

Geological architecture and history of the Antigua volcano and carbonate platform: Was there an Oligo–Miocene lull in Lesser Antilles arc magmatism?

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1 Geological architecture and history of the Antigua

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3 Miocene lull in Lesser Antilles arc magmatism?

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29 ABSTRACT

30 Since the acceptance of plate tectonics, the presence of calc-alkaline magmatic 31 rocks is recognized as evidence of subduction. But under specific geodynamic 32 circumstances, subduction may occur without generating magmas. Here, we 33 investigate the Cenozoic northern Lesser Antilles arc where, from sparsely exposed 34 magmatic records, Eocene-Oligocene and Pliocene magmatic flare-ups and a Miocene 35 lull were postulated. Nevertheless, most of the arc is submarine, so it is challenging to 36 discern lulls and flare-ups from sampling bias. We make a review of the magmatic 37 evidences exposed onshore in the Lesser Antilles and investigate in detail the island 38 of Antigua that exposes an Eocene to Miocene volcanic sequence and platform 39 carbonate series that coincide with the postulated lull. By combining, lithostratigraphic analysis, structural mapping, ⁴⁰Ar/³⁹Ar geochronology, and 40 41 biostratigraphy we refine the magmatic history of the island and date the arrest of 42 extensive arc magmatism at 35 Ma, with minor activity until 27 Ma. No magmatic 43 products are interleaved with the platform sequence until the latest Oligocene, 44 confirming a lull in northern Lesser Antilles arc magmatism, that may have lasted ~ 45 20 Ma. We propose that the magmatic activity contributed to the paleo-(bio-46)geographical evolution of the Eastern Caribbean region with crustal thickening 47 during flareup favouring the rise of terrestrial pathways and thermal subsidence 48 during lull responsible for its demise.

Fault kinematic analysis together with anisotropy of magnetic susceptibility suggests that magmatic arrest is not associated with a change in stress field during Oligocene. We speculate that slab flattening triggered by progressive curvature played a role in the temporal shut-down of the northern Lesser Antilles arc.

54 INTRODUCTION

Active volcanic arcs and associated calc-alkaline magmatic rocks are recognized as closely associated with, and being the result of, modern subduction zones (e.g., Tatsumi et al., 1983; Davies and Stevenson, 1992; Pearce and Peate, 1995). Based on that observation, geological records of volcanic arcs have become widely used as argument to date and reconstruct contemporaneous paleo-subduction zones (e.g., Li et al., 2008; Merdith et al., 2021; Cawood et al., 2009). But is the reverse also true ? Is absence of arc magmatism evidence against subduction?

62 Worldwide, spatial and temporal lulls in magmatism are identified with the absence of 63 calc-alkaline magmas in the rock record. Such gaps are observed in the trans-Mexican 64 belt (Ferrari et al., 2001, 2012), the Andes (Kay and Coira, 2006; Gutscher et al, 65 2000; Rosenbaum et al., 2021), the archetypal Cascade arc of the western USA 66 (Glazner, 2004), the Nankai trough near Japan (Cross and Pilger, 1982; McGeary et 67 al, 1985), Taiwan (Yang et al., 1996), Sumatra (Zhang et al., 2019), and in Tibet (Ma 68 et al., 2022). In the western European Alps, subduction of the Tethys ocean did not 69 produce long-lasting magmatic activity (e.g., McCarthy et al., 2020). Such paucity of 70 magmatic evidence is typically explained by specific variations in geodynamical 71 parameters that may affect the downgoing plate and the upper-plate, such as flat-slab 72 subduction (McGeary et al, 1985, van Hunen et al., 2002, Martinod et al, 2013, Zhang 73 et al., 2019; Ma et al., 2022), subduction of hyperextended, dry mantle (McCarthy et 74 al., 2020), or changes in convergence rates (Cross and Pilger, 1982), but not as an 75 absence of subduction.

In the Eastern Caribbean, the Lesser Antilles region host an arc for which magmatic
flare-ups and lulls has been postulated (Briden et al., 1978; Bouysse and Westercamp,
1990). At first-look, the Lesser Antilles arc is a textbook example of ocean-ocean

79 subduction (e.g., MacDonald et al., 2000). The N-S trending Lesser Antilles trench 80 accommodate 2 cm/year of westward motion of North and South America relative to 81 the overriding Caribbean plate (Pindell and Dewey, 1982; Boschman et al., 2014, 82 Symithe et al., 2016) (Fig. 1). Marine magnetic anomalies in the Cayman Trough, that 83 forms a pull-apart basin on the Caribbean-North American plate boundary, 84 documented constant and stable westward plate motion since 50 Ma (Leroy et al., 85 2000). This subduction is associated with a currently active, well-developed modern 86 volcanic arc that consists of 17 active volcanoes forming islands spread over ~800 87 km. Nevertheless, the arc rocks exposed on these islands are mainly recent (Pliocene 88 to Present-day) and the magmatic record shows significant breaks in volcanism along 89 sections of the arc during both the Late Paleogene and Miocene, especially in the 90 northern part of the arc (Brown et al., 1977; Briden et al. 1979; Bouysse and 91 Westercamp, 1990; MacDonald et al., 2000; Legendre et al. 2018; Noury et al., 2021). 92 In the northern Lesser Antilles, older arc rocks are confined to the islands of the 93 'Limestone Caribbees', that are located in the forearc of the modern arc (Fig. 1, Fig. 94 2, Table 1). The Limestone Caribbees contain well-developed Eocene (~45 Ma) to 95 early Oligocene (~28 Ma) volcanic records, overlain by platform carbonates. From 96 the period between 28 Ma to 20 Ma, only sparse records of magmatic activity have 97 been reported from the northeastern branch of the Lesser Antilles arc (Briden et al., 98 1978, Legendre et al., 2018, Cornée et al., 2021, Noury et al., 2022) (Fig. 2, Table 1). 99 From 20 Ma to 4 Ma, no record of magmatic activity is reported in the Northern 100 Lesser Antilles (Fig. 2, Table. 1). This interval could represent a lull in magmatism or 101 simply be a sampling bias as exposure are sparsely dispersed on islands. Miocene 102 volcanic record could also be buried below younger volcanoes or located offshore.

An answer to these questions may come from Antigua, that displays a magmatic unit whose age was previously estimated from Oligocene to Miocene based on K-Ar whole rock analysis (Nagle et al., 1976; Briden et al., 1978) and where the only complete Oligocene to Miocene sedimentary sequence of the Limestone Caribbees is preserved.

Uncertainties on the K-Ar ages, that are partly rejuvenated by a hydrothermal event (Gunn and Roobol, 1976; Briden et al., 1978), on the age and thickness of the sedimentary sequence (Mascle and Westercamp, 1983; Multer et al., 1986; Weiss, 111 1994) and the absence of structural data and of a description of the tectonic architecture of the island lead to uncertainties on the timing of the geological events that affected the island and consequently on the age of the arrest of the northern Paleogene Lesser Antilles arc (even questioning the existence of its arrest).

115 In that perspective, we constrain the magmatic and stratigraphic architecture 116 and evolution of the island, by developing (1) the detailed lithostratigraphy record of 117 the island, in which we analysed the temporal and spatial relationships between the 118 previously identified lithological units; (2) a first mapping and analysis of the tectonic 119 structures deforming the lithological units; (3) an updated geological map according 120 to our lithostratigraphy and structural analysis. We aim to refine the duration of 121 magmatism and the duration and depositional setting of sedimentary rocks (which 122 may or may not overlap) by establishing (4) age estimates of key volcanic and intrusive units using ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ geochronology and (5) an updated facies analysis and 123 124 foraminiferal biostratigraphy of the marine units. To estimate whether changes in 125 magmatism correlate with tectonic changes, we perform on the scale of Antigua (6) a 126 kinematic analysis using small-scale syn- and post- depositional faults; and (7) an 127 anisotropy of the magnetic susceptibility (AMS) study to complement the structural

128 analysis and estimate the stress field, and changes therein, that existed during 129 sedimentation. Finally, we aim at putting our results in most recent regional structural, stratigraphic and paleo-geographic frameworks (Philippon et al., 2020a; Marivaux et 130 131 al., 2020; Cornée et al., 2021) by providing land-sea correlations using seismic lines 132 to the west and south of Antigua acquired during the Antilles IV oceanographic cruise 133 (Bouysse and Mascle, 1994). We will use our results to evaluate the presence and 134 duration of a lull in Lesser Antilles magmatism and discuss our results in terms of 135 possible geodynamic triggers for anomalous magmatism.

