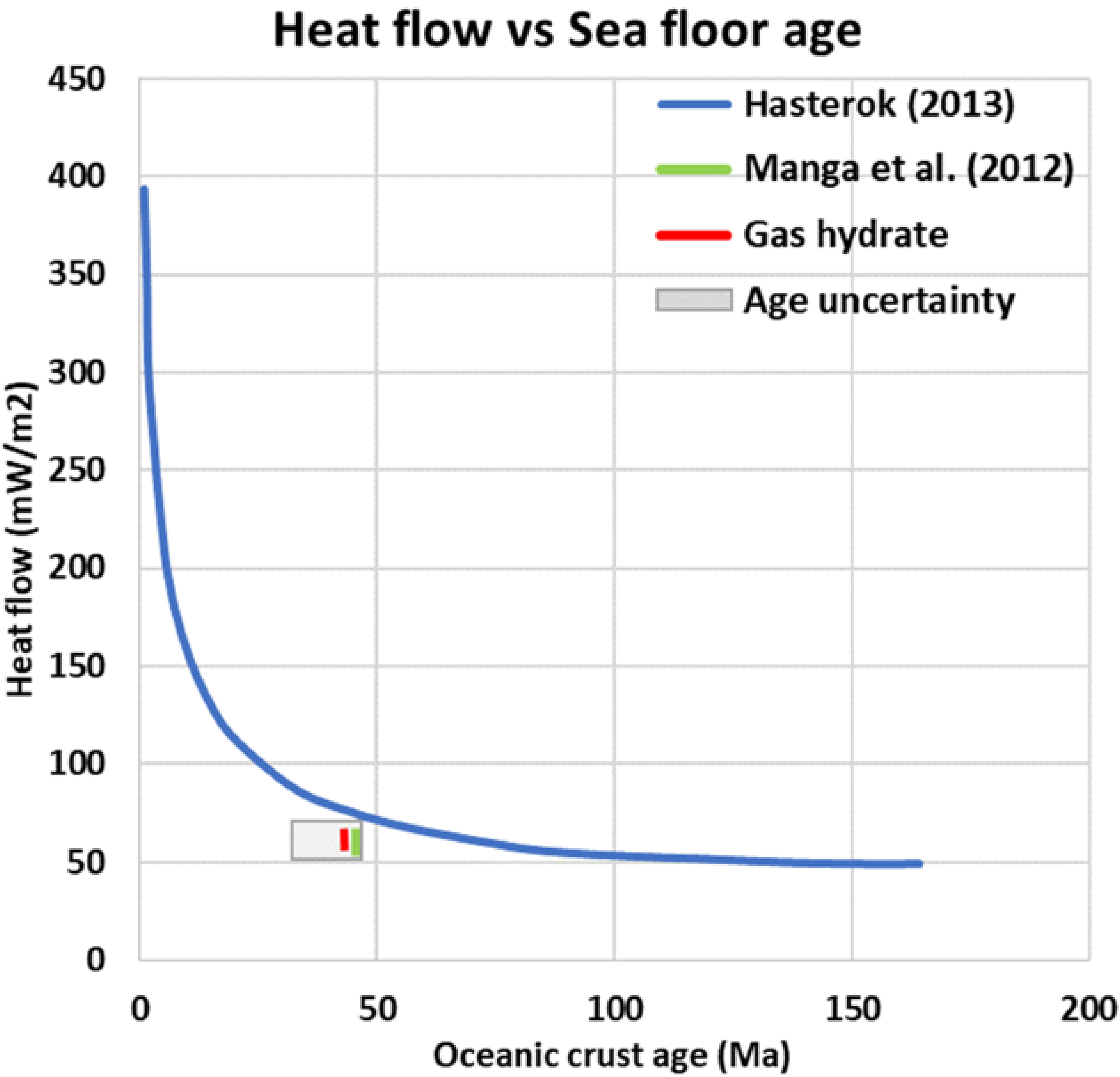

A.
62ºN
60ºN
13ºN
11ºN
Grenada Basin
Tobago Basin
Aves Ridge
Lesser Antilles Volcanic Arc
Barbados
Fig. 16B
Fig. 16C
Trinidad
B.
Northwest
Southeast
Figure 14C
Gas hydrate
V.E. X3
Seismic (default)
6000.00
4000.00
2000.00
0.00
-2000.00
-4000.00
2 Km
0.5 Km
Sea floor
Late Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
Late Eocene
Middle Eocene
Top Basement
Moho
Maturity window
C.
West
East
V.E. X3
Seismic (default)
6000.00
4000.00
2000.00
0.00
-2000.00
-4000.00
1 Km
0.4 Km
Sea floor
Late Pliocene
Late Miocene
Middle Miocene
Early Miocene
Oligocene
Late Eocene
Middle Eocene
Top Basement
Moho
Maturity window

Figure 17. Plot of three heat flow values from the Grenada and Tobago Basins used to infer the age of the underlying oceanic crust in the deepest, central part of both basins. Hasterok et al. (2013) compiled heat flow from areas of oceanic crust to construct a curve relating heat flow and age of oceanic crust. If we assume the age of the oceanic crust in both basins is late Eocene and post-dates the age of the Middle Eocene half-grabens in both basins, present-day heat flow based on the Hasterok et al. (2013) graph would be 70-75 $m/W/m^2$. Manga et al. (2012) used heat flow probe measurements from the central Grenada basin 160-200 km north of the study area (location is shown in Figure 4) to estimate a heat flow range of 55-65$m/W/m^{2,}$ which would predict an oceanic crust age of Eocene (50 Ma) to late Cretaceous (90 Ma). The third method for estimating heat flow measured the depth of the hydrates in both basins and is based on deeper hydrates reflecting lower heat flow and shallower hydrates reflecting higher heat flow (Hodgson et al., 2014, Wang et al., 2017). This method yielded a heat flow of 58-64 $m/W/m^2$ in both basins, which according to the Hasterok et al. (2013) curve, would yield an age for the oceanic crust of Eocene (50 Ma) to late Cretaceous (85 Ma).


