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1 2 3	Polyphase deformation and strain migration on the Septentrional-Oriente Fault Zone in the Windward Passage, Northern Caribbean Plate boundary
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8	Key Points:
9 10	• The present-day structure in the Windward Passage implies a polyphase evolution with at least 4 stages of deformation.
11 12	 Motion on the Septentrional-Oriente Fault in the Windward Passage began in early Pliocene time and has generated an estimated ~80 km offset
13 14 15	• Onset of motion in the Windward Passage is key to revealing Neogene structural evolution of the northern Caribbean plate.
16	Keywords: Windward Passage, Septentrional-Oriente Fault Zone, Northern Caribbean plate,

17 strain migration, strike-slip faults, Hispaniola

18 Abstract

19 Oblique collision between the Caribbean plate and the Bahama Banks has lead an eastward migration of the northern Caribbean plate boundary by successive southward jumps of major 20 strike-slip faults. The Septentrional-Oriente Fault zone (SOFZ) defines the present-day northern 21 Caribbean plate boundary accommodating most of the eastward escape of the Caribbean plate. 22 Here, we reevaluate the complex history of the SOFZ along the Windward Passage area between 23 the easternmost region of Cuba and the northwest of Haiti. Based on seismic reflection and 24 swath-bathymetric dataset we interpret the structure and tectonic pattern of the Windward 25 Passage. The tectono-sedimentary framework of this large strait shows contrasting patterns of 26 deformation linked to a complex polyphase tectonic history of dominantly strike-slip faulting. 27 SOFZ segments offset the seismic units and yield key markers of displacement along the fault 28 system. Our study provides structural and stratigraphic insights into the relative timing of 29 deformation along the Windward Passage and presents new elements that constrain the 30 southeastward jump of the north Caribbean plate boundary to its present-day position. We 31 32 propose dates for the identified seismic units based on the correlation of offshore deformation phases recorded in the Windward Passage sedimentary cover with major paleogeographic 33 reorganization episodes described onland (Late Eocene, Late Oligocene, Middle Miocene and 34 Late Pliocene). By restoring the offset of the seismic units, we demonstrate that at least ~80 km 35 of left-lateral motion has occurred on the SOFZ, and that the SOFZ has been active since the 36 Pliocene. 37

38 **1 Introduction**

39 Relative plate motion at most convergent plate boundaries is oblique to the boundary itself (Philippon & Corti, 2016). Oblique convergence settings display strain partitioning into 40 boundary-normal and boundary-parallel components of the plate motion vector (Jarrard, 1986; 41 Demets, 1992; ten Brink & Lin, 2004; Chemenda et al., 2000). In oblique convergence settings, 42 the oblique component of motion is often accommodated by strike-slip faults that dominate plate 43 44 interactions (Teyssier et al., 1995; Chemenda et al., 2000). In such cases, strike-slip faults may also form along the edge of the overriding plate to accommodate boundary-parallel components 45 (Fitch, 1972; Jarrard, 1986). This process is called slip partitioning and it has been observed in 46 oblique convergence contexts such as offshore Sumatra (Jarrard, 1986), the Philippine fault 47 (Fitch, 1972), in Taiwan (Lallemand et al., 1999) and in the Lesser Antilles (Symithe et al., 2015; 48 Laurencin et al., 2019). Along the Caribbean–North American plate boundary, the degree of 49 obliquity varies from ~50° North of Cuba, ~20° in the northern Hispaniola Island arc, to up to 50 72° in the northern Lesser Antilles (Calais et al. 2016; Laurencin et al., 2019; Rodríguez-51 Zurrunero et al., 2020). To the north of Hispaniola, the eastward motion of the Caribbean Plate is 52 slowed by its collision with the Bahama Banks. Caribbean plate motion is highly oblique to this 53 portion of the plate boundary (Figure 1)(Demets, 1992; Mullins et al., 1992; Calais et al., 2016). 54 This ongoing oblique collision result in a strong stress coupling between the plates and slip 55 partitioning along the northern edge of Hispaniola (Rodríguez-Zurrunero et al., 2020). North-56 verging fold propagation faults sub-parallel to the Caribbean plate displacement accommodates 57 part of the convergence in Hispanolia's northern coast (Calais et al., 2010). Oblique motion is 58 59 also accommodated by a large-scale, seismically active strike-slip fault system, known as the Septentrional-Oriente Fault Zone (SOFZ), which forms the current northern Caribbean Plate 60 boundary (Leroy et al., 2015; Calais et al., 2016)(Figure 1). 63

The SOFZ trends almost E-W as it runs along the southern coast of Cuban, and straight 63 across the Windward Passage until it steps onland in northern Hispaniola (Figure 1a). The 64 geological setting of the region has been strongly controlled by this large-scale strike-slip fault 65 system (de Zoeten & Mann, 1991; Mann et al., 1995; Rojas-Agramonte et al., 2008). Previous 66 seismic reflection data has led to an initial description of the SOFZ and its related structural 67 framework (Calais & Mercier de Lépinay, 1991; Dillon et al., 1992; Calais & Mercier de 68 Lépinay, 1995; Leroy et al., 2015). However, the initiation of SOFZ remains poorly constrained, 69 as well as the understanding of how the various segments of the system may have functioned as 70 the convergent plate boundary evolved. 71

This paper documents the sedimentary and structural framework associated with the active segments of the SOFZ in the Windward Passage. The study area is located at the contact zone between the North American Plate and the northern boundary of the Caribbean Plate. The Windward Passage may have recorded a wealth of information concerning tectonic events at the Caribbean–North American plate boundary. It is thus a critical witness to the kinematic evolution of the Caribbean Plate.

The main goal of this study is to understand how the tectonic context of oblique collision with strain partitioning within the Windward Passage since the Eocene has led to the current sedimentary and structural framework. We present high-resolution multibeam bathymetry and ~3000 km of multi-channel seismic reflection profiles that image the Windward Passage domains, mapping the SOFZ fault trace and related morphological features (Figure 2). Deformation events recorded in the sedimentary cover were time-correlated with major onland 84 deformation events in southern Cuba and Northern Hispaniola. Our intent is to (i) constrain the

deformation styles in time through interpretation of the sedimentary record, (ii) infer the

structural framework that existed prior to inception of the SOFZ, and (iii) better understand the

current structures associated to this major fault system. We discuss the critical time markers for
 inferring the stratigraphic interval that defines a timeframe for the initiation of left-lateral strike-

inferring the stratigraphic interval that defines a timeframe for the initiation of left-lateral strike
 slip motion on the SOFZ within the Windward Passage and its subsequent migration. We

accurately define the active tectonics of the Northern Caribbean plate boundary, providing a

- 91 better understanding of the regional tectonics.
- 92

93 2 Tectonic Settings

94 Since Paleocene times, the Caribbean–North American plate boundary has undergone progressive reorganization in response to the diachronous collision between the Cuban-95 Hispaniola Arc and the Bahama Banks (Gordon et al., 1997; Iturralde-Vinent & Macphee, 1999; 96 Mann et al., 2002). This collision has caused a change in the Caribbean-North American relative 97 98 plate motion from NNE to E (Pindell et al., 2005; Boschman et al., 2014). Along the Cuban Arc, strain partitioning and large-scale strike-slip faulting took place. The northern Caribbean plate 99 boundary underwent a series of jumps. During the initial stages of collision, the boundary 100 coincided with the eastern Yucatan transform margin. Accommodation of relative plate motion 101 migrated progressively southward as each new fault systems developed and was subsequently 102 replace by a younger fault system starting with the development of the Pinar fault (Paleocene), 103 followed by the La Trocha fault (Early Eocene), and then the Cauto fault (middle Eocene) in 104 Cuba (Figures 3a and 3b). As the plate boundary shifted southward to the Oriente Fault zone 105 (OFZ) (early Oligocene), the Cuban block became attached to the North American Plate 106 resulting in the separation of Cuba and Hispaniola, which until then had formed a single block 107 (Figure 3c)(Calais & Mercier de Lépinay, 1992; Leroy et al., 2000; Rojas-Agramonte et al., 108 2008; Wessels, 2019). The OFZ transcurrent plate boundary must have been located north of 109 Hispaniola during the Miocene until Pliocene times (Figures 3d, 3e and 3f)(Erikson et al., 1998). 110 However, as the system evolved the northern end of the OFZ gradually became inactive and the 111 strike-slip motion between Cuba and Hispaniola shifted southward (Calais & Mercier de 112 Lépinay, 1995), extending into the northwestern peninsula of Hispaniola to form the 113 Septentrional fault (Late Pliocene) and establish the current Septentrional-Oriente Fault Zone 114 (SOFZ) (Figures 1b, 3f and 3g) (Calais et al., 2016; Escuder-Viruete and Pérez, 2020). 115