136 GEOLOGICAL SETTINGS

137 **Regional setting**

The Lesser Antilles arc developed above a west-dipping subduction zone that 138 139 accommodates the convergence between the Caribbean upper plate and the 140 downgoing North and South America plates. The plate boundary between the North and South American plates is diffuse, as relative motion between the two is minor 141 142 (e.g., Pindell and Kennan, 2009; Fig. 1). To the north and south, the Caribbean plate 143 boundary changes to E-W trending transforms, sinistral in the north and dextral in the 144 south (Pindell and Kennan, 2009; Fig. 1). The transition is abrupt in the south and 145 accommodated by a slab tear but gradual in the north along a curved plate boundary 146 overlying a curved, amphitheater-shaped slab with a north(west)ward increase in 147 subduction obliquity (Govers and Wortel, 2005; van Benthem et al., 2013; 2014) (Fig. 148 1). This plate configuration developed around 60-40 Ma ago when the Caribbean 149 plate motion relative to the Americas changed from NE-ward to E-ward (Boschman et 150 al., 2014; Montes et al., 2019). Before that, the Eastern Caribbean plate boundary 151 consisted of an oblique subduction at the origin of the Great Caribbean Arc that

extended from Cuba to the south of the Aves Ridge (Fox et al., 1971; Bouysse et al.,
1985; Christeson et al., 2008; Neill et al., 2011, Allen et al., 2019, Padron et al., 2021,
Fig. 1). After the kink, the subduction became orthogonal and the arc jumped
eastward toward the Limestones Caribbees.

156 At regional scale, a north-south morpho-structural dichotomy is observed 157 along the curved Lesser Antilles trench: the southern back-arc region hosts the 158 Eocene Grenada basin with a flat bathymetry and a mean depth of 2800 m and thin 159 oceanic crust (Garrocq et al. 2021, Padron et al., 2021). To the north, the seafloor is 160 rough, mean bathymetry is 1400 m, and the arc crust is thicker (Schlaphorst et al., 161 2018). The Northern Lesser Antilles region, hosts a middle to late Eocene fold and 162 thrust belt (Philippon et al., 2020a) in which subsequently, the trench-parallel 163 Kalinago extensional basin opened in the late Eocene to early Oligocene (Bouysse et 164 al., 1990; Legendre et al., 2018; Philippon et al., 2020a; Cornée et al., 2021; Fig. 1).

From the late Oligocene to middle Miocene, the Northern Lesser Antilles forearc became deformed by V-shaped extensional, perpendicular to the trench basins that opened from late Oligocene to middle Miocene time (Fig. 1). That may suggest intensification of the trench curvature (Philippon et al., 2020b; Boucard et al., 2021). These basins are crosscut by trench-parallel normal faults since middle Miocene that accommodate fore-arc subsidence (Boucard et al., 2021).

171 Offshore investigations in the southern Kalinago basin and its extension south of 172 Antigua island (Willoughby sub-basin) showed that the sedimentary infilling was 173 composed of three megasequences (MS) separated by regional unconformities 174 (Sequence Boundaries, SB) : a late Oligocene to early Miocene megasequence (MS4) 175 resting above a deformed basement and topped by the early- middle Miocene major 176 erosional surface (SB4) indicative of a regional uplift; middle to present day

megasequences (MS5 to MS 6-7) representative of a subsidence of the Kalinago and
Willoughby basins (Cornée et al., 2021; Fig. 11, Appendix 3). No conic structures or
chimneys, that could have been representative of a fossil volcanic activity were found
on seismic lines.

181 The present-day Lesser Antilles magmatic arc consists primarily of calc-182 alkaline volcanoes forming islands from Grenada in the south to Saba in the north 183 (Macdonald, 2000) (Fig. 1). These islands span a trench-parallel arc, with a north-184 westward kink at the latitude of Martinique (Fig. 1).

185 To the south, the Pliocene to present-day arc is superimposed on older arc 186 rocks. In Grenada and the Grenadines, these rocks are upper Eocene to Miocene calc-187 alkaline dykes, volcanic arc rocks and volcaniclastic deposits (Briden et al., 1979; Westercamp et al., 1985; Andréïeff et al., 1987; Speed et al., 1993; Donovan et al., 188 189 2003; Rojas-Agramonte et al., 2017; White et al., 2017) (Fig. 2, Table 1). In 190 Dominica, Martinique, and Sainte-Lucia, older arc rocks consist of well-developed 191 latest Oligocene to Miocene volcanics (Le Guen de Kerneizon et al., 1983, 192 Westercamp et al., 1985, Briden et al., 1979, Germa et al., 2011, Smith et al., 2013) 193 (Fig. 2, Table 1).

In the north, the onset of recent arc volcanoes occurred during the Pliocene to present-day on Saba, St-Eustatius, St-Kitts and Nevis, Monserrat, and Guadeloupe (Baker, 1984; Defant et al., 2001; Samper et al., 2007; Hatter et al., 2018; Favier et al., 2019). These eruptive centers are located on the western shoulder of the Kalinago basin, 50 to 20 km westward from the older eruptive centers preserved in the NW-trending 'Limestones Caribbees' islands (St-Martin, St-Barthélemy, Antigua) on the eastern shoulder of the Kalinago basin (Fig. 1).

201 The Limestone Caribbees host platform carbonates overlying extinct volcanoes, that 202 are preserved in flat bathymetric high (Anguilla and Antigua Banks). These banks are 203 bounded to the east by V-shaped basins (Fig. 1). On St-Martin, arc volcanism 204 developed an Eocene volcaniclastic series (Dagain et al., 1989) intruded by a 29 Ma 205 granodioritic pluton and associated dykes and sills (Noury et al., 2021), and last 206 magmatic activity is represented by a submarine volcanic breccia of 24.4 Ma (Cornée 207 et al., 2021, Fig. 2, Table 1). In St-Barthélemy, magmatic rocks consist of submarine 208 tholeiitic and calk-alkaline lavas (45 to 39 Ma), granodioritic plutons (33.5 to 30 Ma) 209 and local tholeiitic lavas (24.5 Ma, Legendre et al., 2018; Philippon et al., 2020a; 210 Fig.1, Table 1). On Antigua, current dating (K-Ar whole rock analysis, Nagle et al., 211 1976; Briden et al., 1979) supports arc magmatism from the Late Eocene to Miocene 212 and comprises plutonic and volcanic calc-alkaline rocks (Basal Volcanic Suite) and an 213 Oligocene volcaniclastic series (Central Plain Group, Gunn and Roobol, 1976; Briden 214 et al., 1979; Mascle and Westercamp, 1983) (Fig. 2, Table 1).

215 Geo

Geology of Antigua

The first geological study of the lithologies of Antigua by Vaughan (1919) described coral associations and larger benthic foraminifera. Martin-Kaye (1959) subdivided the island in three NW-SE trending geological units, the Basal Volcanic Suite (BVS), the Central Plain Group (CPG) and the Antigua Formation (Fig. 3).

The Basal Volcanic Suite is a mountainous region exposed on the west side of the island, which includes the island's highest point (Mont Obama, 402 m). The suite consists of lava flows and pyroclastic rocks, dykes, and domes of predominantly basaltic, andesitic, and dacitic compositions and with island-arc type geochemical signature (Christman, 1973; Gunn and Roobol, 1976; Fig. 3). Basaltic dykes are also found crosscutting the topmost stratigraphic units (CPG and Antigua Fm.) and are

226 thus considered as the last magmatic pulses exposed on the island (Martin-Kayes, 227 1959, 1969; Fig.2). Whole rock K-Ar analyses for volcanic rocks of the BVS gave ages ranging between 38.5 ± 2 Ma (middle Eocene) and 20 Ma? (minimum age, early 228 229 Miocene) (Nagle et al., 1976; Briden et al., 1979). 230 The Central Plain Group is described as a ~1500m of terrestrial volcaniclastic 231 rocks (conglomerates, sandstones, mudrocks, tuffites) derived from volcanism and the 232 erosion of the Basal Volcanic Suite (Mascle and Westercamp, 1983; Multer et al., 233 1986; Weiss, 1994). These volcaniclastic rocks are interbedded with lacustrine 234 limestones, which contain petrified wood, charophytes, ostracods, and freshwater 235 gastropods (Brown and Pilsbry, 1914; Trechman, 1941; Martin-Kayes, 1959, 1969; 236 Mascle and Westercamp, 1983; Weiss, 1994; Donovan et al., 2014, Fig. 3). Thomas

(1942) and Martin-Kayes (1959, 1969) also suggested that there may be patches of
marine carbonates interbedded with the CPG (e.g., the Seaforth limestone, Fig. 3) that
they interpreted as episodic marine invasions.

