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Special Collection:
A fresh look at the Caribbean plate geosystems

Key Points:

- The Old Bahamas Channel offers insights into the Caribbean's early tectonic history dating back to the Pangea breakup
- Bahamian carbonate banks formed as reefs on top of tilted blocks following the Pangea rift and were later affected by fault reactivation
- The Eocene northern Caribbean plate boundary aligns with the Cuban Transform Fault, reactivated in the Cuban orogenic and post-orogenic phases

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Protracted Evolution of a Plate Boundary: Eastern Cuba Block and Old Bahamas Channel

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Abstract The Eastern Cuban block has experienced a complex tectonic history characterized by plate interactions, resulting in a diverse array of geological features observable in the offshore sedimentary record. We investigate the tectonic evolution of offshore Eastern Cuba, specifically in the Old Bahamas Channel and its surrounding areas, by integrating multi-channel seismic (MCS) reflection and published geological data. Our analysis employs stratigraphic frameworks and MCS data to assess deformation and key geological events in the region. We highlight the complex tectonic history of the Eastern Cuban block, marked by significant geodynamic events, such as rifting, the subduction of the oceanic Proto-Caribbean plate, and syn-orogenic and post-orogenic phases. The seismic units observed in the majority of the study area reveal the early evolution of the Northern Proto-Caribbean margin, subsequently impacted by the Cuban orogeny and the reactivation of the Cuban Transform Fault zone corresponding to a former plate boundary. We propose estimated ages for the seismic sequences, correlating them with available well data from neighboring regions. This study offers valuable insights into the tectonic history and geological evolution of offshore Eastern Cuba, contributing to a more comprehensive understanding of the region's geodynamic development.

1. Introduction

The evolution of basins and structures at plate boundaries is strongly influenced by the vast history of plate movements they have undergone and the nature of these plates. In the Caribbean region (Figure 1), the North Cuba area was significantly impacted by regional plate motions that occurred during the fragmentation of Pangea, the emergence of the Proto-Caribbean arm of the Atlantic Ocean, and the north-eastern migration of the Caribbean plate between the Americas. Indeed, the origin of the Caribbean region can be traced back to the Triassic breakup of Pangea and the associated Proto-Caribbean continental passive margin linking the Gulf of Mexico to the Atlantic through the Cuba fracture zone (FZ) (Klitgord et al., 1984) (Figure 2). This evolution comprises the development of the Proto-Caribbean oceanic crust, its subduction below the Caribbean plate, and the Late Cretaceous collision and transfer of the NW Caribbean plate, including Cuba, to the North American plate (Iturralde-Vinent & Lidiak, 2006; J. L. Pindell et al., 1988).

The evolution of the Caribbean domain, from the early stages to its present configuration, is well-documented in the geology of Cuba. The thick Jurassic-Cretaceous strata and the interlayered basaltic rocks in Cuba provide significant evidence of the geological processes that occurred during the early evolution of the Proto-Caribbean continental passive margin (Figure 2b). This margin was formed by the North American and South American plates facing the Proto-Caribbean Seaway (Figures 2b and 2c), which opened after the Pangea breakup. This vanished seaway connected the Atlantic and Pacific oceans from the Middle Jurassic to the Early Cretaceous. Remnants of the Proto-Caribbean oceanic lithosphere are present in ophiolitic units, outcropping along northern Cuba (Andó et al., 1996; Cobiella-Reguera, 2005; Iturralde-Vinent et al., 2016; Rui et al., 2022) and also in the western part of the Demerara plateau (e.g., Gómez-Romeu et al., 2022).

During the Cretaceous-Paleocene period, arc activity due to Proto-Caribbean oceanic plate subduction caused the exhumation of metamorphic, meta-volcanic, and meta-sedimentary rocks, providing evidence of the various phases of the Cuban orogen's evolution (Iturralde-Vinent et al., 2016). The Proto-Caribbean oceanic crust was entirely consumed due to subduction, leading to the collision of the northern border of the Caribbean plate with the Bahamas domain. This collision resulted in welding the Cuban Arc to the North American plate and played a significant role in establishing the current configuration of the Caribbean realm.

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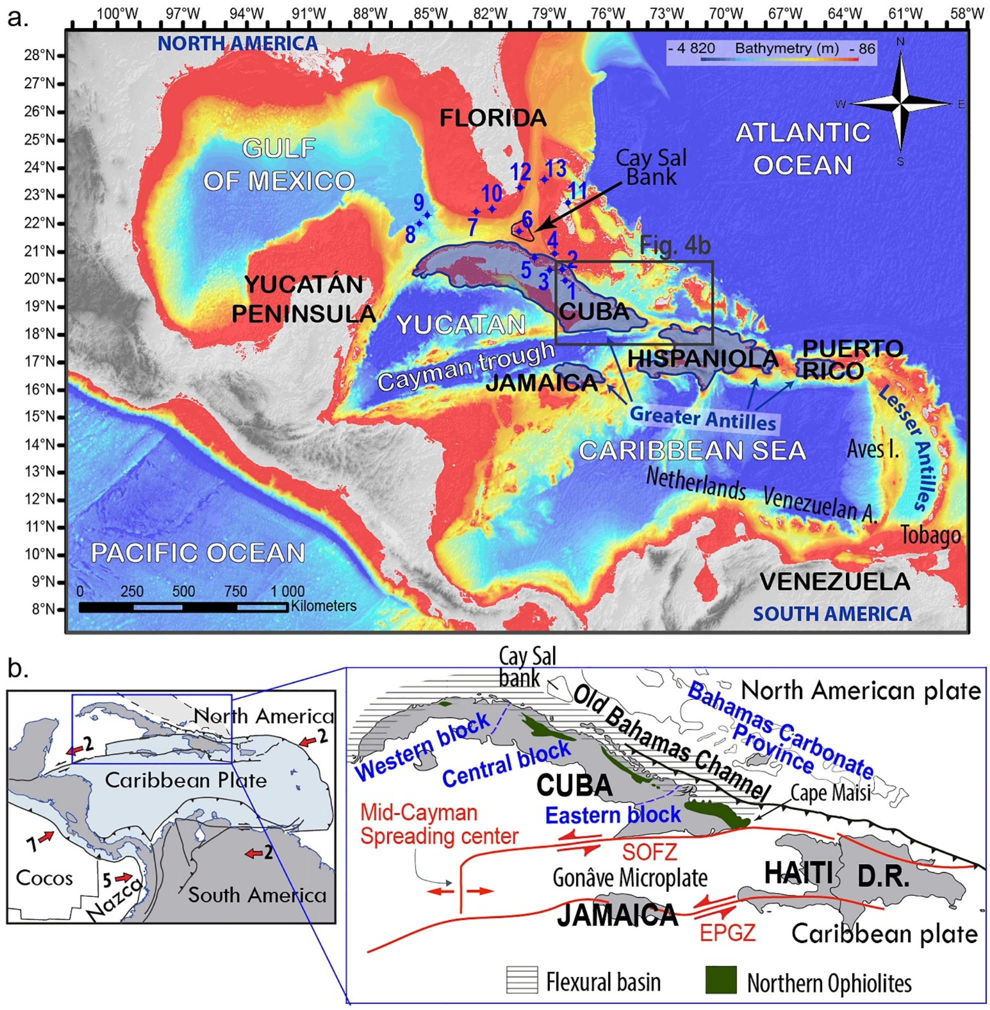

Figure 1. Regional map of the Caribbean Sea area. (a) Topo-bathymetric map of the Caribbean Sea area. Onshore regions are in gray. The Greater Antilles archipelago consists of the four largest islands in the Caribbean: Cuba, Jamaica, Hispaniola, and Puerto Rico. Locations of academic and industrial key wells in South Florida, Bahamas, and Cuba are indicated by the blue dots with the following numbers: (1) Tina 1 and 2; (2) Cayo Coco 1 and 2; (3) Collazo 1; (4) Doubloon-Saxon; (5) Cayo Fragoso; (6) Cay Sal; (7) Marquesas 826; (8) ODP 535; (9) ODP 540; (10) Pine key; (11) Andros Island; (12) Williams; (13) Great Issac. (b) Main tectonic plates in the Caribbean region (numbers are in cm/y) and detailed view of the tectonic context of the Northern Boundary of the Caribbean Plate (on the right side). DR: Dominican Republic; SOFZ: Septentrional Oriente FZ; EPGFZ: Enriquillo Plantain Garden FZ.

While the intricate multi-phase history of this region along with the tectonic plate interactions were recorded onshore Cuba (Iturralde-Vinent et al., 2008, 2016; Moretti et al., 2003; Rojas-Agramonte et al., 2008), much of the history recorded offshore remains unexplored. This study presents a comprehensive offshore analysis of the Eastern Cuban Coast using a multi-channel seismic (MCS) reflection and swath-bathymetric data set from the Haiti-SIS and 2 cruises (e.g., Leroy et al., 2015). We aim to establish a seismic stratigraphic framework for the offshore Eastern Cuban block (Figure 1c) by examining the reflection characteristics found within seismic sequences and correlating them with previously identified seismic sequences described in exploration wells and vintage seismic data within the surrounding regions.

Our analysis reveals that the seismic units observed in most of the area reflected the early evolution of the Northern Proto-Caribbean continental margin relative to the Bahamas Carbonate Province and were subsequently affected by the Cuban arc orogeny. We propose likely ages for the seismic sequences based on correlations with available well and dredge data from the neighboring regions (Figure 1a). We show that the geological features in

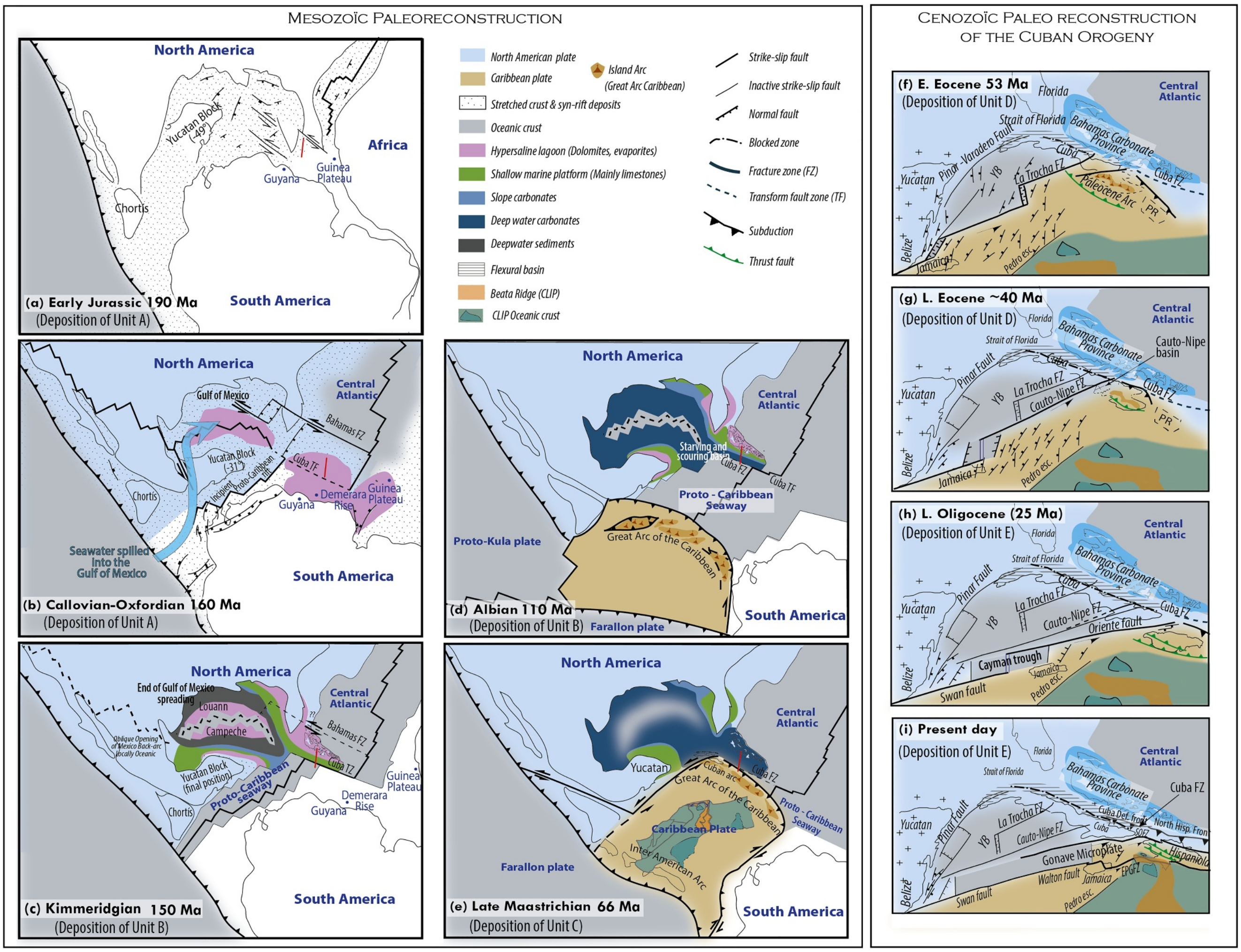

Figure 2. Paleo-geodynamic reconstructions of the Caribbean region. Left panel: with the associated sediment deposits from the Early Jurassic to Late Cretaceous. Right panel: Cenozoic paleo reconstruction of the Cuban orogeny from the Early Eocene to Present-day. The sediments being very pellicular are not represented. See the text for explanations and references.

the offshore sedimentary records of Eastern Cuba are the result of various plate interactions, such as rifting, subduction, strike-slip, collision, and obduction, that have influenced its tectonic history.

2. Geological Setting: A Synthesis

The Caribbean plate mainly consists of an oceanic igneous plateau with a 15 km-thick crust and, locally, some thick blocks of transitional and continental crust affinities and a few places of a 5 km-thick oceanic crust (Burke et al., 1984; Diebold et al., 1981; Kerr & Tarney, 2005; Mauffret & Leroy, 1997; Mauffret et al., 2001). Four plates surround the Caribbean plate: North American, South American, Cocos, and Nazca (Figure 1b).

2.1. Northern Proto-Caribbean Passive Margin

North America, South America, and Africa formed the supercontinent Pangea during the Paleozoic and Early Triassic (Salvador, 1987). The rifting process between North America and Africa began in the Late Triassic, resulting in the stretching and thinning of continental crust during the Early and Middle Jurassic (Figures 2a and 2b) (Marton & Buffler, 1993, 1994). During the continental breakup, the Bahamas area was a transform zone linking the young Gulf of Mexico and the Atlantic Ocean as well as the Cuba transform zone for the southern part of the Gulf of Mexico (Figures 2b and 2c) (Klitgord et al., 1984; Marton & Buffler, 1994; Masaferro & Eberli, 1999; Ross & Scotese, 1988; Sheridan et al., 1988).

