1   Title: Sediment accumulation and paleoceanography of the northeastern Caribbean: IODP Site U1396 off

2   Montserrat, Lesser Antilles

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28

29 **Abstract**

30 Site U1396 was piston cored as a part of Integrated Ocean Drilling Project Expedition 340 to

31 establish a long record for Lesser Antilles volcanism. A ~150 m sediment succession was

32 recovered from three holes on a bathymetric high ~33 km southwest of Montserrat. A series of

33 shipboard and newly-generated chronostratigraphic tools (biostratigraphy,

34 magnetostratigraphy, astrochronology, and stable isotope chemostratigraphy) were employed

35 to generate an integrated age model. Two possible chronostratigraphic interpretations for the

36 Brunhes chron are presented, with hypotheses to explain the discrepancies seen between this

37 study and Wall-Palmer et al. (2014). The recent Wade et al. (2011) planktic foraminiferal

38 biostratigraphic calibration is tested, revealing good agreement between primary datums

39 observed at Site U1396 and calibrated ages, but significant mismatches for some secondary

40 datums. Sedimentation rates are calculated, both including and excluding the contribution of

41 discrete volcanic sediment layers within the succession. Rates are found to be 'pulsed' or highly

42 variable within the Pliocene interval, declining through the 1.5-2.4 Ma interval, and then lower

43 through the Pleistocene. Different explanations for the trends in the sedimentation rates are

44 discussed, including orbitally-forced biogenic production spikes, elevated contributions of

45 cryptotephra (dispersed ash), and changes in bottom water sourcing and flow rates with

46 increased winnowing in the area of Site U1396 into the Pleistocene.

47

48

49 **INTRODUCTION**

50   Montserrat Island is part of the Lesser Antilles island arc in the Caribbean Sea. The

51   Lesser Antilles arc has a volcanic history dating back to the mid-Oligocene, though the western

52   arc has been active since the early Miocene (Macdonald et al., 2000). Montserrat is one of the

53   youngest islands in the arc and was subaerially built over three major volcanic centers, the

54   oldest deposit dated to ~2,600 ka (Harford et al., 2002). The current phase of volcanism began in

55   1995 and at South Soufrière Hillshas produced numerous volcanic deposits that range from

56   pyroclastic material deposited on land and in the surrounding ocean, to substantial marine

57   debris flows mapped using bathymetric surveys (Le Friant et al., 2010; Crutchley et al., 2013).

58   Because ~65% of volcaniclastic material is transported into the ocean after an eruption (Le

59   Friant et al., 2010), it is critical to establish a robust geologic record from detailed offshore data.

60   The history of Montserrat volcanism has been largely extended by the use of offshore

61   sediments, and is an area of active research (e.g., Cassidy et al., 2013, 2014; Le Friant et al., 2008,

62   2010; Trofimovs et al., 2010; Shipboard Scientific Party, 2012; Wall-Palmer et al., 2014; McCanta

63   at al., 2015). This history also has relevance to the hazards posed by volcanic activity to the

64   surrounding communities. Landslides, in particular, may be a source of concern as potential

65   tsunamogenic events, because they emplace substantial amounts of material (>380 X 10^6 m^3)

66   into the ocean in a short period of time, as seen both in the modern (e.g., Herd et al., 2006) and

67   geological record (~14 ka; Trofimovs et al., 2010). Although some landslides and debris

68   avalanches have been associated with the recent activity of the Soufrière Hills volcano (e.g.,

69   Herd et al., 2006), landslides identified in the geological record have less certain affinities and

70   may be related to rapid sea-level rise associated with transitioning from glacial to interglacial

71   conditions (Trofimovs et al., 2010; Coussens et al., 2016). Understanding the past history of

72   volcanic activity in the Lesser Antilles, and the frequency and cause of previous landslides, is

73   therefore important for the prediction of future potential geohazards. With that in mind,

74   Integrated Ocean Drilling Program (IODP) Expedition 340 cored three sites to examine the

75   structure, composition, and history of the sediments surrounding Montserrat. Here, we discuss

76   hemipelagic sedimentation from U1396, a coring site situated on a topographic high with low

77   sedimentation rates, and where erosion is likely minimal.

78   During the Pliocene and Pleistocene, the Caribbean Sea is sensitive to the presence or

79   absence of the Panamanian Isthmus, separating the Atlantic and Pacific oceans (e.g., Groeneveld

80   et al., 2014). Precise timing and the oceanographic impacts of the Panamian Isthmus closure

81   remains a controversial issue that has yet to be resolved (see discussion in Molnar, 2008). Some

82   authors suggest that the closure increased meridional overturning circulation (e.g., Keigwin,

83   1982; Haug and Tiedemann, 1998; Osborne et al., 2014) while others suggest, for instance, a

84   profound shift to oligotrophic waters (e.g., Chaisson, 2003; Jain and Collins, 2007). Although

85   these hypotheses could be interrelated, their studies suggest differences in timing, with

86   differences greater than a million years.

87   Biostratigraphy is inherently imprecise. As all of the data are biological, they are thus

88   filtered through various 'noisy' processes. Planktic foraminifera, for example, are prone to

89   ecological and climatological fluctuations, and regional distributions controlled by

90   oceanographic processes (Bé & Tolderlund, 1971), all of which can affect the stratigraphic level

91   of highest and lowest appearances. Taphonomic processes, such as winnowing or differential

92   preservation, for example, can also change the true 'Top' or 'Bottom' of a species. Despite

93   inherent difficulties, the utility and value of planktic foraminiferal biostratigraphy is well-

94   established. Most biostratigraphic calibrations use meridional zonation schemes, divided into

95   'tropical' or 'tropical-subtropical' zonation schemes, while additional subdivisions (Atlantic vs.

96   Pacific Ocean calibrations) alleviate some of the regional differences. The recent Wade et al.

97   (2011) calibration refined existing datums from Berggren and Pearson (2006; and references

98   therein) and established a number of new datums. Wade et al. (2011) also used the Cande and

99   Kent (1995) geomagnetic polarity timescale, as well as more recent astrochronologically-

100   calibrated timescales (Pälike et al., 2006; Lourens et al., 2004) to produce robust datum ages.

101   However, while these dates are robust at a single site or regionally, it is not commonplace to

102   define an 'error' for the datums. Biostratigraphic originations, even in rapidly spreading

103   species, are at best only geologically instantaneous, as a species cannot arise simultaneously

104   around the globe. Similarly, true biological extinctions are likely a series of regional extinctions

105   that finally culminate in the complete elimination of the entire species. One reason that planktic

106   foraminifera persist as a premier biostratigraphic system is due to their wide, and largely

107   homogenous, biogeographic ranges (Bé & Tolderlund, 1971). Thus, their 'regional' originations

108   and extinctions occur at the scale of tropical-subtropical subdivisions.

109   IODP Site U1396 (Figure 1) presents an ideal locality to verify the last 4.5 myr of the

110   Wade calibration. Shipboard analysis suggests that the sediments from Site U1396 represent

111   relatively continuous sedimentation and an excellent paleomagnetic stratigraphy was recovered

112   (Expedition 340 Scientists, 2013). Shipboard planktic foraminiferal and nannofossil

113   biostratigraphic analyses determined that all primary datum species, and the majority of the

114   secondary datum species, were present at the site. Detailed shipboard core descriptions

115   established five main units (A-E). Unit A is represented by approximately 40 cm of bioclastic

116   sand near the sediment water interface. Unit B is a ~110-m thick sequence of hemipelagic mud

117   interrupted by layers of tephra. Unit C is likely an artifact coring, 'flow-in' from a pumice layer

118   resulting an abnormal stratigraphy. Unit D is a volcanic breccia, whereas Unit E is similar to

119   Unit B (Expedition 340 Scientists, 2013). Units B and E constitute the vast majority of

120   sedimentation at this site.

121   The aim of this study is twofold. The first aim is to produce a robust age-model at or

122   near the marine isotope stage resolution. Although the recovered sediments cannot address

123   early aspects of the Panamanian Isthmus closure history, which occurred in the Miocene

124   (Keigwin, 1982; Haug and Tiedemann, 1998), it can address questions about the final closure

125   (~3-4 Ma) and the impacts on the biota, productivity, and circulation with the Caribbean Sea

126   (e.g., Jain and Collins, 2007). The ~150 m cored deposits at Site U1396 represent 4.5 myr of

127   sedimentation. We built a robust age-model to address these questions.

128   Second, this site presents a good opportunity to test the newly-established datums from

129   Wade et al. (2013). To those ends, several chronostratigraphic tools were employed.

130   Astrochronological tuning was performed on the color reflectance parameter L* (Brightness)

131   from shipboard physical properties data using the 'astrochron' package within the R

132   programming environment (Meyers, 2014; R Core Team, 2015). A ~9-kyr resolution benthic

133   foraminiferal $\delta^{18}O$ record was generated and compared to the LR04 benthic foraminifera stack

134   (Lisiecki & Raymo, 2005). Planktic foraminiferal biostratigraphy was also carried out at the

135   same resolution (~9 kyr), to provide support for the other chronostratigraphic techniques and to

136   be checked against the calibrations.

137

REGIONAL SETTING AND SHIPBOARD RESULTS

138

139   Site U1396 is located at 16°30.49′N, 62°27.10′W at ~800 m water depth. It is roughly

140   southwest from the island of Montserrat sitting atop a bathymetric high. Coring at this site was

141   hypothesized to limit the occurrence of turbidites, allowing for a more continuous record of

142   volcanism than possible in other areas offshore of Montserrat. In addition, the sedimentation

143   rates determined for the nearby CARMON-2 site (Le Friant et al., 2008) suggested it would be

144   possible to extend the existing geologic history to 4-5 Ma (Expedition 340 Scientists, 2013). Three

145   holes were cored at Site U1396 using advanced piston coring. Holes U1396A and U1396C each

146   consist of 15 cores and are continuous over 135 m and 140 m, respectively, whereas Hole B is a

147   single 10 m core taken to replicate 340-U1396A-2H which suffered a shattered liner during

148   coring. Lithostratigraphy between the holes correlates well (see below), excluding a single unit

149   (Unit C) in U1396C, which contained a substantial interval of basal flow-in of pumiceous sand

150   (Jutzeler et al., 2014), which does not occur over the same thickness in U1396A. Shipboard age

151   determination suggested that the base of U1396C was older than U1396A, so U1396C was

152   selected as the main hole for biostratigraphic and stable isotope study.

153

154   **METHODS**

155   **Depth scales and shipboard data**

156   Description of the core, preliminary calcareous nannofossil and planktic foraminiferal

157   biostratigraphy, and physical properties data collection (e.g., color reflectance) were all

158   performed onboard the R/V *JOIDES Resolution* during IODP Expedition 340. The initial

159   shipboard age model and resulting sedimentation rates for the Pliocene (~4 cm/kyr) and

160   Pleistocene (~2 cm/kyr) were determined by the paleomagnetic reversal stratigraphy and

161   supported by nannofossil and planktic foraminiferal biostratigraphy (Expedition 340 Scientists,

162   2013). A composite depth scale (CCSF-A) was generated with a primary splice (CCSF-D)

163   (Hatfield 2015). The CCSF-D record relies heavily on core sections from Hole U1396A, in part

164   because it is the most complete record as two 10 cm whole rounds were consistently taken from

165   each Hole C core shortly after core recovery. A tool was created in the R computing

166   environment (R Core Team, 2015) to place off-splice data and all preexisting and newly-

167   generated data into the CCSF-D scale. Figure 2 depicts the process of splicing the color

168   reflectance data and lithostratigraphic data from the initial CSF depth scale to the CCSF-A

169   depth scale, and finally onto the continuous splice. The L* (brightness) and lithostratigraphy

170   data sets both agree well with the magnetic susceptibility based correlation of Hatfield (2015),

171   indicating the compositing process is robust (Figure 2b). We use the revised assessment of the

172   paleomagnetic reversal record here (Hatfield, 2015) rather than the one generated shipboard.