Heat flow vs Sea floor age
Hasterok (2013)
Manga et al. (2012)
Gas hydrate
Age uncertainty
Heat flow (mW/m2)
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
Oceanic crust age (Ma)

Estimating paleowater depth. The paleowater depths for the Grenada and Tobago Basins were estimated using paleofauna, paleoflora, and planktic foraminifera from outcrops in Grenada and the Grenadines (Jung, 1971; Speed et al., 1993) and clinoforms observed from offshore seismic data because of the lack of well data available for the deepwater areas of both basins. Because the outcrops on Grenada and the Grenadines were uplifted during the Oligocene, these paleowater depths were only applied to this area of Eocene sedimentary rocks.

Clinoform estimates were made by decompacting clinoforms observed on seismic reflection lines in the Tobago Basin (Punnette et al., 2020). This paleodepth estimate was based on the height of the clinoforms from the topset to the bottomset. The height of the clinoforms was then multiplied by a decompaction factor of 1.4 to account for the sediments' compaction over time, resulting in a paleowater depth of 302 m.

Basin modeling to understand hydrocarbon maturity. Pseudo wells were located in the structurally and bathymetrically deepest areas of southern Grenada and Tobago Basins (Fig. 4) and were used to constrain a 1-D basin model. The geochemical data used for the potential source rocks are from the Dragon field located southeast of the Tobago Basin in the Venezuelan maritime zone (Schneider et al., 2012).

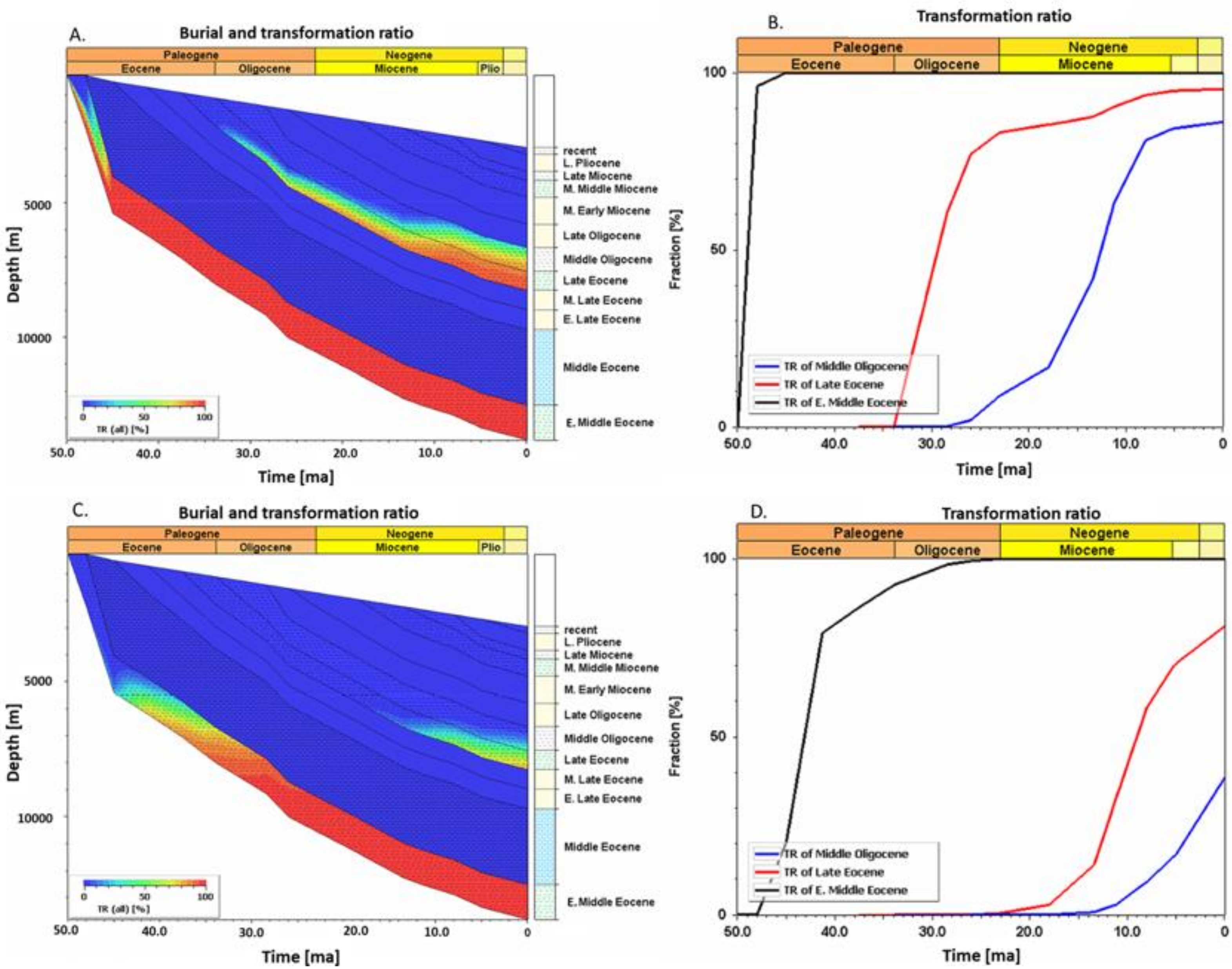
The source rocks within the Grenada Basin and Tobago Basin are inferred by Schneider et al. (2012) to be either type III or type II source rocks. Nearby discoveries in the Trinidad maritime zone to the east have included both thermogenic and biogenic gas discoveries (Alvarez et al., 2020; Punnette et al., 2020). I identified two gas hydrate fields (Fig. 16), a chimney with amplitude anomalies (Fig. 21), and a polarity reversal (Fig. 21) within the Grenada and Tobago

Basins (Fig. 16; Fig. 21). These observations support the presence of mature source rocks within the basins.

