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1 **Eocene-Oligocene large-scale circulation of the East Asian summer**
2 **monsoon recorded in neritic carbonates of the proto-South China Sea**

3
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12
13 **Abstract**

14 When the modern features of large-scale Asian monsoonal circulation were set-up is poorly
15 constrained and pre-Neogene monsoonal archives are rare. This study investigates the temporal
16 evolution of neritic carbonates in the proto-South China Sea to reconstruct East Asian monsoonal
17 currents and winds during the middle to late Paleogene. Analysis of three-dimensional seismic
18 and well core data from the North-West Palawan block reveals the occurrence of a set of thick
19 (>125 m), aggrading *Halimeda* bioherms, early Oligocene in age. By analogy with Holocene
20 green algal buildup counterparts, they are interpreted to form in nutrient-rich areas subject to
21 upwelling currents and reflect the early presence of a strong coastal jet in the Proto-South China
22 Sea, as seen today during the summer monsoonal season. The analysis of the underlying mixed
23 carbonate–siliciclastic ramp shows that mesotrophic conditions already prevailed during the late
24 Eocene, thus suggesting that modern-like summer East Asian Monsoon large-scale circulation
25 was possibly active as early as the late Eocene in the Proto-South China Sea. Evidence for

26 upwelling currents vanishes in late early Oligocene carbonate-producing biota, that are
27 characterized by the significant development of euphotic hermatypic coral communities
28 reflecting lower nutrient concentrations. This turnover coincides with the opening of the modern
29 South China Sea and is interpreted to result from the southward drift of the North-West Palawan
30 block which placed the area away from the Chinese margin and the coastal jet. Our results
31 highlight therefore that many of the features of the summer East Asian Monsoon large-scale
32 circulation are rooted in the middle Paleogene.

33

34 **Keywords:** monsoon, carbonates, Paleogene, Southeast Asia, *Halimeda*, coastal jet.

35

36 **1. Introduction**

37

38 Carbonate-producing biota are sensitive to many environmental factors including water
39 temperature, light penetration, nutrient concentration, water chemistry, nature of substrate,
40 stratification and circulation patterns within the water column and hydrodynamic regime (e.g.
41 Hallock and Schlager, 1986; Mutti and Hallock, 2003). These factors are primarily controlled
42 by global climate and geodynamics and operate at different time and space scales. For that
43 reason, qualitative and quantitative variations in neritic carbonate production have proven to be
44 excellent records of paleoclimatic and paleoceanographic changes during the Cenozoic in the
45 Indo-Pacific realm (e.g. Mathew et al., 2020), the Caribbean (Reijmer et al., 2002) and the
46 Mediterranean (Cornacchia et al., 2021). In the Indian Ocean, they are influenced by the large-
47 scale monsoonal circulation and document the evolution of the South Asian Monsoon on
48 geological time scales (Betzler et al., 2009).

49 Like the South Asian Monsoon, the East Asian Monsoon (EAM) is associated with a large-
50 scale circulation that supplies moisture from the Sunda seas, the Pacific, and the South China

51 Sea (SCS) to East Asia in summer. This summer circulation is characterized by strong southerly
52 winds over the SCS, which are amplified by Sundaland topography and form a southwesterly
53 coastal jet offshore Vietnam (Xie et al., 2003) (**Fig. 1A**). The coastal jet generates a well-marked
54 upwelling zone in the SCS (Dippner et al., 2007), activity of which has been tracked as early as
55 the early Miocene in heterozoan carbonate systems (Wu et al., 2019). Earlier records of EAM
56 large-scale circulation are rare: on land, paleovegetation reconstructions suggest the presence
57 of a summer, monsoon-like rainy season since at least the middle Eocene (Quan *et al.*, 2012;
58 Licht *et al.*, 2014; Spicer et al., 2016; Sorrel *et al.*, 2017). This proto-monsoonal regime has
59 been either attributed to the seasonal migration of the intertropical convergence zone (ITCZ;
60 Spicer et al., 2016; Farnsworth et al., 2019) or a weak sea-breeze circulation (Tardif et al.,
61 2020). Other authors argued for a major stage of wetting in the Late Eocene, around 36 Ma
62 (Zheng *et al.*, 2022).

63 The study of the Paleogene carbonate systems in the proto-SCS, before the opening of the
64 modern SCS starting in the middle Oligocene (Briais et al., 1993; Li et al., 2014), enables to
65 reconstruct past upwellings and provide insights into potential large-scale monsoonal
66 circulation. They thus provide a key approach to elucidate early EAM dynamics. Hydrocarbon
67 exploration boreholes and seismic acquisition performed on the North Palawan Block
68 (Malampaya Field) (**Fig. 1B**), revealed the occurrence of Early Oligocene algal-dominated,
69 aggrading carbonate buildups overlying a Upper Eocene mixed carbonate-siliciclastic ramp
70 (Fournier et al., 2005). The present paper aims at 1) characterizing changes in carbonate
71 producing biota during the Late Eocene and Early Oligocene, 2) interpreting the carbonate
72 factories in terms of paleoceanographic settings and upwelling dynamics based on
73 sedimentologic and paleoecological analysis of cores and comparison with modern analogues,
74 and 3) drawing implications on the paleoceanographic evolution of the proto-SCS and early
75 EAM.

77 **2. Geological setting**

78

79 The SCS is the largest marginal sea of the western Pacific region and results from rifting and
80 seafloor spreading along the South China margin (**Fig. 1**). The SCS was preceded by the
81 Paleogene proto-SCS, a sea of similar amplitude bracketed between the Chinese margin and
82 Borneo (Zhou et al., 1995; Hall, 2002; Morley, 2016). Slab-pull effects related to subduction
83 of the proto-SCS beneath north-west Borneo resulted in early to middle Paleogene rifting along
84 the South China margin and separation of the Calamian–North Palawan–North Borneo micro-
85 continent (CPBC; Hall, 2002). Oceanic sea floor spreading initiated at ca 32-31 Ma and resulted
86 in the southward drift of the CPBC and the opening of the modern SCS between the Chinese
87 margin and the CPBC (Briais et al., 1993; Hutchison et al., 2000; Clift et al., 2008; Li et al.,
88 2014). During the Early-Middle Miocene, the CPBC collided with the accretion wedge of the
89 Paleogene subduction zone of Borneo-North Cagayan, marking the final disappearance of the
90 proto-SCS and causing the end of SCS seafloor spreading (dated at ca. 15 Ma; Briais et al.,
91 1993; Li et al., 2014). There is little evidence for Eocene-earliest Oligocene syn-rift carbonate
92 sedimentation (Fournier et al., 2005), but widespread carbonate platforms are recorded in upper
93 Oligocene and lower Miocene deposits on both the northern (e.g. Wu et al., 2019; Mathew,
94 2020) and southern margins of the SCS (Malampaya, North Palawan basin: Fournier et al.,
95 2005; Reed Bank: Ding et al., 2015; Dangerous Ground: Steuer et al., 2014). Carbonate
96 platforms from the North Palawan block were drowned during the Middle Miocene because of
97 increased subsidence, down-warping of the northwestern part of the block and important clastic
98 supply from the uplifted Palawan Island (Fulthorpe and Schlanger, 1989). Older Paleogene
99 carbonate systems can be found on the CPBC and are associated with the northern margin of
100 the proto-SCS (Fournier et al., 2005).

101 Our study area, the gas and oil field of Malampaya (**Fig. 2**), is located in the deep-water (850
102 m to 1200 m) block SC 38 in offshore Palawan on the North Palawan Block (part of the CPBC).
103 Located 3000 m below the modern sea level, this late Eocene to early Miocene carbonate
104 buildup consists of a 5 km long, 1-2 km wide, and 600 m thick NE-SW oriented body. Previous
105 works on the Malampaya buildups focused on the Nido Limestone reservoir (late Rupelian to
106 Burdigalian); it is made of aggrading, cyclic shallow-water carbonate units dominated by
107 seagrass-related foraminifers, red algae and corals (Fournier et al., 2004; 2005) and punctated
108 by repeated subaerial exposures (Fournier et al., 2004; 2007). Syn-depositional tectonic
109 deformation of the Nido Limestone has been shown to control carbonate accumulation and
110 preservation on top of the buildup (Fournier et al., 2005). There is so far no detailed
111 petrographic and sedimentological investigation of the pre-Nido (Eocene-early Rupelian)
112 carbonates.

