Deep crustal structure and tectonic origin of the Tobago-Barbados ridge

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Abstract

The north–south-trending Tobago-Barbados ridge (TBR) extends 250 km from its southern end at the island of Tobago to its northern end at the island of Barbados. On Tobago, exposed metasedimentary and metaigneous rocks have been identified as fragments of a Mesozoic primitive island arc, whereas on Barbados, exposed sedimentary rocks record Paleogene development of the Barbados accretionary prism (BAP). We integrate gravity data with seismic refraction data, well constraints, and seismic reflection data to improve our understanding of the TBR's crustal structure, uplift mechanism, along-strike compositional variations in the crust, and tectonic origin. Three 2D gravity models suggest that the TBR is underlain by a "pop-up" crustal block uplifted in the trench between the overriding Caribbean plate and the westwardly subducting South American plate. At approximately 11.75° N, the character of the TBR changes over a distance of 60 km from a symmetrical and more elevated, crystalline, thrust fault-bounded structure to a west-verging thrust belt that is less elevated. The symmetrical pop-up and asymmetrical, west-verging thrust belt accommodate east–west, subduction-related shortening that deforms the westernmost edge of the BAP. We think that the crystalline basement of the southern and central TBR is the buried, northeastern continuation of Mesozoic intraoceanic-arc crust and metamorphic belt of Tobago that accreted along the eastern margin of the Great Arc of the Caribbean during its subduction polarity reversal in the early Cretaceous.

Introduction

Regional tectonic setting of the Tobago-Barbados ridge

The present-day leading eastern edge of the Caribbean plate has experienced a complex tectonic history during its 100 Myr, eastward migration between the North and South American plates (Burke, 1988; Weber et al., 2001b; Escalona and Mann, 2011). The northern and southern boundaries of the Caribbean plate are bounded by complex strike-slip fault zones, including regions of transpressional and transtensional deformation, whereas Jurassic-Cretaceous Atlantic oceanic crust is being subducted on the eastern edge to form the Late Cretaceous to recent, Lesser Antilles volcanic island arc (Wadge and Shepherd, 1984) (Figure 1a and 1b). The Tobago-Barbados ridge (TBR) occupies an outer-arc high position on the leading edge of the Caribbean plate (Figure 1c), and it is actively colliding with and suturing onto northeastern South America at the southern end of the TBR near Tobago (Figure 2e).

The TBR forms a 20–60 km wide, curving, bathymetric ridge (Figures 1a, 1b, and 3a). The ridge is largely cored by crystalline basement, and it is located in the east of the curving and deeply buried subduction trace of the Lesser Antilles arc (Alvarez et al., 2016). The regional free-air satellite gravity map shown in Figure 1b reveals that the TBR is flanked by gravity lows marking the deepest basement and thickest sedimentary fills of the Barbados Basin east of the TBR and the Tobago Basin west of the TBR. South of the Demerara Fracture Zone (DFZ), the TBR is a well-defined, positive, gravity high flanked by these two deep basins. To the north, the TBR widens near Barbados and is no longer flanked by strong gravity lows that characterize the Tobago and Barbados Basins in the south.

Approaching its southern end, the TBR is rotated clockwise from a north–south trend to a more northeast trend as the southernmost TBR approaches right-lateral, strike-slip faults bounding the southern margin of the Caribbean plate (Figure 2e). At its northern end, the TBR terminates along the northwest-trending St. Lucia Ridge by normal faults of the Barbados fault zone related to northwestward migration of the Lesser Antilles forearc sliver (Lopez et al., 2006; Feuillet et al., 2010; Philippon and Corti, 2016). Down-to-the-northeast displacement on normal faults of the Barbados fault zone produces a steep gravity gradient along the St. Lucie Ridge and extending eastward into the Lesser Antilles forearc (Figure 1b).

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Tectonic evolution of the Caribbean plate and Lesser Antilles subduction zone

An eastern Pacific-derived Caribbean plate tectonic model has been tested for decades, and it is now supported by a variety of existing geologic and geophysical data (Pindell and Dewey, 1982; Burke, 1988; Robertson and Burke, 1989; Pindell and Barrett, 1990, Mann, 1999; Escalona and Mann, 2011; Neill et al., 2013). From Tri-