The 1-D basin models were constructed using both constant and variable heat flow (Fig. 18; Fig. 19). Constant heat flow models were based on the present-day heat flow estimates from shallow heat probes (Manga et al., 2012) and from the depth of the BSR above the two identified gas hydrate fields (Fig. 16). Variable heat flow models utilized the average heat flow of oceanic crust based on age estimates from Hasterok (2013) (Fig. 16). Comparison of the two different heat flow models provided a sensitivity test for heat flow values used in the basin models (Figs. 18, 19).

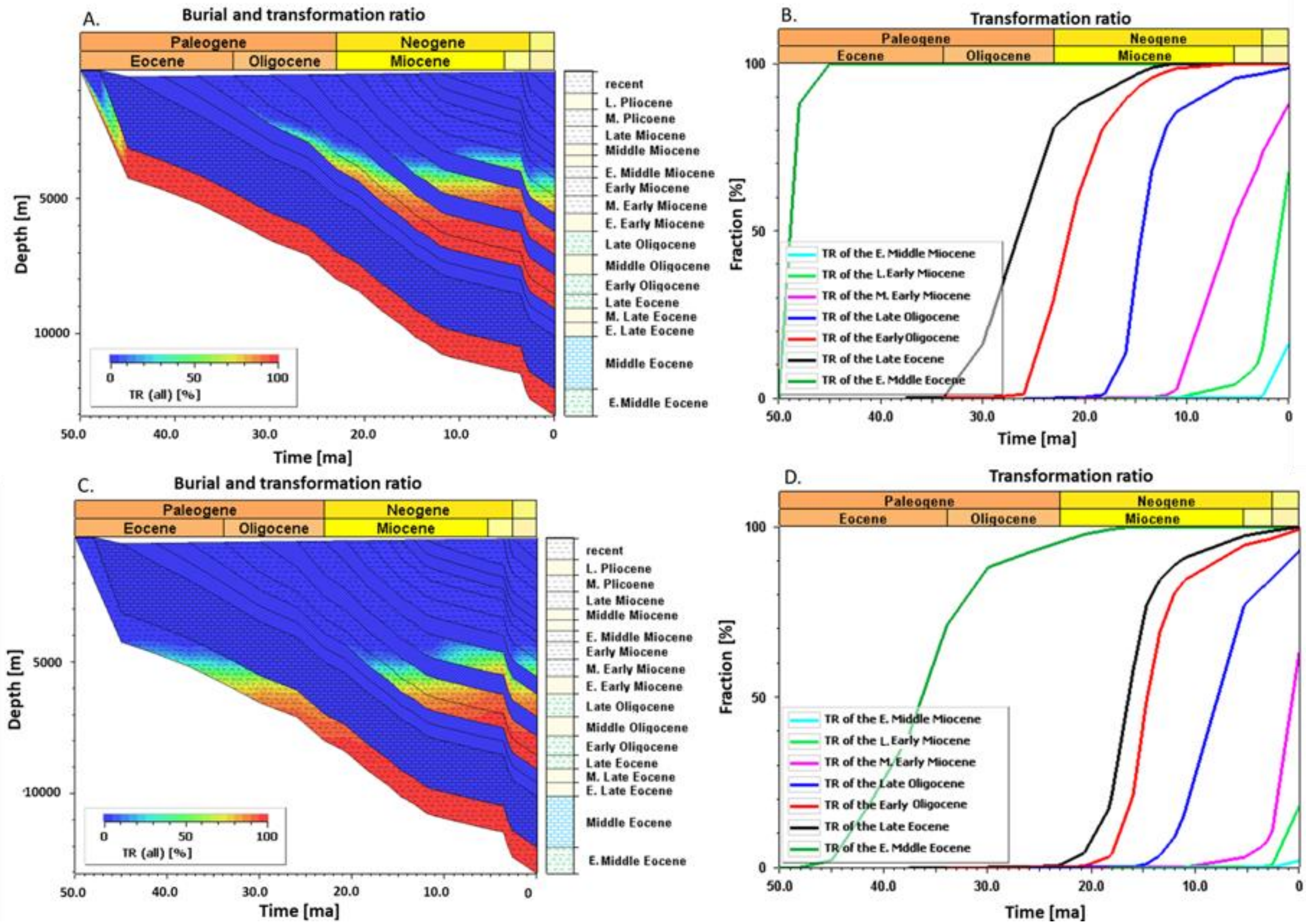
The variable heat flow models result in much earlier maturation of the source rocks when compared to the constant heat flow models (Fig. 18; Fig. 19). Both the constant and variable heat flow models predict that most of the source rocks in the Grenada and Tobago Basins reached maturity by the Miocene (Fig. 18; Fig. 19). Additionally, the burial plots of both basins show that the Grenada Basin is a deeper basin than the Tobago Basin and that the increased sedimentation rate in the Tobago Basin began in the Oligocene (Fig. 18A, C; Fig. 19A, C).

Figure 18. The two 1-D basin models for the Grenada Basin use an estimated heat flow (parts A and B) and a constant heat flow (parts C and D) to examine the impact of heat flow on the basin models. **A)** The burial plot with the transformation ratio shows that the early Middle Eocene matured very rapidly due to the high heat flow associated with oceanic crust formation. The Late Eocene to Middle Oligocene potential source rocks have reached at least 80 percent transformation. **B)** The transformation ratio diagram for the high heat flow model reveals that the Late Eocene source rock began maturation during the emergence of the LAVA, and the Middle Oligocene source rock began maturation during the period of (Early Miocene) transpressional folding and faulting. **C)** The early Middle Eocene and Late Eocene source rocks now mature at a much later time due to the lower constant heat flow. **D)** The lower heat flow also causes the early Middle Eocene and Late Eocene to mature significantly later times during the Middle Eocene and Late Miocene, respectively.