113

114 **3. Database and methods**

115

116 The data set consists of a 3-D seismic survey acquired by Shell Philippines in 2002 and well
117 data from three wells (MA-1, MA-2 and MA-5) having reached the Eocene and Early Oligocene
118 carbonates. The non-SEG seismic polarity convention has been used (negative amplitude means
119 positive reflection coefficient). The well-to-seismic tie used in this study is that of Fournier and
120 Borgomano (2007). The correspondence between sedimentary units and the main seismic
121 horizons from the Eocene-Lower Oligocene interval is reported in **Fig. 3**. The interpretation of
122 the base of carbonates (BN horizon) and top of the Early Oligocene algal buildups (R20.1
123 horizon) has been revised in the present work. The chronostratigraphic framework of the
124 Malampaya buildup is based on the letter stage classification, a large benthic foraminifera
125 biozonation (Adams, 1970; Renema, 2007). Key foraminiferal taxa used for the

126 biostratigraphic analysis and corresponding letter stages are reported in **Fig. 4B**. In contrast to
127 previous works (Fournier et al., 2004), the base of Lower Te stage (**Fig. 4B**) has been defined
128 by the last downhole occurrence of *Heterostegina (Vlerkina) borneensis* instead of that of the
129 rotaliid *Neorotalia mecatepecensis* which has been reported from Rupelian (Td) limestones in
130 Java (Lunt and Renema, 2014).

131 A total of 42 thin-sections from the Eocene-Early Oligocene interval has been prepared from
132 core and side-wall samples (in wells MA-1 and MA-2) as well as from cuttings (in well MA-5)
133 and analyzed for detailed petrographic characterization using a conventional transmitted
134 polarized light microscope. Quantitative analysis of the biota has been performed by point-
135 counting (300 points) using *JMicroVision* software.

136

137 **4. Results**

138

139 **4.1. Chronostratigraphic framework and well-correlation**

140 The base of the carbonate succession is late Eocene in age (Tb letter stage after Adams, 1970;
141 Renema, 2007) in wells MA-1, MA-2 and MA-5 (**Fig. 4** and **Fig. 5**), based on the co-occurrence
142 of *Pellatispira* and *Discocyclina*. Rupelian deposits (Tc-Td letter stage) have been identified
143 within an up to 85 meter-thick interval, on the basis of the occurrence of *Nummulites*,
144 *Halkyardia* and *Borelis pygmaeus* together with the lack of strictly pre-Oligocene taxa such as
145 *Discocyclina* and *Pellatispira*. The presence of *Cycloclypeus* in the upper part of the Rupelian
146 interval in MA-2 (**Fig. 4**), allows characterizing the late Rupelian (Td stage). The base of
147 Chattian deposits has been defined as representing the last downhole occurrence of
148 *Heterostegina borneensis*. The Eocene-Oligocene carbonate succession was subdivided by
149 Fournier and Borgomano (2007) into 6 depositional units (SR1, SR2, SC1.1, SC1.2, SC2.1 and
150 SC2.2). According to the revised biostratigraphic framework, SR1 is late Eocene in age (Tb),

151 SR2 would correspond to the early Rupelian (Tc) while SC1.1 is comprised entirely within the
152 late Rupelian (Td). The base of Chattian deposits closely corresponds to SC1.2 unit which is
153 characterized by repeated subaerial exposures (Fournier et al., 2004). Based on the revised
154 chronostratigraphic framework and seismic horizon constraints, a well-correlation panel has
155 been established between wells MA-1, MA-2 and MA-3 (**Fig.3**), showing the significant
156 thickening of early Rupelian unit SR2 at well MA-2.

157

158 **4.2. Seismic geomorphology of early Rupelian buildups**

159 The 3D interpretation of Base Nido (BN), R10.1 (Top Eocene) and R20.1 (Top early Rupelian)
160 reflectors reveals the occurrence of four main high-relief buildups (Buildups A, B,C,D: **Fig. 6**
161 and **7**), corresponding to the SR1 unit, whose basal diameter ranges from 800 to 1300 meters
162 and a set of adjacent smaller buildups. Buildups B,C, D are nearly conical in shape while
163 buildup A exhibits a flattened top. Around well MA-2, internal reflectors within Buildup A are
164 mound-shaped and display downlap terminations onto Top Eocene reflectors. Similar downlap
165 terminations are present within buildups B and C (**Fig. 6** and **7**) but internal reflectors exhibit
166 apparent steeper slopes and locally a more chaotic expression. Below buildups A, B, C and D,
167 Top Eocene and Base Nido reflectors are crosscut by nearly vertical faults thus suggesting that
168 buildups developed on crests of tilted blocks (buildups B,C,D: **Fig. 7**) or on horst structure
169 (Buildup A: **Fig. 6**). The western flank of Buildup A is onlapped by top Rupelian (C11.1)
170 reflector while the eastern flank is onlapped by low amplitude reflectors from the Miocene
171 Pagasa siliciclastics (**Fig. 2D-E**). Buildups B, C and D are overlain by westward dipping Pagasa
172 deposits. The westernmost buildup (Buildup A) has been penetrated by well MA-2, thus making
173 possible the quantification of dimensions, thickness and slope dips of such carbonate bodies
174 and enabling the determination of the nature of carbonate producers. The interval velocity
175 (**Supplementary Material S1**) of early Rupelian unit (SR2) calculated from well-to-seismic

176 tie results (5040 m/s) is very consistent with the value computed from the integration of sonic
177 log (5070 m/s). Based on computed interval velocity (5040 m/s) and two-way-time thicknesses
178 measured from seismic data, the maximum thickness of early Rupelian buildups has been
179 estimated to range from 125 m (Buildup A) to 580 m (Buildup C). Estimated dip angles of
180 buildup flanks range from 21° (Buildup A) to 42° (Buildup C). Quantified morphological
181 parameters for buildups A, B, C and D are displayed in **Table 1**.

182

183 **4.3. Late Eocene and Early Oligocene depositional facies and facies associations**

184

185 The nature of the carbonate producers leading to the construction of the aggradating carbonate
186 buildups revealed by 3D seismic interpretation (**Fig. 6 & 7**) has been determined by means of
187 a detailed petrographic analysis of the cores and thin sections from well MA-2, located in the
188 upper part of the Buildup A southern flank. The underlying Upper Eocene carbonates have been
189 investigated from the analysis of cores, side-wall samples and cuttings from wells MA-1, MA-
190 2 and MA-5. Grain composition of analysed samples is summarized in **Supplementary**
191 **Material S2** and average composition is displayed in **Fig. 8**.

192

193 ***4.3.1. Late Eocene Facies Association (EFA): quartz-rich bryozan, foraminiferal,*** 194 ***coralline algal limestones***

195 In spite of a relative homogeneity in bioclastic composition, two depositional facies have been
196 identified within the late Eocene interval in wells MA-1, MA-2 and MA-5 (**Fig. 3**), based
197 essentially on distinct depositional texture and quartz grain content.

198 **Facies FE1: Quartz-rich, foraminiferal-coralline algal grainstone**

199 FE1 facies, identified in the lower part of the Upper Eocene interval in wells MA-1, MA-2 and
200 MA-5 (**Fig. 3**), consists of a foraminiferal-coralline algal grainstone with significant
201 proportions (average: 27%) of angular to sub-angular, fine to medium-grained quartz particles
202 (**Fig. 8 & 9A-B**). Large benthic foraminifers (27% of grains in average) dominate the biotic
203 assemblage together with fragments of encrusting coralline algae (24%). The foraminiferal
204 assemblage is dominated by lense to flat-shaped *Discocyclusina* and *Pellatispira*, commonly
205 displaying broken edge. *Nummulites* and miliolids are scarce. Subordinate components are
206 bryozoans (13%) and echinoderms (5%). The intergranular space is entirely occluded by coarse
207 sparry calcite cements.