On the Island of Hispaniola, the SOFZ and the North Hispaniola fault (Deformation 116 front) partition the oblique convergence into boundary-parallel and boundary-normal 117 components (Rodríguez-Zurrunero et al., 2019, 2020). The SOFZ accommodates most of the 118 left-lateral strain of the current Caribbean-North American relative plate motion as a major 119 transpressional fault system. Using GPS measurements and block modelling, Calais et al. (2010) 120 estimate that the SOFZ currently accumulates elastic strain at a rate of 12 ± 3 mm yr⁻¹. While the 121 North Hispaniola fault accommodates 2 to 6 mm/yr of ~N-S shortening, and the Trans-Haitian 122 belt accommodates about 4 mm yr⁻¹of ~N-S shortening (Figure 1a). 123

124 The Windward Passage area is a large strait separating the eastern extremity of Cuba 125 from the northwestern peninsula of Hispaniola (Figure 1b) (Calais, 1990). The area consists of a 126 submarine plateau, the Windward Passage Sill (WPS) (Goreau, 1989) and an adjacent 127 sedimentary basin, the Windward Passage Deep (WPD) (Calais & Mercier de Lépinay, 1995). A

- 128 forward-propagating imbricated zone of contractional structures characterizes the WPS on its
- northern edge and delimits the deformation front (Figure 2)(Goreau, 1989; Dillon et al., 1992,
- 130 1996; Rodríguez-Zurrunero et al., 2019). There, sediments of the adjacent Hispaniola basin are
- tilted to the north and incorporated into the WPS structure. To the south, the WPS is bounded by
- the WPD, an east-west trending elongated basin. The WPD is about 120 km long and 15 km
 wide with depths ranging from 1100 to 3780 m (Figure 2a). The evolution of the WPD is
- interwoven with SOFZ formation, which crosses its entire length running from the southern
- 135 Cuban margin eastward to the northern Hispaniola margin (Figure 2b). Calais & Mercier de
- 136 Lépinay (1995) correlate offshore seismic sequences recognized in the WPD to successive
- 137 tectonic and sedimentary events recorded onshore in Cuba and Hispaniola. These authors
- associate these correlated onshore-offshore events with the successive collisions of the northern
- 139 Caribbean mobile terranes against the Bahama Bank.

140 **3 Data and Methods**

141 Multichannel seismic reflection and multibeam bathymetric data were collected during cruises HAITI-SIS 1-2 (2012-2013) onboard the R/V L'Atalante from the Flotte 142 Océanographique Française (Leroy, 2012; Leroy and Ellouz-Zimmermann, 2013; Leroy et al., 143 144 2015). Multibeam bathymetric data collected during NORCARIBE geophysical cruise in November–December 2013 aboard the Spanish R/V Sarmiento de Gamboa is used to fill the 145 gaps in our data coverage (Leroy et al 2015; Rodríguez-Zurrunero et al., 2020). In this paper, we 146 147 focus on the Windward Passage area where ~3000 km of seismic profiles have been acquired (Figure 1b). Seismic reflection data are recorded using a source comprising two GI air guns (2.46 148 L, 300 in3) and a streamer with 24 traces (600 m long) operated at c.a 9.7 knots (fast and light 149 seismic system). The multichannel seismic reflection data were processed using classical steps 150 including CDP gathering (fold 6), binning at 25m, detailed velocity analysis, stack and post-stack 151 time migration. All the seismic reflection profiles presented are time migrated. Multibeam 152 bathymetry data were acquired simultaneously along seismic profiles and gridded with a spacing 153 of 50 m. The gridded bathymetry data was augmented with the GEBCO Digital Atlas 154 (https://www.gebco.net/data and products/gebco digital atlas/) with an 800m resolution to 155 provide an almost full coverage (Figure 1a). The processed seismic data are interpreted using 156 Kingdom IHS Suite[®] software. Maps are plotted with ArcGIS[®] software. We use the seismic 157 reflection dataset to identify sedimentary units, deformation style and spatio-temporal evolution 158 of the tectonic structures. Morphological analysis of the seafloor based on swath-bathymetric 159 data is carried out to identify the surface signature of tectonic features (Figure 2). We identify 160 faults by either sediment horizon offsets or by the fault plane seismic reflection itself in the 161 available seismic profiles. 162

163 **4 Results**

164 4.1 Seismic stratigraphy

165 Seismic units are hereafter described by geographic sectors and ordered from the acoustic 166 basement to the most recent one (Unit 4). We summarize the corresponding facies in a table 167 (Figure 4). For both areas, WPS and WPD, the top of the acoustic basement corresponds to a 168 rough surface on some profiles (Figures 5, 6 and 7), and it may outcrop in the structural highs of 169 the study area (Figure 5, km 40-55). Acoustic energy is insufficient to image beneath the top of 170 the observed acoustic basement (labelled unconformity Uc1). The presence of seabed multiples 171 usually hampers the description of internal geometry of the acoustic basement. When seismic

reflections are observed within the acoustic basement, the reflectors are discontinuous to chaotic,
 medium-high amplitudes that may terminate upward against the irregular and rugged

medium-high amplitudes that may terminate upward against thunconformity Uc1 (Figures 4, 5 and 6).

175 4.1.1 Windward Passage Sill

176 Within the Windward Passage Sill (WPS), we define three main seismic units above the

177 acoustic basement that correspond to seismic units previously defined by Calais and Mercier de

Lépinay (1995). The lower unit (Unit 1) is characterized by a thick series (>1s TWT) with at
least two internal angular unconformities (Uc1a and Uc1b, Figures 6 and 7) that separate distinct
sub-units of distinct facies and geometries (Units 1a, 1b and 1c; see Figure 4 for detailed

180 sub-units of distinct facies and g181 reflections attributes).

At the base of Unit 1, the seismic facies is transparent (Unit 1a in Figures 4 and 7, km 65-182 85), then well-defined by parallel high frequency reflections in its upper part (Unit 1c, Figure 4). 183 Most of Unit 1, especially its base, appears to have been folded and then eroded as indicated by 184 unconformities Ucla and Uclb (Figure 7, km 65-85). In the northern flank of the WPS high, 185 Units 1a and 1b onlap the angular unconformity Uc1 (Figure 6, km 33-43) and Unit 2 is not 186 187 present. The second seismic unit in the WPS (Unit 3) is separated from the Unit 1 by an angular unconformity labelled Uc3 (Figures 4 and 6). Unit 3 layers are tilted and folded and were 188 deposited in the syncline depressions formed by the previous folding of Unit 1, with a succession 189 190 of onlap terminations in a well-layered sequence (Figure 6, km 25-40).

The angular unconformity Uc4 is observed at the top of Unit 3 and separates Unit 3 from the more horizontally layered high-frequency reflectors of uppermost Unit 4 (Figures 4 and 6). Our seismic profiles through the WPS illustrate the lateral thickness variation of Unit 4. The thickness of this unit increases from north to south (Figure 6, km 40-20) and more clearly from west to east: increasing from 160 m in the western part (conversion of 0.2 s TWT by using a Pwave velocity of 1600 m/s for less consolidated sediments; Figure 7) to up to 480 m in its eastern part near the Tortue Island (Figures 6 and 8d).