A.
Burial and transformation ratio
Paleogene
Neogene
Eocene
Oligocene
Miocene
Plio
Depth [m]
5000
10000
Time [ma]
50.0
40.0
30.0
20.0
10.0
0
TR (all) [%]
recent
L. Pliocene
Late Miocene
M. Middle Miocene
M. Early Miocene
Late Oligocene
Middle Oligocene
Late Eocene
M. Late Eocene
E. Late Eocene
Middle Eocene
E. Middle Eocene
B.
Transformation ratio
Fraction [%]
100
50
TR of Middle Oligocene
TR of Late Eocene
TR of E. Middle Eocene
C.
Burial and transformation ratio
D.
Transformation ratio

Figure 19. The two sets of 1-D basin models for the Tobago basin use an estimated heat flow (part A and B) and a constant heat flow (part C and D) to examine the impact of heat flow on the basin models. **A)** The burial plot with the transformation ratio shows a lower sedimentation rate during the Eocene than the Grenada Basin and an increased sedimentation rate starting in the Oligocene. **B)** The transformation ratio diagram indicates that the sediments deposited before the middle Early Miocene have become mature. **C)** Using the lower constant heat flow, the source rocks mature at a much later time. **D)** The transformation ratio diagram modeled with the reduced heat flow indicates that the majority of the source rocks are mature during the Miocene.


A.
Burial and transformation ratio
Paleogene
Neogene
Eocene
Oligocene
Miocene
Depth [m]
5000
10000
TR (all) [%]
0
50
100
recent
L. Pliocene
M. Plicoene
Late Miocene
Middle Miocene
E. Middle Miocene
Early Miocene
M. Early Miocene
E. Early Miocene
Late Oligocene
Middle Oligocene
Early Oligocene
Late Eocene
M. Late Eocene
E. Late Eocene
Middle Eocene
E. Middle Eocene
50.0
40.0
30.0
20.0
10.0
0
Time [ma]
B.
Transformation ratio
Fraction [%]
TR of the E. Middle Miocene
TR of the L. Early Miocene
TR of the M. Early Miocene
TR of the Late Oligocene
TR of the Early Oligocene
TR of the Late Eocene
TR of the E. Mddle Eocene
C.
D.

2.4 Discussion

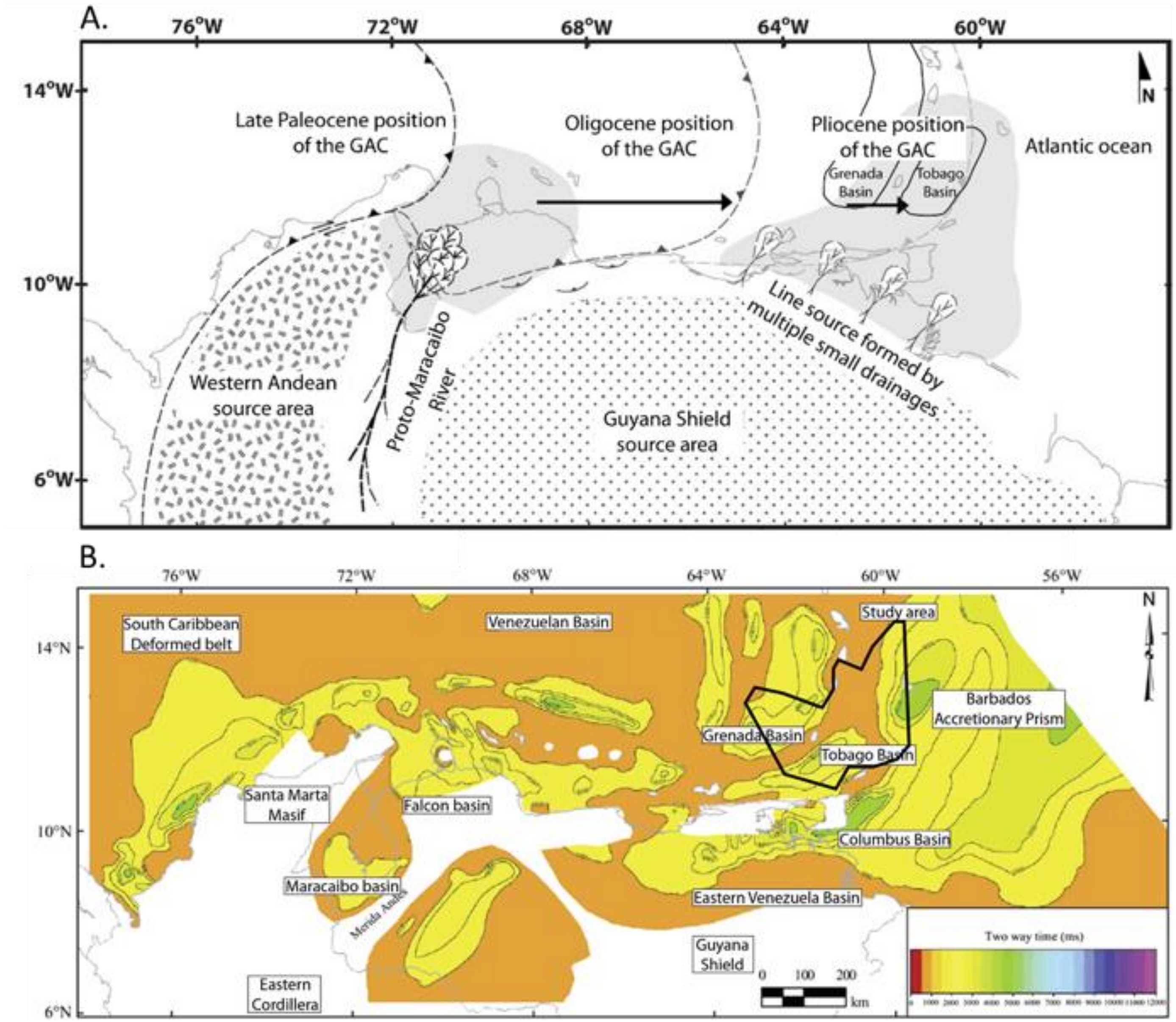
Influence of the Oligocene uplift of the LAVA on the stratigraphy of the Grenada and Tobago Basins. The data presented in this thesis supports the hypothesis of Aitken et al. (2009) that the Grenada and Tobago Basins formed as a single, oceanic-floored forearc basin located trenchward (eastward) of the late Cretaceous-Paleogene volcanic arc of the Aves ridge. During this time, this single, forearc basin received 4-5 km of clastic sedimentary rocks mainly from continental South America via the Proto-Maracaibo deltaic system that flowed southwest-to-northeast during Paleogene times (Aitken et al., 2009; Xie et al., 2010) (Fig. 20).