173   Hatfield (2015) did not correlate Core 340-U1396A-2H into the composite section due to issues

174   with the magnetic susceptibility record of the disturbed core. Using both the core description

175   and core photos of Cores 340-U1396A-2H, U1396C-1H, and U1396C-2H we now place 340-

176   U1396A-2H on the U1396A CCSF-A scale using an offset of 1.71 m using lithostratigraphic

177   correlation.

178

179   **Generation of an 'Event-Free' section**

180   Volcanic sedimentation derived from eruption (syn-eruptive *sensu* Carey and Schneider,

181   2011) is geologically instantaneous. Ash deposits, for example, are frequently darker in color

182   than hemipelagic material, and so impart stochastic noise (from a cycle perspective) to an

183   analysis of the expected cyclic bands of sediment produced by Milankovitch or glacial-

184   interglacial periodicity. Also, hemipelagic material is deposited at a different, quasi-continuous,

185   sedimentation rate than the 'instantaneous' ash deposits. Removal of the discrete volcanic

186   deposit intervals, such as ash beds, should result in a cleaner hemipelagic stratigraphic column,

187   and potentially a series of Milankovic-style frequencies that are less dominated by noise.

188   However, this does not alleviate the issue of dispersed ash, as documented by ODP Leg 165 in

189   the Caribbean (Sigurdsson et al. 1997) and within the upper several meters of U1396C (McCanta

190   et al., 2015). An R function was employed to remove the volcanic sediments from the

191   stratigraphy. The function employs the shipboard core description to identify the various

192   sediment types with a major lithology type of volcanic origin, and then removes their

193   thicknesses from the stratigraphy. It then recalculates the depths for the rest of the stratigraphy

194   as if the volcanic sediments were not there resulting in a CCSF-NV (No Volcanics) scale (Figure

195   2 depicts this process). The CCSF-NV scale allows the comparison of three distinct

196   sedimentation rates: composite (hemipelagic+volcanic), hemipelagic, and volcanic.

197

198   **Astrochronological tuning**

199   Astrochronology is a method of age determination that employs the known frequencies

200   of various astronomical parameters (e.g., obliquity) and some high-resolution dataset, in this

201   case sediment brightness, to derive an age model. Astrochronologically tuning of the

202   sedimentary record from Site U1396 was not done independently of other age diagnostic

203   criteria. Instead, approximately half the paleomagnetic datums were used to generate a

204 hemipelagic sedimentation rate (linear sedimentation rate without the thickness of volcanically-

205 sourced sediments). Astrochronological analysis was then performed using 'astrochron', a

206 package developed for R (Meyers, 2014). Tuning was performed in intervals ~0.5 myr in length.

207 L* was interpolated to 3-kyr intervals, prior to the evolutive harmonic analysis (EHA). The

208 stratigraphic sequence was padded to approximately double the number of points in the

209 interpolated dataset. The window size for the EHA was 140-kyr with a step of 3-kyr. EHA

210 results (e.g., fig 3) suggest the presence of tunable frequencies, despite the still substantial

211 component of noise.

212 Tuning was performed so that there was as good an agreement between age diagnostic

213 criteria and orbital or glacial-interglacial frequencies as possible, but, as previously noted, the

214 signal is still prone to substantial noise due to data interpretation, core recovery, and

215 sedimentological factors. A slight offset in the splice correlation could result in a missed portion

216 of a cycle at splice points, for example. If the sedimentation rate were 4 cm/kyr, an offset in the

217 splice of 2.5 cm would result in a loss of ~1/4 of the 41-kyr obliquity cycle. This would manifest

218 in the EHA diagram by splitting the observed frequency into two pieces, one higher frequency

219 and one lower, with a gap in the middle (Meyers and Sageman, 2014). It is also possible that

220 removing all volcaniclastic beds is overly cautious; some of those sediments may not be

221 geologically instantaneous and may be from redeposition of volcanic components (post-

222 eruptive *sensu* Carey and Schneider, 2011). The presence of cryptotephra (dispersed ash)

223 changes the L* value of the sediments away from the predicted orbital or glacial-interglacial

224 pattern, and increases the bed thickness. The wide window (140-kyr) accounts for this increase

225 in noise, but it induces a lag. An example of this effect is the smearing of frequencies around the

226   employed paleomagnetic datums. In Figure 3 the white lines above and below the black anchor

227   datum are where the EHA begins to record a change in sedimentation rate; the smearing is a

228   result of the change from one linear sedimentation rate to the next. The window size was a

229   compromise between accounting for this noise and creating an age model responsive to

230   sedimentation rate changes.

231

232   **Micropaleontologic methods**

233   A total of 596 samples were examined for biostratigraphically-important species. Two

234   different strategies were used for sample choice. Within the upper 7 m of Site U1396, a sample

235   spacing of 5 cm (~0.5-2 kyr) was used (these samples were previously used in Wall-Palmer et

236   al., 2014). Below 7 mbsf a sampling resolution of ~9 kyrs was used, based on the shipboard age

237   model, but excluding volcanic sediments. All samples were checked against the Jutzeler et al.

238   (2016) coring disturbance compilation and were found to be outside of all intervals with coring

239   disturbances. For samples below 7 meters, samples were dried for ~24 hours, then soaked in a

240   mild Sparkleen® solution for 24-72 hours, a step necessary to free foraminifera from

241   surrounding sediment. Sediment was washed over a 63 µm sieve before being dried for ~24

242   hours in a 40-50°C oven. Prior to being inspected, samples were dry-sieved over a 150 µm sieve.

243   All identification was performed at the >150 µm size fraction, following the taxonomy of

244   Kennett & Srinivasan (1983). Ages for the biostratigraphic datums follow the Wade et al. (2011)

245   astrochronological calibration (and references therein).

246   Samples within the upper Pleistocene-Holocene Brunhes chron were inspected for

247   *Globorotalia menardii* and *G. tumida*, as the abundances of those taxa have been shown to

248 fluctuate in response to glacial-interglacial cycles (e.g., Ericson and Wollin, 1968; Kennett and

249 Huddlestun, 1972). This biozonation scheme has been employed globally and locally with

250 success (e.g., Reid et al., 1996). Here it was used to continue the data collection of Wall-Palmer

251 et al. (2014), extending their record of %*G. menardii-tumida* (undifferentiated) to the first

252 geomagnetic reversal (i.e., base of the Brunhes chron). Following the Wall-Palmer et al. (2014)

253 methods, samples were dry-sieved over a 355 μm sieve, then a split to ~300 individuals was

254 performed using a microsplitter. Total planktic foraminifera and *G. menardii-tumida* tests were

255 counted.

256   Individual foraminifera from near the top or bottom of their range were imaged on a

257 Carl Zeiss EVO 50 XVP scanning electron microscope to corroborate the positions of the datums

258 described within this work. The selected foraminifera were placed on a piece of carbon tape,

259 and then coated with a 4 nm thick coating of carbon or platinum prior to imaging.

260

261 **Stable isotope analysis**

262   Three species of benthic foraminifera (*Planulina wuellerstorfi, Cibicidoides mundulus,* and

263 *Cibicidoides robertsonianus*) and one species of planktic foraminifera (*Globigerinoides ruber*)

264 provide a stable isotope chemostratigraphy for Site U1396. *P. wuellerstorfi* was most common

265 until 25 m CCSF-A (~1.5 Ma), although it was absent in some samples throughout this interval.

266 In these cases, *C. mundulus* was used in place of *wuellerstorfi,* but within the upper ~10 m

267 *mundulus* was also scarce, and *C. robertsonianus* was used instead. Within the top 7 m, sample

268 volume was reduced (to alleviate the depletion of the core with the 5-cm resolution), and so a

269   mixture of all three species was used. *Globigerinoides ruber* was used through the Brunhes chron

270   to address low variability within the benthic $\delta^{18}O$ record (see below).

271   Preservation state was variable through the study interval. Specimens were graded on a

272   'pristine' - 'frosty' - 'bad' scale. Pristine individuals were glassy, with no infilling. Frosty

273   individuals were opaque, or had mild infilling. 'Bad' individuals, which were only used in rare

274   instances where there was no other choice, had overgrowths, broken final chambers, or

275   moderate infilling. The best-preserved individuals were used for isotopic analysis, though tests

276   were generally 'frosty' throughout the study interval. A table of $\delta^{18}O$ values, ages, species, and

277   preservation grade can be found in the supplemental information. The only general trend

278   identified in preservation was a gradual decrease in the frequency of well-preserved benthic

279   foraminifera with increasing depth, though examples of good preservation were found near the

280   base of Site U1396.

281   *Planulina wuellerstorfi* was typically used in preference to either *Cibicidoides* species. 41

282   samples contained sufficient individuals from two species to allow isotopic offsets to be

283   generated between the species. The number of individuals analyzed in each sample varied (see

284   supplemental information), but was typically only three to four, due to the large mass of the

285   benthic tests. Approximately nine individuals of planktic *Globigerinoides ruber* were used in each

286   analysis. The majority of samples were run at the University of Massachusetts-Amherst Stable

287   Isotope Laboratory on a Finnigan Delta XL+ with a Kiel III automated carbonate preparation

288   system (>7 mbsf; these are in black, red, and brown on Figure 4). All data are reported in delta

289   notation against the VPDB standard. Replicated analyses of UMass house standard material

290   have a 1σ error of 0.08‰ $\delta^{18}O$. The rest of the samples were run at the National Oceanography

291 Centre, Southampton using a Europa GEO 20-20 mass spectrometer with an automatic

292 carbonate preparation system (0-7 mbsf; orange on Fig. 4).

293

294 **RESULTS**

295 **Astrochronology**

296   Brightness (L*) in the shipboard color reflectance dataset (Expedition 340 Scientists,

297 2013) was found to have cyclicity on orbital periods (Fig. 3), despite noise present outside of the

298 expected orbital signals. Tuning resulted in mild offsets from the sedimentation rate derived

299 from linearly interpolating between paleomagnetic reversals, and there appears to be a

300 continuous record of sedimentation at this site. It should be noted that tuning was performed

301 attempting to fit all available chronostratigraphic information and the results of Wall-Palmer et

302 al. (2014) (See 5. Discussion). Most of the deviations from paleomagnetically-derived ages are

303 within the 0-50 kyr range.

304

305 **Benthic isotope values**

306   Stable isotope results largely agree with the expected general pattern of glacial-

307 interglacial cycles, with variability decreasing with depth. There is a gradual trend towards

308 increasing $\delta^{18}O$ values, with a mean value of ~2‰ for 100-150 CCSF-A, increasing to ~2.5‰ for

309 50-10 CCSF-A. Strong (>1‰) variability in the record is seen beginning around 30 mbsf until 0

310 mbsf, with a marked step towards higher values observed at ~80 CCSF-A.

311   The offset in $\delta^{18}O$ values between the three species was calculated (Figure 5). Most $\delta^{18}O$

312 offsets were within the propagated instrumental error for the two $\delta^{18}O$ measurements (~0.1‰

313   for each measurement, and therefore ~0.14‰ for offsets). The mean offset between *Planulina*

314   *wuellerstorfi* and *Cibicidoides mundulus* was ~0.062‰ (n=25), while *Cibicidoides mundulus* and

315   *Cibicidoides robertsonianus* was ~-0.011‰ (n=14). Only two samples contained both *Planulina*

316   *wuellerstorfi* and *Cibicidoides robertsonianus*, and they displayed a mean offset of -0.105‰. No

317   stratigraphic trends were noted with respect to the offsets.