240 The Antigua Fm. is composed of carbonate deposits overlying the CPG, in which 241 volcanic deposits have not been recognized. It comprises numerous coral patches and 242 associated bioclastic carbonate deposits, upward and laterally changing into deeper 243 marine carbonate deposits in the east (e.g., Martin-Kayes, 1959, 1969; Persad, 1969; 244 Mascle and Westercamp, 1983; Multer et al., 1986; Weiss, 1994). The estimated 245 thickness of the Antigua Fm is 350 to 550 m (Mascle and Westercamp, 1983). Based 246 on the study of larger benthic foraminifera, planktonic foraminifera, ostracods, and 247 calcareous nannofossils, the age of the Antigua Fm has been estimated as Late 248 Oligocene (Chattian) (Vaughan, 1919; Van den Bold, 1966; Martin- Kaye, 1959, 249 1969; Persad, 1969; Mascle and Westercamp, 1983), consistent with five strontium 250 isotope ages ranging from 26 to 28 Ma (Robinson et al., 2017, Fig. 3) and with recent

251 preliminary age determinations of Cornée et al. (2021). Previous geological studies 252 did not investigate the tectonic architecture or structural history of Antigua. 253 The three units composing the island are affected by sub-greenschist hydrothermal 254 alteration that could be responsible for rejuvenation of K-Ar ages (Briden et al. 1978). Gunn and Roobol, (1976) observed albitised plagioclases and chloritised 255 256 orthopyroxenes and groundmass in the Basal Volcanic Suite. In the Central Plain 257 Group, bright green chloritised tuffites were described by Martin-Kaye (1959, 1969) 258 and Jackson et al. (2013). In the Antigua Fm, this alteration phase is found in the form 259 of silicified limestones (Strang et al., 2018).

260

261 METHODS

262 Field investigation

Three field campaigns (2018, 2019, and 2020) were conducted to investigate the tectono-magmatic history of Antigua. Exposure within the interior of the island is poor due to thick alluvial, colluvium, or vegetation cover. Exposure is most abundant along the coast, even though numerous private properties hampered a full remapping of some coastal portions. Nevertheless, we updated the geological map by mapping the first-order lithostratigraphic units and regional structures (unconformities, faults, dykes), and investigating the relations between units (Fig. 3).

Because the Antigua formation outcrops are isolated, we coupled microfacies and biostratigraphy with lithostratigraphy to reconstruct the general sedimentary organization (Fig. 4, Appendix 1) and paleo-environments (Fig. 10). We logged eight sedimentary sections in the Central Plain Group (CPG) and ten in the Antigua Fm. (Fig. 4, Appendix 1) and used dated isolated exposures from road cuts or along the

seashore (e.g., Galleon, Military Camp, Marble Hill, Fort James, Nelson Dockyard,
Piggots, Willoughby Bay), continuous cross-sections along the shoreline (e.g., Half
Moon Bay, Devil's Bridge, Pigeon Beach) and quarries (Burma, Newfield, Pares,
Parnham) (Fig. 3, Fig. 4). We collected some 400 structural measurements
(bedding orientations, faults, striaes) and reported these on the map (Fig. 3,
Appendix 4).

281

⁴⁰Ar/³⁹Ar geochronology

For ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ geochronology, we collected samples from volcanic and igneous 282 283 rocks of the BVS (Fig. 3). To understand the magmatic evolution of the island, we 284 collected all types of magmatic material that were recognized in the island, targeting 285 the least altered outcrops. Samples consist on an andesitic lava (ANT 20.4, Fig. 5C) 286 crosscut by a rhyolitic dyke (DWB-B, Fig. 5C), a dacitic dome (ANT 6.8, Sugar Hill) 287 a quartz-dioritic pluton (ANT 20.8, Old Road) and two mafic dykes, one crosscuting 288 the CPG (ANT 20.12, Fig. 3, Fig. 5B) and the other that pierce the base of the Antigua Fm (ANT 20.6, Fig. 3). ⁴⁰Ar/³⁹Ar step-heating analyses were performed at 289 Géosciences Montpellier (France, detailed methodology in Appendix 5). Raw data of 290 291 each step and blank were processed and ages were calculated using the ArArCALC software (Koppers, 2002). Ages are statistically analyzed in two ways: ³⁹Ar released 292 293 spectra and inverse isochrones. Plateau ages are calculated from at least three consecutive 39 Ar release steps comprising up to 50% of total 39 Ar_K released and 294 295 overlapping at the 2σ -confidence level (Fleck et al., 1977). Isochrone ages are 296 accepted when mean square weighted deviation (MSWD) is close to 1 and the 40 Ar/ 36 Ar intercept close to the (40 Ar/ 36 Ar)_{atm} value. All results are given at the 2 σ 297 298 uncertainty.

299 Microfacies and biostratigraphy

300 For microfacies and fossil content determination, 35 thin sections were 301 analyzed from the carbonate rocks of the Antigua Fm. and ten from volcaniclastic 302 rocks and lacustrine limestones of the CPG, collected from the 18 logged sections 303 (Fig. 4, Appendix 1). The microfacies were associated to a depositional environment 304 following the classification of Wright and Burchette (1996) and Flügel (2010), 305 supplemented by the larger benthic foraminiferal content (BouDagher-Fadel, 2018a) 306 (Fig. 10, Appendix 2). The biostratigraphic analyses were only carried out for the 307 marine Antigua Formation (the CPG only contains undatable freshwater gastropods), 308 and were based on a complete inventory of larger benthic and planktonic foraminifera 309 taxa identified in the thin sections. We used the zonal calibrations of BouDagher-310 Fadel (2015, 2018b) for the foraminifera, calibrated against the time scale of 311 Gradstein et al. (2012).

312 Fault analysis

313 We employed the right dihedron methods to inverse fault kinematics and interpret the 314 paleo-stress tensor using WinTensor software (Angelier, 1979; Delvaux and Sperner, 315 2003). WinTensor allows the rotational optimization of the obtained tensor by 316 performing iterative tests of tensors to minimize a misfit function. We perform these 317 inversions with sets of data consisting of fault strike, dip, plunge of the striations and 318 beddings offsets (Appendix 4). The quality of inversion is given by QRw (world 319 stress map quality criteria) ranging from A (good) to E (poor) depending of the 320 amount of data used for the inversion (n), the ratio between the amount of data used 321 for the inversion over the amount of input data (n/nt), deviation between observed and 322 theoretical slip direction (α_w) , the sense of slip confidence level (Cl_w) and the type of 323 structure (fault, fracture, shear zone).

324 Anisotropy of the magnetic susceptibility (AMS)

325 To supplement fault kinematics analysis, we used anisotropy of the magnetic 326 susceptibility (AMS) to determine the petrofabric of samples of the CPG and of the 327 Antigua Fm. and determine the direction of tectonic paleo-strain. We drilled 71 328 paleomagnetic cores of fine-grained rocks over 8 sites (Fig. 9A). Samples were 329 collected with a petrol-powered, water-cooled drill and oriented with a magnetic 330 compass. The local magnetic declination (14° W in January 2020) was corrected on 331 all samples. Non-demagnetized standard specimens were measured using an AGICO 332 KLY-3S Kappabridge at the Geosciences Montpellier palaeomagnetic laboratory. 333 AMS is defined by an ellipsoid with the principal axes $k_{max} > k_{int} > k_{min}$ used as strain 334 indicator (Jelinek, 1978; Parés et al., 1999; Maffione et al., 2015). Undeformed sediments display a so-called sedimentary fabric where k_{max} and k_{int} are dispersed 335 336 within the plane of magnetic foliation (F), which is parallel to the sedimentary stratification, and K_{min} is the pole to the bedding plane. A tectonic fabric can overprint 337 338 the sedimentary one, and produce a magnetic lineation (L) by aligning the k_{max} axes 339 parallel to the maximum axis of stretching (σ_3). In this study we have used the 340 magnetic lineation as a paleo-strain proxy to determine the nature and direction of the 341 tectonic strain. The AMS parameters were evaluated using ANISOFT 5.1 software 342 according to Jelinek statistics (Jelinek, 1978; Chadima et al., 2020).

343

344 **RESULTS**

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⁴⁰Ar/³⁹Ar geochronology of the BVS

The Basal Volcanic Suite (BVS) crops out in the southwest of the island and is mainly composed of andesitic lavas and pyroclastic deposits. These are crosscut by rhyolitic dykes (Fig. 5C) and intruded by a dacitic dome at Sugar Hill and at Seaforth

Bay (Fig. 3). At the site of Old Road, a small stock of quartzitic diorite, previously described by Christmann (1973) is intruded by ENE-WSW rhyolitic dykes similar in appearance with the one crosscutting the andesitic lavas (Fig. 5C, 5D). To the southeast, at Nelson Dockyard, mafic dykes intrudes the CPG. To the northeast and southeast (Devil's Bridge) similar dyke are found intruding the Antigua Fm. (Fig.3, Fig. 5A, 5B). No consistent bedding dip is apparent in the BVS; the pyroclastic rocks have bedding that vary between 0 to 30° around local eruptive centers (Fig. 3).