From observations of the regional Eocene isochore shown in Figure 8, the more westward-located Grenada Basin received a thicker influx of Eocene clastic rocks (4.5-5.5 km) than the Tobago Basin (4-4.5 km) (Fig. 20). By the beginning of the Oligocene, the Proto-Maracaibo delta had been abandoned as the result of the uplift and blockage by the northern Andean Mountains (Escalona and Mann, 2011). As a result, the main fluvial system draining the northern Andes transferred to the Orinoco system that completely bypassed the Caribbean Sea and traveled eastward to Trinidad, where it emptied into the Atlantic Ocean (van Andel, 1967; Diaz de Gamero, 1996; Xie et al., 2010; Osman et al., 2020).

As the LAVA was intruded and emerged as a north-south-trending ridge during the Early Oligocene, this ridge uplifted and upturned the adjacent Eocene sedimentary rocks on both its sides and caused the depocenters of both the Grenada and Tobago Basins to shift away from the elongate ridge of the LAVA. The linear LAVA Ridge then acted as an Oligocene and younger linear, north-south barrier that permanently separated the two flanking basins. With the LAVA in place as a barrier, there was an increase in the thickness of the Oligocene to Late Miocene age units (5-3 km) within the Tobago Basin – as compared to the Oligocene to Late Miocene thickness in the separated and more distal Grenada Basin (2 km) - that likely reflects the influence of the Orinoco delta whose effects appeared in Trinidad during the Miocene (Diaz de Gamero, 1996; Osman et al., 2020; Punnette et al., 2020) (Fig. 15).

When comparing the thickness of the Grenada and Tobago Basins to their adjacent basins within the southern Caribbean, these two basins are relatively thicker than the neighboring basins in the Paleogene, reflecting the likely influence of the Proto-Maracaibo delta. More lasting depocenters during the Neogene reflect the likely increasing influence of the Orinoco delta (Escalona and Mann, 2011) (Fig. 20).

Figure 20. A) Paleogeographic map of northern South America modified from Xie et al. (2010) showing the evolution of the deltaic systems of the Maracaibo and Orinoco Rivers. From the Late Paleocene to the Early to Middle Miocene, the Maracaibo deltaic system contributed clastic sedimentary rocks into southern Caribbean basins until the Maracaibo system became blocked by the uplift of the northern Andes. Once the northern Andes were formed, the Maracaibo system was redirected eastward to contribute to the east-flowing Orinoco system that included four smaller deltaic systems south of the Grenada and Tobago Basins. **B)** Isopach maps are modified from Escalona and Mann (2011) and show that the Grenada Basin and Tobago Basins have similar thicknesses during the Neogene as compared to adjacent basins.


A.
76°W
72°W
68°W
64°W
60°W
14°W
10°W
6°W
N
Late Paleocene position of the GAC
Oligocene position of the GAC
Pliocene position of the GAC
Grenada Basin
Tobago Basin
Atlantic ocean
Line source formed by multiple small drainages
Western Andean source area
Proto-Maracaibo River
Guyana Shield source area
B.
76°W
72°W
68°W
64°W
60°W
56°W
14°N
10°N
6°N
N
South Caribbean Deformed belt
Venezuelan Basin
Study area
Barbados Accretionary Prism
Grenada Basin
Tobago Basin
Santa Marta Masif
Falcon basin
Columbus Basin
Maracaibo basin
Merida Andes
Eastern Venezuela Basin
Guyana Shield
Eastern Cordillera
0 100 200
km
Two way time (ms)

Constraints from 2-D gravity modeling. 2-D gravity modeling shown in Figure 5D extends 1,050 km from the southeastern Caribbean and Aves Ridge to the subducting, oceanic crust of the Atlantic Ocean. The Aves Ridge and LAVA are interpreted as unrifted and full-thickness island arc crust (20-24 km) with the western areas of both basins exhibiting thinned island arc crust (15-17 km) that was extended by half-grabens of Middle Eocene age (Fig. 5).

The gravity model in Figure 5D tested the existence of thinner arc crust beneath the half-grabens and was able to maintain a close match to the observed gravity measurements. The presence of north-south-trending, Middle Eocene half-grabens supports a period of east-west extension as proposed in all three of the tectonic models shown in Figure 3.

The existence of oceanic crust beneath the deeper areas of the Grenada and Tobago Basins indicates that extension of the arc crust gave way to oceanic spreading sometime after the Middle Eocene. The calculated and observed gravity measurements exhibit a small error of 15 mgal that are consistent with the observed Moho reflector observed on the MCG AS seismic reflection lines (Fig. 6B, C; Fig. 11B, C) and that have been observed at comparable depths on seismic refraction lines that includes the inference by Christeson et al. (2008) of oceanic crust beneath both basins with a crustal thickness of 4–10 km.

Evidence for a working petroleum system in the Grenada and Tobago Basins. The Grenada and Tobago Basins remain underexplored, frontier basins with sparse seismic grids and no deepwater wells. In order to assess if there is a working petroleum system within both basins, I compiled direct hydrocarbon indicators (DHIs) from the seismic grid.

These DHIs include: 1) prominent bottom simulating reflectors (BSRs) within two large gas hydrate fields; 2) a gas chimney with amplitude anomalies; and 3) a polarity reversal (Fig. 16; Fig. 21).