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The Pangea rifting leads to the development of grabens and half-graben structures in the Proto-Caribbean margin (Marton & Buffler, 1994; Padilla y Sánchez, 2016; J. Pindell & Kennan, 2001; Salvador, 1987) (Figure 2a). Syn-rift facies were intercepted by offshore wells (Figure 1a) (Iturralde-Vinent, 2003; Jacobs, 1971), which penetrated Jurassic redbeds (most like Callovian age) above crystalline basement rocks interpreted as belonging to the Proto-Caribbean continental crust constituting the Northern American basement (Meyerhoff & Hatten, 1968, 1974).

Graben and horst morphology prevailed during the Jurassic (Figure 2b) before the opening of the Gulf of Mexico and the upcoming Proto-Caribbean Ocean (Figure 2c; Gaumet et al., 2004; Ladd & Sheridan, 1987; Padilla y Sánchez, 2016; J. Pindell & Kennan, 2001; Schenk, 2008; Sheridan et al., 1981). Most of the continental rifted zones emerged during the Middle Jurassic (Gaumet et al., 2004).

Early Jurassic rifting caused marine water influx, creating shallow water conditions (Epstein & Clark, 2009; Iturralde-Vinent et al., 2016; Ladd & Sheridan, 1987; Moretti et al., 2003; Walles, 1993). Middle Jurassic syn-rift redbeds were succeeded by evaporites in hypersaline lagoons (Figure 2b; Gaumet et al., 2004; Padilla y Sánchez, 2016). Plate reconstructions by Klitgord et al. (1984) suggest that the Gulf of Mexico was isolated from Atlantic waters until the Callovian time due to the barrier formed by the elevated Florida-Bahamas region. However, plate reorganizations during the Early Callovian period (Figures 2b and 2c) may have opened up restricted waterways to the Proto-Caribbean margins (Klitgord et al., 1984).

The increased plate separation between North America and South America/Africa allowed a restricted influx of marine waters into the Gulf of Mexico from both the Pacific and potentially the Atlantic. Fossil-rich marine sediments in Mexico indicate a Pacific Ocean branch connected to the Gulf of Mexico in the Late Bathonian and Callovian periods (as shown by the blue arrow in Figure 2b) (Salvador, 1987). Extensive salt deposits formed in the Gulf of Mexico, and a minor evaporite basin developed in the composite Bahamas domain, Demerara rise, and Guinea Plateau region (pink areas in Figure 2b) (Hudec et al., 2013; Lewis et al., 1991; J. Pindell & Kennan, 2001; Walles, 1993).

The accumulation of 4,500–5,800 m of shallow-water carbonates and evaporites found on Andros Island and Cay Sal Bank deep wells is attributed to subsidence during the Late Jurassic and Early Cretaceous periods, as documented by Furrazola-Bermúdez (1964), Khudoley (1967), and Uchupi et al. (1971) (Figure 1a). A hundred meters of highly deformed halite and gypsum were found in the Punta Alegre Formation (Wells: Collazo-1 and Tina-1) (Figures 1a and 3). The salt has been dated as Middle Jurassic, possibly Callovian (Figure 3) (Cousminer et al., 1957).

Between the central Atlantic and Proto-Caribbean spreading systems, the Bahamas and Cuba fracture zones (FZs) formed a wide transform area (Klitgord et al., 1984). These FZs separate Mesozoic marginal sedimentary basins of the Proto-Caribbean continental passive margin as the Bahamas, South Florida, and the southeastern Gulf of Mexico basins (Figure 2c) (Klitgord et al., 1984). During the Jurassic period, the Bahamas FZ formed first in the southern boundary of the North American plate (Bahamas FZ in Figure 2b). With the ongoing Proto-Caribbean spreading and the end of the Gulf of Mexico spreading, the Bahamas FZ is abandoned, and a narrow Jurassic transform zone, called the Cuba FZ, was formed (Cuban FZ in Figure 2c) (Klitgord et al., 1984).

In the time interval from Albian to Late Maastrichtian, the crust (Proto-Caribbean seaway) south of the Cuba FZ was consumed by the Cuban subduction zone (Figures 2d and 2e), and a thick carbonate pile was deposited in the southern and southeastern areas of the Bahamas platform (Figure 3).

2.2. Bahamas Domain

The Bahamas Carbonate Province was established during the Late Jurassic on the thin crust formed by the breakup of Pangea (Masaferro & Eberli, 1999). The Bahamian reef formation is also believed to have started in the Late Jurassic to the Mid-Cretaceous period due to shallow water conditions resulting from rifting, allowing a large carbonate deposition (green area in Figure 2c). The steep-sided slopes of the Bahamas were built by reef accretion (Sheridan et al., 1969), and the distinctive "bank-trough" morphology observed in the Bahamas Carbonate Province is believed to have resulted from a combination of various tectonic events and the erosive action of deep-water currents (Mullins & Hine, 1989). During the Mesozoic, the Bahamas mega-platform evolved into a banking system (Denny et al., 1994). Two hypotheses have been proposed in the literature to explain the origin and morphology of Bahama's carbonate banks: (a) The first hypothesis, known as the "Graben hypothesis" (Mullins & Lynts, 1977), proposes that the modern physiography of the Bahamas arises

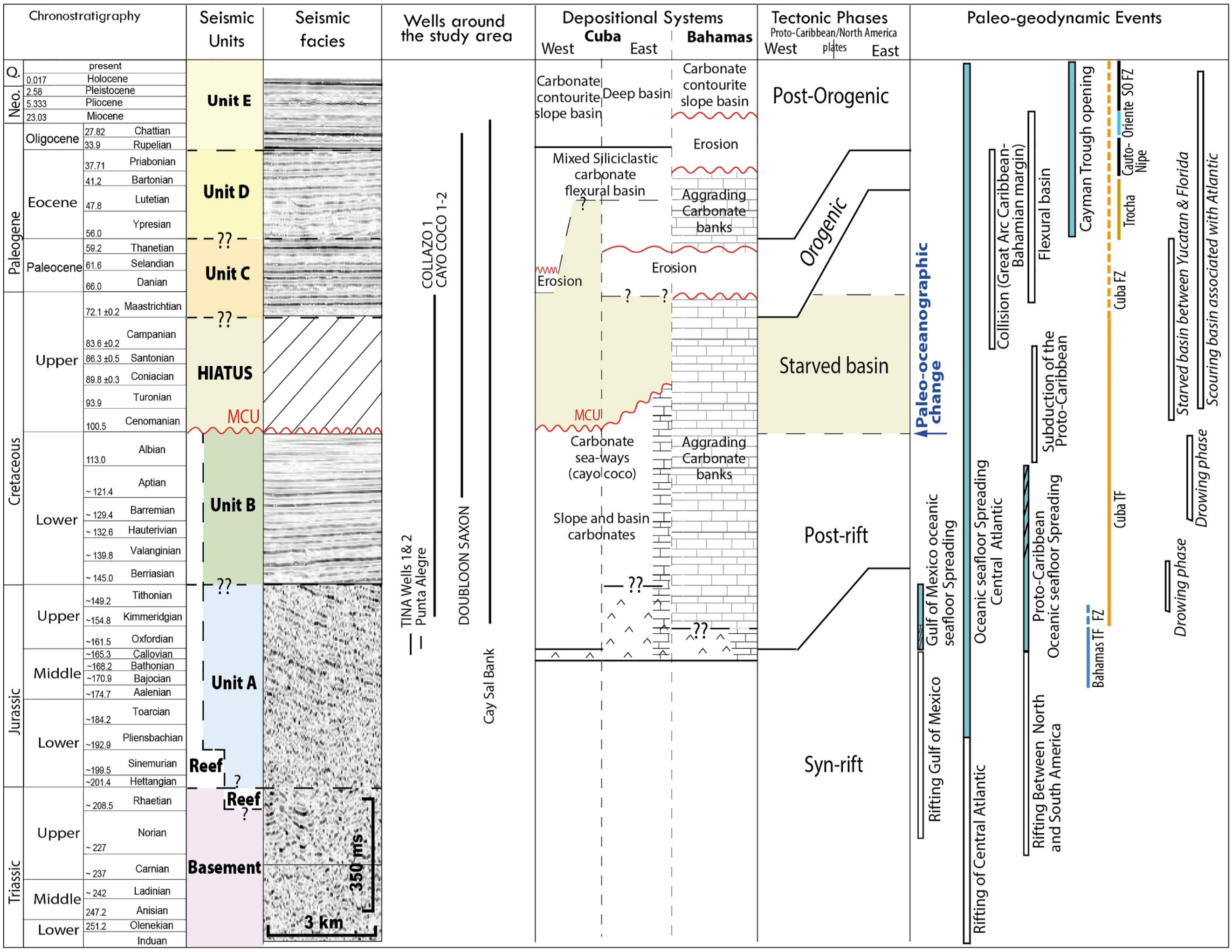

Figure 3. Seismo-stratigraphic chart of the eastern Cuba-Bahamas area based on the seismic survey Haiti-Sis 2 and published wells. It enables the correlation of depositional systems, tectonic phases, and paleo-geodynamic events in the region.

from the configuration of rifted continental margins (horsts and grabens) formed when North America rifted from Africa. According to this hypothesis, the deposition of shallow water carbonate banks was restricted to horsts/paleo-highs, while the grabens were filled with deep-water sediments. (b) The second hypothesis, known as the "Megabank hypothesis" (Bryant et al., 1969; Meyerhoff & Hatten, 1968; Schlager & Ginsburg, 1981), suggests that during the Late Jurassic to the Mid-Cretaceous, an extensive shallow-water carbonate platform developed from the West Florida shelf to the Bahamas. Carbonate banks persisted in various forms throughout the Bahamas region during the Late Cretaceous and the beginning of the Cenozoic (Eberli & Ginsburg, 1987; Ladd & Sheridan, 1987; Sheridan et al., 1981).

Shallow-water conditions persisted in some areas of the Bahamas archipelago during the Late Jurassic, and the Bahamas platform was characterized by a vast restricted marine lagoon under arid climate conditions during this time (Figure 2c). Dolomitic facies from the Lower Cretaceous period discovered in deep exploratory wells in Florida attest to a shallow water environment at this period (Marquesas 826, Big Pine Key 373, and Williams 1, as reported by Applegate, 1984) (Figures 1 and 2d). During the Albian, the Yucatan is shallow and suitable for the deposition of dolomites and evaporites (Figure 2d). In addition to these findings, homogeneous hyper-saline lagoons were also observed to still develop in the Cayo Coco Formations (Figure 2b) (Cayo Fragoso I and Cayo Coco 1–2 wells, Figure 1; Gaumet et al., 2004).

The Bahamian area underwent a major transgressive event in the upper part of the Jurassic (Kimmeridgian) (Gaumet et al., 2004). The Upper Tithonian period then marked a deepening trend, enhancing connections between the Gulf of Mexico and the Proto-Caribbean domains. The transgression that initially started in the Late Kimmeridgian had its peak during the Berriasian period, leading to the submersion of the region and the formation of deep carbonate deposits (Figures 2c, 2d, and 3) (Gaumet et al., 2004). In the southern part of the Florida-Bahamas Mega platform, dolomitic facies were followed by these slope and shallow carbonate deposits, while slope carbonate deposits expanded across the Eastern Cuban area (Figure 2d). The deepening trend of the Late Jurassic-Early Cretaceous led to a reduction in reefal-lagoonal deposits in the southeastern Bahamas (Green and pink areas in Figure 2d). However, localized shallow water build-ups persisted, contributing to the present "bank-through" morphology of the Bahamas (Figure 1) (Gaumet et al., 2004).

While shallow conditions prevailed in the Bahamian area, the drowning event during the Berriasian period led to the sealing of the tilted blocks in Western and Central Cuba. This event caused a uniform deposition of deep-sea carbonates (blue in Figure 2d) over the Jurassic syn-rift, which was characterized by a siliciclastic sequence interspersed with thin layers of black shales and sandstones (Gaumet et al., 2004; Moretti et al., 2003).

2.3. The Proto-Caribbean Seaway

During the Lower Jurassic to the Early Kimmeridgian, the Yucatán block moved southward and rotated about 49° counterclockwise, causing the opening of the Gulf of Mexico and Proto-Caribbean seaways (Figures 2a–2c) (Marton & Buffler, 1994; J. Pindell, 1985; J. Pindell & Dewey, 1982; J. Pindell & Kennan, 2001; Schouten & Klitgord, 1994). The oceanic crust underlying the central Gulf of Mexico drifted apart from the previous salt basin into two salt bodies, the southern (Campeche) and northern (Louann) (Hudec et al., 2013; Marton & Buffler, 1994) (Figure 2c). The Yucatan block reached its present position by the Early Kimmeridgian, and the Gulf of Mexico assumed its present configuration (Figure 2c) (Padilla y Sánchez, 2016).

The cessation of Yucatán's rotation allowed for the formation of a single, slightly reorganized Proto-Caribbean oceanic ridge system, which linked the Pacific and Atlantic Oceans (Figure 2c). Rui et al. (2022) suggested that the Proto-Caribbean plate was initiated before 137 Ma (Figure 2c). The oceanic crust was generated at multiple spreading centers during the Jurassic and Early Cretaceous, forming an oceanic domain called the Proto-Caribbean Seaway (Figures 2c and 2d) (Giunta & Orioli, 2011). This domain evolved into the Proto-Caribbean Seaway and will, thereafter, disappear in subduction under the Caribbean plate (Figures 2d and 2e).

During the Early Cretaceous period, the east-dipping subduction of the paleo-Farallon plate bounds the North and South America plates and the Proto-Caribbean seaway (Figure 2d). Much of the Proto-Caribbean crust has been overridden by the Pacific-derived Caribbean plate, leaving only fragments of Proto-Caribbean crust that have either been accreted to the Caribbean plate or thrust onto South America (Figures 2d and 2e) (Neill et al., 2014). During the Late Cretaceous period, the east-dipping subduction beneath the inter-American Arc ceased and was superseded by SW-dipping subduction of the Proto-Caribbean oceanic crust, which resulted in the formation of the Great Arc of the Caribbean (Figures 2d and 2e) (Escuder-Viruete et al., 2014; Hastie & Kerr, 2010; Hastie et al., 2013; J. Pindell & Dewey, 1982; J. Pindell et al., 2012).

2.4. Cretaceous Caribbean Plate

The subduction of the Proto-Caribbean seaway gave rise to the "Great Arc of the Caribbean" (as defined by Burke, 1988), which was a composite of several island arc systems with debated origin and complexity, including much of the present-day Great Antilles, Aves Ridge, and Netherlands-Venezuelan Antilles, as well as Tobago and allochthonous terranes in Venezuela (Figure 1, Neill et al., 2014; Wright & Wyld, 2011).