356 The andesitic lava (sample ANT20.4) yields a plateau age of 18.57 ± 1.26 Ma 357 with 82.07 % of Ar released (Fig.8, Table 2). Individual steps show large errors, 358 especially for low temperature degassing steps, resulting from high atmospheric 359 contamination. Consequently, all data cluster along the ordinate axis of the inverse 360 isochron diagram. The inverse isochron calculations for the steps corresponding to the 361 plateau yielded a concordant age of 19.74 ± 2.46 Ma with MSWD = 1.52 for an initial 40 Ar/ 36 Ar ratio of 297.8 ± 1.5 indicating that the trapped 40 Ar/ 36 Ar is indistinguishable 362 363 from atmospheric ${}^{40}\text{Ar}/{}^{36}\text{Ar}$.

364 The rhyolitic dyke (sample DWB-B) that crosscuts the andesite lava flow 365 (sample ANT20.4) vields a hump-shaped spectrum with a mini-plateau age (cumulative 39 Ar released ~40 %) of 35.32 ± 0.16 Ma. The inverse isochron 366 367 calculations for the steps corresponding to the mini-plateaus yielded concordant ages of 35.06 ± 0.61 Ma (MSWD = 1.93, initial 40 Ar/ 36 Ar ratio of 301.9 ± 7.3) with the 368 trapped ⁴⁰Ar/³⁶Ar indistinguishable from atmospheric ⁴⁰Ar/³⁶Ar. The low and high 369 370 temperature degassing steps yield younger ages between 10 and 15 Ma and exhibit compositions poorer in ⁴⁰Ar and richer in ³⁸Ar than the central part, indicating that 371 372 they correspond to a secondary phase (Fig. 8, Table 2).

373 Plagioclase populations from the dacitic dome of Sugar Hill, previously dated

with K-Ar geochronology at 20.8 Ma (Nagle et al., 1976, Fig. 3), yield a plateau age of 29.76 \pm 0.22 Ma for the central part of the spectra corresponding to 68.59% of the ³⁹Ar released. The inverse isochron age of 29.74 \pm 0.62 Ma is concordant with an MSWD = 2.03 and an initial ⁴⁰Ar/³⁶Ar ratio of 298.9 \pm 9.4, indicating that the trapped ⁴⁰Ar/³⁶Ar is indistinguishable from atmospheric ⁴⁰Ar/³⁶Ar (Fig. 8, Table 2).

379 Analysis of the plagioclase population of the quartz diorite (ANT 20.8) yields 380 a staircase spectrum without a plateau ranging from 10 Ma for low temperature 381 degassing steps to 28 Ma at high temperature. The total fusion age is 22.88 ± 0.29 Ma. To aid interpretation of the measured spectra and the thermal history, we 382 performed an inverse modelling of the ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ spectra of the plagioclase population 383 384 from the dioritic pluton with QTQt software (Gallagher, 2012). The inverse QTQt model for the plagioclase 40 Ar/ 39 Ar spectrum suggests that the diorite sample 385 386 underwent a steady cooling at a rate of $\sim 5^{\circ}$ /Ma since ~ 25 Ma (Fig. 8).

387 Despite a large error on individual steps related to atmospheric contamination, 388 analysis of the groundmass of the basaltic andesite dyke crosscutting the Central Plain 389 Group (ANT20.12) yields a plateau age of 27.03 ± 1.89 Ma corresponding to 90.99 % 390 of the ³⁹Ar released (Fig. 8, Table 2). The inverse isochron yields a concordant age of 391 27.73 ± 2.94 Ma with an MSWD = 0.48 and an initial ⁴⁰Ar/³⁶Ar ratio of 297.3 ± 3.2 392 indistinguishable from atmospheric ratio. Low-temperature individual degassing steps 393 show larger errors and yield younger ages (10 to 20 Ma).

For the basaltic andesite dyke intruding the Antigua Fm (ANT 20.6) we analyzed both plagioclase and groundmass populations. The plagioclase analysis yields a plateau age of 30.50 ± 0.70 Ma with a large error on degassing steps corresponding to 97.98 % of the ³⁹Ar released (Fig. 8, Table 2). Calculated inverse isochron show indistinguishable trapped and atmospheric ⁴⁰Ar/³⁶Ar and an age of

 30.57 ± 0.81 Ma with MSWD = 0.74 for an initial 40 Ar/ 36 Ar ratio of 297.7 ± 5.4. 399 400 Analysis on the groundmass population did not yield a plateau and a hump-shaped 401 spectrum with younger low and high temperature individual steps (~15 Ma) with a poorer ⁴⁰Ar and richer ³⁸Ar composition. However, the total fusion age obtained on 402 403 groundmass (30.54 \pm 0.27 Ma) is concordant with the plateau age obtained from 404 plagioclase population analysis.

405

406

Lithostratigraphy, microfacies and biostratigraphy

407 Central Plain Group

408 The CPG comprises various terrestrial clastic rocks, lacustrine limestones, 409 volcaniclastic mud and debris flows and conglomerates interpreted as alluvial fan deposits, volcaniclastic clay-rich deposits, tuffites, and lapilli-rich beds. These are 410 411 well exposed at St-John, Corbison, to the NW, and at the site of All Saints, in the 412 central part of the island (Fig. 3; Fig. 4, Appendix 1). To the SE, the volcaniclastic 413 deposits of the CPG are topped by the lacustrine limestones of Christian Hill that 414 contain feldspar and quartzitic debris (Fig. 3; Fig. 4). We interpret the volcaniclastic 415 series as deposited in an alluvial plain system with lakes (where the limestones 416 formed) and ephemeral braided alluvial fans (cf. Nemec and Steel, 1984) that was 417 located at the foot of a volcanic edifice located to the SW and corresponding 418 nowadays to the Basal Volcanic Suite. Volcanic activity during deposition of the CPG 419 was ongoing, as recorded by tuffites and lapilli-rich deposits. We mapped 420 discontinuous exposures of a tuffite member that is bright green in color and easy to 421 recognize in the field, which we use as a marker in our cross section (Fig. 3; Fig. 4, 422 Appendix 1). The CPG is overall a monoclinal succession striking ~ NW-SE and

423 dipping 10° toward the NE (Fig. 3). In the vicinity of normal faults, dips vary and 424 may be up to 30° (Fig. 3).

425 Previous maps (Martin-Kaye, 1969; Christman, 1973) suggested that the CPG 426 is overlying the BVS, but we carefully studied the contacts and did not find this 427 relationship: rather, the CPG is interfingering with the BVS, as a syn-magmatic 428 sedimentary sequence adjacent to the main volcanic edifice. This is supported by the 429 presence of volcaniclastic deposits within the CPG at Willoughby, Pigeon beach and 430 Galleon (Fig. 3, Fig. 4). At Nelson Dockyard, the volcaniclastic and green tuffite 431 layers of the CPG are intruded by mafic dykes (Fig. 5A) that follow a NW-SE 432 trending normal fault (Fig. 5B). From the NE-SW cross-section (Fig. 3), we estimate 433 a minimum thickness of 200 m for the CPG, but the true thickness may be much 434 thicker as the base of the sequence is not exposed.

435

436 Antigua Formation

437 At Galleon, Pigeon Beach, Five Island, Fort James, and Seaforth, patches of few 438 meter-thick, reefal limestones are observed resting either above the CPG or the BVS 439 (Fig. 3, Fig. 4). Previous authors (e.g., Thomas, 1942, Martin-Kaye, 1969, Bouysse 440 and Westercamp, 1983) interpreted these as interbedded in the CPG, but our 441 observations rather show that these patches are always unconformably overlying the 442 CPG and preserved in the hanging walls of normal faults. From microfacies analyses, 443 we dated these marine limestones from Zones P20 (Rupelian, 30.3-29.2 Ma) to P21b-444 P22 (Chattian, 28.1-23 Ma).

The Antigua Fm. is exposed in the east of the island, upon the CPG. Local observations (St-John, Fig. 6A) and the regional shallower monoclinal orientation striking N140° and dipping 5° toward NE indicate an angular unconformity between

the CPG and the Antigua Fm (Fig. 3). The minimum thickness of the Antigua formation is 80m and is estimated from section logging in Burma Quarry (Fig.4, Appendix 1). From the cross-section (Fig. 3), we re-evaluate its thickness to 160m. Centimeter-size sub-horizontal stylolite are observed within the top beds of the Antigua Fm. (Fig. 3, Fig. 6B and 6C, Fig. 8) showing that the thickness of the Antigua Fm. must have been perhaps some several hundred meters thicker, but the overburden was later removed.