The hydrate fields were observed along the western edge of the LAVA and along the western edge of the Tobago-Barbados Ridge (Fig. 16). The gas chimney is emanating from the crest of a large fold along the southern Grenada Basin with amplitude anomalies near the base of the chimney (Fig. 21 B). The polarity reversal is observed within the Tobago Basin and terminates in an updip stratigraphic pinch out (Fig. 21 C, D).

The largest areas with interpreted gas hydrates in the study area occur along the western edge of the LAVA within the Grenada Basin and along the western Tobago-Barbados ridge in the Tobago Basin (Fig. 15). Both gas hydrate areas are located above large, thick-skinned faults that penetrate through the sedimentary column and downward into the underlying crystalline arc basement. These faults appear to act as migration pathways for thermogenic gas that is being generated at deeper depths (5-2 km) within the basin. The basin modeling in Figure 18 and Figure 19 show that if a source rock were deposited before the Early Miocene to Oligocene, this source rock would be mature, depending on the values of heat flow used.

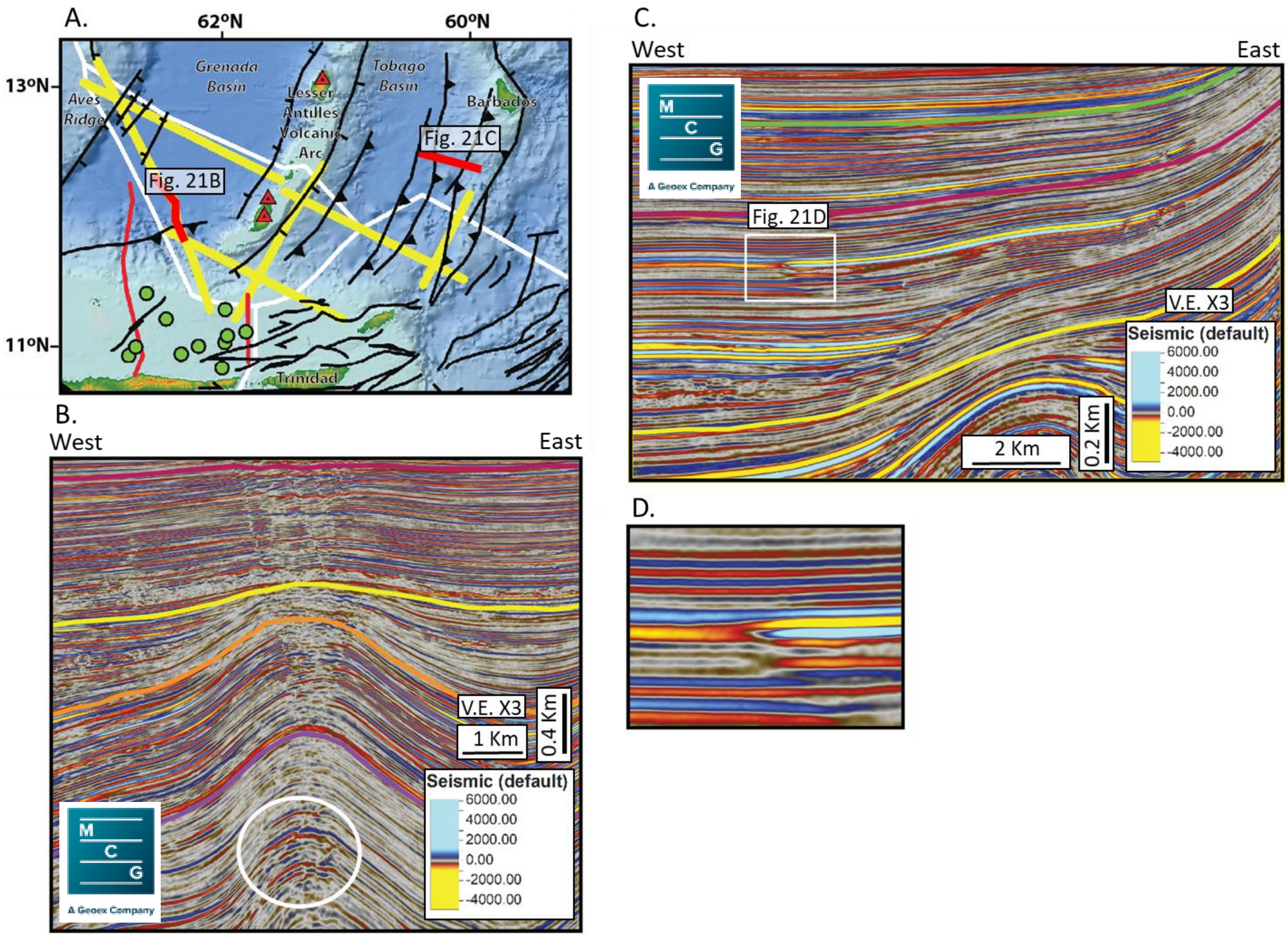
There are three different reservoir and trap types present within the deepwater Grenada and Tobago Basins. The three features include: 1) inverted normal faults along the western margin of the Tobago Basin (Figs. 12, 14); 2) transpressional folding and inverted normal faults along the eastern margin of the Grenada Basin (Fig. 11); and 3) sand-rich, submarine channel systems within the Miocene section of both the Grenada and Tobago Basins (Fig. 9).

The inverted normal faults and large folds along the western edge of the Tobago Basin act as large structural traps for any hydrocarbons produced by deeper Eocene to Oligocene source rocks. Transpressional folding associated with the collision of the Great Arc of the Caribbean with the South American Plate during the Early to Middle Miocene has affected the southern area of the Grenada Basin (Ysaccis, 1997) (Fig. 11).

The submarine channel system within both basins provides stratigraphic traps associated with two major canyon systems. The channel system composed mostly of sandstone would serve as an effective reservoir. The observed channel system is also covered by a primarily transparent unit in the seismic data and is interpreted as shale or siltstone, which could act as a seal (Fig. 9).