The Great Arc of the Caribbean marked the leading edge of the Pacific-derived Caribbean plate from the Cretaceous to the Paleocene (Figures 2d and 2e). Remnants of the fossil convergent margin preserved in fore-arc units, along with the earliest magmatic arc sequences, provide evidence that this volcanic arc originated during the Early Cretaceous period and ended in the Paleogene period when the subduction ceased (Cobiella-Reguera, 2009). The subduction of the Proto-Caribbean plate first, then of the North American plate, ceased due to the collision between the Bahamian platform and the Caribbean plate and the termination of further northward motion of the Caribbean plate (Figures 2f–2i).

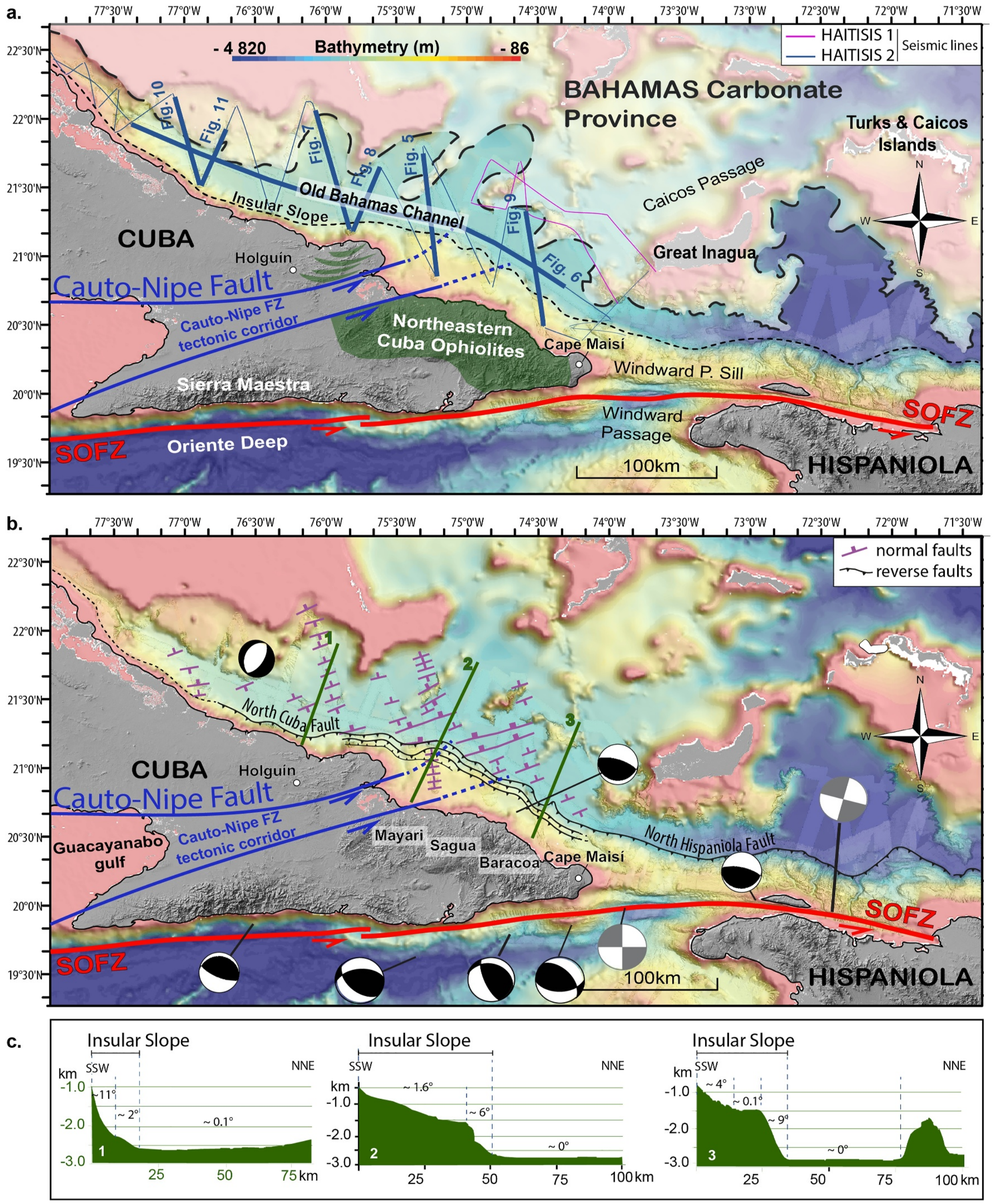

Figure 4. (a) Bathymetric map showing the positions of seismic sections collected during cruises HAITI-SIS 1–2 (Leroy, 2012; Leroy & Ellouz-Zimmermann, 2013; Leroy et al., 2015). Bold lines show the location of the seismic profiles shown in this paper. The short-dashed black line represents the base of the insular slope. The large-dashed black line represents the limit of the banks and ridges (b) Structural map of the study area based on the interpretation of seismic profiles. The focal mechanisms are for $M > 5$ earthquakes from the CMT database, except for the M_w 4.7, 17 Dec 2022 normal faulting on a NE-SW oriented fault plane in the south of the Bahamas Carbonate province (c) representative bathymetric profiles across the insular slope of Eastern Cuba, revealing depths up to 3 km and slope gradients ranging from 11° to zero. Locations of the bathymetric profiles are shown in (b).

By the Maastrichtian period (Figure 2e), the position of the Caribbean plate was constrained to the North by evidence of accretion of the Eastern Cuba ophiolites (Figure 4). These ophiolites are believed to be relics of the Proto-Caribbean oceanic lithosphere, emplaced during the Early Maastrichtian, before the Paleogene collision of the NW Caribbean and North American plates (Figures 2d and 2e, Andó et al., 1996; Cobiella-Reguera, 2005;

Iturralde-Vinent et al., 2016; Rui et al., 2022). Cobiella-Reguera (2005) suggest that the eastern Cuba ophiolites were rapidly exhumed to the surface and displaced horizontally northward during an intense but brief tectonic event in the Early Maastrichtian.

2.5. Cuban Arc

Cuba is the largest island in the Greater Antilles (Figure 1). The Cuban Arc has witnessed and recorded numerous significant geological events within the Caribbean realm. Following the Cretaceous-Paleogene subduction beneath the Great Arc of the Caribbean, the collision between this volcanic arc and the southern margin of the North American plate resulted in a complex geological history linked to an orogenic phase (Figure 2).

Cuban geology has been well-studied (Gaumet et al., 2004; Iturralde-Vinent, 1998; Iturralde-Vinent et al., 2008, 2016; Khudoley, 1967; Moretti et al., 2003; Pardo, 2009; Rosencrantz et al., 1988). Cuba is an archipelago of the Late Cretaceous-Eocene age that records geological units of three major tectonic phases: (a) A pre-orogenic phase, with the sedimentary evolution of the northern Proto-Caribbean Passive margin from the Jurassic up to Campanian (Figure 3). (b) An orogenic phase, when the northward displacement of the Great Arc of the Caribbean and the subduction of the Proto-Caribbean basin stopped, then the collision occurs in the southern margin of the North American plate between the Late Cretaceous (Figure 2e) and Middle Eocene (Figure 2g) (Echevarria-Rodriguez et al., 1991; Malfait & Dinkelman, 1972). During this process, Cuba was progressively welded to the North American plate (Leroy et al., 2000; Oliveira de Sá et al., 2021; J. Pindell et al., 2006; Ramos & Mann, 2023) during a (c) post-orogenic phase in which several left-lateral strike-slip faults shifted the Caribbean plate's relative motion from NNE (Maastrichtian) to E (Middle Eocene) (J. Pindell et al., 2005). As a consequence, these left-lateral strike-slip faults fragmented the Cuban orogen and formed several strike-slip corridors (Figures 2f–2h). These corridors include the Eastern Yucatan Margin (Upper Cretaceous), the Pinar-Varadero (Paleocene), La Trocha (Early Eocene), Cauto-Nipe (Middle/Late Eocene), and Oriente Fault Zones (Early Oligocene) at the northern edge of the Cayman trough (Leroy et al., 2000; Oliveira de Sá et al., 2021; Rojas-Agramonte et al., 2008) (Figures 2f–2h). According to this structural inheritance, the Cuban mainland is divided into three structural blocks: Western, Central, and Eastern Cuba (Draper & Barros, 1994; Iturralde-Vinent, 1998; Lewis & Draper, 1990) (Figure 1b).

The sedimentary rocks outcropping in the west and center of Cuba have been assigned to the Eastern Yucatan margin (Haczewski, 1976; J. Pindell, 1985; Ramos & Mann, 2023) and the southern margin of the Bahamas platform, respectively (Draper & Barros, 1994; Lewis & Draper, 1990; Pardo, 2009; Pszczółkowski, 1999). Mesozoic sedimentary rocks of the North American plate continental margin are widely distributed within the Western and Central Cuban blocks (Meyerhoff & Hatten, 1974). However, they do not crop out in the Eastern Cuba block (also called the Oriente block) (Figure 1b).

The geological features of the Eastern Cuba block (Oriente block or Cuba Oriental) differ from those of the other regions in Cuba from the Upper Paleocene to the Early Middle Eocene. Up to the Early Middle Eocene, the tectonic blocks of Eastern Cuba, Hispaniola, and Puerto Rico formed a single block (Figure 2g). During this time, the Cauto-Nipe basin constituted an extension of the Yucatán basin (YB in Figures 2f and 2i) *sensu lato*, representing the ancient boundary between the North American and Caribbean plates (Figure 2g). This configuration explains the absence of arc-continental collision processes in the Cuba Oriental during the Paleogene, as occurs in the rest of Cuba (Caballero & Cabrera, 2003a; Ramos & Mann, 2023).

During the Middle Eocene, the Eastern Cuban block collided with the Bahamas, and a left-lateral activity developed along the Cauto-Nipe basin (Figure 2g) (Iturralde-Vinent & Macphee, 1999; Vázquez-Taset et al., 2020). Vázquez-Taset et al. (2020) describes the coexistence of extensive and compressive structures in the Cauto-Nipe Corridor. The authors associated these structures with local transtension and transpression regimes controlled by the left lateral activity of strike-slip faults in this corridor (Figure 2g). The tectonic activity in the Cauto-Nipe fault zone began to wane in the upper Oligocene (Figure 2h), which coincides with the transfer of slip to the Oriente Fault, the current boundary between the Caribbean and North American plates (Figures 2h and 2i) (Iturralde-Vinent & Macphee, 1999; Oliveira de Sá et al., 2021; Rojas-Agramonte et al., 2008; Vázquez-Taset et al., 2020).

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3. Data and Methods

MCS reflection and multibeam bathymetric data were collected during HAITI-SIS 1–2 (2012–2013) cruises onboard the R/V L'Atalante from the *Flotte Océanographique Française* (Leroy, 2012; Leroy & Ellouz-Zimmermann, 2013; Leroy et al., 2015).

2D seismic reflection data were recorded using a source comprising two GI air guns (2.46 L, 300 in 3) and a streamer with 24 channels (600 m-long) operated at c.a 9.7 knots (fast and light operating seismic system from GENAVIR/IFREMER). The MCS reflection data were processed using a standard workflow, including CDP gathering (6-fold), binning at 25 m, detailed dynamic velocity analysis, stack, and post-stack time migration. All the seismic reflection profiles presented are time-migrated using distinct filtering for the sediments and the seismic basement (bandpass filter for the sediments 20-28-100-128/12-18-32-70 Hz and for the basement 6-18-32-55-6-18-24-35 Hz).

Multibeam bathymetry data were acquired simultaneously along seismic profiles and gridded with a spacing of 50 m. The data from the NORCARIBE 2013 cruise (Rodríguez-Zurrunero et al., 2019, 2020) complement the bathymetric map. The gridded bathymetry data were completed with the GEBCO Digital Atlas (Weatherall et al., 2015) with an ~800 m resolution to provide almost full coverage (Figures 1 and 4).

The processed seismic data are interpreted using Kingdom IHS Suite© software. Maps are plotted with ArcGIS© software. We use the seismic reflection data set to identify seismic horizons and units, as well as their geometrical disposition, and then to interpret seismic units, deformation style, and spatiotemporal evolution of the tectonic structures. Morphological analysis of the seafloor based on swath-bathymetric data is carried out to determine the surface expression of tectonic features. We identify faults by either sediment horizon offsets or the fault plane seismic reflection itself in the seismic profiles. It is important to note that the correlations performed are only relative due to spatial gaps between areas with well-developed seismic stratigraphy, the gaps derived from wells and dredges, and the seismic data within the surrounding regions.

4. Results

4.1. Morphology of the Study Area

The Old Bahamas Channel is a strait that lies between the northern coast of Cuba and the southern edge of the Bahamas Carbonate Province (Figures 1b and 4a). It spans from the Cay Sal Bank and runs in a southeasterly direction for about 160 km up to it reaches its endpoint between Cape Maisí in Cuba and Inagua Island in the Bahamas (Figures 1b and 4).

The Old Bahamas Channel is approximately 22 km wide at its narrowest point, but it gradually widens southeastward along the Holguín and Cape Maisí, reaching a width of about 70 km (Figure 4a). On bathymetric maps, the channel is represented as a deep-water basin (around 2,800 m-deep) punctuated northward by small banks and ridges (Figure 4a). Its bathymetric expression is generally flat (Figure 4c), similar to those of abyssal plains. However, between the coast of Holguín and Cape Maisí, these flat gradients are contrasted by the steeper gradients of the Cuban insular slope, which can range from 1° to 9° (as seen in Figure 4c). Compared to its western portion, the northern insular slope off Holguín and Cape Maisí is notably wider, with a range of 30 km wide to the North of Holguín up to 50 km wide in the area adjacent to the Cauto-Nipe tectonic corridor (Figure 4).

4.2. Seismic Stratigraphy

The 2D MCS data (represented by the solid lines shown in Figure 4b) were used to determine the main seismic units and related structures in the study area. Interpretation of seismic profiles allowed us to recognize eight seismic units based on: (a) their seismic facies (e.g., amplitude, lateral continuity, and frequency of internal reflectors), (b) bounding discontinuities, and (c) stratal architecture. The seismo-stratigraphic units were distinguished and labeled from older (Unit A) to younger (Unit E) in addition to the acoustic basement (Figure 3). Other local but distinctive seismic units are the Bahamian reefs and ophiolites (Figures 5–11).