Toward the east, close to Tortue Island, the seismic profiles display an unconformity that 198 truncates the horizontally stratified, undisturbed reflectors of Unit 4 (unconformity Uc4a in 199 200 Figures 8b and 8c). Unit 4 is therefore subdivided into two sub-units: Unit 4a that shows parallel high frequency reflectors and Unit 4b with parallel moderate frequency, low-amplitude reflectors 201 interspersed with thin chaotic beds (see Figure 4). The thickness of Unit 4b varies from north to 202 south (Figures 8a and 8b) and from west to east (Figures 8c and 8d). On the northern slope off 203 Tortue Island its thickness reaches 0.6 s TWT (~480m thick)(Figure 8d, km 25-30). Westward, 204 this sub-unit is almost completely eroded (Figures 6 and 8c). Recent mass wasting processes 205 probably affected the shape of the slope in the WPS area, eroding the upmost part of Unit 4b. 206

- 207
- 208 4.1.2 Windward Passage Deep

209 Sedimentary units in the WPD area do not show clear correlations with those found in the 210 WPS. Units 1 and 4 are common to both areas (Figures 4 and 6). However, in the WPD these 211 units show some slightly differences in their facies (Figure 4):

As observed in the WPS area, Unit 1 consists of parallel to sub-parallel high-amplitude and low-frequency reflections onlapping the basement in the WPD area (Figure 6). Punctually,

its seismic facies become transparent to chaotic and the unit displays lateral variations of 214

thickness (Figure 4). Its bottom geometry is barely visible on seismic data. In the WPD area the 215 Unit 1 does not clearly display distinct sub-units as described in the WPS area. 216

Unit 2 is a distinct sedimentary unit present only in the WPD area (Figures 6, 7 and 9). It 217 overlies Unit 1 on the angular unconformity Uc2 (Figure 10). Its thickness and internal reflection 218 pattern vary throughout the basin. In the north wall of the WPD (southern flank of the WPS), 219 Unit 2 is perched (Figure 5). Unit 2 is thus defined by parallel to sub-parallel continuous 220 reflectors, which are onlapping the steeply dipping Uc1 unconformity at its northern boundary 221 (Figure 5, km 25-40). Its thickness is about 1.2s TWT (~960m thick; conversion of 1.2 s TWT 222 by using a P-wave velocity of 1600 m/s for less consolidated sediments), and it thickens slightly 223 northward (Figures 5 and 6). In the basin, the southern part of Unit 2 displays lateral variations 224 of thickness from east to west (Figures 7 and 9). Unit 2 reaches a thickness of almost 1.3s TWT 225 $(\sim 1040 \text{m thick})$ in its eastern part (Figure 11). The internal reflection pattern changes gradually 226 from plane-parallel reflectors, low-amplitudes and low-frequency at its base to flat-lying, high 227 amplitudes and high-frequency at its top (Figure 4). Its seismic facies, thickness and deformation 228 pattern changes laterally within individual seismic lines. For example, the thickness can be about 229 0.6s TWT (~480m thick) southward and 1.2s TWT northward (see Figure 10). The most recent 230 upper parts of Unit 4 are characterized by flat-lying strata that overlie Unit 2 strata in the deep 231

- basin (Figure 9). 232
- 4.2. Structural Analysis 233
- 234

4.2.1. Windward Passage Sill structural features

WPS area is characterized in seismic reflection profiles by a topographic high deformed 235 by faults and series of folds (Figure 7). Numerous imbricated thrusts, mainly synthetic to the 236 deformation front to the north (Figure 6, km 40 - 60), affect the acoustic basement and 237 progressively steepen its northern slope. On the southern slope of the WPS, north dipping blind 238 239 thrust faults are inferred from the geometry of the folded and shifted acoustic basement. Presently, gravity-driven normal faults shift the seafloor on the southern edge of the WPS as 240 proposed by Rodriguez-Zurrunero et al. (2020). 241

A near-straight fault trace runs towards west along the north flank of the WPS (Figures 6, 242 km 35-40, and Figure 7, km 70- 80). The recent study carried out by Rodríguez-Zurrunero et al. 243 (2020) revealed that this fault strand seems to be aligned with the neotectonic SOFZ segment in 244 the south flank of Septentrional Cordillera (Figure 1a). Its westward termination coincides with a 245 narrow deformation zone with sub-vertical faults that displace the acoustic basement and the 246 sediment layers in the central part of the WPS (wrench faults in Figure 12a, km 60-65). The 247 deformation can be followed eastward on parallel seismic lines (Figures 7, km 70-77, and 248 Figure12b, km 48-53) and interpreted as a positive flower structure oriented NW-SE. The 249 overlying, parallel-bedded sediments appear to be tilted and displaced by the uplift of this 250 positive flower structure (Figures 7 and 12a). This uplift of the seabed by the wrench fault 251 strands of the flower structure created a wide synform located south of the wrench faults (Figures 252 2 and 12a). This synform is clearly observable in the seabed as an elongated east-west trending 253 depression (Figure 2). In the westernmost part of the WPS, this positive flower structure takes 254 the form of an NNW-SSE trending antiform with relief of about 350m (Figure 2). The 255

disturbance of the seafloor and shallow sediments indicate tectonic activity is currently occurring
 along this structure (Figure 12).

Confined between the WPS synform and the WPD, an isolated structural high 258 characterizes the southwestern part of the WPS, named the WPS high (Figures 2, 5 and 7). This 259 structural high is bound by opposing north- and south-dipping reverse faults (Figure 12a, km 35-260 50). These bounding reverse faults trending E-W with opposing \sim 45° dips delimit the WPS E-W 261 high. The highly benched slope of the WPS, may be the direct consequence of activity on these 262 reverse faults. However, the stepped morphology of the slope suggests that gravity-driven 263 mechanisms may play an important role in its shape by promoting slope erosion (Figure 6, km 264 265 20-25).

266 4.2.2 The Windward Passage Deep structural features

267 SOFZ activity has clearly left a morphologic imprint on the seafloor study area (Figure 2) 268 and affected the entire sedimentary record of the WPD area (Figures 5 to 11).

A network of reverse faults forms a small bulge and trough (1.5 km wide) (Figure 5, km 18-23). These faults are sub-vertical and seem to merge at depth along a main fault strand that may be associated with the SOFZ (Figure 9). The internal structure, which displays faults with an opposing dips on either side of this bulge, is typical of a positive flower structure (Figure 10, km 25-30). The main fault segments and several subordinate strands of this flower structure are imaged on the seafloor mainly as the edges of antiforms (Figure 2).

275 Expression of the SOFZ on seafloor of the WPD allows us to identify five distinct segments according to azimuth changes. The western 83-km-long segment, Segment 1 (S1 in 276 Figure 1), runs offshore Cuba through the Punta Caleta high, from 74°50'W to 74°05'W and 277 trends N82°E. A second 50-km-long segment (S2) runs from 74°10'W to 73°35'W and trends 278 N83°E. Segments S1 and S2 have been considered as individual segments based on two distinct 279 traces on the seismic sections and bathymetric data (Figures 1 and 2), despite short interruptions 280 281 of rupture traces on the seabed (Figure 2). The boundary between S1 and S2 corresponds to a contractional jog which forms a relatively small bulge (about ~300m high, Figures 2 and 7), 282 associated with a distinct change in azimuth of almost 1°. The boundary between Segments 2 283 and 3 is marked by a change of slope oriented N015° and a sharp azimuth change of 7-8° (Figure 284 2). Segment 3 is 74-km-long and trends N90°E. At its western end it runs along the rupture at 285 73°40'W. Eastward, over a distance of a few kilometers, the fault trace is characterized by a 286 287 large azimuth change of 10°, that marks the boundary between S3 and S4. From 72°57'W, a Segment 4 trends N100°E to the south of the Tortue Island (Figure 1). 288

These active segments of the present-day SOFZ identified on the bathymetric map also 289 appear at depth, in the seismic reflection data (identified on the figures by segments S1 to S4). 290 The width of deformation associated with the SOFZ is narrower in the central part of the WPD 291 292 (Figure 2, 73°40'W and 20°02'N) and wider at its extremities (6 km wide). Deformation linked to the flower structure spreads out eastward and the sedimentary cover is highly affected by its 293 fault branches (Figures 6, 9, and 11). In this area, the most recent sedimentary units (Units 2 and 294 4) and the unconformities Uc4 and Uc4a appear to have been folded and faulted (Figures 6 and 295 11). The present-day offset and roughness of the seafloor indicate ongoing faulting in this area. 296

These E-W oriented SOFZ segments divides the WPD into a northern block, which we assume to be fixed, and an eastward-moving southern block. Deformation seems to be concentrated in the northern block forming a perched sedimentary block (~10 to 20 km wide,
Figures 7, km 30-45, and 5; km 20-40) characterized by a thick sedimentary deposit (about 1.2 s

- TWT, Figure 5). Upwarping of Units 1 and 2 and the folding along this perched sedimentary
- block, indicate that the WPD northern block is under a compressional stress field. The perched
- block is bound to the north by a southward-dipping normal fault that offsets the Units 1 and 2
- and the acoustic basement (Figures 5, 6, 7 and 9). Unit 2 thickens northwards toward the fault,
- highlighting a syntectonic wedge related to an earlier stage of normal faulting (Figures 5 and 7).