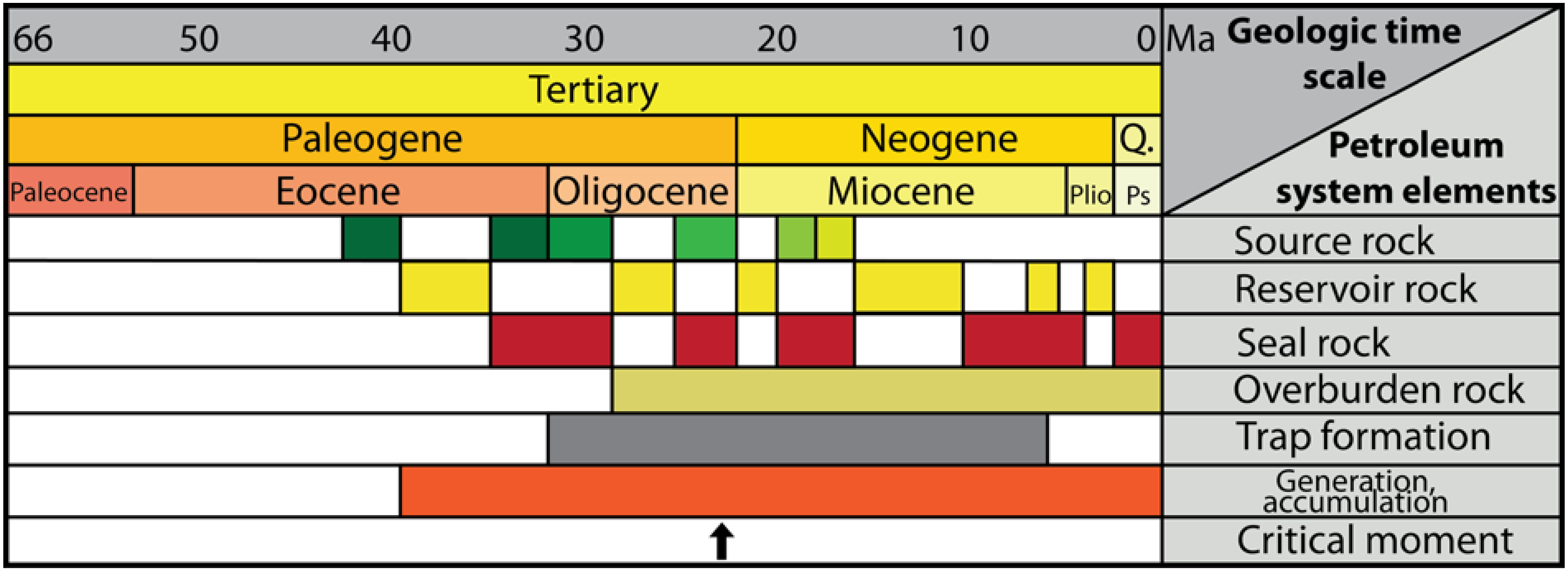
The presence of observed hydrocarbon indicators and potential traps is supported by basin modeling and reinforces the case for a working petroleum system within deepwater Grenada and Tobago Basins. The petroleum system elements and critical moment are summarized for both basins in Figure 22.

Figure 21. A) Location map of two post-stack-depth migrated (PSDM) 2-D MCG AS lines within the Grenada and Tobago Basins shown as red lines. **B)** Proposed gas or oil chimneys emanating from the crest of an Early to Middle Miocene transpressional fold structure located along the eastern edge of the Grenada Basin. The white circle notes the location of stacked amplitude anomalies near the base of the seismic chimney. **C)** The polarity reversal marks the possible location of a hydrocarbon water contact that connects with an updip, stratigraphic pinch out. **D)** Zoom of the polarity reversal observed in C that marks the possible location of a hydrocarbon and water contact point. Source of seismic lines courtesy of MCG AS.



A.
62ºN
60ºN
13ºN
11ºN
Grenada Basin
Tobago Basin
Aves Ridge
Lesser Antilles Volcanic Arc
Barbados
Fig. 21C
Fig. 21B
Trinidad
B.
West
East
V.E. X3
1 Km
0.4 Km
Seismic (default)
6000.00
4000.00
2000.00
0.00
-2000.00
-4000.00
C.
West
East
Fig. 21D
V.E. X3
2 Km
0.2 Km
Seismic (default)
6000.00
4000.00
2000.00
0.00
-2000.00
-4000.00
D.

Figure 22. Critical moment chart summarizing the inferred hydrocarbon system elements of the Grenada and Tobago Basins. The critical moment occurred during the Oligocene when the Middle Eocene source rock became mature and traps associated with the emergence of the LAVA begin to form. The transpressional folding within the Grenada Basin formed large, anticlinal traps during the Middle Miocene. The submarine channel system observed within both basins provides reservoir sand units and provides stratigraphic traps during the Middle to Late Miocene.


66
50
40
30
20
10
0
Ma
Geologic time scale
Petroleum system elements
Tertiary
Paleogene
Neogene
Q.
Paleocene
Eocene
Oligocene
Miocene
Plio
Ps
Source rock
Reservoir rock
Seal rock
Overburden rock
Trap formation
Generation, accumulation
Critical moment

2.5 Conclusions

1) Free-air, satellite gravity maps compiled for this study reveal three main crustal types in the area of the Lesser Antilles volcanic arc (LAVA): 1) the late Cretaceous Caribbean Large Igneous Province (CLIP) and Mesozoic oceanic crust of normal thickness underlying the eastern part of the Venezuelan basin to the west of the Lesser Antilles; 2) Cretaceous to Paleocene island arc crust on the north-south-trending, elongate ridges of the Aves and Tobago-Barbados Ridges; and 3) oceanic crust of Eocene age underlying the deepest areas of the Grenada and Tobago Basins (Fig. 2A).