208

209 **Facies FE2: Quartz-bearing, bryozoan, foraminiferal, coralline algal packstone**

210 Facies FA2 is a quartz-bearing (10% of the grain content in average) packstone (**Fig. 8 & 9C-**
211 **D**) whose biota is dominated by bryozoan (28%), encrusting coralline algae (27%) and large
212 benthic foraminifers (26%) with minor proportions of echinoderms (5%). Quartz particles are
213 typically fine-grained and angular. Similarly to FE1, the foraminiferal assemblage is dominated
214 by *Discocyclusina* and *Pellatispira* together with scarce *Nummulites*, agglutinated foraminifers
215 and miliolids.

216

217 **4.3.2. Early Rupelian Facies Association (ERFA): *Halimeda*-coralline algal-** 218 ***foraminiferal limestones***

219 **Facies FR1: *Halimeda* floatstone-rudstone**

220 Facies FR1 consists of a *Halimeda* rudstone or *Halimeda* floatstone with a coralline algal-
221 foraminiferal grainstone matrix (**Fig. 10A-D**). Sediment is dominated (from 30 to 66% of the

222 grain fraction; average: 42%: **Fig. 8**) by 3–8mm-long segments of rarely broken *Halimeda*
223 segments . Typically, the segments are chaotically jumbled, sometimes vertically-oriented (**Fig.**
224 **10A-D**), thus forming large (mm-scale) and irregular shelter cavities. Encrusting coralline
225 algae are the main skeletal grain forming the grainstone matrix (26% in average of the whole
226 skeletal fraction) and are preserved as medium-grained fragments. Articulated coralline algae
227 are also present (5%). The foraminiferal assemblage is dominated by porcelaneous forms (10%
228 in average of the whole skeletal fraction) including miliolids, alveolinids (*Borelis pygmaeus*),
229 soritids and peneroplids. Hyaline forms are scarcer and mainly consist of lense-shaped to flat
230 *Nummulites*. Corals are uncommon (0.25% in average) and preserved as small fragments of
231 branching colonies. The intergranular space may be partially, geopetally filled by peloidal
232 micrite (**Fig. 10A & D**) and the residual pore space may be preserved or occluded by various
233 generations of sparry calcite cements. The occurrence of lime mud sediment postdating
234 perigranular calcite cements in sheltered cavities (**Fig. 10A**) strongly suggest very early, syn-
235 depositional cementation of the sediment.

236

237 **Facies FR2: Coralline algal-foraminiferal-*Halimeda* packstone**

238 Facies FR2 is a coralline algal-foraminiferal packstone encasing sparse and well preserved
239 *Halimeda* thalli (**Fig. 10 E-F**). FR2 is present as meter-thick beds, intercalated within FR1.
240 Encrusting coralline algae are the dominant skeletal component (41% in average: **Fig. 8**) while
241 benthic foraminifers and *Halimeda* represent respectively 26% and 14% of the grain fraction.
242 Echinoderms are a subordinate but significant skeletal component (6%). The foraminiferal
243 assemblage is composed of flat-shaped *Nummulites* and *Amphistegina*, together with
244 textulariids, miliolids and few planktonics. Pteropods (**Fig. 10E**) and solitary coral (**Fig. 10F**)
245 are occasionnaly present.

246

247 **Facies FR3: Rhodolitic floatstone**

248 Facies FR3 has been reported only at the base of the early Rupelian interval and forms a 3-
249 meter-thick interval of rhodolitic floatstone which is made of lumpy to fructicose rhodoliths,
250 up to 5 cm in diameter, embedded within a foraminiferal-*Halimeda* packstone (**Fig. 10G**).
251 Rhodoliths represent the dominant skeletal component (46%), while benthic foraminifers and
252 *Halimeda* represent respectively 17% and 28% of the grain fraction (**Fig. 8**). In contrast to facies
253 FR1 and FR2, *Halimeda* thalli are generally broken as well as most of the foraminiferal tests.
254 The foraminiferal assemblage is composed of operculinids, *Amphistegina*, miliolids,
255 alveolinids together with scarce planktonics.

256

257 **5. DISCUSSION**

258

259 **5.1. Late Eocene mixed carbonate-siliciclastic ramp: a record of syn-rift**
260 **transgression**

261 The quartz-rich foraminiferal- coralline algal grainstone (FE1 facies) sampled in the lower part
262 of the late Eocene interval from the three analyzed wells contain abundant robust *Discocyclus*
263 thus suggesting shallow, tropical, agitated, open marine waters in inner ramp setting (Sinclair
264 et al., 1998). The lack of matrix mud as well as the broken edges of foraminiferal tests in facies
265 FE1 support also a high energy setting. The other dominant foraminiferal taxa, *Pellatispira*, is
266 known to preferentially thrive in the lower part of the upper photic zone and the upper part of
267 the lower photic zone (Romero et al., 2002), such a bathymetric interval being equivalent with
268 the mesophotic zone and upper oligophotic zone of Pomar (2001). The association of oligo-

269 mesophotic biota and high-energy markers consistent with a deposition above the fair-weather
270 wave-base (<20 m) may suggest: 1) turbid water conditions since decreased light penetration
271 rates induce a shift of the mesophotic zone toward shallower location (e.g. Pomar et al., 2014),
272 or 2) the occurrence of internal waves breaking obliquely to the sloping ramp (Pomar et al.,
273 2012). Additionally, large benthic foraminifers such as *Discocyclina* and *Pellatispira* have a
274 mixotrophic nutrition, which favours their development in low-nutrient conditions, and
275 therefore they preferably thrive in oligotrophic habitats (e.g. Mutti and Hallock, 2003, Hallock
276 and Pomar, 2009).

277 In FE2, the foraminiferal association is similar to that of FE1 but the facies differs in displaying
278 a lime mud matrix, a higher content in bryozoan and finer-grained quartz sand particles. The
279 presence of matrix mud is indicative of low-energy environments, the abundance of bryozoan
280 is likely to represent low-light and nutrient-rich environments and the decreased quartz sand
281 size may suggest a more distal location relatively to terrigenous supplies. Fine-sized quartz
282 grains can be explained by the input of suspended particle supply from erosion of the hinterland
283 (the crest of the Malampaya tilted block: **Fig. 2B**). Facies FE2 likely occupy a slightly deeper
284 position, below the fair-weather wave base, within a nutrient-enriched oligophotic environment.
285 Robust large benthic foraminifera (*Discocyclina*) and fragments of coralline algae likely derive
286 from shallower areas. The present results together with the analogy with other Eocene carbonate
287 systems dominated by large benthic foraminifers and coralline algae (e.g. Romero et al. 2002;
288 Khanolkar and Saraswati, 2019) suggest a carbonate ramp system, subject to terrigenous
289 influxes and characterized by a mesophotic, oligotrophic, turbid-water, high-energy outer inner
290 ramp to mid-ramp (FE1 facies) and an oligophotic, mesotrophic, low-energy outer ramp (FE2
291 facies). Additionally, the vertical upward succession from FE1 to FE2 suggests that the late
292 Eocene carbonate ramp (SR1 unit *sensu* Fournier and Borgomano, 2007) developed during a
293 marine transgression over the Pre-Nido basement.