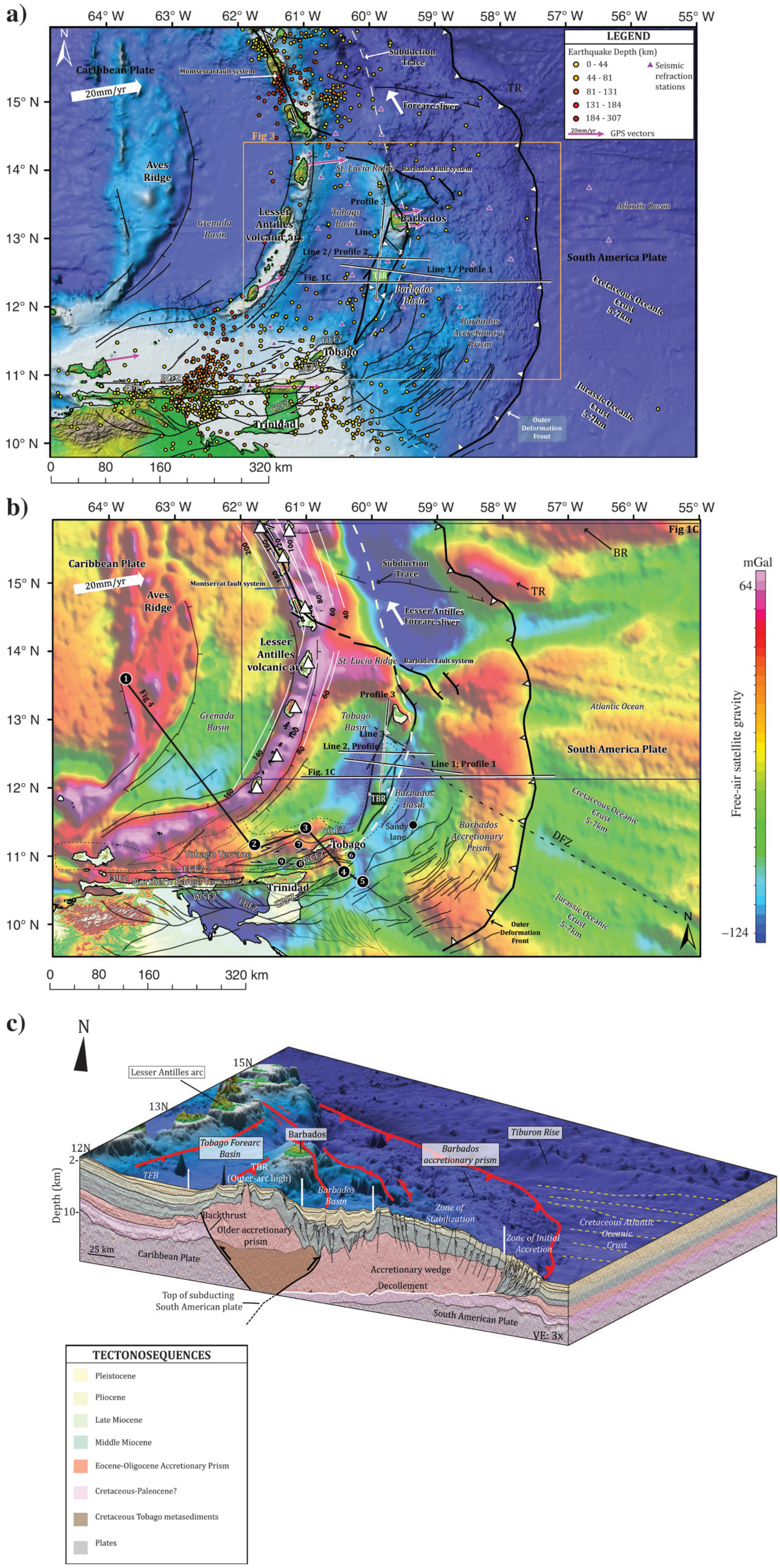

Figure 1. (a) Map of the eastern Caribbean showing the earthquake, structural, and neotectonic setting of the Lesser Antilles subduction zone and the TBR. Earthquake epicenters are from International Seismological Centre (2011). The bold black lines represent plate boundary faults and faults along the TBR. The pink arrows represent GPS vectors relative to a fixed South American plate from Perez et al. (2001) and Weber et al. (2001b). The southern end of the 250 km long, north–south-striking TBR is the island of Tobago, and the northern end is the island of Barbados. Locations of seismic reflection lines (Figure 5a–5f) and gravity models (Figure 6a–6c) are represented by black, gray, and white lines. The publicly available seismic refraction stations used to constrain the gravity models are shown as the purple triangles. Abbreviations: DFZ, Demerara Fracture Zone; HLFZ, Hinge Line Fault Zone; NCFZ, North Coast Fault Zone; ECFZ, El Coche Fault Zone; EPFZ, El Pilar Fault Zone; and TR, Tiburon Rise. (b) Free-air satellite gravity map in km from Sandwell et al. (2014). Depth contours to the subducted South American plate in km are from Wadge and Shepherd (1984). The dashed white south–north line shows the subduction zone trace where South American (Atlantic) oceanic crust subducts westward into the mantle beneath the overriding Caribbean plate. The white triangles are active volcanoes of the Lesser Antilles island arc. Seismic lines crossing the TBR are shown in Figure 5a–5f, and gravity models of the TBR are shown in Figure 6a–6c. Abbreviation: BR, Barracuda Ridge. (c) The 3D block diagram of topographic data (SRTM 30 — Oasis Montaj) generated in Fledermaus showing the TBR as a popup block in a forearc-high position above where the South American plate subducts westward beneath the Caribbean plate. The extent of the 3D block diagram is shown in Figure 1b.

assic through the earliest Cretaceous (210–140 Ma), Pangea rifted apart to create the Central Atlantic Ocean, Gulf of Mexico, and Proto-Caribbean seaway. The Great Arc of the Caribbean (GAC) began forming in the Pacific around Albian times (approximately 140–100 Ma) above a proposed, eastward-dipping subduction zone (Figure 2a). Between 90 and 80 Ma, the Caribbean plate developed in the eastern Pacific as an oceanic plateau (Caribbean Large Igneous Province [CLIP]) on the overriding plate west of the GAC (Burke, 1988) (Figure 2b). Burke (1988) proposes an eastward dipping slab for the early GAC (approximately 140–90 Ma), which dips beneath the Central

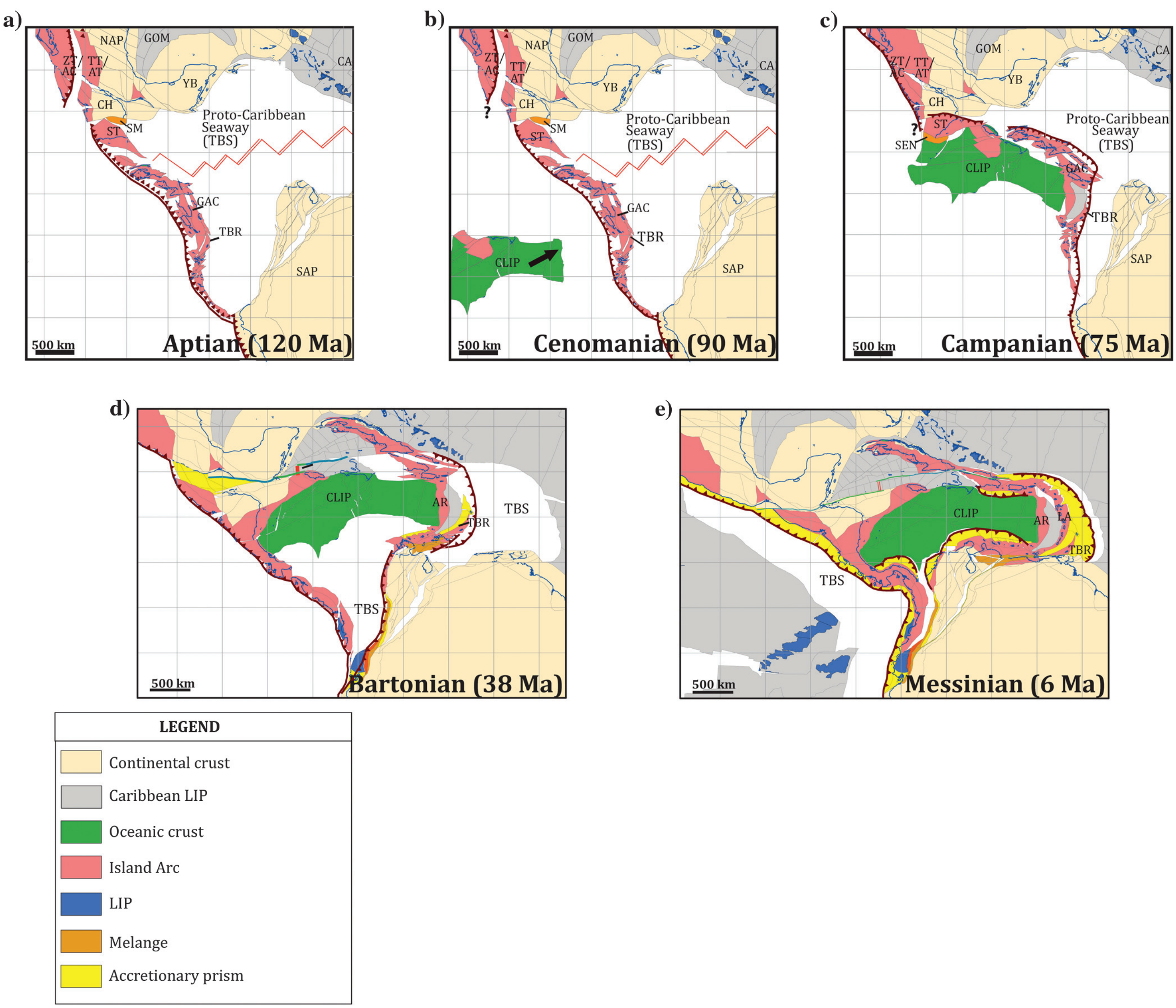

Figure 2. Early Cretaceous-Recent plate reconstructions modified from Sanchez et al. (2016) showing the evolution of the TBR and its relationship to the eastward-facing, GAC. (a) At 120 Ma (Berriasian), the Great Arc is an eastward-facing arc system located in the present-day area of the eastern Pacific. (b) At 90 Ma (Turonian), the Great Arc is consuming the oceanic crust of presumed late Jurassic age in the Proto-Caribbean seaway between North and South America; during this period, another Early-Late Cretaceous arc system was subducted beneath the Great Arc to form an unsubducted wedge that became lodged along the trace of the subducting Caribbean plate. (c) At 75 Ma (Maestrichtian), the east-facing GAC migrates eastward and becomes more arcuate in the map view. (d) At 38 Ma (latest Eocene), the southern part of the eastward-facing arc system collides with the northern coast of South America and rotates into parallelism with the east–west-trending, transpressional margin; the BAP expands during this period with increased clastic sediment supply from South America as shown by the deformed and terrigenous, deep-marine rocks exposed on the island of Barbados. (e) At 6 Ma (latest Miocene), two ages of Atlantic oceanic crust separated by the DFZ are subducting along the Lesser Antilles arc: the less buoyant Jurassic oceanic crust to the southwest and the more buoyant Cretaceous oceanic crust to the northeast. Abbreviations: NAP, North American Plate; CA, Central Atlantic; GAC, Great Arc of the Caribbean; CLIP, Caribbean Large Igneous Province; SAP, South American Plats; TBS, Areas to be subducted; YB, Yucatan block; CH, Chortis block; GOM, Gulf of Mexico; ST, Siuna terrane; SM, Siuna melange; ZT, Zihuatanejo terrane; TT, Teloloapan terrane; AR, Aves Ridge; LA, Lesser Antilles island arc.