4.2.1. Basement

The study area's deepest reflectors consist of primarily disorganized and chaotic reflectors, referred to as the "acoustic basement." These chaotic reflectors of the acoustic basement are interrupted by normal faults that

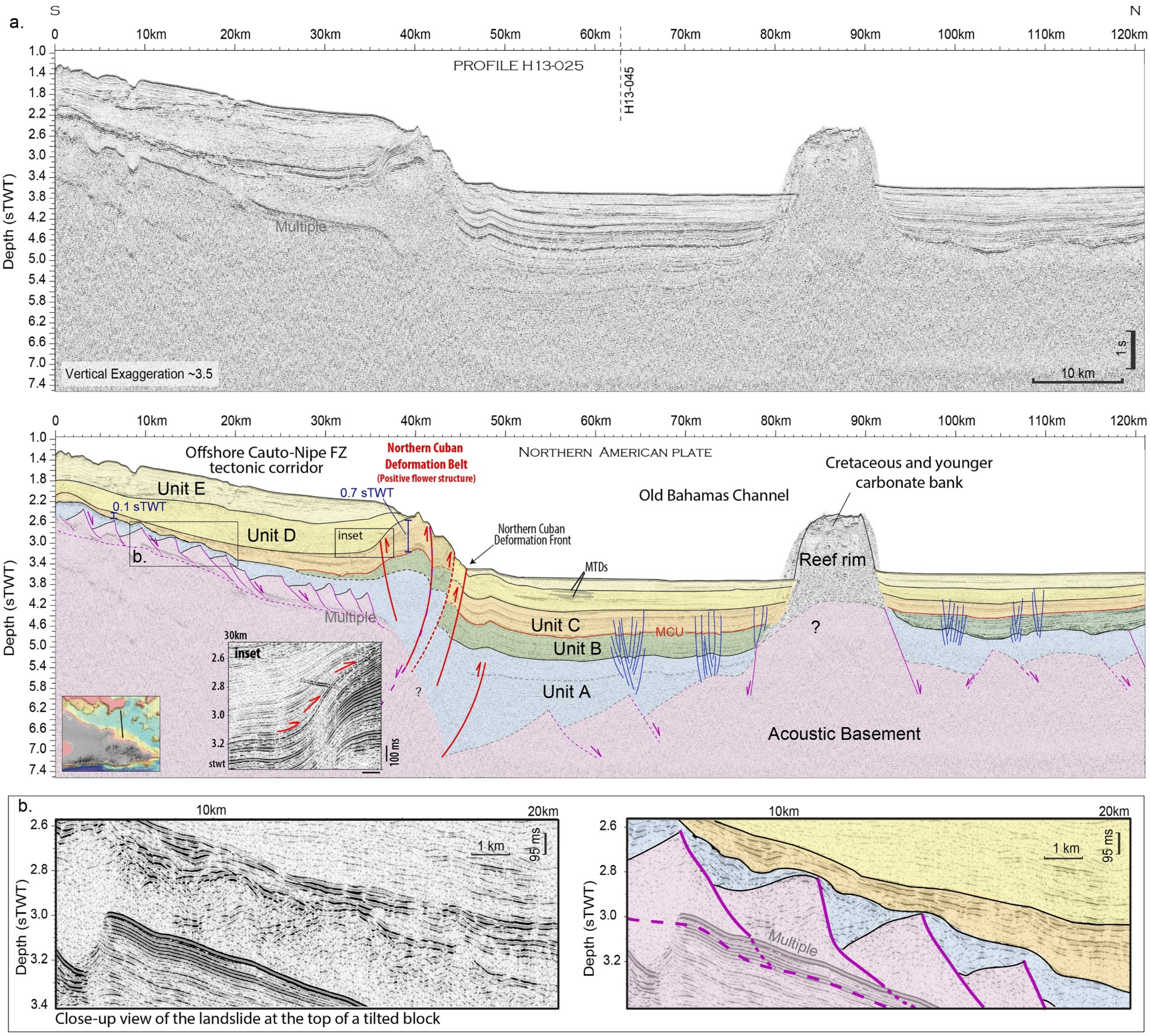

Figure 5. Seismic line H13-025. (a) Multichannel seismic profile across the Old Bahamas Channel, oriented south-north, showing the insular slope architecture created by the folding of seismic units toward the south. The associated pre- and syn-growth strata are discussed in Section 5.1.2. The faults in red represent thrusts and reverse faults, forming the Northern Cuban deformation belt. Normal faults are delineated in violet. Dashed lines in violet denote inferred normal faults deduced from the deformation architecture of Unit A. The blue faults illustrate steep minor faults, which display a combination of normal and reverse offsets described in Section 4.3.3. MCU: Mid-Cretaceous Unconformity. See the seismic line location in the inset and in Figure 4a. (b) Enlarged sector showing a sequence of tilted blocks in a domino style affecting the basement of the insular slope (see location in b).

intersect the deepest traceable reflectors in the seismic sections, creating accommodation space for the deposition of Unit A above. Tilted blocks are inferred from the rugged and stepped morphology of the acoustic basement top (Figures 5–11).

4.2.2. Unit A

Unit A is the deepest seismic sedimentary unit, which exhibits distinct high-frequency parallel reflectors with moderate amplitude and slight local divergent geometry. This unit thickens toward the hanging wall of normal faults and gradually decreases in thickness toward tilted blocks with onlap terminations, forming syn-rift wedges (Figures 3, 5, and 7–9). Toward the west, the roughness of the unconformity at the top of Unit A indicates that it

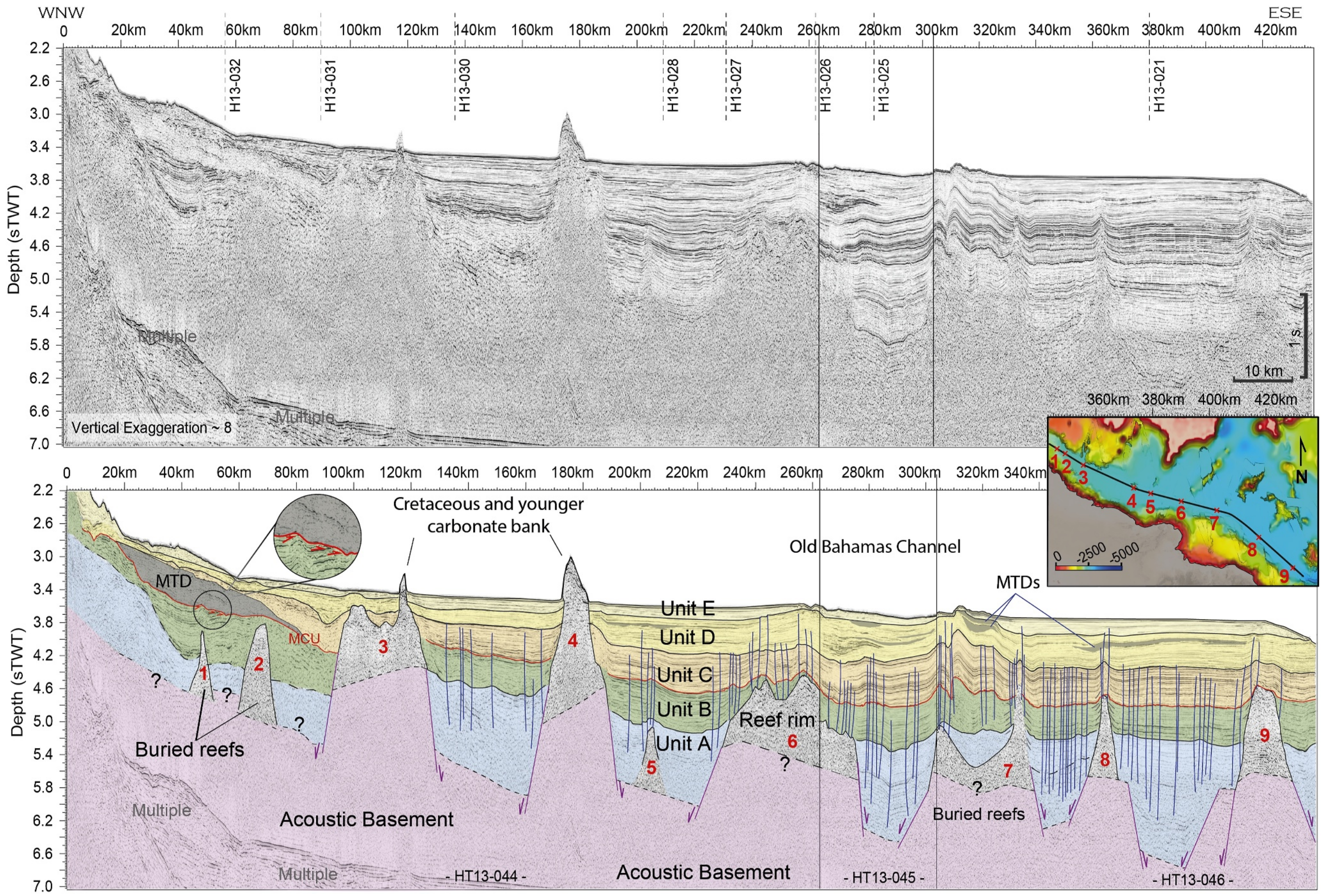

Figure 6. Composite seismic profile (seismic lines HT13-004, HT13-045, and HT13-046) along the Old Bahamas Channel from WNW to ESE. The red numbers along the profile indicate the locations of the identified carbonate mounds. While mounds 3 and 4 emerge on the seabed, the remaining carbonate mounds are buried. Notably, these buried carbonate mounds seem to be a continuation of the carbonate mounds that emerge further eastwards. This relationship is illustrated in the inset, which displays a bathymetric map indicating the position of the seismic profile and the distribution of carbonate mounds along its entire length. Mass transport deposits are represented in gray color. MCU: Mid-Cretaceous Unconformity. See Inset and Figure 4a for the location of the profile.

has undergone significant erosional processes (Figures 10 and 11). The eastern part of Unit A is disrupted by some growth faults (in blue Figures 5b, 6, and 8).

4.2.3. Unit B

Unit B is characterized by high-frequency subparallel to parallel reflectors, displaying moderate to high amplitude, alternated by levels of low amplitude to transparent (Figures 3, 7, and 8).

The deformation patterns within Unit B exhibit significant lateral variability. In the northern limit of the insular slope domain (faults in red in Figures 5, 7–9), Unit B is offset by numerous reverse faults and folds. In the western domain of the Old Bahamas Channel, Unit B is characterized by a rugged unconformity, indicated by the red horizons in the seismic profiles, (Figures 5–11). This unconformity is further accentuated by toplap terminations and truncated reflectors of the overlying Unit C (Figures 6 and 10).

In contrast, moving eastward, the unconformity becomes less pronounced, and Unit B is observed as a draping layer, appearing relatively isopachous with minimal evidence of truncation (Figure 6). However, unlike the western region, the eastern portion of Unit B is disrupted by a series of growth faults, which intersect with Unit A (in blue in Figures 5b, 6, and 8).

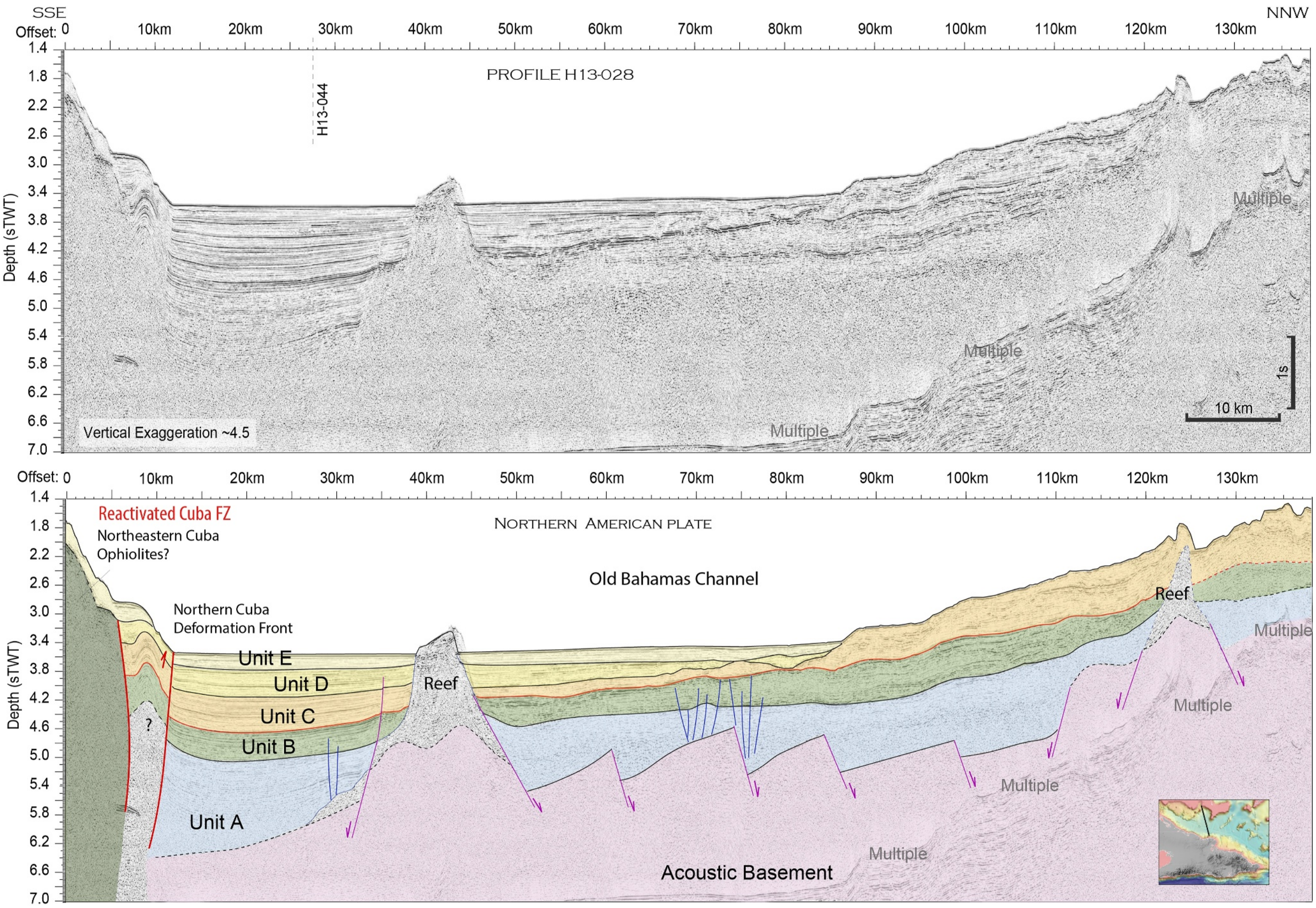

Figure 7. Seismic line H13-028. (a) Multichannel seismic profile across the Old Bahamas Channel, oriented SSE-NNW, showing the abrupt contact between the seismic units A to D with a body toward the south, which we interpreted as the offshore part of the Northeastern Cuban ophiolites outcropping on land. MCU: Mid-Cretaceous Unconformity. See the seismic line location in the inset and in Figure 4a.