318   *Planulina wuellerstorfi* was most commonly used within 150-80 CCSF-A, with *Cibicidoides*

319   *mundulus* and *C. robertsonianus* largely used until ~7 mbsf, and, due to smaller sample sizes, a

320   mix of benthic all three species above 7 mbsf. When *P. wuellerstorfi* was not available (above 80

321   CCSF-A), *Cibicidoides mundulus* was used to supplement, using the offset value generated in this

322   study (~0.062‰). In the case where *Cibicidoides roberstonanius* was the only possible choice, the

323   offsets from *P. wuellerstorfi* to *C. mundulus* and *C. mundulus* to *C. robertsonianus* were used to

324   calculate the composite value (green line, fig. 5A).

325   Benthic foraminiferal $\delta^{18}O$ results follow the trends established by the LR04 benthic

326   foraminiferal stack (Lisiecki and Raymo, 2005). Although the sampling resolution within this

327   study is lower than that of Wall-Palmer et al. (2014), similar trends can be identified between

328   the planktic and benthic $\delta^{18}O$ records. Figure 4 presents the correlations between the

329   astrochronologically-derived ages and the LR04 stack (grey lines). Several intervals were not

330   correlated, mainly due to data-resolution issues, but also due to the obscuring of MIS cycles

331   through other means (see discussion about low benthic $\delta^{18}O$ variability below). Those include

332   around MIS 55 (~1.6 Ma) and around KM2 (~3.1 Ma). There are also several suggested changes

333   to the interval correlated by Wall-Palmer et al. (2014), which are discussed below.

334

Biostratigraphy

335

336   The majority of the datums from Wade, et al. (2011) were found within the sediments at

337   Site U1396 (Table 1, Figure 6). Only *Globorotalia hirsuta, Globoralia hessi, Globorotalia excelsa,*

338   *Globoturborotalia apertura, Globoturborotalita woodi,* and *Globoturborotalita decoraperta* were not

339   found, or were found in such sporadic occurrences they had limited biostratigraphic utility.

340   *Pulleniatina* was not split into distinct species, instead only the presence or absence of

341   *Pulleniatina* spp. was noted. The order of primary datums was found as expected from youngest

342   to oldest: Top *Globorotalia tosaensis,* T *Globigerinelloides fistulous,* T *Globorotalia miocenica,* T

343   *Dentoglobigerina altispira,* T *Sphaeroidinellopsis seminulina,* T *Globorotalia margarita,* and lastly T

344   *Globoturborotalita nepenthes. Globigerinelloides fistulosus* was found only sporadically and was

345   found above the expected range by ~0.5 Myr. *Globorotalia tosaensis* has only a ~100 kyr

346   difference between the U1396 top and the calibrated age, but otherwise the few biostratigraphic

347   species within the Pleistocene are found well outside their expected ranges (see 5. Discussion).

348   Within the Pliocene, the ranges of *G. miocenica, D. altispira, S. seminulina, G. margarita,* and *G.*

349   *nepenthes* all fit very closely to their expected ranges as calibrated by Wade et al. (2011).

350   Secondary datums T *Globoturborotalita obliquus,* T *Globorotalia exilis,* B *Globorotalia*

351   *truncatulinoides,* T *Globorotalia limbata,* T *Globorotalia pertenuis,* B *Globorotlia tosaensis,* B *Globorotlia*

352   *miocenica,* T *Globorotalia plesiotumida,* and B *Globorotalia exilis* were all found close to their

353   calibrated ages. The bioevents Reappearance and Disappearance of *Pulleniatina* were also

354   extraordinarily close to their calibrated ages. In particular, several of the menardellid species

355   (e.g., *G. exilis*) record substantial fluctuations in their populations, so their adherence to the

356   calibrated ages is surprising, but a positive indicator of the robustness of the planktic

357   foraminiferal datums.

358   Several secondary datums, as might be expected, did not conform as precisely to the

359   expected ages. T *Globorotalia flexuosa* was observed within the top sample, and its base (B *G.*

360   *flexuosa*) was found ~1.3 myr earlier than expected. The local top for *G. extremus* was 800 kyr

361   younger than it was expected. T *Globorotalia multicamerata* was ~400 kyr younger than the

362   expected age, but as mentioned previously, all menardellids were subject to substantial

363   fluctuations in population. B *G. miocenica* appears within the U1396 sediments ~200 kyr older

364   than its calibrated age, while B *G. pertenuis* appears 500 kyr older than the calibrated base. T

365   *Sphaeroidinellopsis kochi* occurs ~300 kyr younger than the calibrated age.

366   **Hiatuses**

367   Shipboard chronostratigraphy suggested a gradually decreasing sedimentation rate

368   towards the present (Expedition 340 Scientists, 2013). It also suggested a largely continuous

369   section, without apparent hiatuses. Biostratigraphy largely agrees with the paleomagnetically-

370   derived sedimentation rates, and clustering of biostratigraphic datums, as would be

371   characteristic of a hiatus, is not observed in the U1396 sequence. Although hypothetically

372   evolutive harmonic analysis can be used to identify hiatuses (Meyers and Sageman, 2004), the

373   use of such a large window (140-kyr) and the amount of noise within the signal makes this

374   impossible at Site U1396. Astrochronology suggests that there are instances of lowered

375   sedimentation rate. In the absence of strong evidence for hiatuses, the U1396 benthic and

376   planktic δ¹⁸O isotope time series was correlated to marine isotope stages as if there were no

377   hiatuses.

378

DISCUSSION

Brunhes stratigraphy

This study continues much of the data collection begun in Wall-Palmer et al. (2014). In doing so, some conflicting age diagnostic criteria were revealed within tens of cm from the base of the Wall-Palmer study, suggesting a revision of that chronostratigraphy may be necessary. For example, Wall-Palmer et al. (2014) used a *%Globorotalia menardii-tumida* zonation scheme (Ericson & Wollin, 1968; Kennett and Huddlestun, 1972) successfully employed in the region (e.g., Reid et al., 1996; Le Friant et al., 2008). This scheme relies on the relative abundance of *Globorotalia menardii* or *Globorotalia tumida* (the majority of the flat, keeled planktic foraminifera within these sediments). The zonations are described as abundant (Z, X, V, and T) or not abundant (Y, W, and U). Distinguishing between 'abundant' and 'not abundant' is not always obvious in these sediments (Figure 7, W to early V). Here we continued the %G. *menardii-tumida* counts down to the Brunhes-Matuyama reversal, identifying distinct proportion changes centimeters below the lowest sample analyzed by Wall-Palmer et al. (2014). This extension of *%G. menardii-tumida* data, as well as the longer perspective of the entire Brunnes chron, creates uncertainty for some aspects of the chronostratigraphy of Wall-Palmer et al. (2014).

The most important chronostratigraphic control used by Wall-Palmer et al. (2014) in the lower part of their study interval was the base (B) of *Emiliana huxleyi*. B *Emiliana huxleyi* globally occurs within MIS 8 (~0.27 Ma) or MIS 9 (~0.29 Ma; Ogg et al., 2014). It was identified at ~6.9 m with SEM imaging (Wall-Palmer et al., 2014), but other studies (Aljahdali, 2013, unpublished Masters Thesis, Florida State University) place the first occurrence much higher (~3 m). In

400   addition, the planktic foraminifera datum for Biozones PT1a/1b, T *G. tosaensis* (~0.61 Ma; Wade

401   et al., 2011), was determined to be slightly below the *E. huxleyi* datum. Within the original

402   publication, this was suggested to be a regional difference in extinction, with T G. *tosaensis*

403   occurring at MIS ~8 (0.27 Ma), which is ~340 kyr offset from its calibrated age (Wade et al.,

404   2011). It should be noted that several species discussed later have large offsets from the Wade et

405   al. (2011) biozonation scheme at this site.

406   The following discussion highlights the discrepancies noted within the Brunhes chron.

407   However, the stratigraphy presented in Wall-Palmer et al. (2014) is largely convincing when

408   directly compared with previous studies within the area (Le Friant et al., 2008; Trofimovs et al.,

409   2010). Despite the comparatively low resolution of the new benthic and planktic foraminifera

410   oxygen isotope stratigraphy presented here, the longer perspective of this study highlights

411   discrepancies that are not apparent in those previous studies, which all focus on the uppermost,

412   <~250 kyr seafloor sediment. In addition, oxygen isotope values from MIS 3 to MIS 4 in Wall-

413   Palmer et al. (2014) rise when most records (e.g., Martinson et al., 1984; Lisiecki and Raymo,

414   2005; Le Friant et al., 2008) demonstrate lowering values. There is also a prominent negative

415   shift within MIS 6 (~2‰), when global records (e.g., Martinson et al., 1984; Lisiecki and Raymo,

416   2005) are largely constant. That shift which was correlated to a negative shift in the CAR-MON

417   2 record (Le Friant et al., 2008), but the magnitude at CAR-MON 2 was only ~1‰. In addition,

418   at CAR-MON 2, the MIS 3 to 4 values when correlated with the global stack, rather than the

419   apparently aberrant changes seen in the Wall-Palmer et al. (2014) correlation.

420   There is an additional unsatisfactory correlation in regards to the %*Globorotalia menardii-*

421   *tumida* zonation. In figure 7, the orange bands are zones which should have higher %*G.*

422   *menardii-tumida,* whereas white zones should be lower. Although there is a slight shift at the

423   CAR-MON 2 X Zone to younger ages, the zonal boundaries and abundances are largely as

424   expected (Le Friant et al., 2008), suggesting that a good fit is possible within the region. Within

425   the Wall-Palmer et al. (2014) scheme the divisions between various zones conform poorly to the

426   expected zonation scheme (Fig. 7). For example, Zone X, which should be 'high abundance' has

427   lower abundance on average than Zone W, which should be 'low abundance'.

428   Three possibilities may explain the observed discrepancies (B *E. huxleyi,* T *G. tosaensis,*

429   $\delta^{18}O$ magnitudes, and %*G. menardii-tumida*). First, if the revised stratigraphy proposed in Fig. 7

430   is incorrect and the Wall-Palmer et al. (2014) stratigraphy is correct, the Aljahdali datum is 3 m

431   too high, and there is a condensed section encompassing MIS 9 to 13. This then suggests that

432   MIS 3 has a $\delta^{18}O$ value roughly equivalent to MIS 5 or 7, rather than the much more positive

433   value expected (Martinson et al., 1984; Lisiecki and Raymo, 2005). Although some differences

434   could be attributable to local effects (sea surface temperature or salinity), because these values

435   are derived from the mixed-layer dwelling *Globigerinoides ruber*, the values from CAR-MON 2

436   are similar to those expected (Le Friant et al., 2008). As described above, MIS 6 (as identified by

437   Wall-Palmer et al., 2014) also has a 'spike' of double the magnitude observed elsewhere. Also,

438   the %*G. menardii-tumida* zonation then has a much weaker connection to the glacial-interglacial

439   cycles. In addition to the previously described difficulties in Zones Y-W, the predicted high

440   abundances through zone V are entirely absent. This is in direct opposition to the CAR-MON 2

441   core, where the expected higher values for Zone X are present (slightly later than expected,

442   however), whereas the low absence that defines Zone W is typified by 0%, rather than the

443   increase of ~3-4% observed in the Wall-Palmer et al. (2014) correlation. Despite the poor

444 chronostratigraphic fit described above, it should be stated that B *E. huxleyi* is an exceptionally

445 well-established datum, with a consistently robust MIS 8 appearance within the tropics

446 (Thierstein et al., 1977; Ogg et al., 2012), and as such, should have a higher chronostratigraphic

447 priority than a comparably less precise abundance-based zonation scheme. There are

448 lithostratigraphic correlations that appear to support the Wall-Palmer et al. (2014)

449 chronostratigraphic correlations (Coussens et al., 2016), but they lack the longer time-series

450 present at U1396.