Atlantic and consumes the Caribbean ocean floor (Figure 2b). Fragments of oceanic crust and ultramafic rocks found in southwesternmost Puerto Rico and accretionary prisms of Greater Antilles, Jamaica, Cuba, and Hispanola are used by Burke (1988) to support this eastward-dipping subduction zone. During the Late Cretaceous (approximately 80–75 Ma), the buoyant CLIP failed to subduct beneath this eastward-dipping GAC and this collision led to a subduction polarity reversal as the GAC began to enter the Caribbean region. Figure 2c shows the change to a southwestward subduction direction, which led to the subduction of a vast tract of oceanic crust of the Proto-Caribbean seaway and Atlantic Ocean floor beneath the Caribbean plate (Rowe and Snoke, 1986; Burke, 1988).

Key tectonic phases in the Caribbean plate and GAC evolution that followed the early Cretaceous arc polarity reversal event include: (1) the oblique collision of the Caribbean plate and GAC colliding with northwestern South America by approximately 75 Ma (Figure 2c), (2) the opening of the Grenada and Yucatan back-arc basins that separated the extinct Aves Ridge segment of the GAC from the active Lesser Antilles arc during the Paleocene (Hall and Yeung, 1980; Bird et al., 1993) (Figure 2d), (3) the Paleogene growth and widening of the Barbados accretionary prism (BAP) (Speed and Westbrook, 1984) (Figure 2d), (4) the Miocene bifurcation of the northern segment of the Lesser Antilles island arc along the Kallinago, intra-arc rift basin (McCann and Sykes, 1984), (5) the progressive, west-to-east, emplacement of allochthonous GAC fragments by transpressional faulting along the coast of northern South America (Burke, 1988; Snoke et al., 2001) (Figure 2d and 2e), and (6) the Middle Miocene collision of the Caribbean plate with northeastern South America in the vicinity of Trinidad (Figure 2e), which produced a period of major uplift and erosion (Escalona and Mann, 2011).

Limitations of previous TBR crustal studies

The TBR has been previously interpreted as an accretionary wedge that was backthrust to the west over the Tobago Forearc Basin (Westbrook, 1975; Torrini and Speed, 1989; Unruh et al., 1991) (Figure 1a). Using seismic refraction and reflection data, previous authors proposed that the TBR is composed of stratified Barbados sedimentary rocks of varying thickness and overlying a high-velocity (4–5 km/s) crustal layer that lacks coherent reflectors (Ewing et al., 1957; Officer et al., 1957; Kearey et al., 1975; Westbrook, 1975). Ewing et al. (1957) note that most of the seismic refraction structural profiles constructed through the ridge were not able to image the intensive, folding, and thrust faulting that affected the BAP.

Previous geophysical surveys (Ewing et al., 1957; Officer et al., 1957; Kearey et al., 1975; Westbrook, 1975) lacked the depth of penetration to precisely image the structure and composition of the basement beneath the TBR. Alvarez (2014) used 2D seismic reflection profiles and a previous version of free-air, satellite gravity data (Sandwell and Smith, 2009) to interpret the lithology and deeper structure of the TBR. Even the deeply penetrating, seismic reflection lines used by Alvarez (2014) were unable to distinguish the sedimentary versus crystalline parts of the TBR.

The northern and southern ends of the TBR are exposed as extensive, onland outcrops, and they are better studied by previous workers than the deeply submerged and buried, central part of the TBR (Figure 3a–3d). At the northern end of the TBR, the island of Barbados exposes four geologic formations: (1) the Eocene-Oligocene Scotland Formation that consists of sand, clay, and coarse conglomeratic sand (Torrini et al., 1985; Speed, 1994; Chaderton, 2009); (2) the middle Miocene Oceanic Formation that contains deep marine pelagic clay, marl, interbedded volcanic ash beds (Barker and Poole, 1980; Speed et al., 1989; Speed, 1994), and thin turbidites (Speed and Larue, 1982; Torrini et al., 1985; Torrini and Speed, 1989); (3) the middle Miocene Joe's River Formation of clay, sand, and limestone intruded as diapirs (Barker and Poole, 1980; Speed et al., 1991); and (4) a Quaternary, reefal limestone unit that locally caps the island.

Tobago is a steep-sided, fault-bounded, and elongate island that marks the subaerially exposed, southern part of the TBR (Figure 3a). Mesozoic oceanic-arc crust is exposed on Tobago and can be subdivided into three, east—west-trending lithologic belts: (1) the North Coast Schist that consists of low-grade metamorphosed and volcanogenic rock, (2) the ultramafic-tonalitic Tobago Plutonic Suite, and (3) the Tobago Volcanic Group (Snoke et al., 2001) (Figure 3d). An explanation of the contrasting geology between these two subaerial endpoints of the TBR (Tobago and Barbados) has not been attempted by previous workers.

Snoke et al. (2001) note that rock assemblages cropping out on Tobago resembled those of the larger Tobago Terrane that was previously defined as a fault-bounded, allochthonous crustal block that forms a forearc-high at the eastern, leading edge of the Caribbean plate and is separated from the Northern Range of Trinidad by the right-lateral El Coche Fault Zone (Speed and Westbrook, 1984; Speed and Larue, 1985; Speed and Smith-Horowitz, 1998) (Figure 1b). Wells such as HH6-1, KK6-1, LL9-1, North Basin-1, and Alice 1 that penetrated its basement (locations shown in Figure 1b) confirm the existence of Jurassic and Cretaceous, relatively high velocity (3000–3500 m/s), igneous and layered metasedimentary rocks (Ewing et al., 1957; Burke, 1988; Holcombe et al., 1990, Jiang et al., 2008; Punnette, 2010; Alvarez et al., 2016) (Figure 4).

The geologic history of the Tobago Terrane and Tobago suggests that the South American-Caribbean plate boundary zone has experienced the tectonic accretion of several Mesozoic allochthonous terranes (Cerveny and Snoke, 1993; Snoke et al., 2001; Neill et al., 2012, 2013). Tectonic models of the Caribbean plate indicate that the Tobago terrane has translated approximately 1100 km eastward relative to South America and the Caribbean plates since the Early Cretaceous (Burke, 1988;

Robertson and Burke, 1989). Although the southern end of the Tobago terrane near the island of Tobago has been described in the literature, the submerged, central, and northern parts of the TBR have not. Robertson and Burke (1989) speculate that the presumed Cretaceous accretionary and arc terrane outcropping on Tobago continued for at least 100 km to the northeast of this island but the northern extension of Tobago (TBR) remains understudied in the region.

Objectives and significance

In this paper, we use a multidisciplinary approach to generate an integrated model of the TBR that describes the variation in its structure and composition and explores the origin of the TBR within the context of Caribbean regional tectonics. We use the most recent version of satellite gravity data (Sandwell et al., 2014) that more accurately capture the details of the crustal structure of the TBR (Figure 1b). We then integrate this satellite gravity data with (1) ship-based, high-resolution 2D seismic reflection and gravity data provided by Spectrum, (2) publicly available seismic refraction stations (Ewing et al., 1957; Edgar et al., 1971), and (3) well data compiled by Jiang et al. (2008) (Figure 4).