455 In the northwestern part of the island, the formation comprises: ~10 m- thick 456 coarse-grained cross bedded siliciclastic carbonates; 18 m-thick foraminiferal 457 packstones dated from Zones P18-P21a (Rupelian, 33.9-28.1 Ma) to P21b (Chattian, 458 28.1-26.8 Ma); 45 m thick coral biostromes (Fig. 6E) and foraminiferal wackestones 459 to packstones, dated to Zones P21 to P22 (upper Rupelian-Chattian) in their 460 lowermost part (Fig. 4, Fig. 10, Appendix 1 and 2). In the central part of the island the 461 Antigua Fm. comprises, from bottom to top: ~10 m-thick coarse grained mixed 462 carbonate and volcaniclastic grainstone with corals, dating from zones P18 to P21a 463 (Rupelian, 33.9-28.1Ma); 8m- thick foraminiferal wackestones and coral beds dating 464 from zones P21b to P22 (upper Rupelian-Chattian, 29.2-23 Ma); 5.5 m- thick 465 planktonic foraminiferal wackestones dating from zones P21b - P22 (Chattian) to 466 P22b-N4 (upper Chattian-Aquitanian, 24-21 Ma) in the uppermost part (Fig. 4, Fig. 467 10, Appendix 2 and 3). The southeastern part of the Antigua Fm is made of few 468 meter-thick foraminiferal wackestones dated to Zones P18-P21a (Rupelian, 33.9-29.2 469 Ma) (Half Moon Bay) or Zones P22-N4 (upper Chattian-Aquitanian, 26.8-21 Ma) 470 (Devil's Bridge) (Fig. 3, Fig. 4, Fig. 10, Appendix 1 and 2). The presence of several 471 interbedded mixed volcaniclastic-carbonate rocks indicates occasional mass flow deposition. 472

473 The Antigua Fm was deposited in low angle reefal carbonate ramp setting 474 above the BVS and the CPG (Fig. 10). The sequence is composed of inner ramp coral 475 biostromal beds (Fig. 6E) changing southeastwards into planktonic foraminifera-rich 476 wackestones. An upward deepening trend is also recorded from reefal deposits in the 477 lower part of the formation to muddy, mid to outer ramp deposits in its uppermost 478 part. Our biostratigraphic constrains show that the Antigua Fm was deposited from 479 the late Rupelian (Zone P20, 30.3-29.2 Ma) to the late Chattian-Aquitanian (Zones 480 P22-N4, 26.8-21 Ma) (Fig. 10, Appendix 2).

The Antigua Fm includes reworked and weathered volcaniclastic beds that we
interpreted as turbidites or tempestites (Fig.4, Appendix 1) but nowhere did we find
volcanic ash or pumice deposits interbedded in the Antigua formation.

484

485 Structure and kinematics of Antigua

486 Mapped and outcrop-scale faults are normal faults that may be roughly 487 subdivided into three clusters: ~N020° ($\pm 020^{\circ}$), N090° and ~N140° ($\pm 020^{\circ}$). The fault 488 planes dips on average about 60° and show dip-slip slickenslides and displacements 489 up to tens of meters (Fig. 7). The N020° and N090° faults are observed in the three 490 units of Antigua but the N140° faults are absent in the Antigua Fm. The CPG and Antigua Fm strike parallel to the N140° faults suggesting that these faults are 491 492 responsible for the main orientation of the island's stratigraphy. The trend of 493 Antiguan coastlines is controlled by each of these three fault populations: the 494 northweastern and south-eastern shores are trending NE-SW, the southern shore is E-495 W trending and the northeastern and southwestern shore display a series of NW-SE 496 trending deep and narrow bays and capes. Although no direct crosscutting evidence 497 has been found in the field, at map scale the N20° faults seem to intersect the N90°

and N140° faults, especially to the north of Liberta Hill and Christian Hill and on the
southeastern and northwestern coasts (Fig. 3). The N090° and N140° faults are well
visible in the CPG where they shape the landscape with the footwall consisting of
100- 200 m high hills that trend NW-SE (Christian Hill, All Saint Hill, Fig. 3).

502 At site scale, paleo-stress tensors indicate pure to radial extension with the 503 direction of stretching varying from NNW-SSE to E-W. Strike-slip faults were 504 observed only at one site (Old Road, Fig. 9A). Some sites display slightly oblique-slip 505 normal faulting (Fig. 9A). Evidence for syn-sedimentary activity was observed for 506 N090° faults at Fort James (injectites, Fig. 7A) and at Newfield (abrupt facies 507 changes and reworked reefal blocks across the fault, Fig. 6B). At Nelson Dockyard, a 508 N140° trending fault was intruded by a mafic dyke that we dated to 27.03 \pm 1.89 509 (ANT20.12), giving a minimum fault age.

510 As the N020° and N090° faults are observed in the three units of Antigua but the N140° faults are absent in the Antigua Fm, we assume that N20° and N90° faults 511 512 postdate N140° faults. Moreover, there is no clear cross cutting relationships between 513 N020° and N090° fault suggesting that they might be synchronous, therefore while 514 performing the kinematics inversion, we split our dataset separating N140° trending 515 faults from the N020°-N090° dataset, according to our filed constraints and 516 observations. For the N140° faults set, we obtained a paleo-tensor with σ_1 = $N255^{\circ}/80^{\circ}$, $\sigma_2 = N120^{\circ}/0^{\circ}$, $\sigma_3 = N020^{\circ}/10^{\circ}$, indicating that these faults 517 518 accommodated a NNE-SSW stretching (Fig. 9C). The paleo-tensors obtained for the 519 E-W and N-S trending faults show a subvertical σ_1 , a sub-horizontal N130°-trending σ_2 , and a sub-horizontal, N030° trending σ_3 indicating NNE-SSW stretching (Fig. 520 521 9C). Due to the limited number of observed faults and lack of kinematics indicators 522 on fault planes, the quality of the tensors is poor (i.e., class D). Nonetheless, the

obtained tensors provide no evidence for major changes in the stress field during
deposition of the Antigua Fm: strain is minor, and characterized by a NNE-SSW
stretching direction that did not vary much during the Oligocene (Fig. 9C).

526

527 Anisotropy of the magnetic susceptibility (AMS)

Site mean susceptibility (k_m) of sites in the CPG (31.31-76.55 x 10⁻⁴ SI) and in 528 Antigua Fm $(0.052-25.59 \times 10^{-4})$ are indicative of a significantly high concentration 529 530 of ferromagnetic minerals. Corrected anisotropy degrees are low (P' < 1.06) with 531 values ranging from 1.014 to 1.058, suggesting a relatively weak tectonic overprint (Table 3). The shape of AMS ellipsoid varies from oblate (T > 0, F > L) to triaxial (T 532 533 ≈ 0 , F \approx L) with a dominance of oblate ellipsoids, indicating that the tectonic fabric 534 has only partially overprinted the original sedimentary fabric (Borradaile and Jackson, 535 2004) (Table 3). Pure sedimentary fabrics are recognized at sites CH, TU1, CO and 536 PA, where k_{int} and k_{max} are randomly distributed within a plane sub-parallel to the 537 stratification (Fig. 9B). Tectonic fabrics are recognized at sites TU2, FJ, FI and DB, 538 where a well-defined (i.e., $e_{12} < 30^{\circ}$) magnetic lineation is observed (Fig. 9B, Table 539 3). This magnetic lineation is sub-horizontal to shallowly plunging towards NNE to 540 NE (Fig. 9B). This direction is sub-parallel to the regional NNE-SSW stretching 541 direction estimated from the fault kinematic analysis from the Basal Volcanic Suite, 542 the Central Plain Group and the Antigua Fm. (Fig.9C).

543

544 **DISCUSSION**

- 545 Geological evolution of Antigua
- 546 Late Eocene early Oligocene magmatic activity

547 With a combination of field observations, lithostratigraphy, biostratigraphy, and ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ dating we establish the duration of magmatic activity in Antigua and 548 549 subsequent sedimentation. The lithostratigraphy of Antigua shows that magmatism 550 formed the Basal Volcanic Suite, and was active during the deposition of the 551 volcaniclastic Central Plain Group, but not during the deposition of the Antigua Fm 552 (Fig. 3). The stratigraphically lowest (tuffites) and highest (lacustrine limestones with 553 volcanic debris) units of the CPG that we observed in the field contain evidence of 554 explosive volcanism (Appendix 1). In the Antigua Fm. all volcanic elements are 555 reworked as clastic sediment but no evidence for explosive (ash deposits or pumice) 556 or effusive volcanism (intercalated lavas) was observed (Fig. 8B, Appendix 1). Our 557 field observations corroborate seismic interpretations of lines offshore Antigua, where 558 in megasequences interpreted to reflect the Oligocene and Neogene deposits, no 559 magmatic features (conic shaped bumps) were identified (Cornée et al., 2021; Fig. 11, 560 Appendix 3).