451   Second, if the Wall-Palmer et al. (2014) datum is valid and the Aljahdali datum is

452 incorrect, and the rest of the Wall-Palmer et al. stratigraphy is not correct, then this would

453 represent a >100 kyr earlier origination for *E. huxleyi* than previously identified. As stated

454 above, B *E. huxleyi* has a remarkably globally synchronous first appearance at MIS 8 (Thierstein

455 et al., 1977), whereas the Wall-Palmer stratigraphy suggests it occurred within MIS 13. This

456 scenario to solve the discrepancy seems unlikely. A possible explanation for the *E. huxleyi*

457 datum presented by Wall-Palmer et al. (2014) may be due to downhole contamination, making

458 the Aljahdali B *E. huxleyi* datum the first *in situ* occurrence (MIS 8; Tierstein et al., 1977; Ogg et

459 al., 2012). The sample cited for the B *E. huxleyi* by Wall-Palmer et al. (2014) (Sample 340-U1396-

460 1H-5, 90-91 cm) only contained rare *E. huxleyi*, while the only other samples examined above

461 (Samples 340-U1396-1H-1, 1-2 cm and 340-U1396-1H-1, 30-31 cm) contained abundant *E.*

462 *huxleyi.* While the sediments used for SEM analysis were procured in the proper fashion

463 (sample edges were trimmed to minimize down-hole contamination, for example), the rarity of

464 *E. huxleyi* within Sample 340-U1396-1H-5, 90-91 cm possibly suggests that they were not in situ.

465 This could account for the ~3 m difference between the two studies.

466   By removing the Wall-Palmer et al. (2104) B *E. huxleyi* control on the chronostratigraphy,

467   we can then fit to several other chronostratigraphic systems to these observations (Figure 7). For

468   example, *G. menardii* Zones X and V now fit with their expected abundances (Fig. 7) and MIS 6

469   no longer has a negative δ18O excursion (MIS 6.4 in Wall-Palmer et al., 2014). Instead, that

470   double peak has been moved to the expected position in MIS 7 and B *Globorotalia tosaensis* also

471   has a smaller offset to the calibrated age (Table 1). It should be noted that this revision uses data

472   that was excluded from Wall-Palmer et al. (2014) because it was within event bed B1/2. There

473   are a greater number of keeled foraminifera within this flow, as seen within the X Zone defined

474   by this study (~25%, Fig. 7). It is difficult to explain the preferential incorporation of keeled,

475   thermocline-dwelling planktic foraminifera (from ~5% up to ~25%) within a bioclastic flow

476   sourced from shallower depths, where those taxa are rare to absent. In fact, the opposite should

477   be true, and shallow-dwelling benthics and mixed-layer planktic foraminifera should

478   overwhelm the *menardii* and *tumida* percentages, making them even rarer. Additionally, this

479   would be during a time interval when those taxa are especially uncommon. Very different

480   hydrographic properties, however, between the keeled and non-keeled make it possible for this

481   apparent anomaly to be due to some sort of sorting phenomena related to the flow. The

482   remainder of this work employs this last hypothesis (fig. 7) as the age model. Despite this

483   interim conclusion, the interval between MIS 9-13 remains unsatisfactory due to the limited

484   isotopic variation (although a hypothesis to explain this observation is discussed later).

485

486   **Biostratigraphy**

487   Relative to the calibration of Wade et al. (2011), very few of the Pleistocene datums at

488   Site U1396 were found where they were expected. *Globorotalia tosaensis* and *G. obliquus* appear to

489   have a robust calibration from the Caribbean perspective, but this may be a function of the

490   limited number of datums within the Pleistocene, relative to Pliocene. Both of the youngest

491   datums, T *Globorotalia flexuosa* and B *G. calida*, appear to have substantially different ranges than

492   the Wade calibration. For B *G. calida*, this is possibly due to regional differences between the

493   Pacific Ocean (the source of the Wade calibration is from DSDP Leg 135; Chaproniere et al.,

494   1994) and the Caribbean Sea. *Globorotalia flexuosa* is also found far earlier than expected. The

495   diagnostic feature of *G. flexuosa* is a ~90° twist on the final chamber, with the rest of the gross

496   morphology resembling an intermediate form between *Globorotalia menardii* and *Globorotalia*

497   *tumida*. Figure 6 (green box) depicts *G. tumida* and *G. flexuosa*, from the sample containing B *G.*

498   *flexuosa.* Also within that sample, very rarely, was an aberrant form of *G. flexuosa* or *G. tumida*

499   with a final chamber appearing to start at 90° to the coiling axis, then twisting back equatorially.

500   This could speculatively be seen as evidence that the '*flexuosa*' form is a simple mutation from

501   the *Globorotalia menardii* sensu stricto, which induces an ~90° torsion in the final chamber, rather

502   than being a true biological species. Further work could elucidate if there is an ecological

503   affinity to the '*flexuosa*' form, or if it has a stochastic appearance in the fossil record, as would be

504   expected of a random mutation of the form. Both of these species, *G. flexuosa* and *G. calida*, have

505   recognition issues as they progress through ontogeny. An adult *calida* resembles a juvenile

506   *Globigerinella aequilateralis*, while *G. flexuosa* without the final chamber could be identified as a *G.*

507   *tumida* or *G. menardii*. As impoverished as the Pleistocene is for datums, these are still poor

508   characteristics for biostratigraphic marker taxa.

509   These two biostratigraphic taxa were used repeatedly shipboard during Exp. 340,

510   because the majority of the sites recovered were younger than any primary planktic foraminifer

511   marker datum, and so these secondary datums had to be regularly employed. Finding these two

512   taxa outside of their expected ranges at Site U1396 calls into question many of the

513   biostratigraphically-derived ages for other sites drilled during Exp. 340. Many of those other

514   sites, however, also have nannofossil biostratigraphic datums. Those ages, which were

515   supported by the B *E. huxleyi*, the nearest nannofossil datum to B *G. calida* (calibrated age), are

516   still considered to be valid under this study.

517   There are comparatively more datums within the Pliocene than the Pleistocene that

518   conform to expectations. Closest to the Pliocene/Pleistocene boundary is B *Globorotalia*

519   *truncatulinoides*, which might better be employed as the PL6/PT1b zonal marker than T

520   *Globigerinoides fistulosus.* The difference between the Pliocene/Pleistocene boundary and the top

521   of PL6 would only change ~120 kyr, and *G. truncatulinoides* is more common, at least in these

522   sediments, than *G. fistulosus.* Both taxa are easily recognizable, the only advantage that *fistulosus*

523   has over *truncatulinoides* is that the projections from a *fistulosus* test are readily identifiable even

524   when broken. Most of the menardellid Top calibrations were accurate at U1396, excluding T

525   *Globorotalia multicamerata.* The spacing between events at U1396, however, was condensed, all

526   taking place within chron C2r. The B *G. fistulosus* occurs later than expected, and within the

527   wrong biozone. This species is very sporadic throughout its entire range (including the upper

528   portion of the range), making both the first and last occurrences uncertain. The T and B *G. exilis*

529   were observed in close proximity to the expected age, though not always within the biozone

530   expected, due to deviations in other marker taxa.

531

Sedimentation

age scheme mismatch

This study employs three different age models, a paleomagnetic reversal record, an astrochronologically-tuned record (between paleomagnetic datums), and marine isotope stage correlations. These different methods have individual strengths and weaknesses. Paleomagnetic reversal ages are precisely known and are relatively well defined in the U1396 record (Hatfield 2015), but during periods of stable polarity the age model is a simple linear interpolation between reversals. Astrochronology provides variable accuracy and precision. The analysis utilizes a number of different parameters, like window size or interpolation step, that all change how responsive the resulting age model is to hiatuses or changes in sedimentation rates, or the upper and lower limits of detectable frequencies. Lastly, MIS correlation is generally precise provided that all marine isotope stages are present and confidence in the result is increased when constrained by the paleomagnetic reversal record. It also has the advantage, if the data-resolution is high enough to detect them, that extremely abrupt sedimentation rate changes can be observed. The same hypothetical abrupt sedimentation rate would be missed by paleomagnetic ages if it were within a single normal or reverse chron. Similarly, the change in sedimentation rate would be smoothed by astrochronology if the window size were not small enough to detect it. However, if all marine isotope stages are not present, or if data density is poor, then correlation becomes less accurate using this method. Because of the three different characteristics of these age models, it is possible to demonstrate the advantages of the different models of age estimations by looking at their offsets.

553   The three non-biostratigraphic age schemes agree well, as seen in Figure 8, when

554   excluding the Brunhes chron (see section 5.1). Figure 9 presents the differences in ages between

555   the various methods of age estimation, paleomagnetically-derived minus marine isotope stage

556   (Mag-MIS) and paleomagnetically-derived minus astrochronologically-derived (Mag-A). If the

557   Brunhes chron is excluded, the Mag-MIS offset is typically larger than Mag-A. This suggests

558   that the astrochronology method is underestimating high sedimentation rates and

559   overestimating low sedimentation rates, if we assume that the MIS ages are near-instantaneous

560   estimates of the sedimentation rate. In intervals where Mag-MIS is smaller than Mag-A, the MIS

561   age seems to be reacting to changes in sedimentation rate more quickly than the

562   astrochronologically-derived ages. Again, this is a weakness of this particular astrochronologic

563   age model, likely due to the large window size, which imparts a 'lag' on the changes in

564   sedimentation rate. A larger window size would mix frequencies over a larger interval, and so

565   react more slowly to changes in sedimentation rate while a smaller window size would react

566   more quickly. Again, the larger window-size was used here to account for the noise in the

567   dataset.

568   All offsets between the various age models were generally smaller than the time

569   between isotope stages. This suggests that although the above discussion is valid, the

570   paleomagnetically-derived ages are robust, and eliminating the 'tuning' step within the

571   methods would likely have not changed the MIS-correlations. This also suggests that this is a

572   continuous section, excluding perhaps some portion of the Brunhes chron.

573

574   *sedimentation rates*

575   The sedimentation rate is calculated in several different forms. First, a linear

576   sedimentation rate was calculated from the paleomagnetic reversal record, both including

577   volcanics and without (Fig. 10). The difference between these two, or the volcanic accumulation

578   rate, is in purple. The non-volcanic, or hemipelagic, sedimentation rate curve is different from

579   previous studies. Shipboard chronostratigraphy described a roughly monotonic decrease in

580   sedimentation rate from 0 Ma to ~4.5 Ma (Expedition 340 Scientists, 2013), which is seen in the

581   total sedimentation rate (Fig. 10). When the thickness of the volcanically-sourced sediments is

582   removed (Fig. 10), the monotonic decrease in rate disappears and the sedimentation rates

583   resemble a step-function. When viewed as a step function, sedimentation rates are ~4 cm/kyr

584   until ~2.2 Ma and ~2 cm/kyr thereafter, partially owing to the increasing thickness of the

585   volcanically-sourced beds from ~3.5-4.5 Ma (purple line, Fig. 10), which account for ~1 cm/kyr

586   of the sedimentation rate. Alternatively there is a gradual decline in sedimentation rate from

587   ~3.5 to ~2.1 Ma, with higher rates before and lower rates after. Either interpretation removes the

588   monotonic increase seen in the sedimentation rate that includes both volcanic and hemipelagic

589   sedimentation.