At the southern boundary of the WPD, a set of reverse and thrust faults forms a ridge-like structural high (Figures 2 and 11, km 25-35). This feature is characterized in the bathymetric data by a steep, uniform, east-west trending scarp ridge. This ridge becomes higher eastward and seems to extend onshore. The scarp may correspond physiographically to the Môle de Saint-Nicolas area in the Northwestern Peninsula (Haiti) (Figures 1 and 2).

In summary, the seismic reflection profiles allowed us to establish a precise structural

map of the Windward Passage Deep (Figures 2 and 13). The sedimentary and structural
 framework are much more complex than found in previous studies. Seismic data demonstrate

- framework are much more complex than found in previous studies. Seismic data demonstrate that the WPD sedimentary cover is deformed by the multiple, near-vertical fault strands of the
- SOFZ, forming a large deformation corridor crossing the whole length of the basin (Figure 13).

316 **5. Discussion**

Our results reveal distinct deformation styles across the Windward Passage with several phases (at least 3 stages of deformation discussed in section 5.1). Thrust faults and folds in the deeper units of the WPS (Figure 6, km 25-45) are compatible with a predominantly contractional deformation phase, while the WPD thick sedimentary cover suggests an extensional deformation phase overprinted by a current transpressive deformation (e.g. Figure 6).

322 Strike-slip systems usually create conditions that allow for the juxtaposition of normal 323 and reverse faults over a comparatively short distances and periods of time. The most likely 324 hypothesis is a polyphase evolution with a compressive phase followed by a short extensional 325 phase and then a recent transpressive phase. In this scenario, the normal faults offset the WPS 326 southern border are the primary mechanism for WPD opening. Flower structures affecting the 327 most recent WPD sedimentary record represent the current transpressive deformational style in 328 the area.

329 5.1 Deformation events in the Windward Passage

330 Since the deformation patterns in the WPS and the WPD are quite different, we discuss 331 them separately in this section, before proposing correlations and time constrains for both areas 332 in section 5.2.

333 5.1.1 Windward Passage Sill

The folded Unit 1 records the first deformation event in the Windward Passage Sill domain (Figure 6). As proposed by Calais & Mercier de Lépinay (1995), folding of Units 1a, 1b and 1c (Figure 6) suggests that a contractional deformation pulse affected the WPS. The presence of minor unconformities within Unit 1 (unconformities Uc1a and Uc1b in Figures 6, 7 and 12) indicates intermittent episodes of erosion during its deposition. Units 1a, 2b and 3b are broadly similar in style and orientation, which implies that their top unconformities correspondto rapid episodes of erosion.

The first episode of contractional deformation may have been active until the deposition of Unit 3, which displays less folding than the underlying unconformable Unit 1. The gentler folding of Unit 3 may be due to weaker contractional deformation, suggesting a second compressive pulse in the WPS.

Angular unconformity Uc4 separates the horizontally ponded strata of Unit 4 from the 345 older folded layers of Units 1 and 3, highlighting a sedimentation hiatus (Figures 4 and 6). 346 Overlying horizontal layers of Unit 4 suggest that the contractional deformation is less 347 pronounced than the earliest contractional stages (Calais & Mercier de Lépinay, 1995). However, 348 349 relatively flat reflectors do not mean a quiet period as proven by the presence of active reverse faults affecting Unit 4 in the WPS (Figure 5, km 40 - 60). The southward thickening of Unit 4 350 351 and tilting of unconformity Uc4 suggest ongoing contractional deformation (Figure 6). It implies a southward tilt of the WPS, possibly related to a recent activity of the imbricated thrust zone 352 353 shearing off the WPS sedimentary strata on its northern slope (Figure 6, km 40-55). Such observations suggest an ongoing compressional stress field in WPS, in particular on its northern 354 limit (Rodríguez-Zurrunero et al., 2020). 355

The positive flower structure in the middle part of the WPS provides evidence of a current strike-slip component in WPS area (Figures 12a, km 60-65, and Figure 12b, km 48-53)(Rodríguez-Zurrunero et al., 2020). Such a fault pattern, suggests that lateral slip, together with thrusting, are the two major styles of deformation operating in the WPS. Both styles of deformation reflect a transpressional tectonic regime that is likely a combined response of the large-scale present-day oblique collision between the Caribbean Plate and the Bahama Banks.

362

363 5.1.2 Windward Passage Deep

In contrast to the folding observed in the WPS, the Units 1 and 2 in the WPD seem 364 relatively less disturbed by the early stages of compressional stress (Figure 6). At the northern 365 edge of the WPD, the acoustic basement is tilted southward and the presence of northward 366 dipping syntectonic wedges through the Unit 2 (Figures 6 and 7) suggests an early N-S 367 extensional tectonics in the WPD area. This extensional stage probably follows Unit 1 368 deposition, which implies that the onset of Unit 1 deposition precedes the opening of the WPD 369 area. A similar extensional stage affecting older folded sedimentary series is described by Calais 370 & Mercier de Lépinay (1991) in the Imias Basin, just to the south of the study (Figure 1). 371

This early extensional tectonic event was related to the opening of the WPD domain and appears to have ceased after Unit 2 deposition. The normal fault identified at the northern boundary of the WPD seems presently inactive since the most recent overlying sediments in the WPD show no evidence of lateral thickening (Figures 5 and 6). The current morphology of WPD area seems to be controlled by transpressional regime with block "ramps" upward along both sides of the basin (Figure 9).

The neotectonic strike-slip regional component in the Windward Passage is apparent in the major SOFZ that crosses the entire length of the WPD (Figure 2). Sets of inward dipping faults that form part of this fault system converge at depth with the main SOFZ segments forming a large positive flower-structure (Figures 5 and 7). The positive flower structure formed by transpressional shear reflects the current transpressional tectonic setting in the area. Because positive flower structures allow only a small amount of shortening, the dominant type of motion on a thoroughgoing fault characterized by this feature must be strike-slip with a transpressive component (Biddle & Christie-Blick, 1985). Our structural observations lead us to infer that the present-day WPD deformation pattern is currently ruled by significant transpression.

387 5.2 Tectonic interpretation of deformation events and onshore correlations

Due to the lack of direct sampling, sedimentary units in the Windward Passage can only 388 be time-correlated based on onshore observations. Calais & Mercier de Lépinay (1995) were the 389 first to time-correlate deformation events in the Windward Passage with four major 390 paleogeographic periods in both southern Cuba and northern Hispaniola domains. The late 391 392 Eocene, Oligocene, Middle Miocene and Late Pliocene paleogeographic stages are largely described onshore (Calais, 1990; Pindell & Draper, 1991; de Zoeten & Mann, 1991; Calais et al., 393 2016; Mann et al., 2002). Each one of these periods corresponds to a drastic reorganization of the 394 395 Caribbean northern plate boundary geometry (Calais & Mercier de Lépinay, 1995). Based on recent kinematic and advances in onshore field work in southern Cuba (Rojas-Agramonte et al., 396 2008) and northern Hispaniola (Leroy et al., 2015; Escuder-Viruete et al., 2015; Escuder-Viruete 397 398 & Pérez, 2020), we propose an alternative correlation of deformation stages in the Windward Passage with the four aforementioned paleogeographic framework in the northern Caribbean 399 Plate (Figure 14). 400

401 5.2.1 Eocene Deformation: Piggyback basins phase

The acoustic basement high observed at the southern boundary of the WPD (Figure 11, km 25-35) may outcrop in the northwestern peninsula of Hispaniola . If this is the case, the acoustic basement sedimentary series would be the equivalent to the detrital sedimentary rocks of Abuillot Formation of Early/Middle Eocene (possibly Paleocene) age (Butterlin, 1960).