The main objectives of this study are to (1) test our hypothesis that the Cretaceous, arc-type basement rocks outcropping on Tobago provide a window into the age, composition, and evolution of higher density basement rocks underlying the submerged, central part of the TBR; (2) evaluate the northward extent of the Mesozoic intraoceanic crust and metamorphic rocks of Tobago along the TBR (Robertson and Burke, 1989);

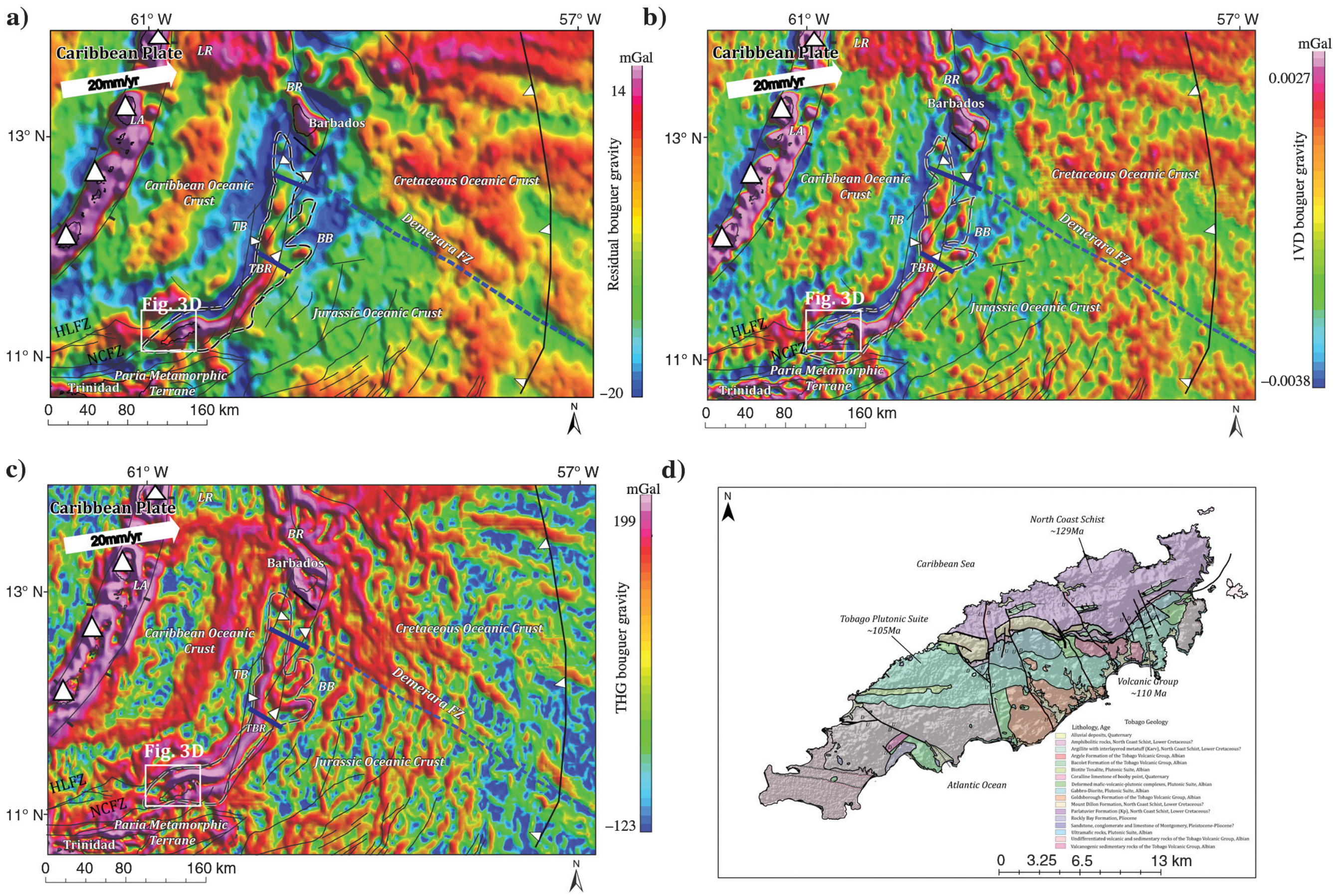

Figure 3. (a) Residual gravity anomaly map produced by upward continuation (10 km) after Bouguer corrections for on- and offshore data in the area of the TBR. (b) First-vertical-derivative Bouguer anomaly map showing the DFZ separating subducting oceanic crust of two ages; projection of this subducted fracture zone to depth coincides with a boundary between the more elevated, southern TBR with a higher gravity anomaly and the lower, multibranched northern TBR with a lower gravity anomaly. (c) Total horizontal gradient Bouguer anomaly map showing the gravity response of the TBR. (d) Geologic map of Tobago modified from Snoke et al. (2001); the location of the Tobago map area is represented by the white box in Figure 3a. The two main geology components of Tobago's basement include (1) the primitive island arc of Jurassic-early Cretaceous age to northwest now metamorphosed to greenschist facies and (2) the younger island arc of late Cretaceous age intruded and erupted on top of the older arc basement on the southeastern end of the island. Abbreviations: LR, St. Lucia Ridge; BR, Barbados; TB, Tobago Basin; BB, Barbados Basin; LA, Lesser Antilles Island arc; HLFZ, Hinge Line Fault Zone; NCFZ, North Coast Fault Zone. The boundaries of the southern, central, and northern segments of the TBR are shown as the bold purple lines, and the bounding edges of the TBR are shown as a dashed black/white outline (Figure 3a–3c).

(3) explore the fundamental differences between the geology of the Tobago and Barbados islands at the endpoints of the TBR; and (4) establish the tectonic origin of the TBR based on our models.

Methods

Although refraction data have remained a powerful tool in crustal-scale potential fields studies (Ewing et al., 1957; Edgar et al., 1971; Kearey et al., 1975; Ludwig et al., 1975; Westbrook, 1975; Boynton et al., 1979; Speed and Westbrook, 1984; Christeson et al., 2008; Alvarez et al., 2016) (Figure 1a), the refraction method lacks the spatial coverage necessary for detailed analyses of Jurassic-Cretaceous crustal elements of the TBR. A modern, high-resolution, 2D seismic reflection data set acquired in 2007 by Spectrum Geo provides much improved, spatial coverage (approximately 10,000 line km of 9–17 s records). However, reflection imaging is handicapped in the Lesser Antilles subduction margin by approximately 12–18 km thick, clastic accretionary wedge (BAP) that includes extensive remobilized and diapiric shale.

To conduct a regional study of lithospheric provinces and basement geometry, we integrate satellite-derived gravity data (Sandwell et al., 2014), with the Spectrum Barbados Long Offset 2007 geophysical survey that includes (1) 2D seismic reflection, bathymetry, navigation, and 2D shipborne gravity data; published seismic refraction data (Ewing et al., 1957; Edgar et al., 1971; Christeson et al., 2008); (2) available well data including the Sandy Lane exploration well; and (3) published thermochronological data from arc basement outcrops on Tobago (Neill et al., 2013) (Figures 1b and 4).

Satellite gravity data

We used gravity data to create regional maps for structural mapping and 2D modeling. The density contrast at the seafloor dominates free-air gravity data.