590   The sedimentation rate constructed from the marine isotope correlations is much more

591   variable than the paleomagnetically-derived sedimentation rates, but still follows the

592   approximate trends defined by the paleomagnetic rates. The rates are particularly variable prior

593   to 2 Ma. Rates are ~6 cm/kyr until ~3.65 Ma, then drop to ~4 cm/kyr from ~2.15-3.65 Ma. There

594   is a slow decline in the rates from ~4 cm/kyr to ~2 cm/kyr from ~2.5- ~1.5 Ma. There is a pulse

595   of sediment roughly coincident with the middle Pleistocene Transition (MPT), with rates

596   varying between ~4 and <1 cm/kyr afterwards. Brightness (L*) shows a particularly good

597   agreement with the sedimentation rates. Figure 10 depicts the sedimentation rates, with the

598   black line representing a running mean of L* with a 100 kyr window to remove higher

599   frequency cycles and examine only the longer-term trends. There is a significant correlation

600   between sedimentation rate and L* (See fig. 10 inset, n = 87, Pearson's r = -0.5416 , p value <

601   0.001). This connection suggests that the lighter sediments (higher L* values) were deposited at

602   a slower rate than the darker sediments (lower L* values). $CaCO_3$% data, from shipboard

603   geochemistry, shows a weak correlation to the L* values throughout the entire record. Although

604   shipboard sampling for $CaCO_3$ measurements attempted to avoid the influence of volcanic

605   sediments and sample purely hemipelagic sedimentation, the distinct possibility that carbonate-

606   free volcanic material, in the form of cryptotephra (dispersed ash), may be influencing the

607    $CaCO_3$% data was suggested by Expedition 340 Geochemistry (Expedition 340 Scientists, 2013).

608

609   *local volcanism / regional effects*

610   There are several possible explanations for the L* to sedimentation rate correlation. First,

611   the additional input of dispersed volcanogenic sediment could strongly affect sedimentation

612   rate. The 3.5-4.5 Ma interval has ~1 cm/kyr observed volcanic sedimentation, whereas the

613   sedimentation is ~4 cm/kyr overall. If we assume, for the sake of discussion, that the flux of

614   purely hemipelagic sediment is constant throughout the entire interval at ~2 cm/kyr (~0-2 Ma

615   rough average sedimentation rate), there is ~1 cm/kyr of unaccounted for sedimentation in the

616   3.5-4.5 Ma interval. As the observed volcanically-derived sedimentation is highest throughout

617   this interval, it seems possible that the undetected dispersed ash, or cryptotephra (e.g. McCanta

618   et al., 2015), throughout that interval may also be high. The lower L* value agrees with elevated

619   cryptotephra, as dispersed ash would darken the surrounding sediments. There are pulses of

620   volcanic sediment at ~1.9 Ma which also coincide with inflections in the brightness. This

621   hypothesis, however, does not agree with the land-based local volcanic history. The Silver Hills

622   Volcano on Montserrat was active ~ 2.6 to ~1.2 Ma (Harford et al., 2002), the oldest land-based

623   date for volcanic activity on Montserrat, and the general trend through this interval at Site

624   U1396 is one of increasing brightness and presumably less volcanic ash and other volcaniclastic

625   sediments. Although the volcanogenic sediments could be sourced from elsewhere (e.g., Palmer

626   et al., 2016), and Montserrat is probably older than just the onland ages, it seems likely that

627   these growth phases of subaerial Montserrat (Fig. 10) should have a substantial impact on

628   U1396. If a hypothesis of the sedimentation rate changes being purely volcanically-forced is

629   true, then one would expect that the growth of the nearest volcano to have an impact. Rather,

630   the data suggest less volcanic influence, or at least slower sedimentation rates, as Montserrat

631   grows larger.

632

633   *gateway changes*

634   The closure of the Isthmus of Panama had a profound effect on the oceanography of the

635   Caribbean Sea. In particular, bottom water connection with the Pacific Ocean ceased by ~4.5 Ma

636   (Keigwin, 1982; Haug and Tiedemann, 1998). Other portions of the Central American Seaway

637   (CAS) history are controversial (for a discussion see Molnar, 2008), owing to the prolonged

638   nature of the closure, and/or the possibility that sea level changes derived from glacial-

639   interglacial cycles could have closed and opened the gateway repeatedly (e.g., Groeneveld et al.,

640   2014). There is evidence that there is no more oceanographic exchange through the CAS by ~4.2

641 Ma (e.g., Jain and Collins, 2007), although other authors place 'final closure' later (~3.2-3.6 Ma;

642 Haug and Tiedemann, 1998). Land animal exchange between the continents is observed at 2.7

643 Ma, offering a strict youngest-limit to the closure history. At 4.2 Ma there is a substantial drop

644 in productivity recorded by benthic foraminiferal assemblages and $\delta^{13}C$ time series at Site 999

645 (Jain and Collins, 2007). Chaisson (2003) observed a distinct change in menardellid evolution

646 between the Atlantic and Pacific Oceans, with the Caribbean Sea forms occupying higher and

647 more oligotrophic conditions. Both productivity and menardellid evolution are linked the CAS

648 closure, which is thought to displace the locus of productivity and upwelling to the Pacific

649 Ocean while the Caribbean Sea experienced growth of oligotrophic conditions. This expansion

650 of oligotrophic conditions is also seen during the interval of highly variable, or 'pulsed'

651 sedimentation rates at U1396. The hemipelagic sediments at U1396 are largely biogenic so there

652 must be a link between productivity and sedimentation rate. This link is not as simple as higher

653 productivity equals higher sedimentation rate because factors like bottom water corrosiveness,

654 siliceous vs. carbonate productivity, or bottom water current strength (among many others)

655 may also alter the sedimentation rate. The confluence of oligotrophic indicators from Site 999

656 and pulsed rates at Site U1396 suggest a possible, but counterintuitive, link.

657   The lower L* values with higher sedimentation rates could suggest that biogenic silica

658 pulses are driving the sedimentation in the lower Pliocene of Site U1396. The sedimentation rate

659 also appears to possibly contain obliquity-forced cycles during the volatile interval. An obvious

660 alternative explanation for the L* values is volcanic sedimentation, but it is difficult to connect

661 obliquity cycles with volcaniclastic sedimentation. Obliquity cycles have been observed in

662 productivity indicators at other locations during the Plio-Pleistocene (e.g., Bolton et al., 2010).

663   The link at Site U1396, however, is highly speculative. The correlations between the $\delta^{18}O$ U1396

664   data and the MIS LR04 stack is, through the highly variable sedimentation rate interval, based

665   on smaller changes in $\delta^{18}O$ because of the smaller glacial-interglacial changes at those times.

666   The time interval between correlation points is also fairly small, and so minor changes in the

667   points used for correlations could produce substantial impacts on sedimentation rates. The high

668   variability is, however, still seen in the astrochronologically-derived sedimentation rates (not

669   shown). The extreme swings in sedimentation rate also suggest that even if MIS stages were

670   moved by tens of cm the magnitude of the pulses in rate may change, the pulses would remain.

671   The high rates also do not correspond to either extreme glacials or interglacials. Indeed,

672   indicators for high seasonality were observed in the benthic analysis at Site 999 (Jain and

673   Collins, 2007) prior to the final closure at ~4.2 Ma. The pulses in sedimentation may indicate

674   that Site U1396, closer to the equatorial Atlantic Ocean, experienced elevated productivity

675   longer than at the more central Caribbean Sea Site 999, or that a long-term trend toward more

676   oligotrophic conditions was punctuated by intervals of higher productivity.

677   There are other gateway changes that could have played a role in controlling

678   sedimentation at Site U1396. Mediterranean Outflow Water (MOW) enters the Atlantic Ocean

679   through the Strait of Gibraltar and is an important component of Atlantic Ocean circulation

680   patterns. Evidence from the Gulf of Cadiz, off the Portugal coast, suggests periods of

681   intensification in MOW strength at 0.7-0.9, 2.0-2.4, and 3.0-3.2 Ma (Hernández-Molina et al.,

682   2014). If this water were to flow into the Caribbean Sea at times, MOW would be the deepest

683   water-mass in the Caribbean Sea due to its high salinity, and thus high density. There is an

684   established glacial-interglacial control on the water entering the Caribbean over the past 200

685   kyr, with more corrosive Antarctic Intermediate Water (AAIW) during the interglacials and less

686   corrosive glacial North Atlantic Intermediate Water (or upper North Atlantic Deep Water)

687   during the glacials (Haddad and Droxler, 1996).

688   Kaneps (1979) suggested increases in Gulf Stream strength throughout the Plio-

689   Pleistocene, interpreting a series of hiatuses on Blake Plateau as intervals of high Gulf Stream

690   velocity. The precise timing of the hiatuses, however, is suspect as the ages are based on 1970-

691   era biostratigraphic calibrations (hence the 1-myr error bars in Figure 10). If Blake Plateau

692   hiatuses and MOW intensifications were roughly synchronous, then MOW flowing into the

693   Caribbean Sea contributed to a strengthened Gulf Stream flow. At Site U1396 there are intervals

694   of elevated carbonate deposition, very roughly coincident, with the Blake Plateau hiatuses and

695   MOW intensifications. This seems counter to the expectation from the literature (e.g., Haddad

696   and Droxler, 1996), as the bottom water bathing Site U1396 would likely be AAIW, a nutrient

697   rich but corrosive water mass. MOW, on the other hand, would be less corrosive, nutrient poor,

698   and warm. The lithostratigraphy from Site U1396 agrees with different water masses bathing

699   the site throughout the Pleistocene. At ~600 ka and again at ~400 ka there are calcareous sand

700   intervals, which are associated with lower sedimentation rate suggesting extensive winnowing

701   removing the fine fraction (discussed in Wall-Palmer et al., 2014). Removing fine sediment

702   would lower the sedimentation rate. These sandy intervals appear to be associated with MIS 15-

703   16 and MIS 10-12. Directly preceding these sandy intervals, the interval from 0.55 to 0.75 Ma is

704   one of low $\delta^{18}O$ variability in the benthic record. A change in Caribbean Sea bottom water may

705   explain the decreased benthic $\delta^{18}O$ variability, if it were episodic, only bathing benthic

706   organisms in warm water during glacials, and a relatively cooler water mass during

707   interglacials. This would have the effect of flattening the curve, effectively removing the benthic

708   glacial-interglacial differences in $\delta^{18}O$ while retaining the observed high planktic $\delta^{18}O$. While

709   the dates for MOW intensification do not agree with the lower variability in benthic $\delta^{18}O$, MOW

710   dates are at present poorly constrained (Hernández-Molina et al., 2014). Currently MOW

711   intensification occurs at ~0.7-0.9 Ma (Hernández-Molina et al., 2014). Our low $\delta^{18}O$ variance

712   interval is ~150 kyr younger, with low sedimentation rate and winnowing occurring at ~0.7-0.6

713   Ma and ~0.5-0.35 Ma, but the mismatch could simply be due to poorly constrained dates from

714   the MOW outflow studies. It should be noted that geochemical evidence points to limited MOW

715   influence in the Caribbean during the Plio-Pleistocene (Osborne et al., 2014), that evidence is

716   only from after 2 Ma, well after the hypothesis described above. The above hypothesis is

717   speculative, but remains a possible explanation for a number of different observations that

718   cannot simply be due to volcaniclastic influence at Site U1396.

719   A second pulse of winnowing coincides with MIS 11. However, low benthic $\delta^{18}O$

720   variability through this interval is likely due to a limited number of $\delta^{18}O$ values, as the sample

721   resolution shrinks to ~50 kyr. While there is similarity between the winnowing pulse at MIS 15

722   and MIS 11, we cannot rule out a data density issue at MIS 11. The planktic record suggests that

723   while MIS 15 benthic variability is limited, MIS 10 and MIS 12 may be missing in a hiatus, as the

724   typical glacial $\delta^{18}O$ values are missing from both benthic and planktic records.

725   Perhaps a more likely connection from gateway changes to rates of sedimentation is

726   thermohaline circulation. Haug and Tiedemann (1998) demonstrated a link between the salinity

727   contrast, formed by CAS closure, between Pacific and Atlantic Ocean. This contrast, with saltier

728   Atlantic Ocean water, helps to boost formation of North Atlantic Deep Water (NADW), which

729   in turn boosts thermohaline circulation. Several studies have demonstrated this link (e.g., Zhang

730   et al., 2012; Osborne et al., 2014) both in proxy reconstruction and inter-model comparison.