295 **5.2. Depositional model for early Rupelian *Halimeda* buildups**

296 Except the lowermost 2 meters of carbonate sediments overlying the late Eocene deposits (core
297 5) which are made of a rhodolithic floatstone (FR3: **Fig. 10G**), the carbonate succession crossed
298 by MA-2 well consists essentially of *Halimeda* floatstone-rudstone (FR1) with thin (meter-thick)
299 occurrences of foraminiferal-coralline algal packstones (FR2) (**Fig. 11**). In FR1 floatstones-
300 rudstones, the peloidal and geopetal nature of the sediment infilling the large cavity formed by
301 the chaotic accumulation of *Halimeda* segments, prior to mechanical compaction (**Fig. 10A-D**),
302 suggests early (microbial?) carbonate precipitation leading to a syn-sedimentary lithification.
303 Additionally, the occurrence of peloidal micrite postdating isopacheous cements (**Fig. 10A**)
304 suggests that early lithification occurred also by means of sparry calcite precipitation. The chaotic
305 orientation and full preservation of *Halimeda* segments are indicative of rapid sediment
306 accumulation resulting from prolific growth of *Halimeda* followed by spontaneous plant
307 fragmentation and limited grain transport. Such a rapid *Halimeda* segment accretion coupled
308 with syn-sedimentary cementation has been shown to result in reef structure development on the
309 slopes of the early Messinian carbonate platform from the Sorbas Basin, Spain (Braga *et al.*,
310 1996). The foraminiferal assemblage from FR1, with common miliolids and porcelaneous
311 epibionts (soritids, *Borelis*) together with lense-to-flat shaped large benthic foraminifera suggest
312 a relatively shallow-water environments (Hallock and Pomar, 2009; Pomar *et al.*, 2014), at the
313 transition between the euphotic and mesophotic zones. The scarcity of micrite particles (except
314 in microbial peloids) in the intergranular space in most samples suggests a minimal water energy,
315 sufficient to remove micron-scale particles. The *Halimeda* floatstone-rudstone likely deposited
316 in a quiet-water environment with minimal wave energy near the fair-weather wave base, within
317 the lower euphotic to upper mesophotic zone (~20 meters water-depth in waters of normal
318 transparency). The aggrading nature of the early Rupelian buildups is likely to be related to the

319 fast accumulation of *Halimeda* segments and syn-sedimentary lithification, thus forming rigid
320 *Halimeda* bioherms resisting to the effect of potential storms and limited the offbank export of
321 sediments. The mud-supported FR2 facies, which is interbedded within FR1 *Halimeda*
322 floatstones-rudstones may represent offbank sedimentation in a slightly deeper and low-energy
323 environment or could be also related to a temporary deepening of the system considering some
324 potential sea-level fluctuations. The foraminiferal assemblage with flat-shaped *Nummulites* and
325 *Amphistegina* (Hallock and Pomar, 2009) suggests oligo-mesophotic environments. The
326 occurrence of planktonic foraminifers and pteropods is also indicative of relatively deep and open
327 marine environments. The presence of *Halimeda* plates in reduced proportions may suggest
328 limited offbank transport from the neighbouring *Halimeda* bioherms. They may also derive from
329 *in situ* fragmentation of sparse *Halimeda* plants growing on a muddy substrate in such oligo-
330 mesophotic environment. In the rhodolithic floatstone FR3, the mud-supported fabric suggests a
331 deposition below the fair-weather wave base. Rhodolith growth forms have been commonly
332 assumed to be controlled by water energy levels and lumpy to fructicose rhodoliths are often
333 associated with low to moderate energy environments (Bosence, 1983). The broken nature of
334 most of *Halimeda* plates and foraminiferal tests suggests the occurrence of high energy events.
335 The foraminiferal assemblage, similar to that of FR2 facies suggests oligo-mesophotic
336 environments. Finally, the rhodolithic floatstone (FR3) may be interpreted as being deposited on
337 the slopes of the buildups, in calm, oligo-mesophotic environments subject to episodic high
338 energy events or may just represent an incipient stage of carbonate factory development (FE3)
339 on some meso-oligophotic environment prior to the development of *Halimeda* meadows. The
340 latter facies, captured in well MA-2 at the base of the buildup may represent a downslope lateral
341 equivalent of FR2 facies, or may be restricted to specific hydrodynamic conditions prevailing
342 during the incipient stages of buildup development.

343

344 **5.3. Halimeda buildups development: a record of offshore upwelling**

345 Seismic interpretation (**Fig. 6 & 7**) show that Halimeda buildups developed on bathymetric highs
346 that are controlled by normal faults associated with rifting of the South China Sea. Increasing
347 subsidence rate toward the southeast associated with block tilting (**Fig. 12**) is likely to be partly
348 responsible for the greater thickness for buildups B, C and D (up to 220 ms TWT, ~580m)
349 compared to buildup A (50 ms TWT, ~125m). These observations indicate that the location of
350 early Oligocene *Halimeda* bioherms was partly driven by small changes of bathymetry controlled
351 by the locus of extensional faults. However, these topographic highs do not fully explain the
352 appearance of *Halimeda* bioherms in the early Oligocene, as many other carbonate systems such
353 as coral reefs (e.g. Gishler and Hudson, 2004) can thrive on shallow bathymetric highs.

354 The distribution of Holocene and modern Halimeda bioherms is restricted to low energy marine
355 tropical environments, with a range of water depth from 20 to 50 meters; they form mounds of
356 up to 140 meters high (Mc Neil et al., 2020). They are today observable in five localities: 1)
357 Kalukalukuang Bank, Eastern Java, Indonesia (Roberts et al., 1988), 2) Nicaraguan Rise, Miskito
358 Channel, South-west Caribbean (Hine et al., 1988), 3) Northern Great Barrier Reef, Australia
359 (e.g. Davies and Marshall, 1985; McNeil et al., 2020), 4) Swain Reefs, southern Great Barrier
360 Reef, Australia (Searle and Flood, 1988), 5) Big Bank Shoals, Timor Sea (Heyward et al., 1997).
361 Additional references are displayed in **Supplementary Material S3**. All of them are located
362 coastward of deep-water upwelling zones: the Halimeda bioherms from the Kalukalukuang Bank
363 are located in the southern Makassar Strait where upwelling occurs annually during southeast
364 monsoon period (Utama et al., 2017); the mounds from the Miskito channel develop in nutrient
365 rich-waters related to the upwelling of the ocean-scale Caribbean Current impinging the steep
366 margin of the Nicaragua shelf (Roberts et al., 1992); the Halimeda algal bioherms from the
367 northern Great Barrier Reef are distributed within a N-S-oriented band located in mid-shelf to
368 outer reef barrier position and appear to develop preferentially in areas where shelf-edge

369 upwelling from the Coral Sea intrudes into the shelf (McNeil et al., 2020); finally, Halimeda
370 mounds from the southern Timor Sea occur in nutrient-rich waters subject to upwelling of water
371 from the Indonesian throughflow during winter SE monsoon (Alongi et al., 2013).

372 The close association of *Halimeda* bioherms with upwelling zones is explained by the high
373 concentrations in nutrients which favour the development of benthic frondose algae, including
374 *Halimeda*, together with benthic suspension feeders (Hallock and Schlager, 1986; Hallock et al.,
375 1988). The development of *Halimeda* buildups during the earliest Oligocene in Malampaya is
376 therefore interpreted as resulting from high nutrient concentration on the northwest Palawan shelf
377 and requires the set-up of an upwelling zone offshore in the Proto-SCS, in the absence of any
378 alternate mechanism to explain high nutrient concentrations. These interpretations date the onset
379 of upwelling offshore the Vietnamese coast back to at least the earliest Oligocene, before the sea-
380 floor spreading of the SCS. The early Cenozoic paleogeographic history of the Palawan
381 Continental Terrane (PCT), on which the studied carbonate systems are located, is controversial,
382 particularly with regard to its pre-drift location along the South China margin (Morley, 2012;
383 Zahirovik et al., 2014). Analyses of heavy mineral and detrital zircon U–Pb age signatures
384 revealed that the PCT was attached to the South China margin from the Cretaceous until the
385 Oligocene oceanization of the SCS (Shao et al., 2017). As a consequence, even though narrow
386 (<50 km), marine troughs have developed during the Late Eocene to Early Oligocene rifting of
387 the SCS, offshore southern China (Baiyung trough, Pearl River Basin: Sun et al., 2020), the PCT
388 was open to the south-east to a wide oceanic basin (the Proto South China Sea) of comparable
389 dimension (around 1500 km of width along a northwest-southeast transect) and orientation as
390 the present-day SCS (**Fig. 1**).