From our 40 Ar/ 39 Ar ages of a rhyolitic dyke (sample DWB-B) and a dacitic dome (sample ANT 6.8) crosscutting the andesite-pyroclastic suite (35.32 ± 0.16 Ma and 29.76 ± 0.22 Ma, respectively; Fig.7, Table 2), and the K/Ar age of Nagle et al. (1976) of an andesitic lava (38.5 ± 2 Ma, Fig. 1, Table 1), we infer that the bulk andesitic and explosive volcanism of the Basal Volcanic Suite occurred in the late Eocene.

We discarded our age of 18.57 ± 1.26 Ma for the andesite from the BVS (sample ANT 20.4) because it is inconsistent with the one of the rhyolitic dyke that crosscut it. We assume that this sample was fully reset during a late (post-magmatic) hydrothermal event as exemplified by the very high atmospheric contamination within it. This is supported by the occurrence of various degrees of sub-greenschist

hydrothermal alteration within the Basal Volcanic Suite (albitized plagioclases,
chloritized orthopyroxenes and groundmass; Gunn and Roobol, 1976), the Central
Plain Group (chloritised tuffites; Jackson et al., 2013) and the Antigua Fm (silicified
limestones; Strang et al., 2018). Such pervasive subgreenschist hydrothermal
metamorphism has been described within the recent arc in the Guadeloupe and may
take place at 1 to 3-4 km depth (Favier et al., 2019).

578 Late volcanic activity occurred in Antigua at the transition between early and 579 late Oligocene and is exemplified by the emplacement of a dacitic dome through the 580 BVS and basaltic andesite dykes through the CPG and the Antigua Fm. The dacitic 581 dome yields a late Rupelian age of 29.76 ± 0.22 Ma (ANT 6.8, Sugar Hill). The mafic 582 dykes intruding the base of the Antigua Fm gives an age of 30.50 ± 0.70 Ma (ANT 583 20.6) that is consistent with the biostratigraphic dating to the late Rupelian (Zone P20, 584 30.3-29.2 Ma). As the CPG is synchronous with magmatic activity of the BVS and 585 capped by the Antigua Fm its age must range from at least 38 to 30 Ma (late 586 Bartonian to late Rupelian). The 27.03 ± 1.89 Ma age of a dyke crosscutting the CPG 587 is the youngest evidence for magmatic activity on Antigua (Fig. 5A, 5B).

588 The quartz diorite stock, now exposed at Old Road, gives only a minimum age of 28

589 Ma, and could represent a late-stage intrusion (ANT 20.8, Fig. 7, Table 2).

590

591 Late Oligocene – early Miocene carbonate platform

592 Following the end of magmatic activity, we observe a change from terrestrial 593 (CPG) to marine environment (Antigua Fm.) during the Rupelian-Chattian transition. 594 The depositional environment of the Antigua Fm. varies both geographically from 595 inner ramp coral biostromal beds (Fig. 6E) to the north-west to planktonic 596 foraminifera-rich wackestones to the south-east and temporally with reefal deposits in

597 the lower Rupelian part of the sequence to muddy, mid to outer ramp deposits in its 598 uppermost part (late Chattian to Aquitanian). We reinterpreted the marine carbonates 599 deposits, previously described as interbedded within the CPG (Mascle and 600 Westercamp, 1983), as residual exposures of the Rupelian lower part of the Antigua 601 Fm, preserved in grabens. This indicates that the Antigua Fm was entirely covering 602 the CPG and, consequently, that a transgressive event occurred in Antigua during the 603 P20 Zone (30.3-29.2 Ma, Rupelian). The late Rupelian-Chattian global sea level 604 variations (tens of meters; Miller et al., 2020) are smaller than those of the 605 depositional environment of the Antigua Fm (tens to hundreds of meters). 606 Consequently, we infer that the Island subsided during the late Rupelian-Chattian 607 interval. Thermal subsidence upon cooling after magmatic activity could have played 608 a role (Moore, 1970; Tallarico et al. 2003).

609 To account for the presence of centimetres long, subvertical pressure-610 dissolution stylolitic peaks (Fig. 6C, 6D) the Antigua Fm must has undergone vertical 611 compaction related to a post-Aquitanian sedimentary pile that was later eroded. In the 612 neighbouring volcanic area, this erosional event and associated exhumation is 613 supported by the outcropping of sub-greenschist facies units, that are thought to be 614 originated from 1 to 3-4 km depth (Favier et al., 2019). In the offshore domain, the 615 megasequence 4 (MS4, Oligocene to Early Middle Miocene in Cornée et al., 2021), 616 that can be correlated to CPG and Antigua Fm, is topped by a major erosive Sequence 617 Boundary (SB5) dated as early middle- Miocene (Fig. 11, Appendix 3) and 618 recognized regionally (Cornée et al., 2021; Boucard et al., 2021). We thus suggest 619 that erosion occurred during early-middle Miocene time. After this period, the island 620 likely remained above sea-level as no post-Aquitanian sediments (aside from 621 Quaternary alluvium) can be observed. Meanwhile, the Willoughby Basin subsided

along the N090° faults bounding the Antigua bank to the South (Fig. 11). This stable position appears consistent with the slow cooling estimated with QTQt modelling of 40 Ar/³⁹Ar spectrum of plagioclase from the quartz diorite (~5° per Ma; sample ANT 20.8, Fig. 8) since 25 Ma at least – a similar cooling rate was recently reported from the granodioritic plutons of St Martin island (Noury et al., 2021).

627

628 A 20 Ma long magmatic lull

629 The geological history we unraveled from Antigua thus includes (1) a main 630 magmatic pulse occurred in Antigua during the late Eocene (continuing to at least 35 631 Ma), (2) magmatic activity continued mainly during the early Oligocene in the form 632 of late-stage dykes and plugs (30.5 to 27 Ma), (3) magmatic activity ceased during the 633 late Oligocene synchronously with a regional transgressive event and a subsidence of 634 the island leading to the development of a carbonate platform completely devoid of 635 evidence of volcanism; (4) an early-middle Miocene exhumation and uplift event 636 responsible for the removal of a part of the volcanic and sedimentary series after 637 which Antigua stayed emerged and stable.

638 From our new age model, we find that, in the northern Lesser Antilles, the 639 main activity of the Paleogene arc occurred between the late Eocene and the early 640 Oligocene and show that magmatism – previously supposed to possibly continue into 641 the Miocene based on K-Ar ages (Nagle et al., 1976; Briden et al., 1979) – waned and 642 came to an arrest by ~27 Ma in Antigua. Small-volume, late-stage magmatism on 643 nearby islands St-Martin (24.4 Ma; Cornée et al., 2021) and St-Barthélemy (24.5 Ma; 644 Legendre et al., 2018) continued slightly longer. The recent arc, located further west 645 in the island of Saba, St-Kitts, Monserrat and Guadeloupe, is active since the 646 Pliocene. Our analysis thus supports a long magmatic lull in the northern Lesser

647 Antilles arc despite ongoing subduction at more or less constant rates (Leroy et al., 2000; Boschman et al., 2014). With our new age model that includes ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ dates 648 and lithostratigraphy, we more accurately constraining it to a ca 20 Ma period lasting 649 650 from the early late Oligocene to the Pliocene. As magmatic flareup contribute to 651 crustal thickening (Ma et al., 2022), the Paleogene activity of the Lesser Antilles arc 652 should have participated to the building of the GrANoLA land (Philippon et al., 653 2020a), an emerged area that was spread out through the Northern Lesser Antilles to 654 Puerto Rico and favoured terrestrial fauna dispersal from South America to Greater 655 Antilles (e.g. Marivaux et al., 2020). The end of magmatic activity and subsequent 656 thermal and tectonic subsidence could have participated to the removal of this 657 pathway during late Oligocene. This is showing the importance of the understanding 658 of the magmatic history of the Lesser Antilles arc in the frame of paleo-(bio-659)geographical history of the Eastern Caribbean region.

660

661 A correlation between end of magmatism and tectonic changes ?

In the Northern Lesser Antilles, a correlation between tectonics and magmatism is suggested by the NW-SE orientation of the Paleogene arc that aligns with the eastern flank of the NW-SE oriented Kalinago basin. This basin opened from the Eocene to the late Oligocene, synchronously with magmatic activity (Cornée et al., 2021).