731   Proxy reconstructions, especially the geochemical reconstructions both from oxygen isotope

732   gradients between Pacific and Atlantic basins and other methods (e.g., Osborne et al., 2014),

733   suggest that this was not a simple single increase, that in fact there were multiple fluctuations in

734   the strength superimposed on the long-term trend of increased thermohaline circulation. These

735   fluctuations in thermohaline circulation were of varying duration, but had ~100-kyr scale

736   durations, and so could be some of the variability that is seen in the sedimentation rates at Site

737   U1396, while the longer term trend in quicker bottom water flow would explain the general

738   trend to slower sedimentation rates at U1396 within the upper portion of the record.

739   Increased bottom water current flow due to increased thermohaline circulation, and

740   therefore increased winnowing, is supported by the qualitative core description. There is a

741   change at Site U1396 to more calcareous sand style sedimentation within the upper portion of

742   the record, away from the lower, more ooze-dominated sedimentation of the lower portion.

743   This can be seen most clearly on the CCSF-NV lithologic section on Figure 2. This mean increase

744   in grain size, likely due to winnowing of the fine-grained material, would decrease the

745   sedimentation rate. In fact, as seen in Figure 7, ooze deposition is coincident with increased

746   sedimentation rate during the Brunhes chron, though this depends on the age model.

747

748   Realistically, the observed changes in sedimentation rate and brightness are a mixture of

749   different factors: volcanic input, carbonate and siliceous productivity, and thermohaline

750   circulation. The period from ~3-4 Ma could have been a period of highly variable productivity,

34 of 52

751   driven by obliquity and incomplete construction of the CAS. Thermohaline circulation, as the

752   CAS had not completely closed, could also have been uneven, and sped up and slowed down in

753   fits, as seen in Osborne et al. (2014), leading to the highly volatile rates observed through that

754   interval. As CAS closure became more complete, the increase in thermohaline circulation drove

755   quicker bottom water circulation over Site U1396, leading to increased winnowing and lower

756   sedimentation rates, resulting in the gradual decline in rates observed. Lastly, the low

757   sedimentation rates, with pulses of winnowing, could have been due to the lower productivity

758   and increased thermohaline circulation and thus variation in bottom water character during the

759   0-2 Ma interval. Throughout the entire section, there must be a substantial fraction of the

760   sedimentation rate controlled by volcaniclastic sediment. The volcanic influence here is only

761   constrained somewhat within this study, further work must be done to detail the degree to

762   which there is dispersed ash within the sediments at Site U1396. This analysis provides the first

763   step to understanding the other, non-volcanic, factors contributing the accumulation of

764   sediment at this location.

765

766   **CONCLUSIONS**

767   1.   Site U1396, drilled ~33 km southwest of Montserrat, contains a relatively continuous

768   sequence of Pliocene and Pleistocene sedimentation. There is a general trend to decreasing

769   sedimentation rate towards the present, both in volcanic and non-volcanic sedimentation.

770

771   2.   The chronostratigraphy of Site U1396 is based on planktic foraminifer biostratigraphy,

772   calcareous nannofossil biostratigraphy, magnetostratigraphy, astrochronology, and oxygen

773   isotope chemostratigraphy (marine isotope stages). The resulting chronostratigraphy provides a

774   detailed framework to reconstruct the paleoceanography and record of sediment accumulation

775   in the northeastern Caribbean.

776

777   3.   A revision of the previous Wall-Palmer et al. (2014) chronostratigraphy is proposed.

778   Here we highlight differences observed in the chonostratigraphic schemes employed and U1396

779   and use the longer perspective of U1396 to develop an alternative hypothesis, which fits better

780   when considering the Brunhes chron as a whole. Although there is a call for further

781   chronostratigraphic investigations, these findings may have dramatic implications for the

782   reconstruction of the volcanic history of Montserrat.

783

784   4.   Two biostratigraphic datums used extensively shipboard (B *Globigerinella calida* and T

785   *Globorotalia flexuosa*) were found to be unreliable at Site U1396. Use of those datums at other

786   Exp. 340 sites should be restricted to occurrences supported by additional chronostratigraphic

787   information (nannofossils, for example).

788

789   5.   There is a strong correlation ($p < 0.001$) between sedimentation rate and L* (brightness).

790   There is weak correlation between ($p < 0.1$) brightness and $CaCO_3$ content throughout the entire

791   record, but some intervals of L* qualitatively appear to be controlled by carbonate content. This

792   suggests that the main phases of Montserrat volcanism may not be contributing strongly to the

793   sedimentation at Site U1396, as the growth of Montserrat (<2.6 Ma) occurs during times of

794   lower sedimentation rates at Site U1396.

795

796   6.   Sedimentation rate at Site U1396 (IODP Expedition 340) is likely controlled by a mix of

797   factors, including volcanogenic, lithogenic, and biogenic sediment sources. A series of

798   hypotheses to explain the rates were explored, with connections to Site 999, a more centrally

799   located Caribbean Sea ODP Site, with suggestions for future work to elucidate the direct causes.

800   Highly variable, but consistently elevated, rates of sedimentation are surprisingly high during a

801   period normally considered to be oligotrophic within the Caribbean Sea. It is suggested,

802   therefore, that a more likely cause is due to bottom water conditions, including episodic

803   changes in bottom water flow rates in the Pliocene and increased winnowing into the

804   Pleistocene, associated with CAS closure through the studied interval.

805

814

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999

1000   **Figure Captions**

1001 Figure 1. Site Map. Map showing surface currents (black), as well as entry points for bottom

1002 waters (grey) to the Caribbean Sea. ODP Site 999 and IODP Site U1396 are highlighted as well.

1003 Base map from R-package 'maps' (Becker et al., 2015).

1004

1005 Figure 2. Stratigraphic data transformation process. First panel depicts major lithology for each

1006 hole (A, B, C) with Color Reflectance Brightness (L*) for each hole (A is red, B green, and C

1007 blue). Key to the colors for the major lithology is shown on the far right. Depths for this panel

1008 are all on CCSF-A.

1009   Second panel depicts the spliced stratigraphy on the CCSF-A depth scale, with each hole

1010 as a distinct column. L* in this panel only includes data included from the splice.

1011   Third panel depicts the composite section on the CCSF-D depth scale, with volcanic

1012   units and hemipelagic/pelagic sediments in distinct columns. L* in this panel is the spliced L*

1013   sequence.

1014   Fourth panel depicts the composite section removing all sediments with a volcanic

1015   major lithology. Both lithostratigraphic column and L* in this panel are not depicted as true

1016   depth, but are depicted on the CCSF-NV non-volcanic depth scale (See text).

1017

1018   Figure 3. Results of 0-1 Ma Evolutive Harmonic Analysis (EHA). Left-most panel is the L*

1019   brightness record, with volcanic sediments removed (CCSF-NV) and put on a paleomagnetic

1020   timescale. Second panel is the spectral power (hotter colors denote higher power). Third panel

1021   is amplitude of spectra (hotter colors denote larger amplitude at depicted frequency). Final

1022   panel is the results of the harmonic F-test, depicting where there is significant spectral power.

1023   The results of the harmonic F-test were used to tune. The horizontal black line on the final panel

1024   depicts a paleomagnetic sedimentation rate control point. White lines above and below depict

1025   the earliest that the EHA 'feels' the abrupt sedimentation rate change which occurs at the

1026   paleomagnetic datum. Note the 'smearing' about that point seen in the changing frequencies

1027   throughout the highlighted interval. Grey lines depict expected orbital frequencies (e

1028   eccentricity, o obliquity, p procession) if the sedimentation rate were constant. The green line

1029   depicts the frequency described by a 100-kyr period.

1030

1031   Figure 4. Summary of transformations from depth (CCSF-D) to Marine Isotope Ages for $\delta^{18}O$

1032   record. A is spliced core description lithostratigraphy, on the CCSF-D depth scale.

1033   Paleomagnetic stripe (B) is from Hatfield (2015; CCSF-D). Planktic foraminiferal biozonation (C)

1034   is from this study, CCSF-D. D separates the individual species δ¹⁸O values (red is *Cibicidoides*

1035   *robertsonianus*, brown is *Cibicidoides mundulus*, black is *Planularia wuellerstofi*, orange is mixed)

1036   and plots them on the CCSF-D depth scale. PMag Age (E) is the species δ¹⁸O records with ages

1037   as defined by a linear sedimentation rate from only paleomagnetic datums. Composite (F) is the

1038   composite δ¹⁸O record on the Pmag Age scale (see 3. Methods). The light grey polygon behind

1039   the δ¹⁸O values is the error associated with the δ¹⁸O measurements (0.1‰ for P. *wuellerstofi,* and

1040   0.14‰ for other species, see 3. Methods). Astro Age (G) employs the astrochonology generated

1041   in this study for ages. LR04 Stack (H) is from Liesecki & Raymo (2005). MIS Age (I) is the

1042   isotopic data with a chronostratigraphy resulting from the correlations between the composite

1043   record (Astro Age, G) to the LR04 benthic stack (H). The LR04 stack then provides the

1044   numerical ages for the final age model (I). Individual grey lines of correlation cannot be traced

1045   across the entire figure, instead they were chosen to elucidate the individual transformations

1046   they connect. Lines from Astro Age (G) to LR04 Stack (H) to MIS Age (I) are continuous,

1047   however. Paleomagnetic stripe in J uses ages from Ogg et al. (2012). Within K, the first

1048   lithostratigraphic column is the hypothetical 'no volcanics' lithostratigraphic column (CCSF-

1049   NV) with age, while the second column is the true lithostratigraphic column with age. All colors

1050   follow Figure 2. All δ¹⁸O scales are the same width.

1051

1052   Figure 5. Histogram of δ¹⁸O offsets between benthic species. A depicts the offset between

1053   *Cibicidoides robertsonianus* and *Planulina wuellerstorfi.* Large black line depicts the combined

1054   machine errors for two measurements. Red line depicts the mean for the values within the

1055 histogram. Because there were only two samples with both species, the green line depicts the

1056 expected offset between *C. robertsonianus* to *P. wuellerstorfi* using *Cibicidoides mundulus* as an

1057 intermediary. B depicts the offset between *Cibicidoides mundulus* and *Planulina wuellerstorfi*.

1058 Large black line depicts the combined machine errors for two measurements. Red line depicts

1059 the mean for the values within the histogram. C depicts the offset between *Cibicidoides*

1060 *robertsonianus* and *Cibicidoides mundulus.* Large black line depicts the combined machine errors

1061 for two measurements. Red line depicts the mean for the values within the histogram.

1062

1063 Table 1. Table of planktic foraminifera biostratigraphic datums. Bolded lines denote datums

1064 used as primary zonal marker, unbolded lines denote secondary datums. Age columns are from

1065 Wade et al. (2011). a denotes an age calibrated to the Cande and Kent (1995) time scale, while b

1066 denotes calibration to the Lourens et al. (2004) astrochronological timescale. Sample is the

1067 highest or lowest sample in which the species was found. Sample Depths CSF-B uses the

1068 midpoint of the sample depths, and the shipboard composite depth scale. T [CCSF-D] and B

1069 [CCSF-D] is the possible range in depths for each datum. T PMag and B PMag is the range in

1070 age for each datum, derived from the linear paleomagnetic ages. T Astro and B Astro is the

1071 range in age for each datum, derived from the astrochronological tuning. T MIS and B MIS is

1072 the range in age for each datum, derived from the correlation to the LR04 benthic $\delta^{18}O$. Offset is

1073 the difference between the midpoint MIS age and the astrochronologically-tuned calibrated age

1074 (Wade et al., 2011). * denotes ages presented in Wall-Palmer et al. (2014). *Globorotalia flexuosa*

1075 was found in the first sample, while *Globorotalia crassaformis* s.l. was found in the last sample,

1076 and so neither datum has a true top or bottom, respectively.