4.2.4. Unit C

Unit C is composed of moderate to high amplitude sub-parallel to parallel reflectors (Figure 3). Seismic reflection profiles in the northern offshore area of the Cauto-Nipe tectonic corridor (see Figure 4a) reveal local thickness variations of Unit C, as the gradual increase seaward from around 0.1 s TWT to 0.7 s TWT along the hanging wall antiform (refer to Figure 5a). This is not observed in other seismic profiles of the same orientation located to the west outside the Cauto-Nipe tectonic corridor (Figures 7 and 8).

The thickness of Unit C also exhibits variation toward the east (from 0.3 s TWT to 0.6 s TWT, Figure 6). However, in the western portion of the Old Bahamas Channel, seismic reflections of Unit C display limited lateral continuity adjacent to a large chaotic/transparent seismic body with only a few distinguishable reflectors (Figure 6, km 20–100 and Figure 10, km 20–40). These chaotic/transparent facies are interpreted as large mass transport deposits (MTDs) situated in the narrower part of the Old Bahamas Channel toward the west.

4.2.5. Unit D

Unit D is characterized mostly by parallel low to moderate-amplitude reflectors (Figure 3).

In the insular slope domain, Unit D fills the accommodation space created by the fold units beneath, outlining a syncline with an E-W axis (Figure 5a, km 0–40) and NW-SE axis (Figure 9, km 0–30). Its thickness reaches almost 1 s TWT (Figure 5). The dip of Unit D reflectors progressively decreases upward near the fold from older to younger levels (Figure 5 inset), creating a syn-tectonic wedge shape that onlaps the upper unconformity of Unit C (refer to Figure 5, km 30–45). This geometry highlights Unit D as a growth strata.

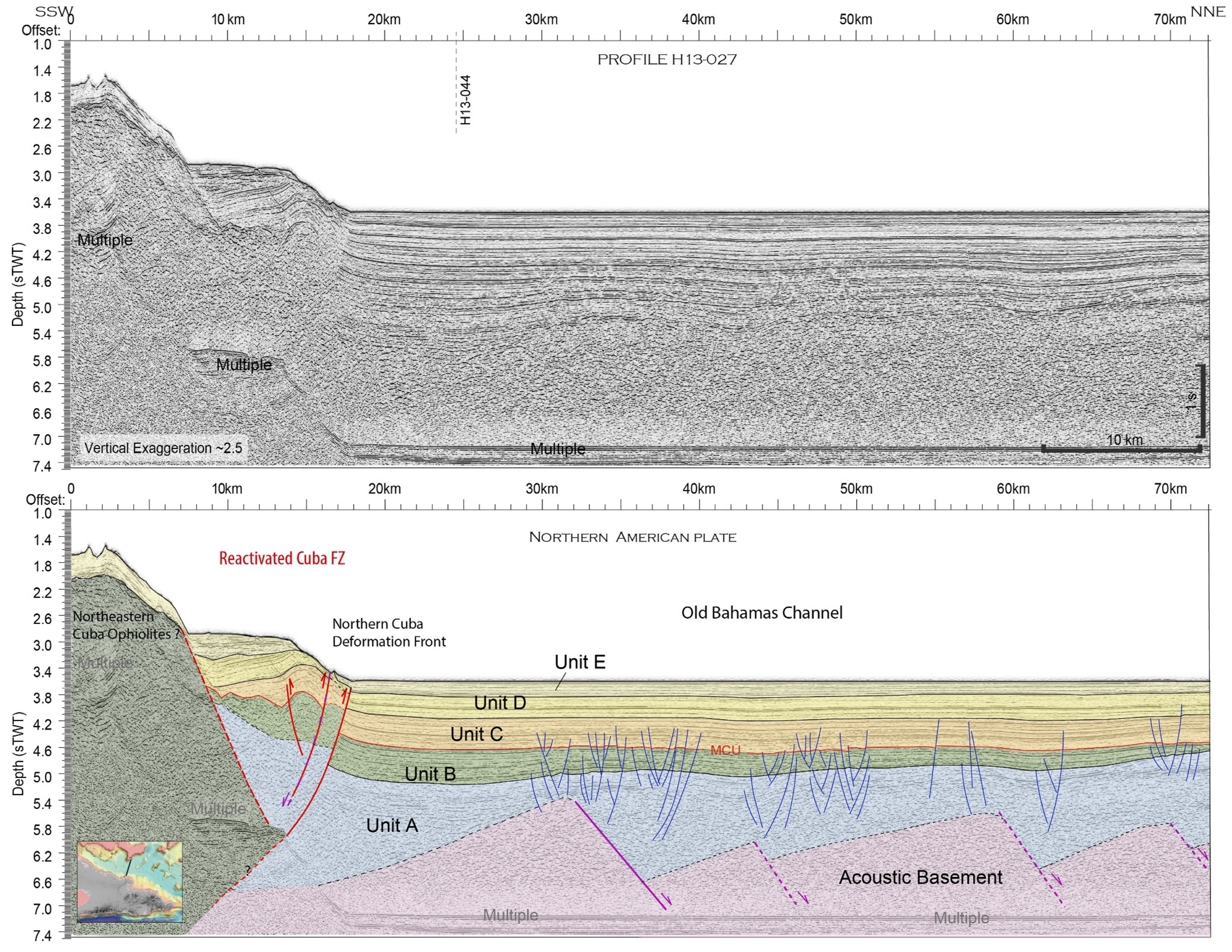

Figure 8. Seismic line H13-027. Seismic profile crossing the Old Bahamas Channel from SSW to NNE. MCU: Mid-Cretaceous Unconformity. See Figure 4a and inset for the location of the profile.

Outside the insular slope domain, Unit D thickness is not greater than 0.4 sTWT (Figures 8 and 9). In the eastern part of the Old Bahamas Channel, the topmost part of Unit D presents several isolated MTDs (Figure 6, km 300–420).

4.2.6. Unit E

Unit E is characterized by continuous plan-parallel reflectors with high amplitudes and high frequency (Figure 3). It is deposited on Unit D mostly without deformation (Figure 6). However, toward the west, where the Old Bahamas Channel is narrower, the upper portion of this unit has undergone extensive erosion (Figures 10 and 11).

4.2.7. Other Seismic Features—Bahamian Highs and Chaotic Bodies

The seismic profiles intersect several Bahamian highs, some of which are also identifiable by the topographic features shown on the bathymetric map (Figure 4). These highs have a distinctive mound shape on the seismic profile and are characterized by irregular, weak, and discontinuous internal reflections (Figures 4 and 5). Some highs reveal evidence of layering at their top (as in Figures 5 and 7). However, reflections are highly attenuated with depth. Certain are well-developed and take the form of ridges on the ocean floor, oriented in NE-SW direction (Figure 4). However, others are completely buried by Units B, C, D, and E (e.g., Figure 6). These buried

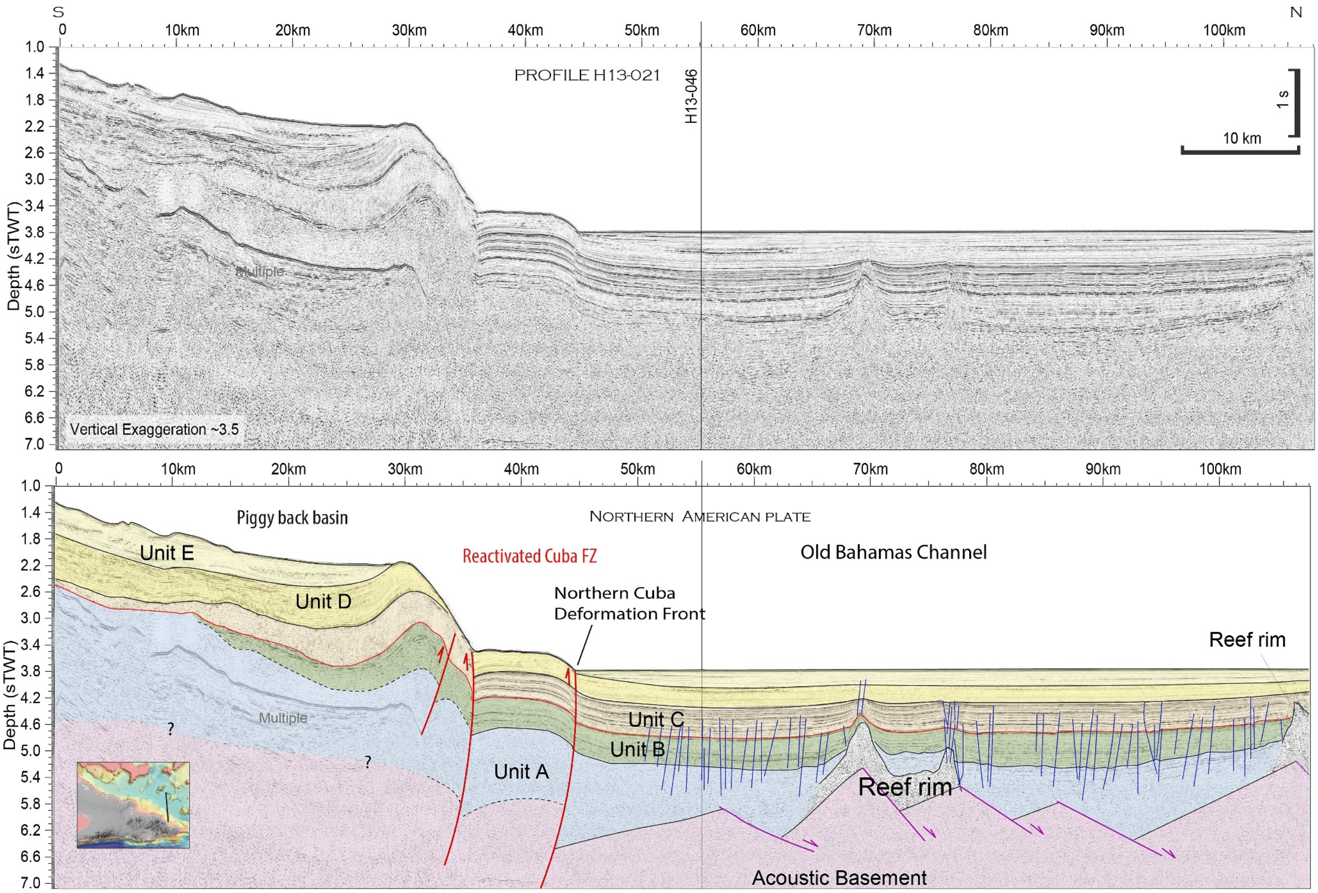

Figure 9. Seismic line H13-021. Seismic profile crossing the Old Bahamas Channel from south to north. MCU: Mid-Cretaceous Unconformity. See the inset and Figure 4a for the location of the profile.

highs appear to be the southwestern extension of the NE-SW oriented carbonate banks that emerge on the seafloor (inset in Figure 6).

Unit B is seen overlapping the flanks of these dome-shaped formations up to it fully overlays them, whereas the more recent Units C, D, and E continue to deposit on top of them. Highs seem to be rooted in basement highs as horst or tilted blocks (Figures 4c, 5, 6, and 7). Toward the east, sediment layers overlying the buried highs are tilted due to the upward growth of these highs (see Figure 6, km 280–450). The onlap terminations against the highs are bent upwards along its flanks. Generally, the vertical upturn remains relatively consistent from Unit A to the top of Unit B, gradually decreasing upwards throughout Unit C (Figure 6).

In the seismic profiles located off the northeastern Cuban Ophiolites and Holguin ophiolites (Figures 1 and 4a), seismic units from the basement up to Unit D terminate westward abruptly against a chaotic body situated on the north coast of Cuba (as shown in Figures 7 and 8). However, due to intrinsic chaotic seismic signals and the presence of seabed multiples, the internal structures of this body are obscured, making the interpretation very difficult. The lateral contact between the chaotic body and the sedimentary seismic units up to Unit D is discordant, but Unit E is observed to overlie the chaotic body at its top.

4.3. Structural Analysis

4.3.1. Tilted Basement Blocks

Significant thickness variation in Unit A implies that it was formed in grabens and half-grabens that were actively subsiding (see Figures 5–7). This syn-sedimentary unit likely accumulated in half grabens and narrow basins during an extensional phase. The thickness of Unit A increases toward the south at the toe of the insular slope,

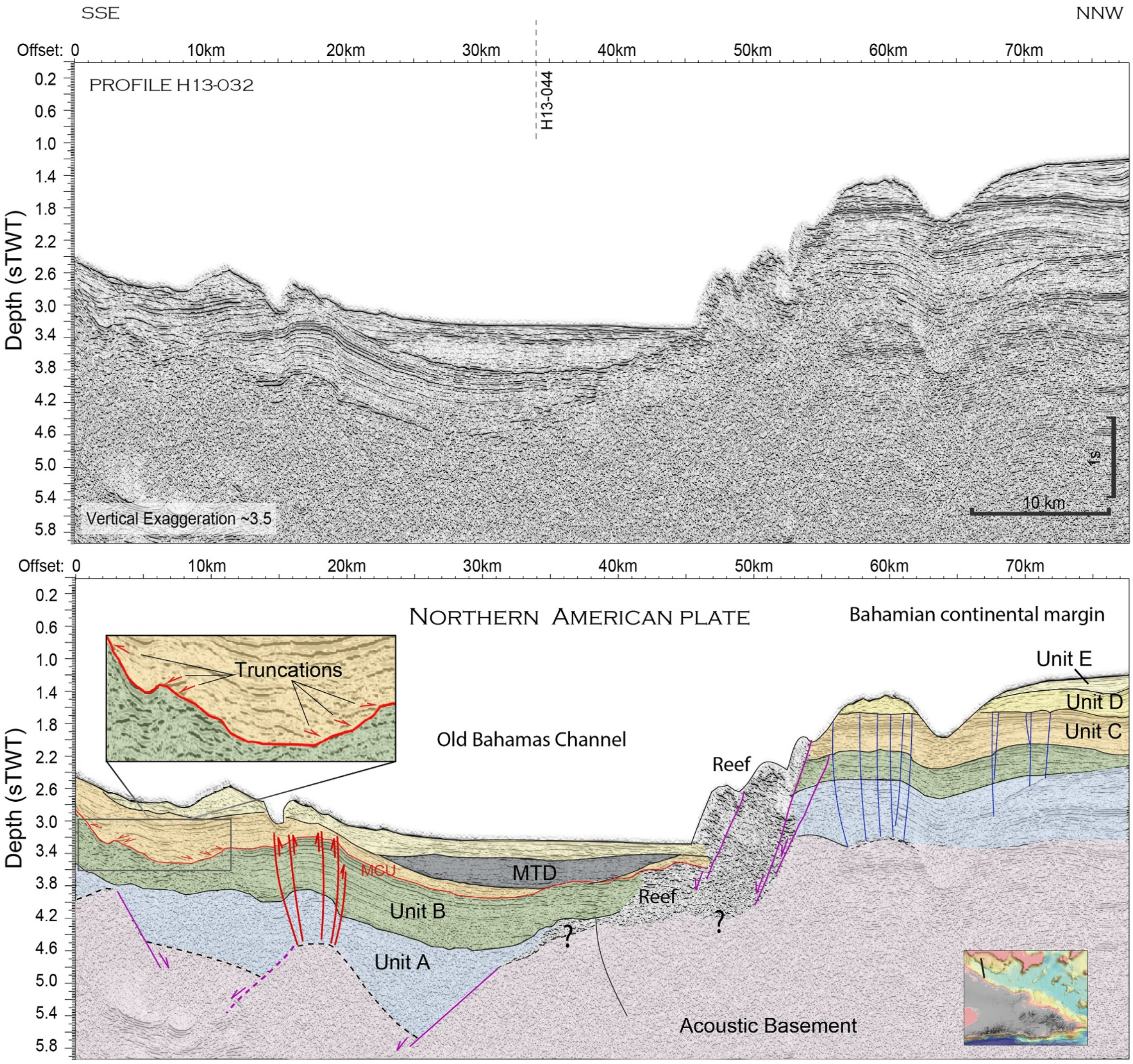

Figure 10. Seismic line H13-032. Seismic profile crossing the Old Bahamas Channel from SSW to NNE. MCU: Mid-Cretaceous Unconformity. See the inset and Figure 4a for the location of the profile.