391

392 **5.4. Paleoclimatic and paleogeographic implications**

393 The genetic link between the upwelling in the modern and Neogene SCS and the southwesterly
394 summer coastal jet offshore Vietnam (Xie et al., 2003; Dippner et al., 2007; Wu et al., 2019)
395 indicates that an early version of the coastal jet was active in the earliest Oligocene (**Fig 1 A &**
396 **B**). This jet is the coastal expression of the large-scale summer EAM circulation over the SCS
397 that carries atmospheric moisture from low-latitude oceanic pools to the eastern and northern
398 Chinese coast. Evidence for an active jet in the early Oligocene contrasts with the weak sea-
399 breeze model proposed for the late Eocene EAM, which does not involve a large-scale summer
400 circulation (Tardif et al., 2020). It remains unclear if a seasonal ITCZ migration over East Asia,
401 as proposed by several studies to explain monsoon-like rainfall in the Paleogene (Spicer et al.,
402 2016, Farnsworth et al., 2019), could seasonally generate such a jet. The modern Australian-
403 Indonesian monsoon, modern analogue for an ITCZ-driven monsoon (Spicer et al., 2016), is
404 driven by the seasonal migration of sea surface temperature maximum from one hemisphere to
405 the other and is associated with weaker and more gradual changes in wind direction and rainfall
406 than the EAM and South Asian monsoons (Wheeler and McBride, 2005). We thus postulate that
407 the early Oligocene jet of the proto-SCS better reflects the set-up of a modern-like EAM summer
408 large-scale circulation than an ITCZ-driven monsoon. Together with evidence for the Eocene
409 set-up of a modern-like winter EAM circulation based on dust records on land (Licht et al., 2016;
410 Meijer et al., 2021), our results suggest that many of the features of the summer and winter EAM
411 large-scale circulation are rooted in the middle Paleogene, which is also consistent with the
412 climate transition noted by Zheng et al. (2022) in Yunnan at 36 Ma..

413 The shift from a late Eocene carbonate ramp (facies FE1 and FE2) to a neritic environment
414 influenced by upwelling waters can first be interpreted as related to a strengthening of the EAM
415 summer circulation and associated jet. This interpretation is yet not straightforward, as inland
416 records indicate a decrease in EAM intensity through the Eocene-Oligocene Transition (Page et
417 al., 2019; Licht et al., 2020), caused by the minor yet significant dependency of the EAM

418 hydrological cycle to atmospheric pCO₂ (Licht et al., 2014; Farnsworth et al., 2019). The 70 m
419 eustatic drop in the earliest Oligocene resulted in the emergence of significant parts of the
420 southeast Asian shelf, a process that increased land-sea thermal contrasts at the continental scale
421 (Toumoulin et al., 2022). This mechanism can explain summer wind strengthening in the earliest
422 Oligocene in a context of decreased moisture supply. However, the biological associations
423 identified in the Late Eocene ramp reveal that nutrient concentrations increased distally:
424 oligotrophic in the inner to middle ramp (Facies FE1) and mesotrophic in the outer ramp (facies
425 FE2). This suggests that Eocene nutrients derived from ocean waters rather than from continental
426 supply. We thus suggest that the upwelling in the proto-SCS (and the summer jet) possibly
427 predated the earliest Oligocene, and that the apparent lack of *Halimeda* in the Eocene deposits is
428 explained by other controlling factors.

429 A bathymetric control on the onset of algal buildups can be ruled out, as both late Eocene and
430 early Oligocene carbonate facies suggest a shallow depth (<50 m) favorable to the development
431 of *Halimeda* bioherms. Sea level drop associated with the Antarctic ice-sheet growth at the
432 Eocene-Oligocene transition possibly resulted in the temporary emergence of our study area;
433 this emergence could mark the top Eocene sequence boundary but left no evidence of subaerial
434 exposure or shallowing trend in the sedimentary record. A decrease of terrigenous supply
435 related to a regional drop of monsoonal intensity, reducing water turbidity and enhancing green
436 algal productivity in the SCS, provides an alternate explanation for the appearance of *Halimeda*
437 bioherms.

438 The disappearance of *Halimeda* build-ups and the shift to a carbonate sedimentation dominated
439 by coralline algae, benthic foraminifers and corals in the late Rupelian Nido Limestone (SC1
440 units) is coeval to the initiation of oceanic sea floor spreading (ca 32-31 Ma) and the opening of
441 the modern SCS between the south Chinese margin and the CPBC (Briaais et al., 1993; Li et al.,
442 2014). The opening of the modern SCS resulted in an increased southward drift of the CPBC,

443 away from the Chinese margin and the coastal jet. In the long-term, these changes must have
444 forced upwelling to jump north of the CPBC, in the modern SCS, which is achieved by the early
445 Miocene (Wu et al., 2019). The disappearance of *Halimeda* buildups on the North Palawan Block
446 (**Fig. 11** and **12**) in the late Rupelian can reflect a possible early jump of the upwelling from the
447 proto-SCS to the modern SCS. The late Oligocene and early Miocene carbonate production on
448 the North Palawan Block was dominated by seagrass related biota (**Fig. 12**) and characterized by
449 significant development of shallow euphotic hermatypic corals (Fournier et al., 2004) thus
450 indicating low to moderate nutrient concentrations. The period spanning from the late Rupelian
451 to the early Miocene was rather a transitory phase where the abyssal depths of the proto-SCS
452 were too far away from the coastal jet to be influenced by Ekman pumping and generate seasonal
453 upwellings, while the modern SCS, with its young and narrow oceanic crust, was too shallow for
454 upwellings to start. The disappearance of *Halimeda* build-ups is therefore interpreted to reflect a
455 possible shut-down of upwelling during the late Rupelian in response to this unfavorable
456 paleogeographic configuration.

457 **6. Conclusion**

458 By coupling the interpretation of three-dimensional seismic data and drill cores, we show that
459 three different carbonate systems succeeded each other from the late Eocene to the late early
460 Oligocene offshore North-West Palawan. These results highlight two major turnovers in
461 carbonate production on the northern margin of the Proto-SCS and later on the southern margin
462 of the SCS, and provide insights into paleoclimatic and paleoceanographic changes in South-
463 East Asia from the Late Eocene to the Early Miocene:

464 -During the Late Eocene, a mixed carbonate-siliciclastic system was dominated by large benthic
465 foraminifers (*Discocyclusina-Pellatispira* assemblage), coralline algae and bryozoan, developed
466 in nutrient-enriched and turbid waters. Nutrients were likely sourced by upwelling currents

467 prevailing in the Proto-SCS while turbidity was controlled by terrigenous supplies from the
468 continent.

469 -During the Early Oligocene, terrigenous inputs ceased on the North Palawan Block and thick,
470 aggrading *Halimeda* bioherms developed at water-depths ranging from 20 to 50 meters, as a
471 result of the combination of high nutrient supplies sourced by upwelling currents, low-turbidity
472 waters and tectonic subsidence.

473 -Such upwelling currents affecting the North Palawan Block are interpreted to reflect the onset
474 of a coastal jet in the Proto-SCS which would have resulted from the set-up of a modern-like
475 EAM summer large-scale circulation as early as the late Eocene.

476 - From the late early Oligocene to the early Miocene, the carbonate production on the North
477 Palawan Block was characterized by significant development of shallow euphotic hermatypic
478 coral communities which indicate a return to lower nutrient levels. Such a carbonate production
479 turnover coincides with the opening of the modern SCS which resulted in a southward drift of
480 the CPBC, away from the Chinese margin and the coastal jet.

481 This study shows the important and often underestimated potential of neritic carbonate systems
482 and carbonate production turnovers to record major oceanographic changes such as those
483 associated with monsoonal activity. Though our results do not address inland monsoonal
484 circulation neither its low-latitude component, they emphasize the early origin of the offshore
485 large-scale monsoonal circulation in East Asia, and contrast with the more recent, supposed age
486 of the modern South Asian large-scale circulation over the Indian Ocean and the Arabian Sea,
487 dated to the middle Miocene (Sarr et al., 2022).