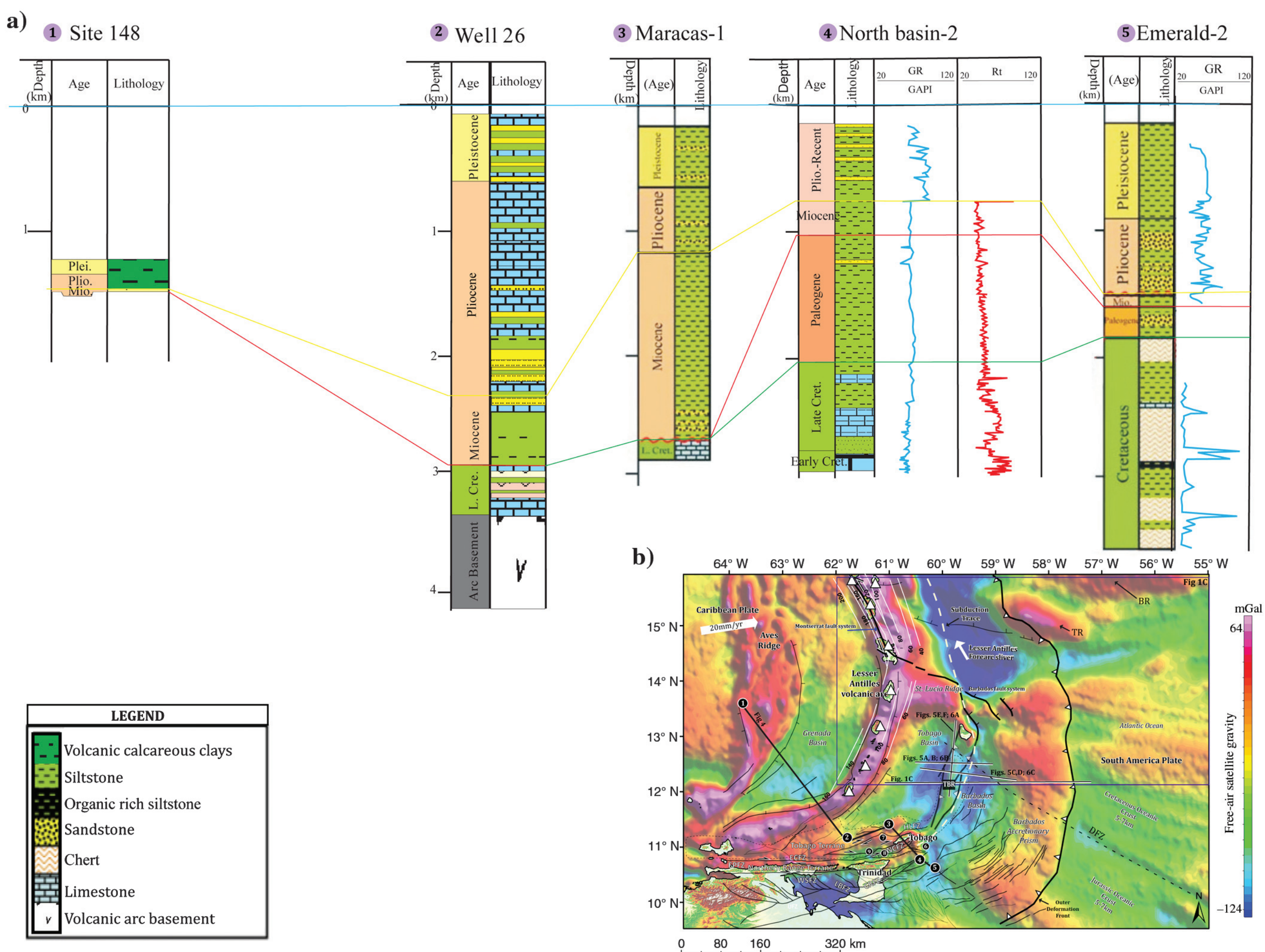

Figure 4. (a) Free-air gravity base map from Sandwell et al. (2014) showing the location of a northwest-to-southeast well log cross section extending from the Aves Ridge, through the Grenada Basin and Lesser Antilles arc, to TBR on Tobago. (b) Well log cross sections profile modified from Jiang et al. (2008) showing the correlation from the Aves ridge through the Tobago Basin and TBR to the eastern offshore area of Trinidad. Well 26 penetrated Cretaceous arc basement of the TBR similar to the outcrops of Tobago; other wells show that the TR although others show the TBR was elevated and the site of limestone deposition by the late Cretaceous. Large unconformities in most of these wells support a strong Miocene and younger uplift event along the TBR.

For the qualitative 2D interpretation, we calculated Bouguer gravity anomalies to minimize this effect by assigning 2.0 g/cm^3 to the water layer. Bouguer gravity data are dominated by the density contrast between the crust and upper mantle. We then applied anomaly enhancement techniques to minimize this long-wavelength effect. Enhancement techniques used in this study include regional-residual separation, filters, and derivatives.

We calculated residual Bouguer anomalies to enhance the anomalies produced by basement deformation of the TBR, expressed as positive-amplitude anomalies (hot colors). To accomplish this, we generated 10 km upward-continuation, regional anomalies and then subtracted those from the original data to generate residual Bouguer anomalies (Figure 3a). Filtered Bouguer anomaly maps created include (1) the first vertical derivative anomaly map that accentuates local anomalies by isolating them from the regional background field (Figure 3b) and (2) a total horizontal gradient map (Figure 3c), which is effective for detecting edges such as faults or terrane boundaries (Blakely and Simpson, 1986; Ferreira et al., 2013).

Seismic interpretation and gravity modeling of the TBR

Following concepts proposed by Mitchum et al. (1977), basement through seafloor horizons were identified in the 2D seismic data as laterally extensive, continuous, and coherent reflectors that represent chronostratigraphic surfaces bounding tectonostratigraphic, depositional units. The seismic horizons and the tectonostratigraphic sequences were characterized using seismic facies analysis including observations of seismic reflection parameters that include amplitude, frequency, geometry, continuity, and onlap relationships. The ages of these tectonostratigraphic packages were extrapolated and inferred from previous seismic interpretation studies, which were tied to more than 30 industry wells from eastern Trinidad and the northeastern South America margin (Jiang et al., 2008; Punnette, 2010; Aitken et al., 2011; Alvarez et al., 2016). Picks of Early Pliocene to Late Miocene horizons were age dated from a biostratigraphic from the Sandy Lane well that was drilled in the southern Barbados Basin, located in Figure 1a (Dolan et al., 2004).

We then converted three seismic profiles that traversed the TB, TBR, and Barbados Basin to depth by using a 2D layer-cake velocity model generated from Midland Valley software. Velocity parameters were based on seismic Vrms data cross-referenced with seismic refraction data to ensure consistency between the velocity inputs. Refraction stations (Ewing et al., 1957) provided deep oceanic crustal velocities that could not be identified in the Vrms data. Layer densities were approximated from their velocities using the velocity-density Nafe-Drake relationship (Ludwig et al., 1970; Brocher, 2005) and the density-depth relationship proposed by Cordell (1973). The five sedimentary tectonostratigraphic sequences were assigned densities ranging from 2.0 to 2.55 g/cm^3; metamorphic rocks were assigned a density of 2.6 g/cm^3; upper crust and lower crust were assigned densities of 2.85 and 2.95 g/cm^3, respectively; and the mantle was assigned a density of 3.3 g/cm^3. Our regional depth-density function is consistent with sparse and relatively shallow log densities from well penetrations.

Three 2D gravity models were constructed along the interpreted, 2D seismic reflection profiles. Gravity modeling was done using the Spectrum Barbados Long Offset 2007 geophysical survey that includes 2D shipborne gravity, bathymetry, and navigation data acquired simultaneously with seismic reflection data by Fugro Robertson.

Crustal provinces from gravity

Variations in residual Bouguer anomalies suggest that the TBR can be subdivided into distinctive southern, central, and northern segments (Figure 3a). The southern TBR is expressed as a continuous linear, positive-amplitude anomaly (hot colors) that extends from the island of Tobago to approximately 11.75 N and separates the deepest parts of the Barbados and Tobago Basins. North of approximately 11.75° N, residual anomalies suggest that the TBR bifurcates into a smaller ridge continuing its northward trend and two individual segments with similar amplitudes splaying off the main trend to the northeast. North of this bifurcation, there is a resumption of a broad positive residual anomaly reminiscent of the southern and central TBR that is flanked by a residual negative moat over Barbados (Figure 3a).

To the east of the TBR, we subdivide the oceanic crust of the Central Atlantic into two provinces to the north and south of the DFZ (Figures 1b and 3a). The Cretaceous crust north of the DFZ is characterized by a regular pattern of northwest-trending, broad linear free-air and residual Bouguer gravity anomalies (Figures 1b and 3a) that parallel oceanic fracture zones that extend to the Mid-Atlantic spreading ridge (Mueller et al., 1997; Alvarez et al., 2016). This pre-Aptian oceanic crust is the remnant western flank of the equatorial Atlantic Ocean that formed as the North American, South American, and African plates separated in the Mesozoic (Speed et al., 1989; Pindell and Kennan, 2007). South of the DFZ, an older Jurassic oceanic crust has been interpreted based on geodynamic and kinematic studies (Mueller et al., 1997; Alvarez, 2014, Reuber et al., 2016) and the identification of Jurassic marine sediments dredged on the northern flank of the Demerara Rise (Hayes et al., 1972).