where a major north-dipping normal fault could have played (Figures 5 and 7). In several NNW-SSE trending seismic reflection profiles (Figures 5 and 7–9), the basement is observed to be tilted toward the normal fault planes, exhibiting a tilted block geometry with a NE-SW orientation and forming asymmetrical half grabens (Figure 4c). The size of the tilted blocks varies across the study area, with smaller blocks measuring approximately 3–5 km in the insular slope domain (Figure 5b) and larger blocks ranging from 10 to 20 km in the deeper part of the Old Bahamas Channel domain (Figure 6). In the insular slope domain, small tilted blocks are bounded by normal faults, likely situated above a concealed decollement crosscutting the top of a large tilted block (pink dashed line below the tilted blocks in Figure 5a—from 0 to 36 km). This decollement is inferred because it is not visible in the seismic profiles due to the seabed's multiple (Figure 5b).

4.3.2. Thrust Faults

Multibeam bathymetry over the insular slope shows one to three ridges displaying a WNW-ESE trend (Figure 4c). This undulating surface morphology is mostly the expression of a narrow imbricate thrust belt where ridges are the surface expression of northward-verging fault-propagation folds along the offshore area adjacent to the Cauto-Nipe corridor (Figure 5, km 35–50 and Figure 9, km 35–45). Major frontal thrust faults at the insular slope base are inferred from the folded and faulted seismic units (Units A to D) in the Old Bahamas Channel.

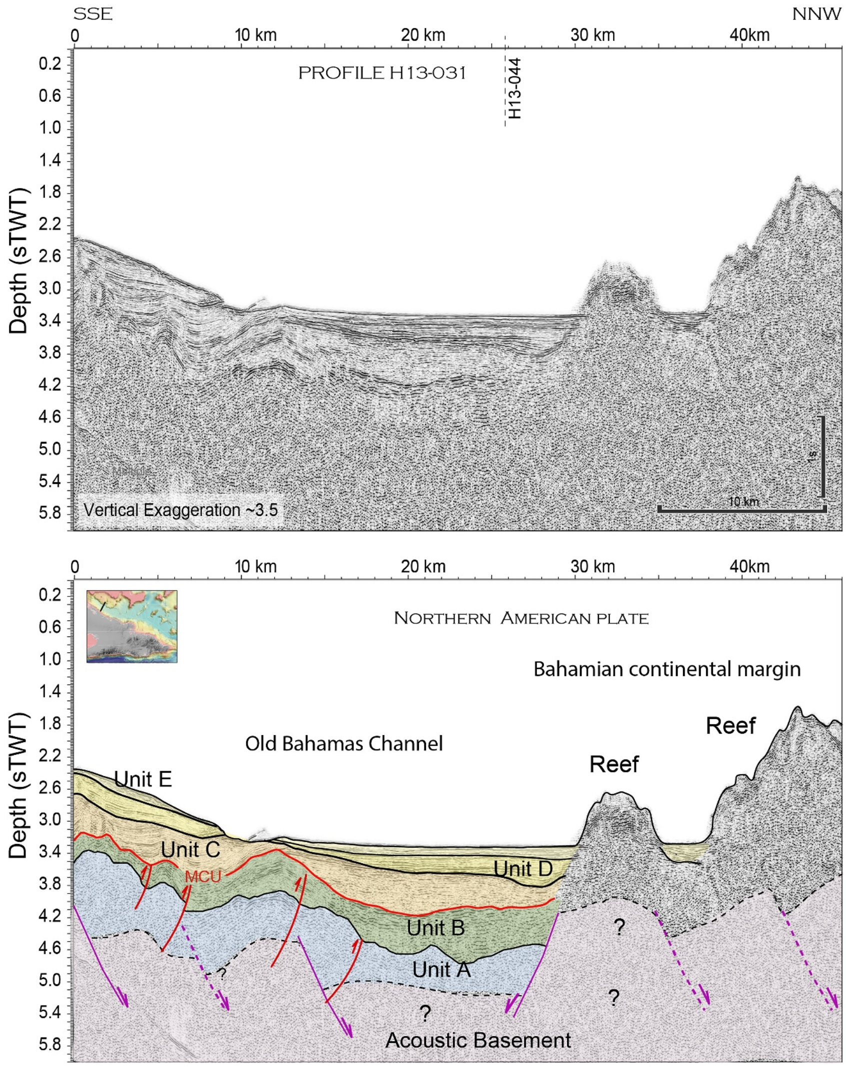

Figure 11. Seismic line H13-031. Seismic profile crossing the Old Bahamas Channel from SSE to NNW. MCU: Mid-Cretaceous Unconformity. See the inset and Figure 4a for the location of the profile.

In the offshore area at the toe of the insular slope, the thrust faults cross-cut the seafloor (Figures 5 and 7–9). In contrast, toward the west, blind thrust fault tip points generally lie within Unit B (Figures 10 and 11). In Figure 11, the folding of Unit B indicates contraction, implying the presence of buried thrusts within this unit. Deformation decreases upwards, with the upper Unit C barely folded. Note how the folding is less effective toward the West through Unit C in Figure 6. However, the folding is still ongoing in the eastern part of the study area, as shown in Figures 7–9.

Thrust faults along the Cauto-Nipe corridor deform the seismic units forming a typical contractional structure with an asymmetrical hanging wall anticline and footwall and a large syncline ranging from 5 to 40 km (Figure 5). Note that Unit D thickens on the trough of the syncline while thinning on the crest of the anticline (inset in Figure 5a), reflecting sedimentary response when the frontal thrust faults were active (Figure 5, km 30–45). Unit D has been deposited in a piggyback basin over a forming synclinal fold in the fault hanging wall. The complementary pairs of high-angle reverse faults bounding northward the Cauto-Nipe basin outline a positive flower structure (Figure 5, 35 km). The fault geometry and thickness variations that alternate in time and space may also suggest that this domain is a heavily sheared area that suffered from transtension and transpression before Unit D deposition along WNW-ESE-trending structures.

4.3.3. Growth Faults

The study area is affected by several steep growth faults that display both small normal and reverse offsets that locally converge at depth (blue lines in Figures 5 and 8). Most of the faults die out downwards toward Unit A and seem to be directly correlated with the older normal faults disrupting the basement. The minor fault branches propagate upward within Unit C in the offshore area of the Eastern Cuban block and in the Bahamian domain (Figures 5–10). Some of these faults extend over the tops of buried reefs and can impact the base of Unit D (Figures 8 and 6).

5. Discussion

5.1. Age of Seismic Units

The stratigraphic framework for the offshore region of Western and Central Cuban blocks was proposed in several works based on outcrops in Cuba (Caballero & Cabrera, 2003a, 2003b; Cruz-Orosa et al., 2012; Iturralde-Vinent, 1998; Iturralde-Vinent et al., 2008; Vázquez-Taset et al., 2020) and in seismic data tied with industry offshore and onshore wells (Gaumet et al., 2004; Masaferro & Eberli, 1999; Moretti et al., 2003; Uchupi et al., 1971; Walles, 1993). However, the stratigraphic setting for the offshore Eastern Cuban block remains uncertain, and the limited availability of sediment cores poses a significant challenge in interpreting the geological history of this region.

To determine the age of the sedimentary units in offshore Eastern Cuba, we reviewed the stratigraphic framework proposed in the literature and correlated it with our MCS data (Figure 3). Time attributions were not directly assigned to the seismic units but were estimated based on the correlation of their facies and deformation patterns, possibly related to major paleo-geodynamic events in the Caribbean region (Iturralde-Vinent et al., 2016) (Figures 2, 3, and 12).

5.1.1. Unit A

Thickness variation in Unit A implies that it was formed in grabens and half-grabens that were actively subsiding and driven by phases of extension (see Figure 5b). Half-grabens were also described in onshore outcrops in Western Cuba (e.g., San Cayetano Formation in Moretti et al., 2003). Masaferro and Eberli (1999) suggest that rifting in the southern Bahamas domain was controlled by several NW-striking strike-slip faults and NE extensional faults, which corroborates our structural interpretation showing similar NE-SW-striking normal faults separating tilted blocks (Figure 4c).

Mullins and Lynts (1977) proposed that the deep-water channels surrounding and dissecting the Bahamas Carbonate Province are influenced by a northwest-southeast structural trend, which parallels the magnetic anomaly trends across the region. These channel patterns would correspond to the major fault pattern along the eastern continental margin of North America, resulting from the rifting of North America and Africa in the Early Jurassic (Sheridan et al., 1981). In this case, the deep channels of the Bahamas are likely influenced and controlled by basement faults, as indicated by several studies (Ball et al., 1971; Glockhoff, 1973; Lynts, 1970; Malloy & Hurley, 1970; Mullins & Lynts, 1977; Sheridan et al., 1981; Talwani et al., 1960). The syn-sedimentary Unit A was probably deposited in half grabens and narrow basins formed during the former Pangea rifting phase (Figure 2a). It is probable that the tilted blocks identified in seismic profiles offshore the Eastern Cuban block were formed during the Triassic-Jurassic interval (Figures 2 and 12a).

Sedimentary rocks in eastern offshore Cuba should not be older than the Early Jurassic or possibly Late Triassic since the continents began to separate in the Middle Mesozoic. Thus, the syn-rift Unit A would then have a Jurassic age. This observation would be supported by offshore wells such as the Great Isaac well #1 (Iturralde-Vinent, 2003; Jacobs, 1971) (Figure 1), which intercepted syn-rift facies, mostly Jurassic redbeds (most like Callovian age) above crystalline basement rocks (Meyerhoff & Hatten, 1968, 1974). In Cuba, the oldest known sedimentary rocks of the Middle Jurassic age were observed on four salt diapiric structures (Cayo Coco) area exposed at Punta Alegre (Collazo 1 well), La Isla de Turiganó, and near Loma de Cunagua (Tina 1 and 2 wells; Haczewski, 1976) (Figures 3 and 12b).

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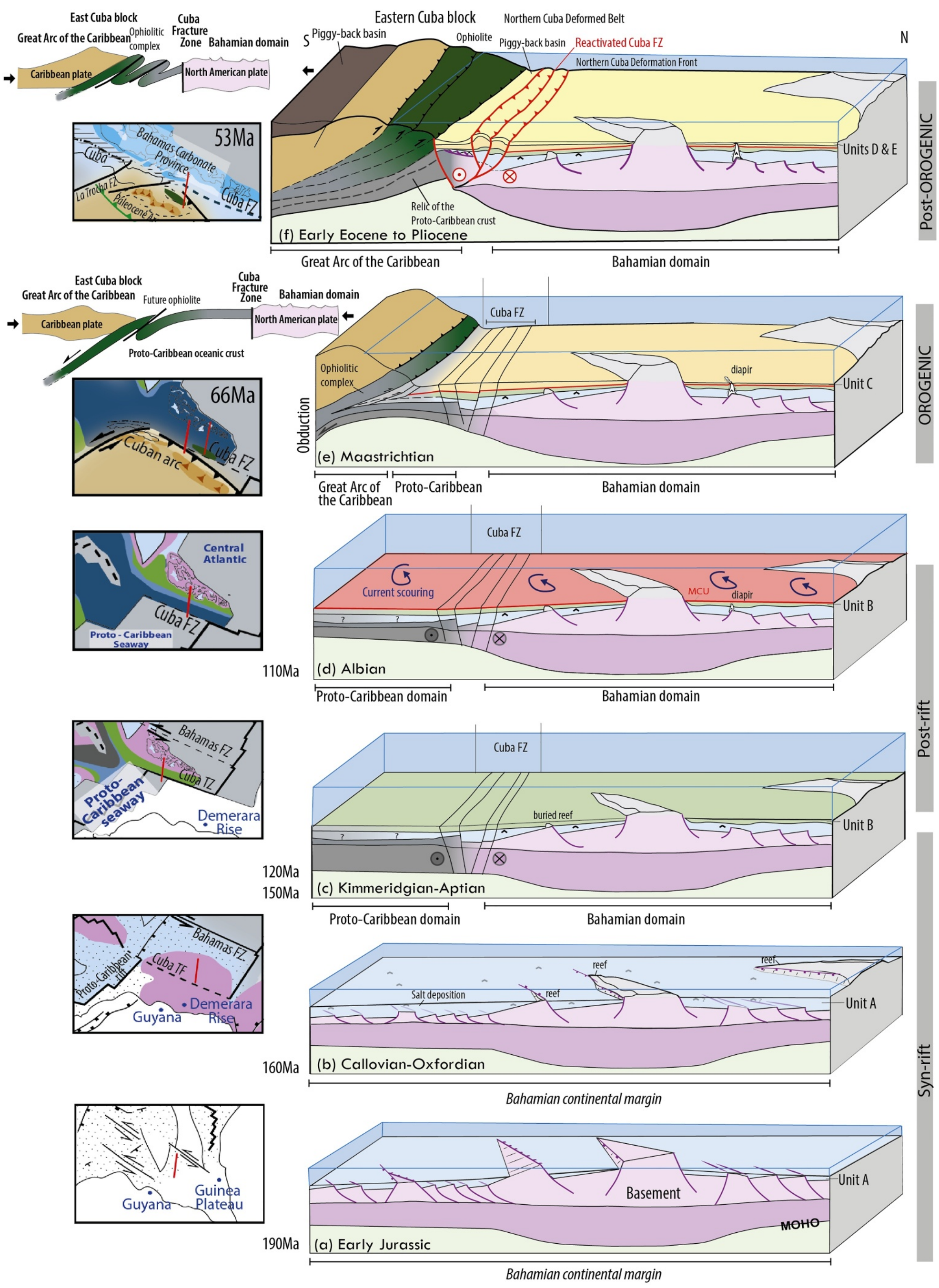

Figure 12. Interpretative geodynamic model for the evolution of the Eastern Cuban Offshore area from Early Jurassic to Present-day. 3D geologic sketches are based on the H13-025 profile (Figure 5) and paleo-reconstructions presented in Figure 2 and the close-up views (see Figure 2 for the captions). (a) During the Jurassic, Pangea rifting led to the development of NE-SW trending horsts and grabens in the proto-Caribbean and Bahamian continental margins. (b) The earliest carbonate banks of the Bahamas Carbonate Province were initiated as reefs accreted on the top of horsts and tilted blocks. (c, d) The emergence of the proto-Caribbean resulted in the creation of a Mid Jurassic-Lower Cretaceous Passive margin, which was later consumed by the subduction of the Proto-Caribbean crust. (e) In the late Cretaceous, the collision of the Caribbean plate with the North American plate formed the Cuban orogenic belt, a thrust system that transformed the Bahamas into a foreland basin. Simplified sketches show the likely ophiolite emplacement on the Eastern Cuban block during the Maastrichtian and its evolution afterward (f) During the Paleocene to the Early Miocene, continuing northeastward migration led to regional uplift. The loading of the Cuban orogeny caused flexural drowning, which persisted until the Middle Eocene. By the Late Eocene, collision decreased, and the Cuban island arc became attached to the North American plate.