488

489

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491

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495

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667 **Figure and Table caption**

668 **Figure 1:** (A) East Asia today with modern summer EAM winds (red arrows); SCJ: Summer
669 Coastal Jet; SCS: South China Sea; (B) East Asia in the late Eocene (after Poblete et al., 2020);
670 red line: SCS rift; black line: North Borneo subduction zone. CPBC: Calamian–North Palawan–
671 North Borneo micro-continent. Our study site is indicated by a yellow star on both figures, blue
672 colors indicate marine areas (dark blue: abyssal depths; light blue: continental shelf); green to
673 brown colors indicate emerged areas (green: low altitude; brown: high altitude).

674 **Figure 2:** A) Location map of the Malamapaya carbonate platform, B) Regional seismic profile
675 showing the development of the Malampaya buildup on the crest of a tilted block. C) Depth
676 map in meters of the top Nido surface and well location (from Fournier et al., 2004). D)
677 Lithostratigraphic column of the Malampaya platform, name and age of the main sedimentary
678 units (modified after Fournier and Borgomano, 2007).

679 **Figure 3:** Correlation panel between wells Malampaya-1, -2 and -5 and correspondence
680 between depositional units and seismic markers. (after Fournier and Borgomano, 2007). Well
681 location is reported on **Fig. 2C**, **Fig. 6** and **Fig. 7**.

682 **Figure 4:** **A:** Malampaya-2 well: porosity and sonic logs, sequences (after Fournier and
683 Borgomano, 2007), seismic markers, distribution of foraminiferal taxa and biostratigraphic
684 interpretations; **B:** Letter-Stage classification (after Boudagher-Fadel and Banner, 1999;
685 Renema, 2007) and the key benthonic foraminiferal taxa used in the present work.

686 **Figure 5:** Porosity and sonic logs, sequences (after Fournier and Borgomano, 2007), seismic
687 markers, distribution of foraminiferal taxa and biostratigraphic interpretations following the
688 Letter-Stage classification. **A:** Malampaya-1 well; **B:** Malampaya-5 well.

689

690 **Figure 6:** Uninterpreted (**A**) and interpreted (**B**) seismic profile (crossline XL1935); **C**) Two-
691 way-time surface of Top Late Eocene (R10.1 reflector) and Top Early Rupelian buildups
692 (R10.2 reflector) and location of crossline XL1935 (**A-B**).

693 **Figure 7:** Uninterpreted (**A**) and interpreted (**B**) arbitrary line crossing buildups A, B,C, D
694 and well Malampaya-2 (location on **C** and **D**); **C**) Two-way-time (TWT) thickness of early
695 Rupelian unit SR1; **D**) Isochron map of Top Early Rupelian (R10.2 reflector).

696 **Figure 8:** Average grain composition of Upper Eocene (FE1, FE2), Lower Rupelian (FR1,
697 FR2 and FR3) and Upper Rupelian (FR4) facies.

698 **Figure 9:** Thin section microphotograph of Late Eocene microfacies: A-B) Quartz-rich,
699 foraminiferal-coralline algal grainstone (Facies FE1); C-D) Quartz-bearing, bryozoan,
700 foraminiferal, coralline algal packstone. Disc.: Discocyclusina; Bry.: bryozoan; CA: coralline
701 algae; Qz: quartz grains (Qz).

702

703 **Figure 10: A-B-C-D**) Thin section microphotograph of early Rupelian microfacies (Facies
704 FR1): *Halimeda*-rudstone showing random or vertically-oriented *Halimeda* segments (Hal.),
705 scarce coral branches (Cor.), flat-shaped large benthic foraminifers (LBF), geopetal peloidal
706 matrix infills (pm) and homogeneous micrite infill postdating isopachous bladed calcite
707 cements (black arrow); **E-F**) Thin section microphotograph of early Rupelian microfacies
708 FR2: Coralline algal-foraminiferal-*Halimeda* packstone (FR2) with sparse pteropod (white
709 arrow), *Nummulites* (Num.) and solitary coral (SC); **G**) Core photograph of macrofacies FR3:
710 Rhodolithic floatstone (Rho.: rhodolith).

711 **Figure 11:** Malampaya-2 well : well-logs, vertical facies distribution, grain composition
712 (point-counting) and facies associations.

713 **Figure 12:** Growth pattern of the carbonate buildups of Malampaya from the late Eocene to
714 the early Miocene in relation to tectonic evolution and paleoceanographic changes.

715

716 **Table 1:** Morphologic features of buildups A, B, C and D.

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719 **Supplementary material**

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723 **Supplementary Material S1:** MA-2 well: well-to seismic tie and interval velocities.

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725

726 **Supplementary Material S2:** Grain composition from point-counting on thin-sections.

727

728 **Supplementary Material S3:** Summary of published modern *Halimeda* bioherms and their
729 geomorphologic and sedimentologic features.

Figure 01

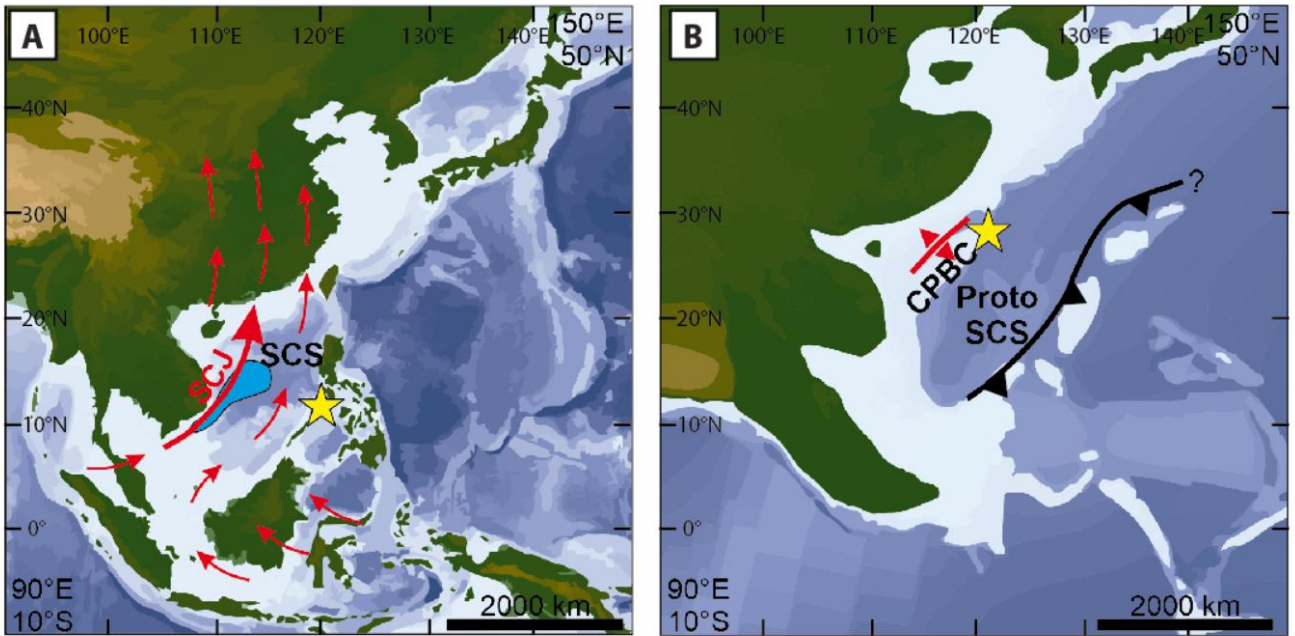


Figure 1: (A) East Asia today with modern summer EAM winds (red arrows); SCJ: Summer Coastal Jet; SCS: South China Sea; (B) East Asia in the late Eocene (after Poblete et al., 2020); red line: SCS rift; black line: North Borneo subduction zone. CPBC: Calamian–North Palawan–North Borneo micro-continent. Our study site is indicated by a yellow star on both figures, blue colors indicate marine areas (dark blue: abyssal depths; light blue: continental shelf); green to brown colors indicate emerged areas (green: low altitude; brown: high altitude).