49 of 52

1077

1078   Figure 6. Summary of differences between Wade et al. (2011) age datums and findings at Site

1079   U1396 with important Scanning Electron Micrographs (SEM). Ages for the biostratigraphic

1080   datums are presented as MIS ages, with the horizontal line corresponding to the

1081   chronostratigraphic position of the top or bottom. Primary datums are bolded. Colored datums

1082   correspond to the SEMs at the sides of the figure. Imaged foraminifera are either from the

1083   sample in which the datum was recorded (e.g., *Globorotalia pertenuis*) or nearby core catcher

1084   samples. Core catchers are not the precise base/top, as CC samples were not included in the

1085   splice. They are as close as was possible, however. All scale bars are 100 μm. *Globorotalia tumida*,

1086   *G. flexuosa* (aberrant form), and *G. flexuosa* are from Sample 340-U1396C-3H, CC. *Globorotalia*

1087   *pertenuis* is from Sample 340-U1396C-6H-3, 112-114 cm. *Dentoglobigerina altispira* is from Sample

1088   340-U1396C-8H, CC.

1089

1090   Figure 7. Summary of the two contrasting interpretations for the Brunhes chron

1091   chronostratigraphy. Left panel depicts the Wall-Palmer et al. (2014) interpretation, with this

1092   revised correlations only from MIS 15 to the base of the figure. Inset grey box is CARMON-2

1093   stratigraphy (Le Friant et al., 2008). Right panel depicts the proposed revision to the

1094   chronostratigraphy. *%Globorotalia menardii-tumida* zonation scheme (orange) is depicted as

1095   correlated to the marine isotope stages by Reid et al. (1996), which ends within zone T (approx.

1096   MIS 19). Black polygon is the *% G. menardii-tumida* from Wall-Palmer et al. (2014), while grey is

1097   the newly-generated data from this study (points denote samples counted). LR04 Stack (grey) is

1098   from Liseicki and Raymo (2005), planktic foraminiferal oxygen isotope stack (purple) is from

1099 Martinson et al. (1987). The B *Emiliana huxleyi* datum within the left panel is the datum

1100 employed in Wall-Palmer et al. (2014), with the calibrated ages from Ogg et al. (2014), while the

1101 blue line (right panel only) refers to the other B *E. huxleyi* (Aljahdali; unpublished Masters

1102 Thesis). Green line is the *Globigerinoides ruber* oxygen isotope record from Wall-Palmer et al.

1103 (2014), with new data beginning at approximately MIS 8 on the left panel, and MIS 13 on the

1104 right panel. Black rectangles are the paleomagnetic chron interpretation from Hatfield (2015).

1105 Sedimentation rates are calculated as m/myr. Stratigraphic columns follow figure 2. Slight

1106 offset in event bed from Wall-Palmer et al. (2014) and the lithostratigraphy presented here is

1107 due to the calculation of sediment ages and slight misfit in the correlated ages in this study. The

1108 event bed is the same as topmost volcanic unit.

1109

1110 Figure 8. Summary of the age vs. depth relationship of the Site U1396 sediments. Paleomagnetic

1111 datums are depicted in red squares, depths are from Hatfield (2015) while ages are from Ogg et

1112 al. (2012). Nannofossil datums are depicted in blue triangles, open for secondary and closed

1113 triangles for primary. Depths for nannofossil datums are from Expedition 340 Scientists (2013)

1114 unless noted as being from Wall-Palmer et al. (2014), ages are from Backman et al. (2012).

1115 Vertical blue line denotes uncertainty in true stratigraphic position of datum. Planktic

1116 foraminifera datums are depicted in green triangles, open for secondary and closed triangles for

1117 primary. Depths are from this study, ages are from the Wade et al. (2011) astrochronological

1118 calibration. Vertical line denotes uncertainty in true stratigraphic position of datum. Black

1119 diamond denotes a ^{14}C date (Accelerator Mass Spectrometry, AMS), and yellow diamond

1120 denotes MIS 5.5 and 6/7, identified within Wall-Palmer et al. (2014). Black line depicts a linear
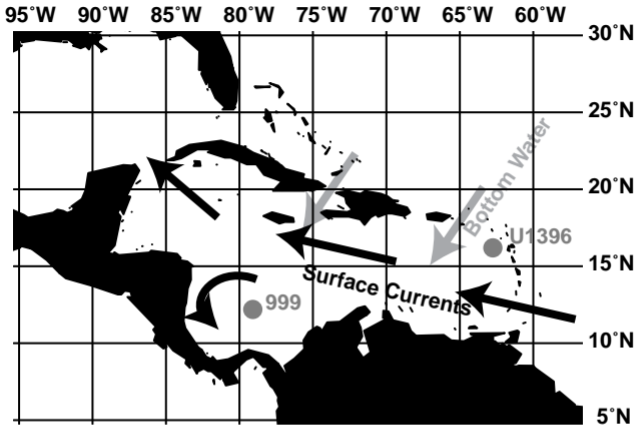
1121   interpolation for sediment age between paleomagnetic datums. The orange line depicts the ages

1122   from the astrochronological tuning. The brown line depicts the ages from the $\delta^{18}O$ correlation to

1123   the Marine Isotope Stages (MIS) within the LR04 benthic $\delta^{18}O$ stack (Liesecki and Raymo, 2005).
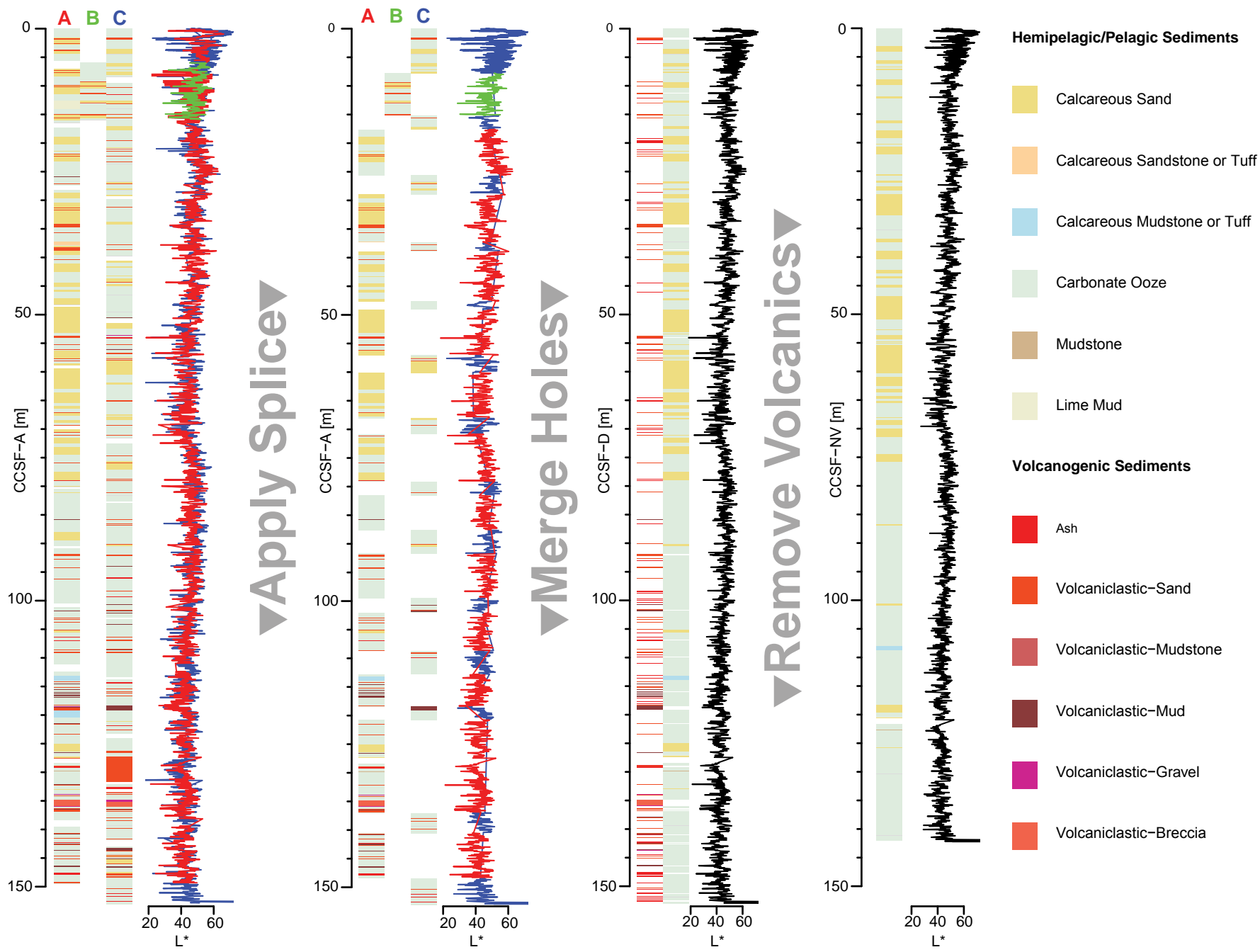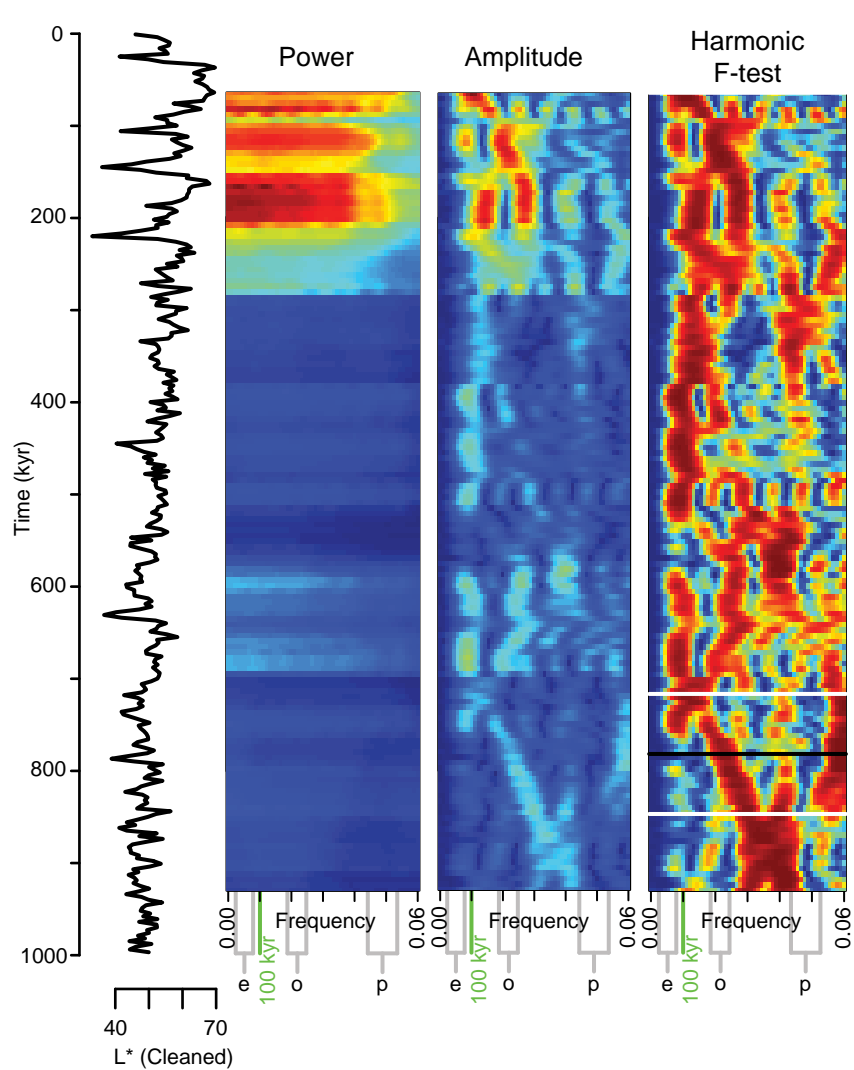
1124

1125   Figure 9. Summary of differences in different methods of age calculation. Orange polygon

1126   represents the difference between the astrochronological ages and the paleomagnetic age for

1127   each sample included in the isotope record. Brown polygon represents the difference between

1128   the marine isotope stage (MIS) ages and the paleomagnetic age for each sample included in the

1129   isotope record. Red horizontal lines correspond to the ages of paleomagnetic reversals (Ogg et

1130   al., 2012).