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5.1.2. Unit B

The peak of transgression during the Berriasian period resulted in a change from dolomitic facies to slope and basin carbonate deposits (Figures 2d and 3) (Gaumet et al., 2004). During this time, restricted clastic inputs dominated western Cuba, with slope and basin carbonates being the primary facies association (Figure 3) (ODP wells 535 and 540; Figure 1).

The seismic facies of Unit B could be correlated with the sequences of the Berriasian-Cenomanian interval in the study of Moretti et al. (2003). These series are similar in their seismic facies and are characterized by high-frequency parallel reflectors that are coherent to transparent. It is likely that slope carbonate deposits also extended over the Eastern Cuban area during this time (Figure 3), while shallow water build-ups persisted locally (as the reef rims showed in Figures 5 and 6). The significant flooding event in the Berriasian time sealed all tilted blocks in Western and Central Cuba, resulting in the homogeneous deposition of deep carbonates over the Jurassic syn-rift (Gaumet et al., 2004). Hence, the Jurassic-Cretaceous boundary marks the end of the main syn-rift phase in the region, as the rifting in the southeastern Gulf of Mexico ceased (Figures 2 and 3) (Gaumet et al., 2004).

The starvation of sediments resulted in erosion and non-deposition across Cuba, and Upper Cretaceous sediments were rarely deposited and preserved in the Gulf of Mexico and the Yucatan margin. A rough Post-Cenomanian unconformity called the "Mid-Cretaceous Unconformity—MCU" truncates the Early Cretaceous deposits in the Gulf of Mexico and Cuba (Gaumet et al., 2004; Moretti et al., 2003). In our MCS profiles, we image a rugged unconformity at the top of the Unit B, likely corresponding to the Mid-Cretaceous Unconformity (MCU) (Figures 5–11). The MCU represents a large hiatus of variable duration (Figure 3). In some localities in the Gulf of Mexico, this hiatus spans almost the entire Late Cretaceous (Well 540, Schlager et al., 1984). In Cuba, MCU developed after the Late Cenomanian and continued until the Maastrichtian or later (Figure 3) (Gaumet et al., 2004; Moretti et al., 2003). The MCU is a combined result of low sediment input, current scouring, and slumping on steep slopes along the Florida-Bahamas Platform (Schlager et al., 1984). However, the reasons for the prevailing non-deposition phenomenon from the Turonian up to the Campanian remain incompletely understood. The closure of the connection between the Pacific and the Proto-Caribbean by the Great Arc of the Caribbean likely caused palaeo-oceanographic changes, which may have led to the MCU regional hiatus (Figure 2d) (Gaumet et al., 2004; Malfait & Dinkelman, 1972; Schlager et al., 1984; Sykes et al., 1982).

5.1.3. Units C, D, and E

Unit C recovered the MCU and was deposited in the Old Bahamas Channel as deep-sea sediments (high frequency, coherent, and parallel reflectors). It would consist of clastics and flysch deposited in the deeper part of the Cuban flexural (foreland) basin (Figure 1b) (Cobiella-Reguera, 2009; Gordon et al., 1997; Moretti et al., 2003). The origin of the large MTD in Figures 6 and 10 is likely associated with the sliding of a portion of Unit C. The MTD deposit displays a few discernible reflectors, suggesting that it comprises blocks likely derived from Unit C. The blocks may slide gradually during a folding phase caused by a collisional event.

Determining pre- and syn-orogenic strata related to the onset of collision indicates that sedimentary units preceding the deposition of Unit D are pre-orogenic strata. In contrast, Unit D is syn-orogenic (Figures 3 and 5), while the continuous plan-parallel reflectors of Unit E indicate post-orogenic strata. This classification implies that the pre-orogenic units are at least as old as the Early Eocene (Figure 3).

5.2. Main Structural and Geological Features

5.2.1. Rifting of the Eastern Cuban Block

The Pangea rifting led to the development of NE-SW horsts and grabens in the Proto-Caribbean and Bahamian continental margins during the Jurassic (Figures 2 and 12; Marton & Buffler, 1994; Padilla y Sánchez, 2016; J. Pindell & Kennan, 2001; Salvador, 1987).

As extension proceeds and uplift occurs on the proximal margin, the differential vertical movement between the proximal and distal parts of the margin increases the slope of the margin. The tilted small blocks in domino observed on the top of the basement in the Cuban margin probably occurred at the end of the rifting along a decollement layer in the pre-rift series (Figure 5b). Such destabilization of tilted block tops has already been observed and proposed on several continental margins in the Gulf of Aden and southern Somalia, for example, (e.g., Autin et al., 2010; Sapin et al., 2021).

5.2.2. Reef Related to Basement Features and Sea-Level Rises

The Bahamian highs corresponding to reefs in the studied region display a distinct NE-SW orientation, indicating that the tilted blocks supporting these reefs and the faults bounding them also have NE-SW orientation (Figures 4a and 4c). This would support the idea that carbonate bank deposition likely began concurrently with or shortly after the extensional phase ended. Likely, the growth of carbonate reefs occurred concurrently with the deposition of Unit A, as shown in Figures 3, 5, and 6. Given the stratigraphic position of the reef rims in seismic profiles shown in Figures 5, 9, and 11, the reef accretion likely developed on top of tilted blocks and ended in the Late Jurassic to the Mid-Cretaceous (Figure 12c). This would agree with the "Graben hypothesis" (Mullins & Lynts, 1977) in which the earliest carbonate banks may have initiated as reefs on the top of tilted blocks raised into the photic zone (J. Pindell, 1985).

Bathymetric data show that the carbonate banks of the Bahamas become deeper toward the south until they disappear in the Old Bahamas Channel (Figure 4). Only a few carbonate banks outcrop in the Old Bahamas Channel, where most of these reefs are buried by Unit B, as in the seismic profiles shown in Figures 6 and 9.

The rate of reef accretion depends on a range of environmental factors, including sea level changes, water temperature, nutrient availability, and ocean circulation patterns (Kuffner, 2018). During periods of sea level rise or tectonic subsidence, coral reefs may be able to keep pace by growing vertically to maintain their position relative to the water surface. However, if the rate of sea level rise or subsidence exceeds the rate at which the coral reef can grow vertically, the reef may become submerged and eventually die off (Kuffner, 2018). The reef burial asymmetry between the northeast and the southwest cannot be explained by a sea level variation that would have had a regional consequence. However, a subsidence rate more important in the south than in the north could explain the burying of these features.

In the Aptian period, the Bahamas Platform underwent back-stepping due to eustasy and subsidence, as documented by Sanchez et al. (1999). Back-stepping of the southern region of the Bahamas platform is probably associated with the ongoing subduction of the Proto-Caribbean seaway under the Caribbean plate from the Middle to Late Cretaceous (Figures 2 and 12). The subduction of the Proto-Caribbean crust beneath the Great Arc of the Caribbean during the Cretaceous period likely caused a flexure in the upper plate (Bahamian domain), which further accentuated subsidence in its southern domain. This process is evidenced by the deepening of the basement towards the south, resulting in increased subsidence in the southern area of the Old Bahamas Channel. The progressive burial of the Bahamian reefs in the southern part and the deepening of the top basement is likely the result of this flexural subsidence (as illustrated in Figures 5–9).

The establishment of a deep basin environment during the Middle-Upper Cretaceous in the southern domain of the Bahamas platform is likely attributed to the flexural subsidence. This phenomenon probably caused the drowning of carbonate banks in the area and their subsequent burial during the Unit B deposition (Figures 2d and 3).

5.2.3. Evidence of Salt

Some dome-shaped forms interpreted as buried reefs (features 1, 2, and 5 in Figure 6) are geometrically similar to salt diapirs, with overlain sediment layers upturned (Figure 6, in gray lines km 340 and km 360) and a localized deformation at the top layers by minor radial faults. In this case, the hypothesis of salt deposition during the extensional phase in the Eastern Cuba region (Figures 2a and 2b) would be evoked, supporting the idea of an evaporative basin where salt deposition occurred in the Old Bahamas Channel.

The salt occurrence in the Punta Alegre Formation in western Cuba (possibly Callovian age, e.g., Cousminer et al., 1957) implies that it is possible to find some salt deposition offshore Cuba. Salt diapirs outcropping on land in the Cayo Coco area (Figure 1) are related to Jurassic evaporite deposits (Bouton et al., 2016; Meyerhoff & Hatten, 1968). This supports J. Pindell and Kennan (2001)'s interpretation that a second evaporite basin with lesser salt was deposited in the Bahamas domain during the Middle-Upper Jurassic under shallow water conditions (Figure 2b).

Salt diapirs were previously reported offshore in the Bahamas mega-platform (Ball et al., 1985; Lidz, 1973). The hundreds of meters of evaporites found on Andros Island, Cay Sal Bank, and Doubloon Saxon deep wells (Figure 1) would support the hypothesis that a Middle-Upper Jurassic evaporitic basin may extend to the Eastern Cuba area. In this case, the upper portion of Unit A would contain evaporitic layers that were subsequently mobilized as upward-moving salt as salt domes or along the flanks of buried carbonate reefs. Deformation patterns and upward domes, potentially salt diapirs, coming from Unit A suggest the earliest salt deposition in the Eastern Cuba area during this syn-rift phase. The upward bending of the onlap terminations against the flanks of the buried reefs implies that these reefs have either undergone upward displacement or that a highly viscous fluid rheology material has moved upwards along their flanks (Figures 6 and 9).

However, the seismic resolution of our seismic lines cannot image these structures in detail. Moreover, considering the geometry of domes 1, 2, and 5 visible in Figure 6, and their similarity and proximity to the buried carbonate banks, we prioritize the hypothesis of buried reefs to explain the origin of these structures.

5.2.4. Structure and Deformation in Insular Slope: Strike-Slip, Compression, Reactivation

The appearance of a bi-vergent fold-and-thrust system similar to a positive flower structure downslope in the insular slope domain could be interpreted as a result of a compressional phase or due to the reverse reactivation of strike-slip faults formed at the onset of a contractional phase. However, the thickening of Units B and C in the insular slope domain, shown in Figures 6 and 10, may have resulted from strike-slip deformation with an extensional component, possibly related to an ancient shear zone. This suggests the possibility of strike-slip activity during the deposition of Units B and C. During this period (Cretaceous), the study area was located on the Cuba FZ, which was considered the plate boundary between the Proto-Caribbean plate and the Bahamian domain (Central Atlantic domain, Figures 2d, 2e, and 12) (Klitgord et al., 1984).

In the offshore prolongation of the Cauto-Nipe tectonic corridor, Units B and C are marked by a variation in thickness, which may be related to a transtensive play during their deposition (Figure 4). This area may correspond to the ancient location of the NW-SE-oriented Cuba FZ, which was recently affected by the activity of the nearly E-W-oriented Cauto-Nipe Faul Zone (Figure 2f). The reactivation of these ancient shear faults during a contractional phase would result in the formation of a flower structure at the deformation front (Figures 5, 8, and 12).

The reactivation of faults is likely associated with a reorganization of the regional stress regime (Bellahsen et al., 2006). This change in the stress regime is also manifested by the presence of minor faults that affect Unit C in the Old Bahamas Channel (shown as blue faults in Figures 5 and 6). These minor faults exhibit both normal and reverse offsets that converge at depth. Most of these faults terminate downward toward Unit A and appear to be directly correlated with older normal faults, suggesting that they are also linked to the stress reorganization that occurred at the beginning of the Unit C deposition. However, their activity diminishes as Unit C is deposited, and they appear to be no longer active during the deposition of Unit D. This plate reorganization could be associated with the end of the subduction of the Proto-Caribbean oceanic plate and the consequent extinction of the Cuba FZ (Figure 2e, Paleo-geodynamic events inset in Figure 3).

Sedimentary units up to Unit E exhibit folding and the northern boundary of the insular slope is delineated by several imbricated thrusts. These features suggest that a period of contractional activity affected the sedimentary record in the Old Bahamas Channel and, in particular, at the northern boundary of the insular slope, indicating a deformation front to the north.

Analysis of pre- and syn-orogenic strata shows that Units A, B, and C are pre-folding strata, while Unit D represents syn-folding strata (Figure 5). The folding mechanism that affected Units A, B, and C created an anticline ridge along the hanging wall frontal thrust and a syncline on top of the moving thrust sheet, forming a piggyback basin that runs alongside the continental slope. This basin extends from the offshore region of the Cauto-Nipe tectonic corridor and eastward until the Windward Passage area (Figures 4, 5, and 9). This piggyback basin trapped the syn-orogenic deposition of Unit D. These compressive features could follow the end of the subduction of the Proto-Caribbean oceanic plate when the Cuba FZ was located against the deformation front (Figure 2e) and associated with the start of the Great Arc of the Caribbean- Bahamian collision phase (Figures 2f and 12).

5.3. Geological Evolution of the Old Bahamas Channel, Eastern Cuba Block

The geological history of the Eastern Cuba block has been shaped by various geodynamic events, including the syn-rift and post-rift phases, the syn-tectonic orogenic phase, the post-orogenic phase and the cumulative effect of shear episodes (Bahamas, Cuba, Cauto-Nipe Transfer/Transform/FZs) (Figures 2, 3, and 12). The stratigraphic findings discovered in Eastern offshore Cuba could be interpreted within the context of these events, as discussed in the following sections.