2) To understand the crustal structure of these crustal types and their boundaries, I constructed a 1,050-km-long, 2-D gravity model that begins on the oceanic crust of the Venezuelan Basin, crosses the Lesser Antilles subduction complex, and extends eastward to the oceanic crust of the Atlantic Ocean. The 2-D gravity model and deeply-penetrating seismic reflection data both confirm that oceanic crust of 4-8 km thickness and inferred Eocene age exists within the deeper areas of the Grenada and Tobago Basins as previously proposed by Bird et al. (1999), Christeson et al. (2007), and Aitken et al. (2009) (Fig. 4B).

3) A 400-km-long regional seismic line shown in Figure 6 revealed the stratigraphic similarities and differences between the Grenada and Tobago Basins. Stratigraphic onlap relations show that both basins were uplifted and inverted during the Early Oligocene (35-23.5 Ma) emergence of the elongate north-south-trending ridge of the nascent LAVA. Depocenters in both basins shifted in a symmetrical manner away from the uplifted, linear ridge of the LAVA (Fig. 13; Fig. 14).

4) Interpretation of seismic reflection lines in both basins reveals the presence of rifted half-grabens in the western portion of both basins, which are filled with Middle to Late Eocene sedimentary rocks (Fig. 11; Fig.12). The half-grabens overlie rifted arc crust of 12-17 km in thickness and trend in a north-south direction. The direction of the opening supports the east-west extension and oceanic spreading as proposed by Bird et al. (1999).

5) Since the Grenada and Tobago Basin are both underexplored and lack well control, the seismic data in the Tobago Basin was directly tied, and the Grenada Basin was indirectly tied to the published seismic lines and wells in the Ysaccis (1997) thesis (Fig. 7). This is the first time that the deeper, Paleogene section of the Tobago Basin has been directly tied to exploration wells in the Venezuelan maritime zone.

6) The regional isochore and surface maps reveal the migration of depocenters from adjacent to the LAVA to their current positions along the northwestern and northeastern edges of the Grenada and Tobago Basins, respectively (Fig. 8). The Eocene depocenters of both basins migrate towards the modern depocenter through the Cenozoic. The Eocene depocenters of the two basins are symmetrical along the southern LAVA for an along-strike distance of 140 km. The Grenada Basin contains 8.5-12 km, and the Tobago Basin has 9-13 km in sediment thickness, with the Grenada Basin having a thicker Eocene section than the Tobago Basin (Fig. 15). The difference in Eocene thickness is attributed to a sediment influx coming from the South American continent to the southwest and the larger accommodation space within the deeper Grenada Basin. The Tobago Basin has thicker Oligocene to Late Miocene units compared to the Grenada Basin, with the thinner units of the Grenada Basin related to the linear ridge of the Oligocene-Recent LAVA that

acted as a barrier for clastic sediments from the Orinoco Delta (Van Andel, 1967; Xie et al., 2010) (Fig. 20).

7) The lithology and facies of both basins are poorly known due to a lack of deep wells. To help provide information on this subject, this study offers a seismic facies classification based on the amplitude, configuration, and continuity within its geologic and stratigraphic framework (Fig. 9). The seismic facies classification includes the identification of mass transport complexes (MTCs) and two major submarine channels.

8) The uplifted oceanic basaltic basement of the Grenada and Tobago Basins in the Grenadines has been radiometrically dated as Eocene (44-34 Ma) basalt originating at an oceanic spreading zone (Fig. 2A, C). This constrains the age of the oceanic crust within the Grenada and Tobago Basin to post-Middle Eocene, but older than Oligocene in age.

9) Radiometric dates have constrained the emergence of the LAVA as Oligocene (34-23.5 Ma) (Fig. 2A, C). This study identifies half-grabens filled by Middle Eocene clastic rocks and has mapped Oligocene sedimentary units onlapping uplifted Eocene sediments adjacent to the uplifted LAVA ridge.

10) The collision of the Caribbean Plate and the South American Plate during the Early to Middle Miocene produced transpressional faults within the Grenada Basin (Fig. 11). These faults provide migration pathways since these faults penetrate the basement and much of the 8.5-12 km thick stratigraphic column in the Grenada Basin. Additionally, the anticlinal folds act as structural traps for the hydrocarbons. The thick-skinned deformation associated with the collision of the two plates is different than the observed deformation in the Tobago Basin. The deformation in the Tobago Basin began during the

Oligocene due to the emergence of the LAVA, and the transpressional deformation in the Grenada Basin began during the Early to Middle Miocene due to the collision of the Caribbean plate with the South American plate.

11) The present-day heat flow gradient of 65 to 60 mW/m^2 was used in the basin model for both the Grenada and Tobago Basins and was based on three different constraints (Fig.17): 1) the stability field of the gas hydrates were used to estimate the local temperature gradient of 58-64 $m/W/m^2$ (Fig. 16); 2) shallow heat flow probe measurements provided the second data point within the Grenada Basin, which provided geothermal gradients of 55-65$m/W/m^2$ (Fig. 4); and 3) a global study on the heat flow of oceanic crust based on age provided a generalized heat flow of 70-75 $m/W/m^2$ (Fig. 17). The cooler temperatures observed by, the shallower borehole and gas hydrate estimates could give a low heat-flow estimate when compared to the heat flow at the crustal level due to the surficial location of the gas hydrates and heat probe measurements.

12) The paleowater depth for both Paleogene sedimentary rocks of the Grenada and Tobago Basins was based on paleofauna, paleoflora, and planktic foraminifera compiled by Speed et al. (1993) and Jung (1971). These samples were collected from outcrops in the Grenadines and were used to help provide data on the tectonic origin of the Grenada and Tobago Basins.

13) Basin modeling compares the effects of a constant heat flow versus a time-varying heat flow (Fig. 18; Fig.19). The basin model with time-variable heat flow matures significantly faster than the constant heat flow. However, both models show that source rocks deposited before the Early Miocene to Oligocene have become mature with the

depth of the gas window at a depth of approximately 3.5 km. The presence of a mature source rock is supported by the presence of two gas hydrate fields, seismic chimneys, and amplitude anomalies that include a polarity reversal (Fig. 21).

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