1131

1132   Figure 10. Summary of sedimentation rates, paleoceanographic events, and sediment character.

1133   Upper panel depicts the L* (brightness) parameter from shipboard measurements. Black line

1134   represents a 100-kyr running mean. Red dots are discrete $CaCO_3$% measurements from

1135   shipboard geochemistry. In the bottom panel, paleomagnetically derived sedimentation rates

1136   are in red (all sediment types), blue (no volcanic sediments), and purple (only volcanic

1137   sediments). MIS-age derived sedimentation rates are in orange (all sediment types) and green

1138   (no volcanic sediments). Inset depicts the correlation between L* and MIS No Volc

1139   sedimentation rates. Blue boxes represent several pertinent paleoceanographic events while

1140   grey depict climatic events (see discussion for citations and numerical dates).

| 95°W | 90°W | 85°W | 80°W | 75°W | 70°W | 65°W | 60°W |

- 30°N
- 25°N
- 20°N
- 15°N
- 10°N
- 5°N

Bottom Water

U1396

Surface Currents

999

Hemipelagic/Pelagic Sediments

- Calcareous Sand
- Calcareous Sandstone or Tuff
- Calcareous Mudstone or Tuff
- Carbonate Ooze
- Mudstone
- Lime Mud

Volcanogenic Sediments

- Ash
- Volcaniclastic−Sand
- Volcaniclastic−Mudstone
- Volcaniclastic−Mud
- Volcaniclastic−Gravel
- Volcaniclastic−Breccia

▶Apply Splice▶

▶Merge Holes▶

▶Remove Volcanics▶

Time (kyr)

Power

Amplitude

Harmonic
F-test

0.00 Frequency 0.06
0.00 Frequency 0.06
0.00 Frequency 0.06

e 100 kyr o p
e 100 kyr o p
e 100 kyr o p

40 70
L* (Cleaned)

A. *C. roberstonanius* vs. *P. wuellerstorfi*

0.14‰
Mean
m-w + *r-m* Offset

B. *C. mundulus* vs. *P. wuellerstorfi*

0.14‰
Mean

C. *C. robertsonanius* vs. *C. mundulus*

0.14‰
Mean

Species Datum	Age (Ma)[a]	Age (Ma)[b]	Sample	Sample Depth CSF-B	T [CCSF-D]	B [CCSF-D]	T PMag	B PMag	T Astro	B Astro	T MIS	B MIS	Offset
T *Globorotalia flexuosa*	0.07	0.07	U1396C/1H/1, 1-2cm	0.015	-	-	-	0.000	-	0.000	-	0.000	0.070
T *Globigerinella. calida*	0.22	0.22	U1396C/4H/6, 125-127 cm	35.764	38.59	38.77	1.914	1.919	1.951	1.955	1.951	1.955	1.733
B *Globorotalia flexuosa*	0.40	0.40	U1396C/4H/3, 47-49 cm	30.723	33.31	33.33	1.724	1.724	1.742	1.742	1.754	1.754	1.354
B *Globorotalia hirsuta*	0.45	0.45	*Not present at Site*										
T *Globorotalia tosaensis*	**0.61**	**0.61**	**U1396C/1H/5, 90-91 cm**	6.905	**-**	**-**					**0.494***	**0.495***	**0.116**
B *Globorotalia hess*i	0.75	0.75	*Not present at Site*										
B *Globorotalia excelsa*	1.00	1.00	*Not present at Site*										
T *Globoturborotalita. obliquus*	1.30	1.30	U1396C/3H/3, 21-23 cm	20.953	22.01	22.51	1.129	1.154	1.106	1.124	1.116	1.140	0.172
T *Goides. fistulosus*	**1.88**	**1.88**	**U1396C/3H/6, 51-53 cm**	25.504	**27.13**	**27.31**	**1.398**	**1.407**	**1.428**	**1.438**	**1.436**	**1.456**	**0.434**
B *Globorotalia truncatulinoides*	1.93	1.93	U1396C/5H/2, 110-112 cm	39.353	43.21	43.81	2.092	2.116	2.113	2.126	2.073	2.092	0.152
T *Globigerinoides extremus*	1.99	1.98	U1396C/3H/3, 85-87 cm	21.560	22.97	23.15	1.179	1.188	1.144	1.152	1.164	1.172	0.812
B *Pulleniatina finails*	2.05	2.04	*Pulleniatina not split*										
T *Globorotalia exilis*	2.10	2.09	U1396C/5H/2, 110-112 cm	39.353	42.96	43.23	2.082	2.092	2.108	2.113	2.064	2.073	0.022
Reappearance of *Pulleniatina*	2.26	2.26	U1396C/5H/6, 3-5 cm	43.986	48.16	48.43	2.226	2.233	2.219	2.228	2.237	2.244	0.019
T *Globoturborotalita woodi*	2.30	2.30	*Not present at Site*										
T *Globorotalia pertenius*	2.60	2.60	U1396C/6H/3, 112-114 cm	50.312	55.33	55.64	2.416	2.424	2.382	2.387	2.362	2.367	0.236
T *Globorotalia miocenica*	**2.39**	**2.39**	**U1396A/6H/2, 125-127 cm**	46.178	**49.91**	**51.46**	**2.273**	**2.313**	**2.261**	**2.297**	**2.270**	**2.288**	**0.111**
T *Globorotalia limbata*	2.39	2.39	U1396C/6H/5, 20-22 cm	52.282	57.36	57.72	2.470	2.479	2.435	2.445	2.421	2.433	0.037
T *Globoturborotalita decoraperta*	2.75	2.75	*Not present at Site*										
T *Globorotalia multicamerata*	2.99	2.98	U1396C/6H/7, 34-36 cm	55.257	60.26	60.86	2.546	2.562	2.532	2.553	2.529	2.548	0.442
T *Dentoglobigerina altispira*	**3.13**	**3.13**	**U1396C/8H/5, 27-29 cm**	71.335	**78.49**	**78.91**	**2.998**	**3.007**	**3.004**	**3.014**	**3.003**	**3.010**	**0.124**
T *Sphaeroidinellopsis seminulina*	**3.16**	**3.16**	**U1396C/8H/7, 14-16 cm**	74.080	**81.51**	**81.82**	**3.090**	**3.101**	**3.085**	**3.098**	**3.077**	**3.085**	**0.079**
B *Globigerinoides fistulosus*	3.33	3.33	U1396C/8H/5, 115-117 cm	72.165	79.77	80.37	3.029	3.049	3.035	3.049	3.025	3.035	0.300
B *Globorotalia tosaensis*	3.35	3.35	U1396A/9H/2, 19-21 cm	73.741	82.17	82.19	3.114	3.114	3.115	3.115	3.105	3.105	0.245
Disappearance of *Pulleniatina*	3.41	3.41	U1396C/9H/5, 124-126 cm	81.801	89.93	90.27	3.333	3.340	3.361	3.370	3.570	3.365	0.058
B *Globorotalia pertenuis*	3.51	3.52	U1396C/13H/2, 30-32 cm	114.688	125.84	125.86	3.993	3.993	4.000	4.000	4.025	4.025	0.505
T *Pulleniatina primalis*	3.65	3.65	*Pulleniatina not split*										
B *Globorotalia miocenica*	3.76	3.77	U1396C/13H/1, 48-50 cm	113.384	124.52	124.54	3.971	3.971	3.971	3.971	3.985	3.985	0.215
T *Globorotalia plesiotumida*	3.76	3.77	U1396A/12H/3, 38-40 cm	103.950	115.79	115.88	3.827	3.828	3.841	3.842	3.850	3.852	0.081
T *Globorotalia margaritae*	**3.84**	**3.85**	**U1396C/12H/5, 135-137 cm**	110.696	**89.85**	**89.83**	**3.331**	**3.341**	**3.359**	**3.370**	**3.355**	**3.365**	**0.490**
B *Globorotalia crassaformis* s.l.	4.30	4.31	*Present in last sample*	139.110	152.75	152.77	4.514	-	4.513	-	4.520	-	
T *Globoturborotalita nepenthes*	**4.36**	**4.37**	**U1396C/15H/6, 62-64 cm**	137.540	**150.64**	**151.10**	**4.465**	**4.475**	**4.454**	**4.466**	**4.466**	**4.475**	**0.101**
B *Globorotalia exilis*	4.44	4.45	U1396C/15H/4, 139-141 cm	135.473	148.88	148.99	4.424	4.426	4.405	4.408	4.426	4.429	0.022
B *Sphaeroidinellopsis kochi*	4.52	4.53	U1396C/14H/6, 60-62 cm	128.202	140.06	140.08	4.234	4.234	4.232	4.232	4.232	4.232	0.298

1

Darker Sediment

CaCO₃%

L* (Cleaned)

Lighter Sediment

L* 50

SedRate (cm/kyr)

MIS All Sed
MIS No Volc

South Soufrière Hill - Soufrière Hills

Centre Hills Volcano

Silver Hills Volcano

SedRate [cm/kyr]

PMag All Sed
PMag No Volc

PMag Only Volc

MOW Intensification Pulses

Panama Final Closure

Intermediate Closure

Blake Plateau Hiatuses

MPT

NHG Onset

Pleistocene

Pliocene

Age [myr]

Site U1396   Wade et al., 2011

Top
Secondary   **Primary**
Bottom

G. tumida

G. flexuosa
aberrant form

FAD *G. flexuosa*

Site U1396 column:

G. flexuosa

PT1a

G. tosaensis

PT1b

G. obliquus
G. extremus

G. fistulosus

G. flexuosa

PL6

|G. calida

G. truncatulinoides
G. exilis

Pulleniatina reappear

G. miocenica

PL5

G. pertenuis
G. limbata

G. multicamerata

PL4

1.**D. altispira**
2.*G. fistulosus*

2   1

4   3

3.**P. seminulina**
4.*G. tosaensis*

Pulleniatina
dissappearence

PL3

G. plesiotumida

6   5   *G. margaritae*

5.*G. miocenica*
6.*G. pertenuis*

PL2

S. kochi

G. exilis

PL1

G. nepenthes

Wade et al., 2011 column:

G. flexuosa
G. calida
G. flexuosa

PT1a

G. tosaensis

1 Ma

PT1b

G. obliquus

G. truncatulinoides
G. fistulosus

2 Ma

G. extremus
G. exilis

PL6

Pulleniatina
reappear

G. miocenica & limbata

G. pertenuis

PL5

G. multicamerata

3 Ma

PL4

S. seminulina   **D. altispira**

G. fistulosus|*G. tosaensis*

Pulleniatina
dissappearence

G. pertenuis

PL3

G. miocenica
G. plesiotumida

G. margarita

4 Ma

PL2

G. nepenthes|*G. exilis*

PL1

S. kochi

LAD *G. pertenuis*

LAD *D. altispira*

LAD *G. margaritae*

U1396 Depth vs. Age

Depth [m, CCSF-D] vs. Age [myr]

Wall-Palmer et al., 2014

Legend:
- Nannofossil Depth Error
- Primary Nannofossil
- Nannofossil Top
- Nannofossil Bottom
  Expedition 340 Scientists, 2013
- Planktic Foram Depth Error
- Primary Planktic Foram
- Planktic Foram Top
- Planktic Foram Bottom
- Paleomagnetic Datum
  Hatfield, 2015
- AMS Date ⎤
- MIS 5.5 & 6/7 ⎦ Wall-Palmer et al., 2014
- Paleomagnetic Age
- Astrochronologically Tuned Age
- Marine Isotope Stage Age