To the west of the TBR, the Tobago forearc basin (TB) is floored by Caribbean oceanic crust that is characterized in the residual Bouguer, first vertical derivative, and total horizontal gradient maps as a curved section of moderate-amplitude gravity anomalies oriented subparallel to the trend of the Lesser Antilles volcanic island arc (Figure 3a–3c). These observed anomalies represent the easternmost edge of the overriding, Caribbean plate that has also been mapped from seismic refraction and reflection data (Christeson et al., 2008).

Interpretation of 2D regional gravity transects across the TBR

Gravity profile 1, central TBR

Profile 1 (Figure 6a) crosses the central segment of the TBR (location shown in Figure 1a and 1b) at approximately 11.75° N where the TBR bifurcates northward into two subparallel ridges. Based on refraction velocity control and observed gravity anomalies, the TB contains 10 km of sedimentary rocks and is floored by a two-layer, 10–15 km thick Caribbean oceanic crust. These observations are consistent with regional seismic refraction profile studies previously conducted throughout the region

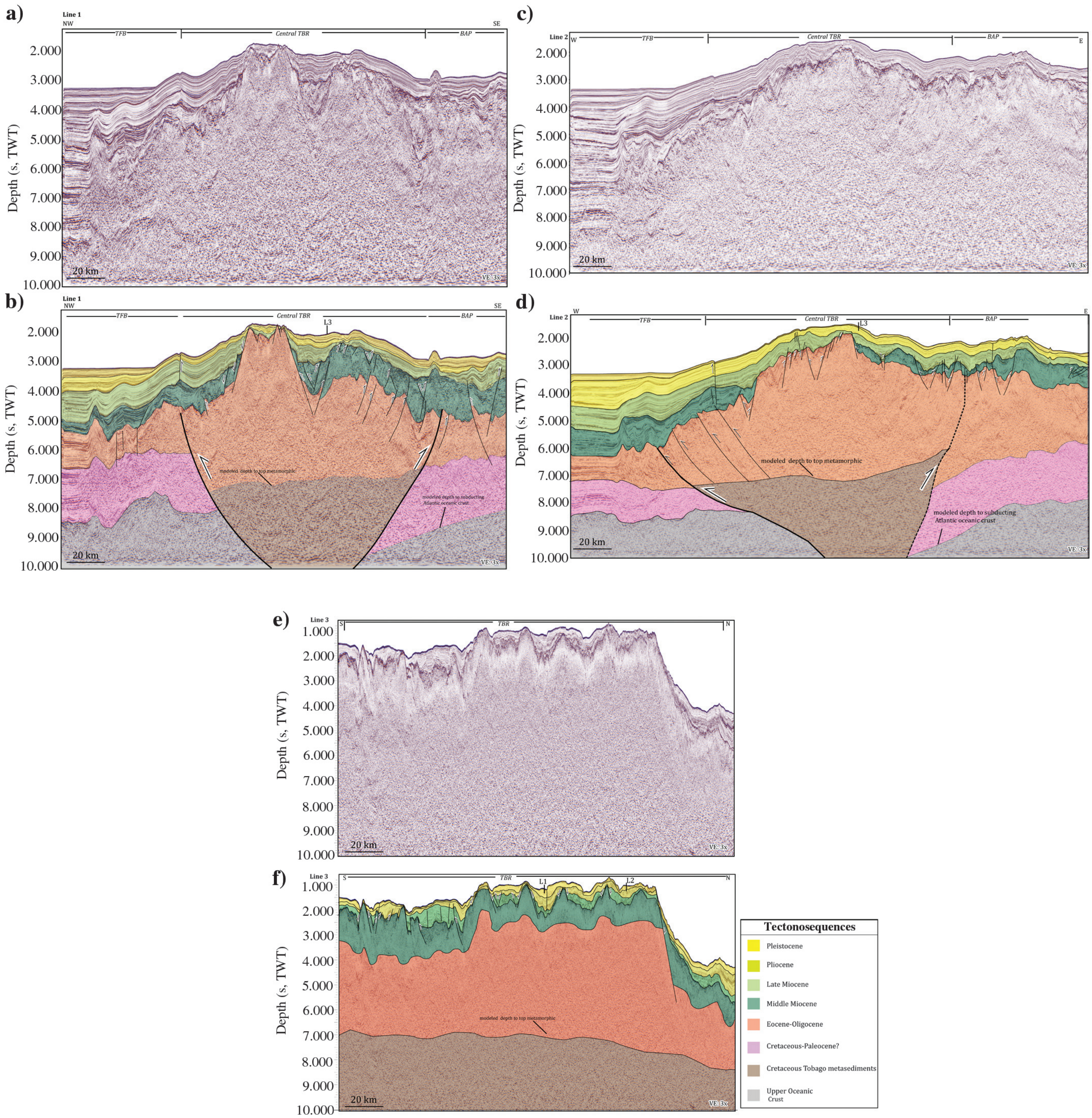

Figure 5. (a) East–west, uninterpreted, seismic dip line across the southernmost, central segment of the TBR (line location is shown in Figure 1a and 1b). (b) Interpreted seismic line from A used to constrain the shallower depths of the gravity model in Figure 6a. (c) East–west, uninterpreted, seismic dip line across the northernmost, central segment of the TBR (line location is shown in Figure 1a and 1b). (d) Interpreted seismic line from C. These interpretations were used to constrain the geometry of the TBR in the gravity model shown in Figure 6b. (e) North–south, uninterpreted, seismic strike line along the TBR (line location is shown in Figure 1a as a gray line with white outline). (f) Interpreted seismic line from E showing the geometry used to constrain the southern part of the gravity model shown in Figure 6c.

(Ewing et al., 1957; Edgar et al., 1971; Ludwig et al., 1975; Case et al., 1990). Seismic reflection interpretations indicate that this segment of the TB experienced Paleocene-Late Miocene, east–west shortening related to westward backthrusting of the TBR over the TB (Figures 5d and 6c).

To the east of the TBR, seismic reflection and refraction data cannot image the top of the eastward-subducting Jurassic oceanic crust beneath the Lesser Antilles arc (Figure 5d). However, gravity modeling of long-wavelength anomalies allows us to interpret top of subducting, oceanic crust at a depth of approximately 15–20 km, and depth to Moho at 26–29 km, suggesting a crustal thickness of approximately 6–10 km. The geometry of the TBR in this model is interpreted as a pop-up structure bounded by thrust-related folding on its western and eastern edges as constrained by seismic reflection data (Figure 5d).

We test our hypothesis that the southern TBR represents the northeastern extension of the Mesozoic oceanic arc crust that underlies Tobago, and ultimately the Tobago Terrane, by modeling a 23 km thick ridge that consists of five layers: (1) 10–12 km-thick Paleogene, accretionary prism sediments (density, 2.45 g/cm^3), (2) metasedimentary rocks of the Tobago terrane (assumed a thickness of 5 km and density of 2.6 g/cm^3), (3) 3 km thick upper crust (density, 2.85 g/cm^3), and (4) 7 km thick lower crust (density, 2.95 g/cm^3) equivalent to the Cretaceous island arc type rocks and metamorphic basement of Tobago (Figure 6a) and also constrained by the wells that penetrate the basement in the region (Figure 4). The resultant gravity model generated an anomaly that closely fits the observed data (the difference between the observed and calculated data is 0.98 mGal).