5.3.1. Post-Rift Phase

Unit B is relatively isopachous and deposited as a draping sequence without tectonic activity, indicating the end of an extensional phase. This unit, along with the younger units above it, is characterized by high-frequency, coherent, and parallel reflectors that are typical of deep basin environments. The hypothesis may be that the extensional phase is followed by a water depth increase due to subsidence and/or a sea level rise, creating space for the deposition of Unit B. This vertical movement impacted the vertical growth of some reefs that were unable to maintain their vertical accretion, leading to their abandonment and eventual burial during Unit B deposition (Figures 6 and 9).

The Bahamas Carbonate Province was likely well-developed during the Upper Kimmeridgian period, with carbonate platforms extending southwards, partially documented in the Cayo Coco Fm. in Central Cuba (Gaumet et al., 2004) (Figure 2c). However, the subsequent drowning phase during the Tithonian period resulted in a regional transgression giving place to deep carbonatic deposits (Gaumet et al., 2004). The deepening trend during the Upper Tithonian made more connections between the Gulf and Proto-Caribbean domains (Figure 2). According to Uchupi et al. (1971), the reefal-lagoonal deposits in the southeastern Bahamas diminished as the region began to subside during Early Cretaceous times. Therefore, channels became deep, and some ancient reefs were buried (Figures 6, 9, and 12d). However, some reefs eventually were perpetuated by reef growth, as shown in Figures 5, 6, and 11, giving rise to the current "bank-through" morphology of the Bahamas (Figures 1 and 2c).

Progressive drowning of the Bahamas platform led to the formation of a deep marine seaway (Gaumet et al., 2004). Since then, several deep marine seaways have continued to dismember the Bahamas Carbonate Province, contributing together with tectonics to the actual bank configuration. The slope of the banks is characterized by strong bottom currents, including turbidites and contourites, and features channelized systems. At the toe of the bank slope, intense current scouring eroded the sedimentary record (see "starved basin and MCU" in Figure 3). Our seismic profiles suggest that the MCU may correspond to the top erosional unconformity of Unit B, unconformity due to the activity of these bottom currents, particularly in the western area of the Old Bahamas Channel (Figures 6, 10, and 11). However, toward the east, this unconformity shows less evidence of erosion and is likely more related to a non-deposition hiatus (Figure 6). It is possible that the eastward basin was deeper than its westward continuity during the Cretaceous period, as the Cuban basins started to deepen after the Aptian (Moretti et al., 2003).

5.3.2. Orogenic Phase

In the Upper Cretaceous, the Proto-Caribbean Seaway was closed, leading to the reactivation of the Cuba FZ, the obduction of the ophiolitic complex, and the collision between the Great Arc of the Caribbean and the Bahamian domain (Figures 2, 3, 12e, and 12f). Pre-existing Bahamas and Cuba Jurassic faults certainly played an important role in the style of deformation generated by the Cuban convergent orogeny.

Eastern Cuba experienced an obduction process during the Maastrichtian (Ophiolitic domain of Holguín and Mayari-Sagua-Baracoa Mountains, shown in Figures 4a and 4b). On the seismic lines crossing the insular slope off Holguín province (Figures 7 and 8), seismic units are shown overlying a thick chaotic body, which could be interpreted as the offshore continuation of the Ophilitic complex in the Northeastern Cuban block (Figure 12e).

During the Late Cretaceous (Maastrichtian)/Early Paleocene, the Bahamas Carbonate Province became involved in the Caribbean-American collision (Figure 2e) (Boschman et al., 2014; Leroy et al., 2000; Mann et al., 1995; Masaferro & Eberli, 1999; J. Pindell & Barrett, 1991; Ross & Scotese, 1988).

According to Massafero and Eberli (1999), this reorganization of the stress regime caused the reactivation of Jurassic faults and, in particular, the major Cuban Transform Fault, which is interpreted in this study as being

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located at the plate boundary between the Proto-Caribbean plate and the Bahamian domain (Central Atlantic domain, Figures 2e, 12d, and 12e). Individual faults branched out from the deep basement, resulting in localized deformation at the toe of the insular slope (Figure 5, km 30–45). Ancient faults were also reactivated in the Cretaceous carbonate platform, and the southern Bahamas underwent fragmentation (see Figure 10, km 45–55 and, Figure 11, km 28–45) (Klitgord et al., 1984; Ladd & Sheridan, 1987; Sheridan et al., 1988).

The collision of the Great Arc of the Caribbean with the Bahamas Carbonate Province resulted in a drastic reorganization of the northern boundary of the Caribbean plate. The collision resulted in the formation of the Cuban orogenic belt, characterized by a thrust system, and turned the Bahamas region into a foreland basin. Consequently, the Bahamas' southern margin was diachronically imbricated in thrusts (Moretti et al., 2003; Saura et al., 2008; Stanek et al., 2009). As a result, a fold-and-thrust belt developed in northern Cuba (Iturralde-Vinent et al., 2008). The accreted belts extend parallel to the axis of the Island (Kerr et al., 1999). The steep margin that rimmed the northern coast of Cuba follows the same thrust front separating the thrust belt from the deep flexural basin northward (the Old Bahamas Channel). The Cuban fold-and-thrust belt moves from West to East, with the earliest deformation (Maastrichian-Palaeocene) occurring in western Cuba and the youngest (Middle Eocene) deformation occurring to the east in eastern Cuba (Figures 2f–2i) (Iturralde-Vinent, 1998; Vázquez-Taset et al., 2020).

The MTDs recorded in the Old Bahamas Channel support this diachronism, as they are younger toward the east (Figure 6). Our observations suggest that MTDs strongly correlate with ongoing collisions in the eastern Cuban block. As the collision starts earlier toward the west, the MTDs are recorded at the Paleocene-Early Eocene (Figure 6, km 20–100 and, Figure 10, km 20–45). However, as the collision progresses eastward and culminates in the collision of the paleo-arc terranes in Eastern Cuba against the paleo-margin of the Bahamas in the Middle Eocene (Cazañas et al., 1998), the MTDs are recorded later in the eastern part of the Old Bahamas Channel (likely in the Middle Eocene, Figure 6, km 300–420). MTDs in the study area may illustrate periods of intense tectonic activity accompanied by seismicity and high sedimentation rates offshore due to onshore erosion.

The pre-orogenic strata of Units A, B, and C have folded along the hanging wall frontal thrust, forming an anticline ridge illustrated in Figure 5. This folding mechanism has resulted in the development of a syncline on top of the moving thrust sheet, which is a common mechanism for forearc basins (Noda, 2016). This process has given rise to a stretched basin that runs parallel to the continental slope, contributing to the present morphology of the insular slope in the Eastern block (Figure 4b). We interpret this depression as a minor piggyback basin that has trapped the syn-orogenic deposition of Unit D (Figure 12f). The syn-tectonic wedge shape of Unit D suggests that its deposition occurred concurrently with the development of the syncline.

The widening of the insular slope and its current morphology would be related to the establishment of this piggyback basin on the northeastern Cuban coast (Figure 4b). The basin extends westward from the offshore region of the Cauto-Nipe tectonic corridor until the Windward Passage area (Figure 4a). According to Oliveira de Sá et al. (2021), the Windward Passage structure is associated with the emplacement of a piggyback basin during the Late Eocene. The diachronous collision with the Bahamas Carbonate Province probably created this piggyback basin that extended eastward.

The asymmetry observed in the deformation pattern between the west and east domains of the Old Bahamas Channel could be explained by the presence of blocks with different rheologies as the rigid Bahamas platform, which may lock the subduction, the shear propagation and lead to collision in a scissors-like manner from west to east (Figures 2d and 2e).

5.3.3. Post-Orogenic Phase and Shear Zone Jumps

According to Mann et al. (1995), Leroy et al. (2000), and recently synthesized by Wessels (2019), there was a shift in relative motion between the Caribbean and the North American plates from NNE during the Maastrichtian period to E during the Middle Eocene period. This change in relative motion led to the formation of NE-SW-oriented left-lateral strike-slip faults and caused the thrust belt to fragment. This was caused by the eastward escape of the Caribbean plate and the presence of the Bahamas rigid block (Figures 12f–12i). Several studies have documented this process, including Rosencrantz et al. (1988), Mann et al. (1995), Gordon et al. (1997), Leroy et al. (2000), Pubellier et al. (2000), and Rojas-Agramonte et al. (2008), Oliveira de Sá et al. (2021).

The onset of the Cauto-Nipe fault zone is Middle-Late Eocene (Leroy et al., 2000; Rojas-Agramonte et al., 2008; Vázquez-Taset et al., 2020), forming a sedimentary basin that separates the two ophiolite massifs exposed in eastern Cuba (Holguín and Northeastern Cuban (Mayari-Sagua-Baracoa) ophiolites; Figures 2, 4, and 5). The deformation front corresponds in this place to this zone (Figures 4 and 5). The strata in the Old Bahamas Channel were probably folded during the Early Eocene during the collision of Cuba with the Bahamas Carbonate Province. The youngest strata of the topmost Unit E (post-orogenic strata) are not folded, testifying to a calmer tectonic phase or a localized one. This phase might be related to the Eastern Cuban microplate displacement that could not continue northeastward, ending the tectonic activity in the Cauto-Nipe fault zone during the upper Oligocene (Oliveira de Sá et al., 2021).

In the uppermost Lower Eocene, the oceanic seafloor spreading of the Cayman through halted volcanic activity in Sierra Maestra (Figure 2f, Unit D). During the Middle Eocene period, Eastern Cuba underwent a significant geological change (Figure 2g, Unit D). During this time, this block was characterized by shallow basins where volcanogenic molasses accumulated, while to the North, a deep basin developed with deposits of fine-grained tuffs. However, deep seas were prevalent in Eastern Cuba during the Middle Eocene.

During the Middle/Late Eocene period, the collision stopped as the Oriente Fault emerged (Figure 12h), causing the separation of Eastern Cuba's terrain from the surrounding region and joining it with the North American plate (Oliveira de Sá et al., 2021). This occurrence is supported by seismic sections, which depict the cessation of tectonic activity through horizontal seismic reflections in the topmost layer, known as Unit E (refer to Figure 12). Nevertheless, some faults affect relatively recent seismic reflections, suggesting the possibility of ongoing tectonic activity localized on the deformation front as shown by seismic activity and the still active uplift of the Cuba coast (Authemayou et al., 2023; Calais et al., 2023) (refer to Figures 4b, 5, 8, and 9).

6. Summary and Conclusions

Our results reveal that the Old Bahamas Channel, Cuba's insular slope, and south Bahamas Carbonate Province experienced multiple phases of deformation since the Jurassic, linked to the complex plate boundary evolution. The presence of normal faults bounding tilted blocks indicates an earlier extensional phase, while the occurrence of thrust faults and folds overprinting these structures along the Cuban margin suggests a subsequent contractional phase with local inversion. Additionally, the presence of wrench faults nucleated in pre-existing structures implies a shear component.

Syn-sedimentary faulting during the rifting phase resulted in tilted blocks and deposition of syn-rift Unit A in the Jurassic period. Carbonate reef accretion in the Southeastern Bahamas began concurrently with or shortly after the syn-rifting phase ended. Earliest carbonate banks initiated as reefs on top of tilted blocks raised into the photic zone during the subsequent drowning phases.

Some buried carbonate reefs could show deformation patterns at their top, which may resemble diapirs and could suggest early salt deposition in Eastern Cuba. Perhaps, during the Callovian period, a scenario emerged wherein a constrained influx of waters was initiated due to plate reorganization, and as the North America and South America/Africa plates underwent increased separation, it gave rise to potential water pathways leading into the Proto-Caribbean margin, both from the Pacific and conceivably from the Atlantic. Is there a potential connection between the salt deposits in the offshore Eastern block of Cuba and the hypersaline basin formation in northern Cuba during the Callovian era, and could this be related to salt deposition in the Gulf of Mexico?

During the Late Jurassic-Early Cretaceous period (post-rift phase), the Proto-Caribbean margin was characterized by shear zones and basement hinge zones. The Cuba FZ separated the Proto-Caribbean Ocean from the Bahamian margin, which was the composite of the North of Cuba and the Bahamas at this time. The Cuba FZ likely formed due to the activation of shear zones along the reactivation of faults that tilted the underlying Triassic-Early Jurassic basement.

The Bahamian margin was a relatively stable tectonic domain characterized by a deep basinal environment from the Middle-Upper Cretaceous until the Proto-Caribbean oceanic crust was entirely consumed beneath the Caribbean plate, leading to the collision of the northern border of the Caribbean plate with the Bahamas domain. This collision led to folding, shortening, and localized salt upwelling along the flanks and atop the Bahamian buried reefs offshore the Eastern Cuban block. This collision resulted in the welding of Cuba to the North

American plate and played a significant role in establishing the current configuration of the Caribbean. These changes also resulted in the establishment of the northeastern Cuban Ophiolites.

The reactivation of ancient Jurassic faults played an important role in the offshore positioning of the northern limit of the Caribbean plate during the Middle Eocene. The present-day frontal deformation at the insular slope corresponds to the cumulative tectonic processes of the Cuba FZ, then the Cauto-Nipe tectonic corridor. Indeed, the offshore placement of the Cauto-Nipe strike-slip system probably corresponds to the ancient Cuban TF, which represents a crustal barrier during the collision of the Eastern Cuban Block with the North American plate. The collision ceased during the Middle to Late Eocene with the development of the Oriente fault, linking Eastern Cuba's terrain to the North American plate. However, reverse faults at the deformation front affect the seafloor, suggesting a potential ongoing localized tectonic activity offshore the Eastern Cuban block.

Our findings contribute to understanding the geological history of the Eastern Cuban block, providing valuable insights into the region's tectonic evolution despite limited sediment core availability and stratigraphic framework uncertainties. The tectonic history of Eastern Cuba has been shaped by various processes related to tectonic plate interactions, including rifting, subduction, strike-slip and transfer fault zones, collision, and obduction. These processes linking the Central Atlantic, Gulf of Mexico, Proto-Caribbean, and Caribbean plates have resulted in distinct geological features that can be observed in the present-day offshore basement and sedimentary records.

Further research, including acquiring additional seismic data and sediment cores, is essential to refine our understanding of the tectonic evolution and its influence on the sedimentary record in this region. The ages provided by our study should be utilized in future research to establish better correlations between Eastern Offshore Cuba and other Cuban blocks.

Data Availability Statement

Bathymetry data and all seismic profiles utilized in this study were sourced from the HAITI-SIS2 oceanographic campaign. The seismic data from HAITI-SIS2 are available upon request through the following website: https://donnees-campagnes.flotteoceanographique.fr/search. For detailed information and direct links to each specific profile used, please refer to the supplementary material accompanying this paper.

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