The Eocene is a period of intense contractional deformation with a broad overthrusting 406 and progressive superposition of geologic formations in Cuba and Hispaniola (Mann et al., 1991; 407 Iturralde-Vinent, 1994; Iturralde-Vinent & Gahagan, 2002; Rojas-Agramonte et al., 2008). The 408 Cuban-Hispaniolan arc-continent collision with the Bahama Banks takes place in the 409 Paleocene/middle Eocene (de Zoeten & Mann, 1991; Draper et al., 1994). During this time, the 410 exhumation of ophiolitic and metamorphic rocks occurred, as well as the cessation of arc 411 volcanism in Hispaniola (Escuder-Viruete et al., 2015). Structures in upper Paleocene to middle 412 Eocene sedimentary rocks are consistent with an evolution from a forearc basin into piggy-back 413 basins at the top of an advancing accretionary wedge (Escuder-Viruete et al., 2015). The folding 414 and thrust faulting of Eocene rocks that induced regional uplift and associated piggy-back basins 415 resulted from the convergence between the north-facing Hispaniola Island arc and the Bahama 416 Banks (de Zoeten & Mann, 1991; Escuder-Viruete et al., 2015). The deformation style of the 417 acoustic basement which is characterized by steep horizons, may reflect a complicated set of 418 older stacked geological units inherited from this middle Eocene paleogeographic framework 419 (Figure 3a). Enhanced uplift during the arc-continent collision may have resulted in subaerial 420 421 exposure and formation of the basal angular unconformity Uc1 that cuts through previously tilted strata (Figure 6). 422

In the late Eocene, the WPS was probably the northernmost continuation of the early piggyback basin formed at the top of the accretionary wedge (Figure 14a, Pindell & Draper, 425 1991; Escuder-Viruete et al., 2015). Its current structure would thus be inherited from this

426 compressive scenario. However, according to Escuder-Viruete et al. (2015), the progressive

movement of the orogenic wedge toward the NE onto the continental margin may have produced
 a short subsidence period. This brief subsidence episode that took place in the Late Eocene must

have created the space that accommodated deposition of Unit 1 above Uc1 (Figure 2a).

- 430 Unconformities Uc1a and Uc1b were probably formed by local episodes of erosion, as the sub-
- 431 units of Unit 1 are similar in both style and orientation (Figure 6). Outcrops of formations
- 432 onshore suggest that this subsidence period was followed by deposition of deep-marine
- 433 sequences (Upper Eocene to lower Miocene) in a relatively stable forearc basin.
- 434 5.2.2 Late-Oligocene: Extensional Phase

We interpret the extensional phase, that peaked during the earliest stages of development 435 of the WPD, to be late Oligocene in age (Figures 3c and 14b). Disruption of Hispaniola and 436 Eastern Cuban blocks started in Early Oligocene (Leroy et al., 2000). The eastern Cuban block 437 becomes attached to the North American plate as the plate boundary jumps to the Oriente fault 438 (Figure 3c, Leroy et al., 2000; Rojas-Agramonte et al., 2008; Wessels, 2019). Oligocene time is 439 described as a tectonically stable period onshore without any significant compressional event on 440 441 Hispaniola (Pindell & Draper, 1991; de Zoeten & Mann, 1991). However, several authors propose an extensional event related to the northern Caribbean boundary stress reorganization 442 that occurred when the Oriente fault development during Oligocene (Calais & Mercier de 443 444 Lépinay 1992; Iturralde-Vinent, 1998; Rojas-Agramonte et al., 2008). Onshore observations of Rojas-Agramonte et al. (2008) in the Sierra Maestra region suggest that contractional structures 445 were overprinted by widespread extensional structures, mainly southward dipping normal faults, 446 in the late Oligocene to Miocene (Figure 3c). Calais & Mercier de Lépinay (1991) also relate a 447 transtentional regime in the offshore southern Cuban coast, which is accompanied significant 448 subsidence of the Oriente deep. Normal faulting on the northern edge of the WPD is probably 449 related to this transfensive episode (Figure 14b). Unit 1 and the acoustic basement are tilted 450 toward the normal fault planes creating accommodation space for the syntectonic deposition of 451 Unit 2 above the unconformity Uc2, which is likely late Eocene-Early Oligocene in age (Figures 452 3c et 14b). Syntectonic deposition of Unit 2 in the WPD may be coeval to the continuous Unit 1 453 deposition in the WPS area. 454

455 5.2.3 Middle Miocene Deformation: Compressional phase

456 We interpret the compressive episode in which Units 1 and 2 undergo contraction to be middle Miocene in age (Figures 3e and 14c). This event is mainly recorded in the WPS. 457 According to Calais & Mercier de Lépinay (1991), a similar event is observed in the Oriente 458 459 deep area (Figure 1a), where the basin sedimentary infill begins to undergo compression at this time. Extensional tectonic may have ceased in the early/middle Miocene times, when the onshore 460 Oligocene basins sedimentary infill begins to fold (de Zoeten and Mann, 1999). From late 461 462 Oligocene to early/middle Miocene time, the OFZ is the locus of large strike-slip faults, with only minor vertical movement (Figure 3d; de Zoeten and Mann, 1991). de Zoeten and Mann 463 (1991) interpret the lack of angular unconformities during this interval as the lack of a significant 464 contractional component. This interpretation is consistent with the oceanic spreading history in 465 the Cayman Through, along the western extension of the Oriente Fault Zone (de Zoeten & Mann, 466 1991; Leroy et al., 2000). Oceanic magnetic anomalies in the Cayman Through suggest more 467

than 200km of left-lateral strike-slip displacement since late Oligocene-early Miocene time 468 (Rosencrantz et al., 1988; Leroy et al., 2000). 469

Late Eocene-Early Miocene formations on Hispaniola (Altamira, Las Lavas, and La Toca 470 Formations, e.g de Zoeten and Mann, 1991) are folded and faulted by a minor compressional 471 episode during the middle Miocene (Pindell & Draper, 1991; de Zoeten & Mann, 1991; Calais & 472 Mercier de Lépinav, 1995; Erikson et al., 1998; Escuder-Viruete & Pérez, 2020). This minor 473 compressional event is associated with the initial development of a restraining bend in northern 474 Hispaniola (Figure 3e) (Erikson et al., 1998; de Zoeten & Mann, 1991, 1999). As restraining 475 bends do not efficiently accommodate the regional transcurrent shear of the fault system (Cooke 476 477 et al., 2013), the middle Miocene was probably a period of active fault evolution including the abandonment and the development of new fault strands. Initiation of new fault strands in the 478 WPS (Figure 3e) and its subsequent migration into the WPD (Figure 3f) may have allowed the 479 fault system to more efficiency accommodate strike-slip stress. At this time, the whole of the 480 Caribbean Plate to the south also experiences an episode of compression (Mauffret & Leroy, 481 1997; Mauffret & Leroy, 1999). 482