Gravity profile 2, central TBR

Profile 2 crosses the northernmost part of the central segment of the TBR and is located approximately 75 km north of profile 1, with a similar orientation (west–east) and length. The model is constrained by refraction velocities and by seismic reflection data (Figure 5b) over the entire extent of the TBR. The Caribbean oceanic crust is modeled to be

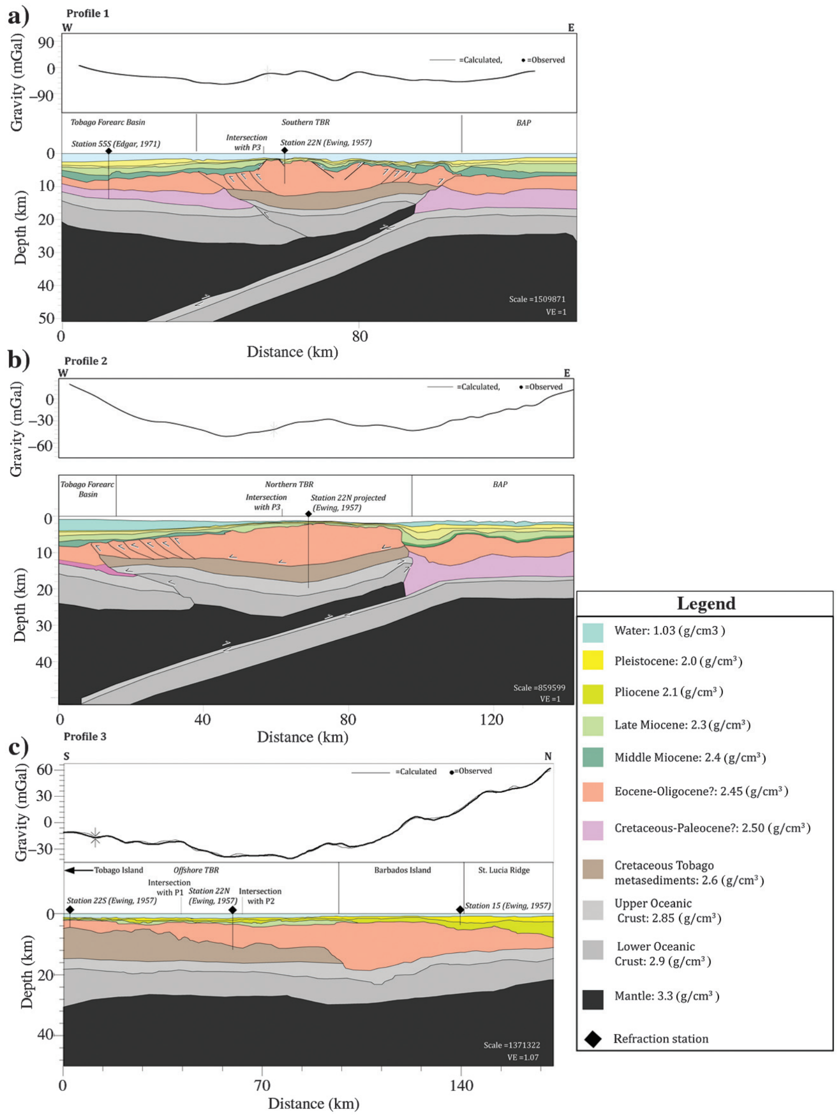

Figure 6. (a) Gravity model based on the east–west seismic section (Figure 5b) across the bifurcated southern segment of the central TBR. Based on refraction velocity control and observed gravity anomalies, the TB contains approximately 10 km of sediments and is floored by a two-layer, 10–15 km thick Caribbean oceanic crust. Gravity modeling of long-wavelength anomalies allows us to interpret top of subducting crust at a depth of −15–20 km, and depth to Moho at 26–29 km, suggesting a crustal thickness of approximately 6–10 km that cannot be reliably interpreted from the seismic reflection data (Figure 5b). The structure of the TBR in this model is interpreted as a pop-up structure that is symmetrically bounded by thrusts and folding on its western and eastern edges as constrained by seismic reflection data (Figure 5b). (b) Gravity model based on the east–west seismic section (Figure 5d) across the northern termination of the central TBR near the island of Barbados. The Caribbean oceanic crust is modeled to be 13 km thick at a depth of 10 km, and the depth and thickness of the subducting Atlantic crust are modeled to be 15 and 7–10 km, respectively. The modeled depth to the Moho is 29 km. The thickness of the crust beneath the TBR is approximately 10 km. The crust is overlain by approximately 5 km of metasedimentary rocks and approximately 10 km of BAP sediments. The difference between the observed and calculated anomalies of 0.5 mGal provides a good fit to the modeled thicknesses, densities, and geometries over the TBR. (c) Gravity model based on south–north-trending, strike profile (Figure 5f) of the TBR between the islands of Tobago and Barbados that shows the variation in the composition, densities, and structure of the TBR. This model shows the northward thinning of the crystalline basement of the TBR and northward thickening of the BAP unit that reaches 18 km in thickness near the island of Barbados.

13 km thick at a depth of 10 km, and the depth and thickness of the subducting Atlantic crust are modeled to be 15 and 7–10 km, respectively. The modeled depth to the Moho is 29 km. The thickness of the crust beneath the TBR is approximately 10 km. The crust is overlain by approximately 5 km of metasedimentary rocks and approximately 10 km of accretionary prism sediments. The difference between the observed and calculated anomalies was 0.5 mGal indicating a good fit to the modeled thicknesses, densities, and geometries over the TBR.

Gravity profile 3, south-to-north transect

To test our hypothesis that the TBR is a northern extension of the Mesozoic arc crust and to determine the northern limit of the Tobago Terrane metasediments, profile 3 was constructed along the trend of the TBR with its southern end located approximately 60 km northeast of Tobago and tied to profiles 1 and 2 (Figure 6a). This model reveals the along-strike relationships between (1) the 5–10 km thick accretionary wedge that has been thrusted over the metasediments of Tobago on the more elevated TBR in the south-central segments; (2) the 18 km thick accretionary prism sedimentary layer overlying oceanic crust beneath Barbados; and (3) the elevated Moho, crust, and thinned sedimentary section at the St. Lucia Ridge. The model also suggests the existence of an 8 km thick metamorphic layer of the TBR underlying the BAP to a depth of 16 km. The crust of the TBR is approximately 10–15 km thick as indicated by a depth to the Moho of approximately 29 km.

Discussion

Crustal composition, structure, and geometry of the TBR

Gravity modeling along profiles 1–2 in Figure 6a–6b suggests that the basement core of the southern-central TBR segments is composed of approximately 5 km thick metasedimentary rocks, 3 km thick oceanic upper crust, and 7 km thick oceanic lower crust. These observations are consistent with the TBRs composition being equivalent to the Cretaceous metacrystalline rocks of Tobago. Therefore, our findings support Robertson and Burke (1989) hypothesis that Mesozoic island arc and metamorphic rocks of Tobago and the larger Tobago Terrane extend more than 100 km to the northeast into the BAP. Gravity modeling along profile 3 (Figure 6c) shows a negative gravity gradient that we accounted for with a tapering wedge of metacrystalline rocks. This gravity model of the TBR suggests that its composition varies along-strike from high-density rocks in the southern and central TBR, to sedimentary rocks of the accretionary prism over oceanic crust of the northern TBR. We propose that the TBR was accreted along the westward-dipping Caribbean subduction zone.

Uplift mechanisms for the southern and central TBR include (1) accretion in the west-dipping subduction zone, (2) underplating of subducting sediments (Noda, 2016), and (3) east–west horizontal shortening related to westward backthrusting of the anomalously wide BAP over the Tobago Basin (Westbrook, 1975; Silver and Reed, 1988; Unruh et al., 1991). East–west shortening produced the pop-up structure described along the central TBR that continues to uplift today (Figures 5a–5d and 6a–6b). The northern TBR near Barbados and the St. Lucia Ridge remains topographically and structurally elevated as the uplifted, footwall block to the system of normal faults that we postulate form the trailing margin of the Lesser Antilles forearc sliver (Figure 1b).

The structural style of the TBR changes over a distance of 60 km as seen in its gravity signature and on seismic reflection lines (Figures 3a–3c and 5a–5d). The southernmost part of the central TBR near Tobago forms a symmetrical and more uplifted pop-up block bounded by inwardly dipping thrust faults on its western and eastern edges (Figure 5b). The northern TBR near Barbados forms a westward-verging, fold-thrust belt that is less elevated than the southern TBR and composed of an approximately 18 km thick section of accretionary prism sedimentary rocks underlain by oceanic crust that was accreted to the front of the Caribbean plate (Figure 5d).These along-strike structural variations in central and northern TBR may also be related to the original variations in crustal properties and thickness of the arc fragment that became lodged in the space between the leading edge of the Caribbean plate and the downgoing Atlantic plate.