At the scale of Antigua, we found evidences for syn-magmatic and synsedimentary tectonic activity. Within the CPG, we estimate a pre- or Rupelian age for the activity of a normal fault at Nelson Dockyard as it is intruded by a dyke dated at 27 Ma (this study). Furthermore, the presence of injectites at Fort James (Fig. 7A), of abrupt facies changes and reworked reefal blocks in Newfield (Fig. 6B) and the NE

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orientation of the magnetic lineation obtained from sites of the CPG and of the Antigua Fm, that are consistent with the NE-SW stretching orientation obtained from paleotensor, strongly suggest syn-sedimentary tectonic activity.

675 Synchronously with the arrest of magmatism, we observe a marine 676 transgression and a tilt of the Central Plain Group resulting in a 5° difference of the 677 mean dip beddings between the CPG and the Antigua Fm. This strongly suggests that 678 the late Rupelian-Chattian transgression reflects tectonic subsidence although thermal 679 subsidence could also have played a role. The gentle northeastward 5° dip of the 680 Antigua Fm and a general deepening of the paleo-environment toward the uppermost 681 part of the sequence indicate that the subsidence is active until at least early Miocene.

682 Our structural observations and AMS measurement does not show a clear 683 change in deformation behavior or directions during Oligocene. Both paleostress 684 tensors indicate a NNE-SSW directed stretching, which remained consistent over 685 time. In the BVS and CPG, this stress field is accommodated by dominant N140° 686 faults and N090° and N020° normal faults. In the Antigua Fm, N140° faults are not recognized and the stress is accommodated by N090° and N020° faults. The absence 687 688 of N140° faults could be indicative of a lowering of the intensity of the deformation. 689 AMS results show that magnetic lineations acquired during syn-tectonic deposition 690 are consistent with the NNE-SSW stretching direction estimated by paleotensors. This 691 confirms that this stretching direction was dominant in Antigua from the early 692 Oligocene to the early Miocene even though different families of faults accommodate 693 it.

With our field and kinematic investigations, we did not see (1) significant
deformation in the Antigua Fm and (2) a change in stress field during the Oligocene.
The decrease or change in tectonic activity on the island is subtle and only outlined by

the absence of N140° faults in the Antigua Fm. Thus it is unlikely to correlate the end
of magmatism to a change in tectonic activity on Antigua.

699 On the island of St-Martin and St-Barthélemy, a switch from pure orthogonal-700 to-the-trench to radial extension is recognized during the early Miocene (Legendre et 701 al., 2018; Noury et al., 2021). In the northern Lesser Antilles region, a change in 702 upper-plate deformation style from back arc rifting (Kalinago basin; Cornée et al. 703 2021) to fore-arc dissecation (V-shape basin, Boucard et al., 2021) as well as drastic 704 vertical motion (Cornée et al., 2021; Boucard et al., 2021) is observed during the 705 Oligocene. Together with the arrest of magmatism, these changes in upper-plate 706 deformation and vertical motion are certainly controlled by subduction related 707 processes and slab parameters variations.

708

709 What controls Lesser Antilles magmatic flare-ups and lull?

The oldest volcanic rocks of the Lesser Antilles arc are ~42 Ma (Philippon et al., 2020a), some 10 Ma younger than the NE-SW to E-W change in Caribbean-North America plate motion that led to the to the formation of the modern day N-S trending Lesser Antilles subduction zone (Briden et al., 1979; Boschmann et al , 2014).

Such a delay is often seen between the onset of subduction and the development of a mature arc (e.g., Stern et al., 2012). During ~ 15 Ma (late Eocene to late Oligocene), volcanic edifices developed on the eastern flank of the Kalinago basin, and in this period, the arc-trench distance, and by inference, the slab angle, remained more or less constant. But by the end of the Oligocene, magmatism ceased in the Northern Lesser Antilles.

Several hypotheses have been proposed to explain this arrest. Bouysse andWestercamp (1990) speculated that slab break-off occurred following the subduction

of a postulated buoyant, thick oceanic crust. But seismic tomographic images reveal a continuous, non-broken slab reaching the mantle transition zone without evidence for breaks (van Benthem et al., 2013; van der Meer et al., 2018; Braszus et al., 2021), and the subduction rate has not changed (Boschmann et al., 2014). If a slab breakoff had occurred, a new slab would have had to quickly formed to re-instate the arc as observed.

Boucard et al., (2021) suggested that subduction erosion occurred during middle Miocene time. Subduction erosion could push an arc towards the hinterland, but the timing of this event (post-middle Miocene) cannot explain the late Oligocene onset of the magmatic lull, and subduction erosion would migrate an arc, rather than stop its activity.

733 Slab flattening is then a third option. Subduction of buoyant features (oceanic 734 aseismic ridges, oceanic plateaus, or seamount chains) is commonly thought to 735 possible trigger flat slab subduction at mantle-stationary trenches (Yang et al., 1996, 736 Gutscher et al., 2000; Gerya et al., 2009; Martinod et al., 2013, Ma et al., 2022). In the 737 Lesser Antilles region, McCann and Sykes (1984) were the first to propose that a 738 former anomalously thick aseismic ridge connecting the Barracuda ridge and the 739 Main Rise (Fig.1) and/or that fragments of the Bahamas platform interacted with the 740 subduction and could have triggered slab flattening and westward migration of the 741 volcanic center. To the North, the thin continental margin below the Bahamas bank 742 diachronously subducted and entered the Greater Antilles subduction zone Antilles in 743 the late Eocene after which subduction on Cuba ceased (Erikson et al., 1990; Mann et 744 al., 2002; Iturralde-Vinent et al., 2008; Granja-Bruna et al., 2010; Cruz-Orosa et al., 745 2012; Lao-Davila et al., 2014). The eastern, ocean-ward end of the Bahamas bank 746 already interacted with the NE Caribbean margin during the Caribbean plate motion

change of the mid-Eocene and there is no clear reason to infer that this interactionallowed for an arc in the late Eocene and early Oligocene, but not in the 20 Ma thatfollowed.

So while slab flattening may be a viable reason to explain the magmatic lull,
the obvious solutions inferring the arrival of buoyant features do not seem
straightforward solutions.

As showed by recent reconstructions of the Caribbean region, a change in the age of the oceanic lithosphere subducted, from a young Proto-Caribbean oceanic crust to an old America's oceanic crust is observed in the eastern Caribbean subduction zone during the end of Oligocene (Braszus et al., 2021). Nevertheless, variation of the age of the subducted oceanic lithosphere might not be by itself sufficient to change the slab dip (Cruciani et al., 2005).

759 Schepers et al. (2017) showed for the Andean subduction zone that flat slabs may also 760 arise when roll-back of a subducted slab is locally impeded, and sub-slab mantle starts 761 to support a flat slab. But the Lesser Antilles trench can be considered more or less 762 stable relative to the mantle since 50 Ma following the kinematic reconstructions of 763 Boschmann et al. (2014) and roll-back was short-lived and restricted to the southern 764 portion of the trench, where the Grenada-Tobago Basin opened in the Eocene (Aitken 765 et al., 2011), before the magmatic lull. So the scenario for the Andes does not apply to 766 the Lesser Antilles arc.

We suggest that slab flattening in the northeastern corner of the Caribbean plate may have originated from the progressive formation of the spoon-shaped, curved slab (Laurencin et al., 2013; van Benthem et al., 2013; Braszus et al., 2021). The westward motion of North America relative to the nearly mantle-stationary Caribbean plate (Boschmann et al., 2014) and Lesser Antilles trench must be associated with

772 westward dragging of the south-dipping Puerto Rico part of the slab (Spakman et al., 773 2018; van de Lagemaat et al., 2018; Parsons et al., 2021). With ongoing absolute 774 westward motion of North America, the E-W segment of the Puerto Rico segment 775 becomes longer (Boschmann et al., 2014), and in the curved area, the slab folds and 776 may flatten (Fig. 12). This curvature and flattening could have been minimal in the 777 Eocene, allowing for a regular volcanic arc, but became progressively more intense, 778 which may explain the long magmatic lull (Cerpa et al., 2021). We speculate that the 779 recent reinstatement of arc magmatism in the northern Lesser Antilles may relate to a 780 recently seismically imaged gap in the slab in the bend area (Meighan et al., 2013) 781 that may have allowed for the slab to steepen (Fig. 12).

782 Evaluating whether this may explain the Pliocene magmatic flareup requires 783 further dynamic and magmatic analysis and is beyond the scope of this paper. We 784 note, however, that if the magmatic lull is caused by slab flattening, the Pliocene 785 flareup may provide a proxy for reorganization in slab dynamics in the northeastern 786 Caribbean region. A detailed kinematic reconstruction of the northeastern Caribbean 787 plate boundary zone back to the onset of magmatism would be helpful to establish the 788 temporal and spatial relationships between subduction and the length of the E-W 789 trench segment east of Puerto Rico, and magmatism.