We propose that during this middle Miocene compressive episode, thrust faults formed in 483 the WPS northern slope. Ongoing compression in the WPS, folded Unit 1 and created space to 484 accommodate Unit 3 deposition (Figure 14c). Simultaneously, the SFZ strand evolved to 485 accommodate part of the ongoing strike-slip stress (Figure 14c). Calais & Mercier de Lépinay 486 (1995) propose an erosional episode during which Unit 1 may have been partially eroded and 487 488 that the eroded material may have filled up the syncline depressions formed by the previous folding of Unit 1, thus depositing Unit 3. Another possible interpretation is that Unit 3 is the 489 equivalent of the Upper Miocene to Lower Pliocene carbonate platform (Villa Trina Fm, e.g. 490 Escuder-Viruete and Pérez, 2020) deposited during a transgressive cycle in the Lower Miocene 491 to late-middle Pliocene in northern Hispaniola (Escuder-Viruete & Pérez, 2020). In the 492 Cordillera Septentrional (Figure 1), the carbonate platform rocks are tilted, faulted and folded in 493 synclines of the upper Eocene-middle Miocene age (Escuder-Viruete & Pérez, 2020). In this 494 case, the local angular unconformity separating upper Eocene-middle Miocene rocks from less 495 folded carbonate rocks onshore in the Cordillera Septentrional (de Zoeten and Mann, 1999) 496 could be the equivalent of unconformity Uc3 observed in the WPS. 497

498

5.2.4 Pliocene to Present Deformation: Transpressional phase

We interpret the current transpressive component in the Windward Passage to have been 499 initiated during Pliocene time (Figures 3f, 3g and 14d). The Pliocene is described as a period of 500 dramatic reorganization of the northern Caribbean Plate boundary (Calais & Mercier de Lépinay, 501 1995; Calais et al., 2016). It is marked by the oblique collision of the northern Hispaniola block 502 within the Bahama Banks (Figure 3f; Calais et al., 2016; Escuder-Viruete and Pérez, 2020). 503 Obliquity of the maximum horizontal stress has promoted the development of a transpressional 504 zone, with oblique motion between Hispaniola and Bahama Banks (Pindell & Draper, 1991). 505 This, in turn, caused activation of WNW- to W-trending left-lateral strike-slip faults that 506 accommodated and continue to accommodate part of the oblique convergence between the 507 Caribbean and North American Plates. This may also be the case for the Septentrional Fault 508 Zone (SFZ) which formed during the Pliocene as well (Figure 3g; Leroy et al., 2015; Calais et 509 al., 2016; Escuder-Viruete and Pérez, 2020). Formation of the Septentrional-Orient Fault Zone 510 (SOFZ) in the Windward Passage occured when the Oriente Fault Zone (OFZ) joined the 511

512 Septentrional Fault Zone (SFZ) (Figure 3f). The SOFZ segments in the WPD likely formed in

the early Pliocene (Figure 14d). Transpressive deformation due to oblique collision prompted the

development of positive flower structures in the Windward Passage (Figures 5, 6 and 7). In the

- 515 WPD area, the positive flower structure forms an antiformal corridor over the SOFZ trace. Units 516 2 and 3 were folded and uplifted (Figure 14d) and this uplift created a strong erosional surface
- 516 2 and 3 were folded and uplifted (Figure 14d) and this uplift created a strong 517 over the whole area unconformity Uc4 (Figures 7 and 14d)
- 517 over the whole area, unconformity Uc4 (Figures 7 and 14d).

The Pliocene is also marked by the uplift of the Cordillera Septentrional (C. Sept. in 518 Figure 3g, Calais et al., 2016; Escuder-Viruete and Pérez, 2020). The great regional uplift 519 triggered the destruction of the upper Miocene-lower Pliocene forearc carbonate platform 520 (Escuder-Viruete & Pérez, 2020). The onset of collision with the Bahama Banks during the mid-521 Pliocene in this area was followed by a regional sedimentary hiatus that persists until late 522 Pleistocene in the northern Cordillera Septentrional (Escuder-Viruete and Pérez, 2020). We 523 correlate the sedimentary hiatus highlighted by the overlying horizontal layers of Unit 4 above 524 the folded Units 1 and 3 (unconformity Uc4 in Figures 4 and 6) to be the offshore equivalent of 525 this regional sedimentary hiatus. If this is the case, Unit 4 would be middle- to late-Pleistocene in 526 age. If so, the onshore equivalent would be the Quaternary coral reef terraces of northern 527 Hispaniola (Isabela Fm, e.g. Escuder-Viruete and Pérez, 2020). This Quaternary formation that 528 includes two main facies onshore, may correspond to Units 2a and 2b in the Windward Passage 529 (Figures 4 and 8). 530

The system of Quaternary coral reef terraces on along the northwest coast of Hispaniola 531 and the southeast coast of Cuban (Môle de St. Nicolas in Figure 1b; Sorel et al., 1991; Calais & 532 Mercier de Lépinay, 1992) implies a period of active compressional tectonic uplift (Escuder-533 Viruete et al., 2020). The onshore extensions of the Western WPS high and of the Eastern WPD 534 correspond to the uplifted areas of Guantánamo and Môle de St. Nicolas respectively (Figure 535 1b). The WPS displays enhanced uplift at its both extremities. Sorel et al. (1991) dates the most 536 recent marine terrace at Môle de St. Nicolas as 80 Ka. In Cuba, Rojas-Agramonte et al. (2008) 537 relate a general uplift of the reefs and detrital limestones from late Miocene to Quaternary as part 538 of a system of marine terraces. The first Pleistocene terrace can be seen at several localities along 539 the Cuban coast, with up to 20 m in Guantanamo area (southeastern Cuba coast, Figures 1 and 540 3). Marine terraces in Guantanamo are more elevated (up to 400 m, Muhs et al., 2017) than 541 others described along Cuban coast supporting the notion of strong and rapid uplift (Iturralde-542 Vinent, 2003). Rojas-Agramonte et al. (2008) interpret this terrace to be related to active tectonic 543 movements along the SOFZ. 544

Active reverse faults cutting the topmost layers of Unit 4 in the WPS high may be 545 associated with the current compressional pulse recorded in the Northern Hispaniola. The 546 collision with the Bahama Banks is also recorded by the formation of fold-thrust structures in the 547 northwestern submarine accretionary wedge, known as the Northern Hispaniola Deformation 548 Belt (NHDB in Figure 1a)(Dillon et al., 1992; Dillon et al., 1996; Rodríguez-Zurrunero et al., 549 2019). Southward tilting of Unit 4 could also be explained by this recent tectonic pulse in the 550 Caribbean-North American Plate boundary that activated thrust faults along the northern limit of 551 the WPS (Figure 5, km 40-60). Moreover, the narrow positive flower structure affecting the most 552 recent sedimentary layers in its middle part of the WPS indicates that the area is undergoing 553 current transpressional deformation (Figure 2). 554

The presence of current transpressive structures across the Windward Passage area confirms the influence of the active transpressional strike-slip component in the area. An oblique-reverse focal mechanism located in the WPD is evidence of transpression in this area

558 (Corbeau et al., 2019). However, the regional approach of Corbeau et al. (2019) shows the

scarcity of this type of event in the northern Caribbean Plate in which most focal mechanisms are

thrust-fault related. The lack of focal mechanisms with left lateral strike-slip component may

561 suggest that the accommodation of the horizontal component of displacement may be mostly 562 aseismic (Rodríguez-Zurrunero et al., 2020) or that there are not enough seismometers to

aseismic (Rodríguez-Zurrunero et al., 2020) or that there are not enough seismometers to
 properly record it. Current compressional deformation is mainly N-S to NNE-SSW as the result

of the collision between the Bahama Banks and Hispaniola (Corbeau et al., 2019).

565 5.2.2 Timing constraints for the SOFZ propagation

The closely spaced seismic lines crossing the SOFZ main segments allowed us to infer
critical time indicators that bracket the interval in the stratigraphic section during which
horizontal strike-slip motion began in the WPD. As the Early Miocene locus of Caribbean NorthAmerican Plate displacement was north of the Cordillera Septentrional (Figure 3d)(Calais &
Mercier de Lépinay, 1995; Erikson et al. 1998), the strike-slip displacement may not have
affected the early WPD sedimentary record at this time.