Figure 02

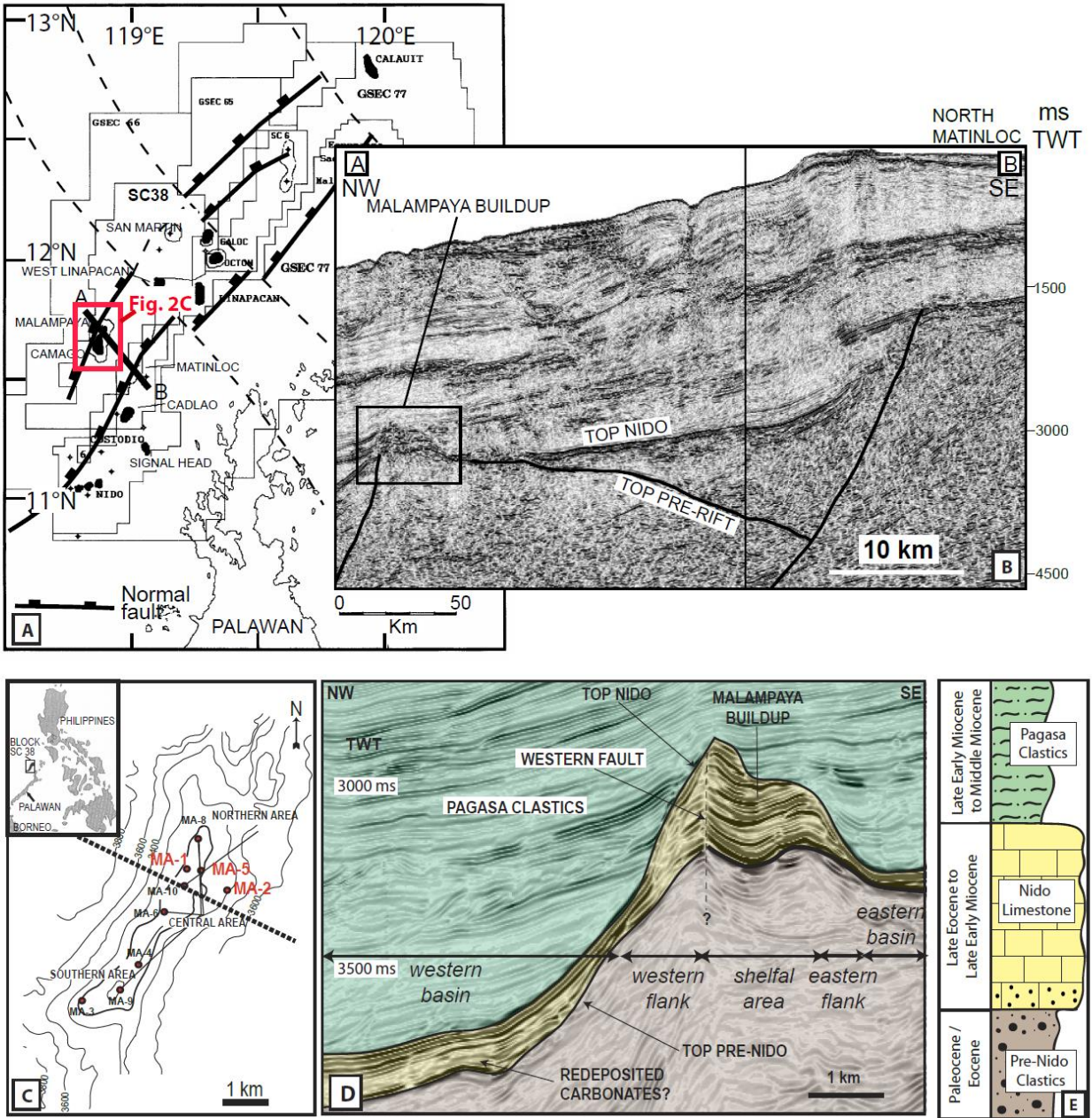


Figure 2: A) Location map of the Malampaya carbonate platform, B) Regional seismic profile showing the development of the Malampaya buildup on the crest of a tilted block. C) Depth map in meters of the top Nido surface and well location (from Fournier et al., 2004). D) Lithostratigraphic column of the Malampaya platform, name and age of the main sedimentary units (modified after Fournier and Borgomano, 2007).

Figure 03

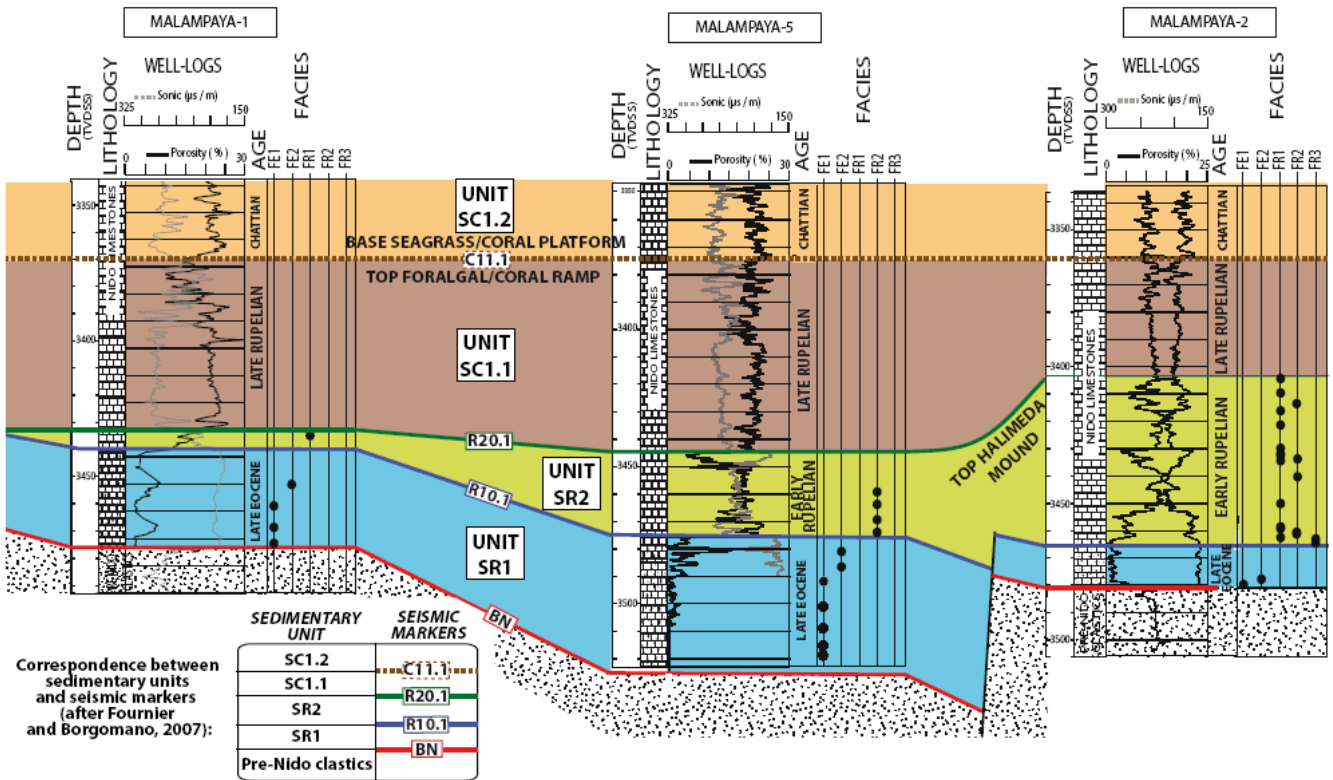
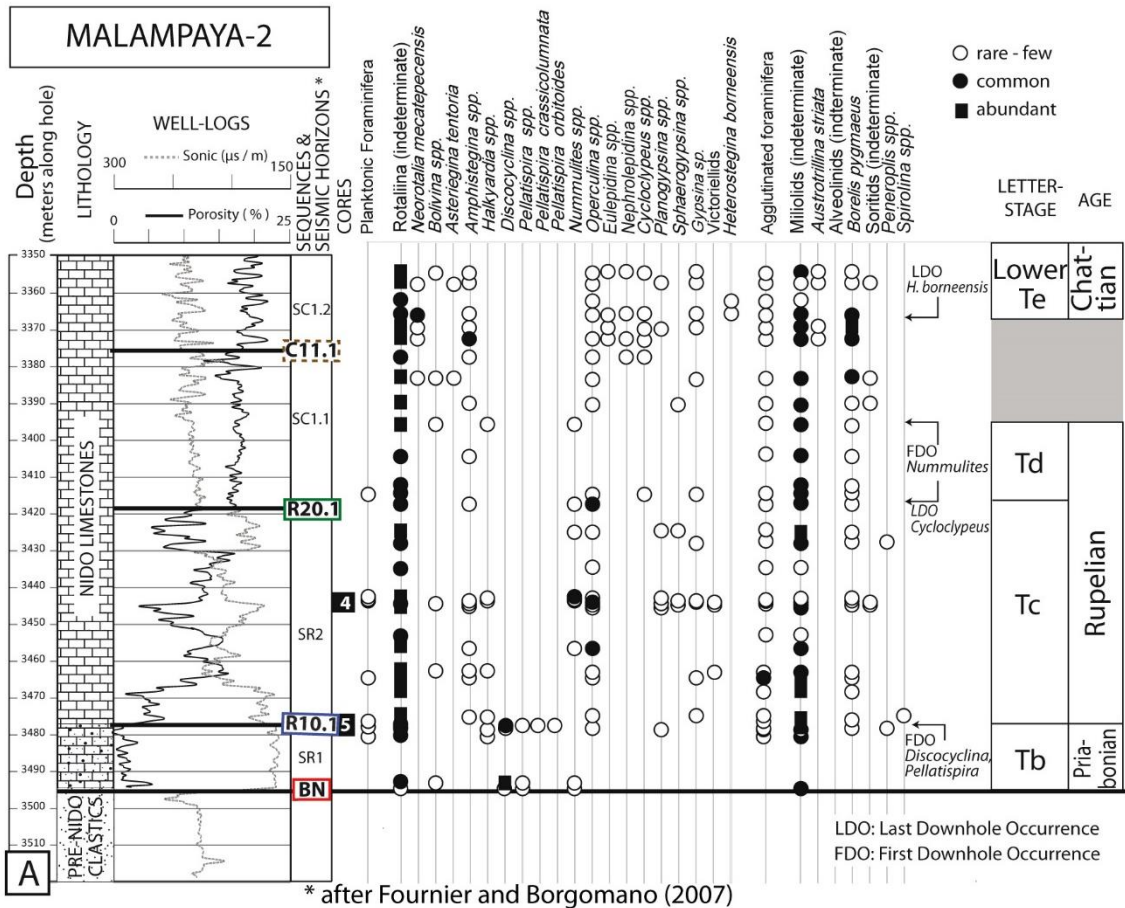