790

791 CONCLUSION

In this study, we revise the geological architecture and history of Antigua and
integrate our findings within the regional frame of both the Lesser Antilles arc
evolution and of the Caribbean upper plate strain pattern.

With lithostratigraphy, structural mapping, ⁴⁰Ar/³⁹Ar dating and biostratigraphy, we revised the geological map of the island and provide a new age

797 model for magmatism and sedimentation of the island. The climax of magmatic 798 activity and concomitant volcaniclastic deposition emplaced during late Eocene and continued until early Oligocene in the form of late-stage domes and dykes. From the 799 800 early Oligocene to, at least, the early Miocene, the island subsided along NW-SE 801 fault, resulting in subsequent transgression and deposition of a carbonate platform. 802 The island was then uplifted and partially eroded during the early-middle Miocene 803 and since that time, the island stayed emerged and stable. With a kinematic analysis 804 coupling paleontensors and anisotropy of the magnetic susceptibility (AMS), we show 805 that minor normal faulting accommodates NE-SW stretching and that, at island-scale, 806 there is not a clear change in deformation style that accompanies the end of 807 magmatism during Oligocene.

808 This integrative geological study of Antigua restricts the period of magmatic 809 activity on this island and definitively confirms the existence of a 20 Ma-long 810 magmatic lull in the northern Lesser Antilles. The Paleogene arc that is also 811 recognized in St-Martin and St-Barthélemy was emplaced along the eastern flank 812 Kalinago basin, synchronously with its rifting. The concordance in the period of 813 magmatic activity and of the occurrence of a large emerged area in the Lesser Antilles 814 (GrANoLA land) suggests that the magmatic evolution of the Lesser Antilles arc 815 could have participated to terrestrial pathways building and demise with crustal 816 thickening during flareups and thermal subsidence during lull.

During the Oligocene, magmatism ceased contemporaneously with a change in upper-plate deformation from back-arc, perpendicular to the trench stretching (Kalinago basin) to fore-arc, parallel to the trench stretching (V-shaped basins). This episode is followed by regional uplift during early-middle Miocene. We postulate that the end of magmatic activity, the change in upper-plate deformation style and vertical

motion may have been triggered by slab flattening originated from the progressive
formation of the spoon-shaped, curved slab. Nevertheless, this is still hypothetical and
further constrains on the kinematic evolution of the northeastern Caribbean plate
boundary back to Eocene are needed to understand the relation between magmatism,
upper-plate deformation and subduction.

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847 FIGURE



Figure 1. Bathymetric map, tectonic and volcanic settings of the Lesser Antilles
subduction zone. The main faults are drawn from Cornée et al. (2021). The study area
(Antigua) is outlined by the white square. Velocity vectors of the Caribbean and
North and South Americas plates are from Symithe et al., 2015.



853

Figure 2. Schematic representation of the dated magmatic and volcaniclastic onshore

855 evidences of the Lesser Antilles arc, from Eocene to present. The references used for

the construction of this sketch are presented in Table 1.



857

858 Figure 3: Revised geological map and synthetic cross-section of Antigua. The map 859 was constructed based on the map of Martin-Kaye (1959, 1969) and Christman 860 (1973), and completed and updated with fieldwork observations, lithostratigraphy and 861 structural measurements. The cross-section is located by a grey line on the map. The 862 tuffite layer (light green) was used as a marker layer in the construction of the cross-863 section. Beddings are plotted on lower hemisphere. The K-Ar ages (Nagle et al., 864 1976; Briden et al., 1979) and the Sr-Sr ages (Robinson et al., 2017) are represented 865 in italic.



866

Figure 4. Stratigraphic synthesis and lithological successions of the Antiguan units.
The locations of the sections are presented in Fig.3. See Appendix 1 for a detailed
description of each sections.



871

Figure 5. Field photography of the Basal Volcanic Suite and of the Central Plain
Group. A: basaltic andesite dykes crosscutting the volcaniclastic deposits of the
Central Plain Group; B: basaltic andesite dyke intruding a NW-SE trending normal
faults and crosscutting the Central Plain Group; C: 35 Ma- old rhyolitic dyke (Sample
DWB-B) crosscutting an andesite lava flow; D: quartzitic diorite stock crosscut by a
rhyolitic dyke.



878

879 Figure 6. Field photography of the sedimentary units of Antigua. A: Unconformity 880 between the Central Plain Group and the lower part of the Antigua Fm, observed at 881 Saint-John. Cross-bedded conglomeratic limestones rest above tilted and eroded silty 882 claystones of the CPG; B: abrupt change from reef platform to forereef slope at 883 Newfield Quarry. Note the presence of blocks slided towards the NE; C: wavy 884 subhorizontal stylolitic surfaces in foraminiferal wackestones, Marble Hill. D: vertical 885 stylolites at Burma Quarry; E: coral beds with diverse massive and platy coral 886 colonies (upper part of the Burma Quarry). For location, see Fig.3.





- 888 Figure 7. Field photography of normal faults and associated high-angle striation at (A)
- 889 Fort James, (**B**) Corbison beach and (**C**) and (**D**) Pares Quarry. Note the presence of
- 890 injectites (sediment injection during earthquakes), representative of syn-sedimentary
- 891 deformation at Fort James.



Figure 8 : ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ spectra and inverse isochron for the samples from Antigua. MSWD = mean square weighted deviation. The thick grey line in the spectra of ANT 20.8 corresponds to the spectrum modeled using QTQt software (Gallagher, 2012). 896



897

898 Figure 9 : A: Kinematic map of Antigua with paleotensors estimated per faults and 899 magnetic lineation estimated from Anisotropy of the magnetic susceptibility (AMS) 900 analysis; B: Schmidt equal area projections of the AMS ellipsoid principal axis for all 901 sampled sites in geographic coordinates. 95% confidences ellipses and associated 902 mean values for each axis are represented by coloured line and empty symbols 903 respectively. Bold black arc represents the mean bedding plane of the site; C: 904 Paleostress tensor obtained from the field data (faults with kinematic criteria and 905 fractures) for the NW-SE trending faults within the Basal Volcanic Suite and the 906 Central Plain Group (to the left) and for the E-W and N-S trending faults of the 907 Antigua Formation (to the right).



909 Figure 10. A: Depositional settings of the Antigua Fm. with ages from the 910 biostratigraphic investigations (Appendix 1 and 2); B: Synthetic sedimentary 911 organization during the late Rupelian and the Chattian. The Antigua Fm was 912 deposited on a northeastward, low-angle dipping ramp. The underlying Central Plain 913 Group was previously faulted and tilted by NW-SE normal faults. For sites location, 914 see Fig.3.





916 Figure 11. A : Time calibrated seismic stratigraphy analysis of the seismic profiles 917 CPEM 508 and 510 (ARCANTE 3 Cruise, Bouysse et al., 1985a, 1985b; Bouysse 918 and Mascle, 1994) from Cornée et al., 2021. Top: non interpreted; below : interpreted. The definition and time calibration follow the seismic stratigraphy chart defined by 919 920 Cornée al. (2021) in the northeastern Lesser Antilles. MS: MegaSequence; SB: Sequence Boundary; **B**: 3D block with seismic profiles 508 and 510 showing the 921 922 onshore and offshore structures in Antigua, Willoughby basin and the V-shaped 923 Meduse basin. Note the erosional character of the SB4 unconformity that seals prior 924 faults affecting MS4.



926 Figure 12 : Schematic 3D sketch of the progressive curvature of the Lesser Antilles

- slab from Eocene to present and its impact on slab dip variation and magmatism
- 928 location.
- 929
- 930
- 931
- 932

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- 1397 **APPENDIX**
- 1398 Appendix 1 : DESCRIPTION OF THE SECTIONS, AGES AND DEPOSITIONAL
- 1399 SETTINGS;
- 1400 Appendix 2 : MICROFACIES AND LARGER BENTHIC FORAMINIFERA
- 1401 CONTENT;
- 1402 Appendix 3 : DESCRIPTION OF THE SEISMIC PROFILES 508 AND 510
- 1403 Appendix 4 : STRUCTURAL MEASURMENTS.
- 1404 Table of the structural measurements collected in the field. Strikes are expressed
- 1405 from 0 to 360° following the right hand rule.
- 1406 Appendix 5 : ⁴⁰Ar/³⁹Ar methodology
- 1407

¹GSA Data Repository item 201Xxxx, [Appendix 1 : DESCRIPTION OF THE SECTIONS, AGES AND DEPOSITIONAL SETTINGS; Appendix 2 : MICROFACIES AND LARGER BENTHIC FORAMINIFERA CONTENT;
Appendix 3 : DESCRIPTION OF THE SEISMIC PROFILES 508 AND 510], is available online at www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org.

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