Geometry trends of Units 1 and 2 suggest that these two units predate initiation of 572 horizontal movement on the SOFZ in the WDP (Figures 5 and 10). Strike-slip motion of S1, S2, 573 S3 and S4 segments appears to have taken place after Units 1 and 2 were deposited (Figure 1b). 574 The approximately E-W trending of these segments divides the WPD into a southern block and a 575 northern block moving past each other as left-lateral strike-slip movement occurs on the fault 576 system. Thickness changes in Unit 2 between the WPD northern and southern blocks may be due 577 578 to the left-lateral southern block displacement (Figures 5, 10, and 11). Bohannon (1975) describes a similar observation elaborated by the correlation of Oligocene and Miocene rocks in 579 southern California. In this region, these formations were originally deposited in continuous 580 nonmarine basin formed by extentional tectonics, but subsequent right-slip faults evolved and 581 have displaced these formations to their present positions. More examples are described in the 582 Wecoma fault in the Cascadia basin, in the offshore Oregon convergent margin (Goldfinger et 583 al., 1996), and at strike-slip fault zones in the offshore regions of Fukushima and Miyagi, Japan 584 (Arato, 2017). 585

586 Unit 2 thickness and seismic facies are used to estimate the left-lateral strike-slip displacement since the inception of the SOFZ segments. Basin configuration before strike-slip 587 fault propagation should be identifiable after restoration of left slip displacement (Goldfinger et 588 al., 1996). The horizontal plane sections are restored to estimate the onset of strike-slip motion. 589 The southern block is translated right-laterally until Unit 2 thickness and seismic facies match on 590 the opposite side of the fault. Corresponding Unit 2 thickness and seismic facies are found on 591 592 seismic lines separated by 80 km in Figures 11 and 5, thus the horizontal distance needed to restore the section is at least ~80 km (Figure 15). However, as each fault strand accommodates 593 594 part of the lateral relative motion, the left-lateral displacement of this unit must have taken place over a much larger deformation zone rather than along a single fault segment (Figure 15). We 595 infer an age of 5.4 ± 0.2 Ma for the onset of SOFZ segments in the WPD. Our estimate is based 596 on the current \sim 14–15 mm yr⁻¹ of left-lateral motion predicted by Benford et al. (2012) for the 597 Oriente Fault and our estimation of 80 km-net slip in the WPD. Time of fault propagation in the 598 599 WPD is then coincident with the Pliocene paleogeographic reorganization. This estimated fault age may include a large error as we consider a slip-rate constant since the late Miocene time. 600

Even though it is known that strike-slip fault systems change the apportionment of fault slip rates as they evolve and some slip rate discrepancy may occur over time (Cooke et al., 2020).

Timing relationship between Oriente and Septentrional fault segments (OFZ and SFZ 603 respectively, e.g. Figure 3) is not clear. According to Calais & Mercier de Lépinay (1995) the 604 plate boundary has been migrating since Late Oligocene-Early Miocene time when the locus of 605 Caribbean-North American Plate motion shifted to the Oriente fault and splaved eastward 606 (Figure 3f). The transcurrent plate boundary must have been located north of Hispaniola during 607 the Miocene until the Pliocene (Calais & Mercier de Lépinay, 1995). However, Pliocene oblique 608 collision of the Bahama Banks with northern Hispaniola (Escudier-Viruete and Perez, 2020) 609 slowed down the Hispaniola's eastward motion with respect to the North American Plate (Calais 610 et al., 1992). Obliquity of the collision transmitted far-field stress to the overriding plate and 611 prompted activation of strike-slip and contractional components within Hispaniola. Partitioning 612 of the external stress field caused activation of the SFZ and uplift of the Cordillera Septentrional 613 (Figures 3g and 3f, Mann et al., 2002; Calais et al., 2016). Because of SFZ formation, the 614 previously location of the major strike-slip fault in the Hispaniola basin was abandoned (Calais 615 & Mercier de Lépinay, 1995). The major strike-slip motion shifted south to the present-day trace 616 of the plate boundary, transferring part of northern Hispaniola (the present-day Cordillera 617 Septentrional of the Dominican Republic) to the North-American plate (Calais & Mercier de 618 Lépinay, 1995; Erikson et al., 1998; Leroy et al., 2015; Calais et al., 2016; Escudier-Viruete & 619 Perez, 2020). 620

Our estimate of the age of the SOFZ segments in the WPD correlates well with ages 621 inferred for onshore strike-slip faults on Hispaniola (Draper et al., 1994; Erikson et al., 1998, 622 Escudier-Viruete and Perez, 2020). Erikson et al. (1998) estimate a similar offset of 85 km for 623 the Septentrional fault segment in Cibao basin in the Cibao Valley (northern Hispaniola, Figure 624 1). Escudier-Viruete and Perez (2020) suggests a similar horizontal displacement of ~88 km, 625 which implies an average ~ 25 mm. yr⁻¹slip rate for the last 3.5 Ma. Draper et al. (1994) related 626 that the CFZ (subparallel to the onshore SFZ; Figure 3g) has accommodated at least 60 km of 627 left-lateral strike-slip since the Eocene. During the Pliocene collision, the major strike-slip 628 motion probably shifted south to the SFZ present location (Calais et al., 2016) as the Oriente 629 fault system splayed eastward running across the WPD and into northern Hispaniola to form the 630 SOFZ (Figure 3f; Calais & Mercier de Lépinay, 1995; Leroy et al., 2015). Moreover, the 631 estimate 16.5 km offset along the Septentrional fault zone segment offshore does presume an 632 onset of motion at 1.8 Ma (Leroy et al., 2015). 633

These discrepancies of displacements imply that until the uppermost Pliocene, the 634 regional stress field is accommodated mainly by the SFZ but that some local-field stress 635 transferred to subparallel splays, such as the Camú fault zone (Figure 1a)(Rodríguez-Zurrunero 636 et al., 2020). However, in the uppermost Pliocene the trace of the OFZ extends offshore parallel 637 to the northern coast of Haiti until it connects with the SFZ in northwestern Dominican Republic 638 (Figure 3f, Leroy et al., 2015). The result of this last regional paleogeographic reorganization 639 formed the current plate boundary which is represented by the SOFZ present-day trace (Figure 640 3g; Calais et al., 1992; Leroy et al., 2015; Calais et al., 2016). The uppermost Pliocene is also the 641 642 age inferred by Escudier-Viruete and Perez (2020) for the oblique collision of the Bahama Banks with the northern Hispaniola. 643

644 **5 Conclusions**

Tectono-sedimentary evolution in the Windward Passage provides critical constraints for 645 the diachronous evolution of the northern Caribbean Plate boundary over Neogene times. Four 646 main seismic units were identified above the acoustic basement in the Windward Passage. 647 Sedimentation in the Windward Passage Sill (WPS) and in the Windward Passage Deep (WPD) 648 probably occurred in a common palegeographic framework until the inception of the early 649 Oriente Fault zone (OFZ). Therefore, syntectonic deposition of Unit 2, distinct to the WPD, 650 marks the beginning of strike-slip stress field in the area. Discrepancies in seismic facies and the 651 deformation patterns present in the seismic units in both geographic areas probably reflects the 652 structural evolution of the earlier transcurrent plate boundary represented by the OFZ until the 653 initiation of the current SOFZ. 654

655 The Windward Passage has recorded at least 4 tectonic events related to the ongoing oblique collision between the Caribbean Plate and the Bahama Banks. In this context, the first 656 tectonic event in the area may correspond to the period of Cuban-Hispaniola Arc collision, in 657 658 which the sedimentary cover of the ancient forearc basin was gradually uplifted recording the formation of piggyback basins along a syn-collisional margin. The second tectonic event records 659 a period of transition between mainly contractional and transcurrent motions. This period is 660 marked by an important paleogeographic reorganization that corresponds to a brief transtentional 661 event that resulted in the opening of the Windward Passage Deep during the OFZ initiation and 662 the consequent disruption of the Cuban and Hispaniola blocks. The last two events are 663 characterized by contractional and then the current transpressional deformation mainly reflects 664 (i) the progressive collision between the Bahama Banks and Hispaniola blocks and (ii) the 665 Caribbean Plate's eastward escape relative to the North American plate. These last stages of 666 deformation are particularly well recorded in the Windward Passage sedimentary cover, which 667 was folded and displaced left-laterally shifted by the SOFZ. Through the Windward Passage 668 Deep, the estimated ~80 km offset of the sedimentary cover on either side of the major fault 669 suggests an early Pliocene inception for the SOFZ segments in this area. This result provides 670 important time constraints on the SOFZ southeastward migration as well as additional 671 information on the time-related evolution of the northern Caribbean Plate boundary. 672