Northern limit of Mesozoic island arc fragments

We noted earlier that the northern end of the TBR extended over a distance of 250 km to at least the island of Barbados (Figure 1a). We propose from geologic results of previous workers that similar, elongate Mesozoic arc fragments may extend over a distance of 100 km from the island of La Desirade to the island of Barbuda (Figure 7). This segment of the northern Lesser Antilles arc was rifted into two, island chains along the Kallinago rift between 7 and 20 Ma — possibly as the consequence of subduction of the buoyant, aseismic Barracuda Ridge (BR) (McCann and Sykes, 1984) (Figure 1a).

The two islands of Guadeloupe (Bass-Terre and Grande-Terre) occupy the area where the Lesser Antilles bifurcates into an older arc segment to the east and younger segment to the west (Figure 7). This segment of the northern Lesser Antilles arc was rifted into two island chains along the Kallinago rift between 7 and 20 Ma — possibly as the consequence of subduction of the buoyant, aseismic BR (McCann and Sykes, 1984) (Figure 1a). The basement of Grande-Terre includes Mesozoic igneous and metamorphic rocks of island arc affinity similar in age and composition to the basement rocks of Tobago (Bouysse et al., 1983; Snoke et al., 2001; Neill et al., 2013).

La Desirade, a small island located southeast of Guadeloupe, lies within the western area of a high-amplitude, unnamed ridge and Bouguer gravity anomaly to the east of the Lesser Antilles volcanic arc (Figure 7). Neill et al. (2010) use the age and geochemistry of its basement rocks to propose that La Desirade is a frag-

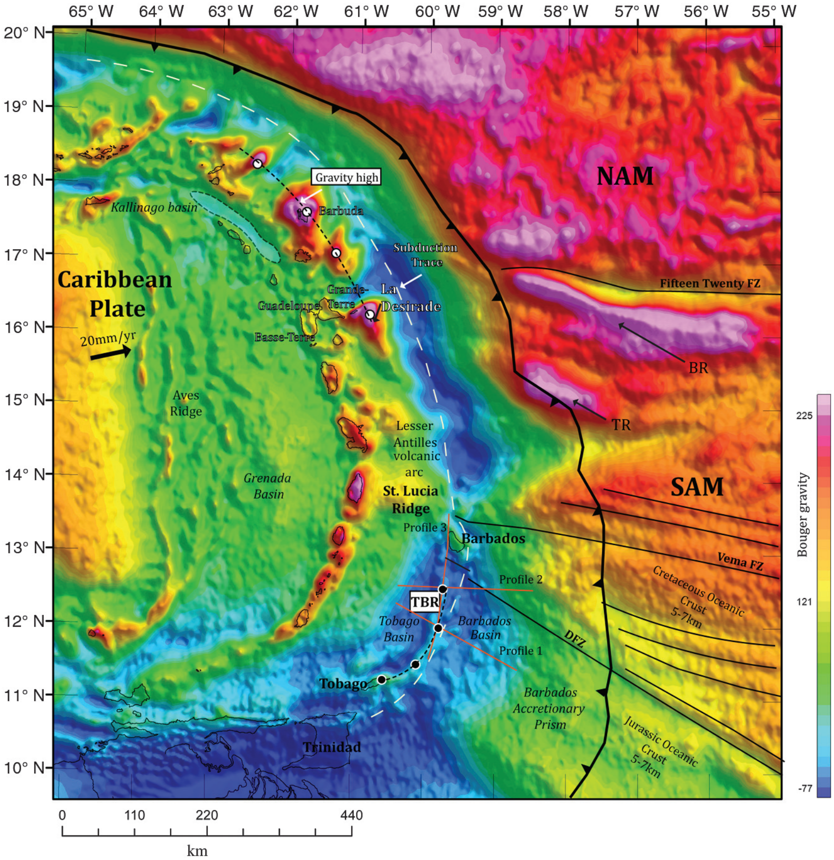

Figure 7. Bouguer anomaly map showing the major tectonic features of the Lesser Antilles island arc system. The white, bold, dashed line represents the subduction trace along the eastern edge of the Caribbean plate. The black dots show the elongate gravity high of the TBR extending from the island of Tobago northward to Barbados. The white dots depict elongate gravity highs extending from the island of La Desirade northward to the island of Barbuda. Basement outcrops on the islands of Grande-Terre and La Desirade include Mesozoic, metamorphic, and igneous arc fragments (Neill et al., 2010). Detailed studies of La Desirade, expressed as a high-amplitude Bouguer gravity anomaly, indicate that the basement ridge from La Desirade to Barbuda formed within a Mid-Cretaceous subduction zone (Neill et al. 2010). We propose that this northern basement ridge was accreted to the eastern edge of the Lesser Antilles island arc along with the TBR during the Cretaceous, arc polarity reversal event.

ment of a Mid-Late Cretaceous subduction zone. Two similar high-amplitude, gravity anomalies extend in a line to the north of La Desirade (Figure 7). The island of Barbuda lies beneath the northernmost anomaly, and we suggest that this gravity trend may represent a submerged and buried basement ridge of arc-related rocks that are similar to the basement of the TBR described to the south (Figure 7). The only outcropping rock units on Barbuda are Miocene-age limestone surrounded by a fringe of Pleistocene limestone. If Barbuda is the northern limit of these Mesozoic arc fragments, there exists the possibility that these carbonates might be overlying a crystalline basement of eastern Pacific-derived Mesozoic intraoceanic arc crust of the GAC system.

Conclusion

An integrated geophysical and geologic interpretation of the geometry and evolution of the TBR based on seismic reflection and refraction data, wells, gravity models, plate reconstructions, and geologic data is summarized below:

1) The TBR is an elongate, 20–60 km wide, fault-bounded, uplifted crustal terrane elevated in the area directly above the deeply buried trench formed where the Atlantic oceanic crust subducts eastward beneath the Caribbean plate (Figures 1c and 3).
2) Gravity modeling across the TBR suggests that the southern and central parts of the ridge is composed of approximately 10–12 km of Paleogene deformed accretionary prism sediments, approximately 5 km thick metamorphic rocks, and approximately 7–10 km of Cretaceous oceanic island arc-type crust. The northern segment of the TBR beneath Barbados is composed of approximately 18 km of accretionary prism sedimentary rocks overlying oceanic crust (Figure 6).
3) The TBR represents an approximately 80 km northeastward extension of the Mesozoic oceanic island arc crust of the island of Tobago along the BAP where it is actively over-thrusting the TB and Barbados Basin (Figure 5a and 5c).
4) The structural style of deformation of the TBR changes over a distance of 60 km (Figure 5). The southern TBR near Tobago forms a symmetrical and more uplifted terrane bounded by inwardly dipping thrust faults on its western and eastern edges. The northern TBR near Barbados forms a westward-verging, fold-thrust belt that is less elevated than the southern TBR and composed of an approximately 18 km thick section of accretionary prism sediments floored by accreted oceanic crust.
5) The primary uplift mechanisms for the TBR, as supported by our gravity modeling, include east–west shortening and westward backthrusting of the 300–450 km wide, BAP along with underplating of subducting sediments derived from the subducting Atlantic slab beneath the TBR (Figure 1c).
6) Our results and interpretations indicate that Tobago and its offshore component, the TBR, represent an unsubducted, arc-derived terrane lodged in an area just east of the buried, lithospheric trace of the westward-dipping Lesser Antilles subduction zone. We postulate that this arc fragment accreted during the Cretaceous during the later phase of westward-directed subduction beneath the GAC (Figure 6).

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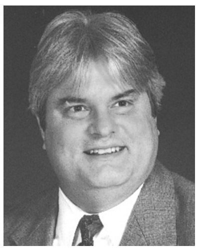

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