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921 Figure Captions

Figure 1. Tectonic map of the northern Caribbean plate boundary. (a) Orange dots indicate the 922 presumed epicenters of Mw > 7 historical earthquakes (from Syed Tabrez et al., 2008). 923 Velocities in mm. a-1 are reported from a block model incorporating the available GPS data, 924 925 velocity vectors are relative to the North American plate (Benford et al., 2012). The parts of the fault system studied in this paper are outlined in red. Red line with black dots represent the fault 926 strand identified by Rodríguez-Zurrunero et al. (2020) in the Windward Passage Sill (WPS). Faults 927 928 in black are from previous studies (Calais & Mercier de Lépinay, 1989, 1991; Corbeau et al., 929 2016; Leroy et al., 2015; Granja Bruña et al., 2014; Leroy et al., 1996; Mann et al., 1995, 1998; Mauffret & Leroy, 1997). Inset: Geodynamic map. NOAM: North American plate; CAR: 930 931 Caribbean plate; MB: Muertos Belt; MCSC: Mid-Cayman spreading center; CT: Cayman trough; D.R.: Dominican Republic; OFZ: Oriente Fault zone; EPGFZ: Enriquillo-Plantain Garden Fault 932 zone; WFZ: Walton Fault zone; SDB: Santiago Deformed Belt; BB: Bahamas platform; BR: 933 934 Beata Ridge (modified from Leroy et al., 2015). (b) Bathymetric map of the Windward Passage area showing the active segments of the Oriente-Septentrional Fault Zone (SOFZ) inferred from 935 distinct geometric fault complexities. Active SOFZ Segments are outlined in red. Blue lines 936 937 represent the seismic sections collected during cruises HAITI-SIS 1-2(Leroy, 2012; Leroy & Ellouz-Zimmermann, 2013; Leroy et al., 2015). Bold pink and blue lines indicate positions of 938 seismic sections in this paper (Figures 5 and 13). Boxe of detailed bathymetry (Figure 2). 939 EPGFZ: Enriquillo-Plantain-Garden Fault Zone; NHDB: Northern Hispaniola Deformation Belt; 940 SOFZ: Septentrional-Oriente fault zone, WPS: Windward Passage Sill, WPD: Windward 941 Passage Deep 942

943

Figure 2. (a) Detailed bathymetric map of the Windward Passage Sill and Deep areas. (b)

- Bathymetric map with structural interpretations. See Figure 1 for location of the map. In the
- Windward Passage Sill area, the activity of wrench faults forms a relief about 350 m high
- 947 structured by an antiform and a synform trending E-W and NW-SE. The Septentrional Oriente
- Fault Zone (SOFZ) represented in bold red lines by the S1 to S4 fault segments, cross-cuts the
- 949 Windward Passage Deep area. Red arrows show the average plate convergence direction of the
- North American plate with respect to the Caribbean (Calais et al., 2016). Multibeam bathymetry
- 951 data from the HAITI-SIS cruises and NORCARIBE (Leroy, 2012; Leroy and Ellouz-
- 252 Zimmermann, 2013; Leroy et al., 2015; Granja-Bruna et al 2014) completed with the GEBCO
- 953 Digital Atlas (https://www.gebco.net/data_and_products/gebco_digital_atlas/).
- 954
- Figure 3. Tectonic setting of the northern boundary of the Caribbean plate from Early Eocene to
- Present-day times, modified from Leroy et al. (2000). See text for discussion.
- 957 B.R: Beata Ridge ; C. Sept. CF: Cauto Fault; CFZ: Camú Fault Zone; EPGFZ: Enriquillo-
- 958 Plantain-Garden Fault Zone; H: Hispaniola block; J: Jamaica; NHDB: Northern Hispaniola
- 959 Deformed Belt; NHFZ: Northern Hispaniola Fault Zone. OFZ: Oriente Fault Zone; SFZ:

960 Septentrional Fault Zone; SOFZ: Septentrional Oriente Fault Zone; WPD: Windward Passage
961 Deep; WPS: Windward Passage Sill; YB: Yucatan Basin; TF: Trocha fault.

962

Figure 4. Overview of interpreted seismic units through the WPD and the WPS areas from Eocene to Present-day. A time calibration is proposed. Units 1, 3 and 4 were first named in the

work of Calais & Mercier de Lépinay (1995) as B, A' and A, respectively. Unc.: unconformity.

Figure 5. Seismic profile covering the Windward Passage Deep (south) and part of the

968 Windward Passage Sill (north). Unit 2 is perched and laterally discontinuous southward. The

- 969 WPS high active reverse faults propagate upwards reaching the seafloor. Faults in red are
- upward spreading strands of wrench faults. Normal and thrust faults are, respectively, outline in
 violet and black colors. Inset 1: Location of the seismic line. Inset 2: Seismic line displayed with
- 972 no vertical exaggeration according to the seafloor.
- 973

Figure 6. Seismic profile crossing the Windward Passage Deep (south) and Windward Passage

975 Sill (north). In the Windward Passage Sill, sediments of unit 1 are deformed by older thrust

faults. Black dashed lines are inferred faults based on the folded unconformities Uc1 and Uc3.
Inset 1: Location of the seismic line.

978

Figure 7: Seismic profile crossing the Windward Passage Deep (south) and Windward Passage
Sill (north). Wrench faults offset the Windward Passage Sill and developed a positive flower
structure. The WPS high buildup-structure bordered by reverse faults indicates uplift along the

982 Windward Passage Sill. See inset and Figure 2 for location of profile

983

Figure 8. Seismic profiles in the Windward Passage Sill with interpreted seismic units and its
 relative unconformities. Inset map shows seismic lines location.

986

Figure 9. Seismic profile across the Windward Passage Deep. Sets of reverse faults are identified
on either edge of the basin. See inset and Figure 2 for profile location.

Figure 10. Seismic profile across the Windward Passage Deep. The unit 2 are uplifted in its
northern border. Faults in red highlight the typical expression of the Septentrional–Oriente Fault
zone (SOFZ) in the Windward Passage Deep. Pre-existing northern border fault firstly with a
normal component and secondly with a reverse component is represented in violet. See inset and

994 Figure 2 for location of profile.

995

Figure 11. Seismic profile across the Windward Passage Deep. Sets of reverse faults structural
high on the southern edge of the basin. The unit 2 thickens toward the fault highlighting a
syntectonic wedge related to a normal faulting. See inset and Figure 2 for profile location.

1000 Figure 12. Two seismic profiles located in the Windward Passage Sill (see inset for location)

1001 with interpreted seismic units and its relative unconformities. (a) A narrow wrench fault

1002 deformation zone shifts acoustic basement and the sediment layers in the WPS central part. (b)

1003 The deformed area can be followed westward on parallel seismic lines. See inset and Figure 2 for

1004 profile location.

1005

- 1006 Figure 13. Four cross-sections across the Windward Passage area showing our summary
- 1007 schematic interpretation from the tectonic framework, as discerned from seismic images
- 1008 presented in this paper. Summary schematic interpretation of the tectonic framework across the
- 1009 Windward Passage, as discerned from seismic images presented in this paper. Inset map shows
- 1010 seismic lines location.
- 1011
- 1012 Figure 14. Sketches of the Windward Passage tectonic evolution in four main tectonic phases
- 1013 from Mid-late Eocene to Late-Pliocene to Present-day. Not to scale.
- 1014
- 1015 Figure 15. Isopach map of the unit 2 showing the 80km displacement of the Windward Passage
- 1016 Deep depocencer though east. Note that the bold reverse branches of SOFZ (north to the S2
- 1017 segment) delimits well the unit 2 depocenter. These two fault strands probably accommodate part
- 1018 of the lateral relative motion during the left-lateral displacement of this unit.



Figure 1







Figure 3.



Figure 4.















Figure 8



Figure 9





Figure 11