Figure 3: Correlation panel between wells Malampaya-1, -2 and -5 and correspondence between depositional units and seismic markers. (after Fournier and Borgomano, 2007).

Figure 04



AGE STAGE		KEY BENTHONIC FORAMINIFERA							LETTER-STAGE			
LATE OLI-GOCENE	CHATTIAN			Nummulites	Halkyardia	Borelis pygmaeus	Neorotalia mecatepecensis	Heterostegina borneensis	Austrorillina striata	Cycloclypeus sp.	Lepidocyclina (Eulepidina) sp.	Lower Te
EARLY OLI-GOCENE	RUPELIAN	Discocyclina	Pellatispira									Td
LATE EOCENE												Tc
												Tb

B

Figure 4: A: Malampaya-2 well: porosity and sonic logs, sequences (after Fournier and Borgomano, 2007), seismic markers, distribution of foraminiferal taxa and biostratigraphic interpretations; **B:** Letter-Stage classification (after BouDadher-Fadel and Banner, 1999; Renema, 2007) and the key benthonic foraminiferal taxa used in the present work.

Figure 05

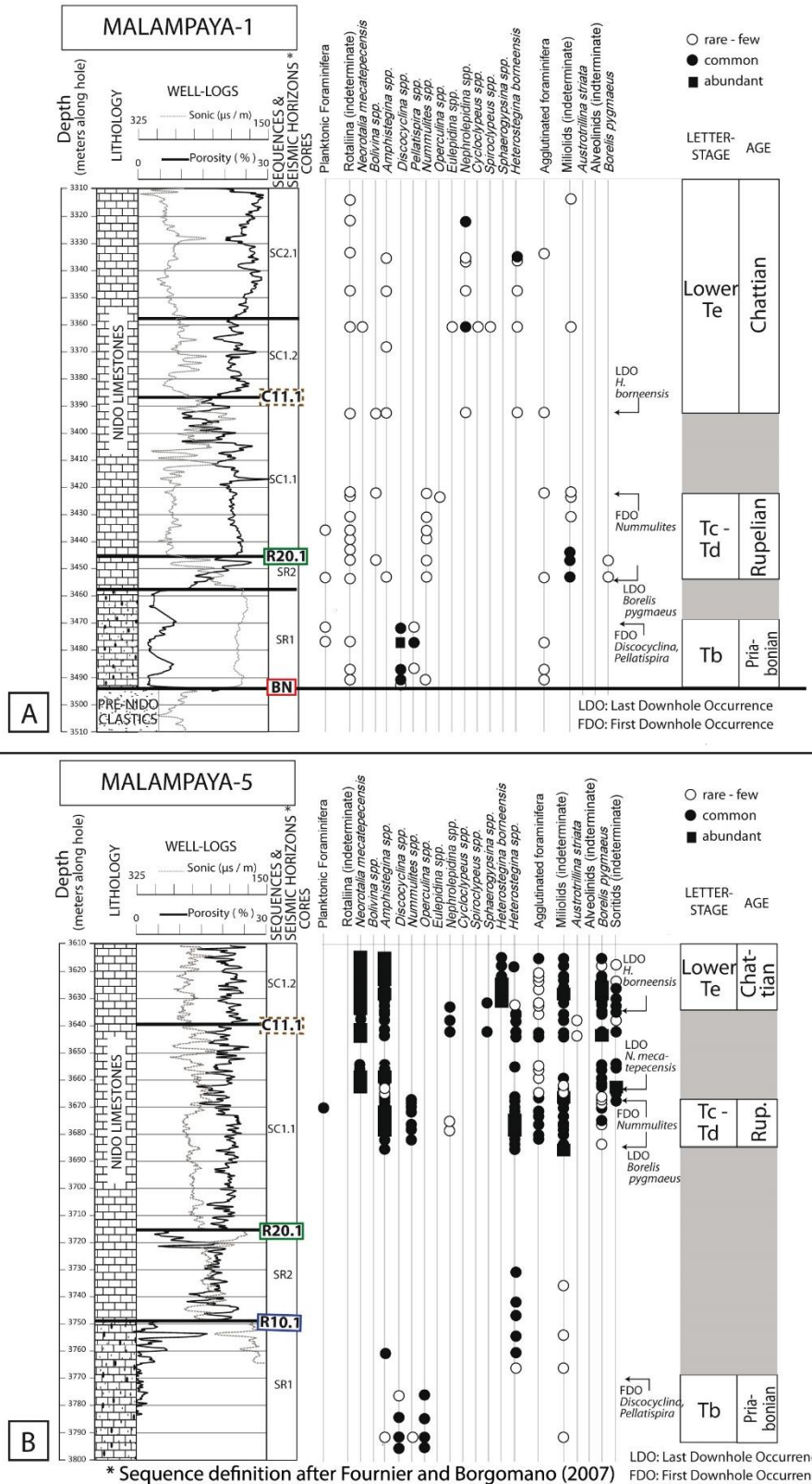


Figure 5: Porosity and sonic logs, sequences (after Fournier and Borgomano, 2007), seismic markers, distribution of foraminiferal taxa and biostratigraphic interpretations following the Letter-Stage classification. **A:** Malampaya-1 well; **B:** Malampaya-5 well.

Figure 06

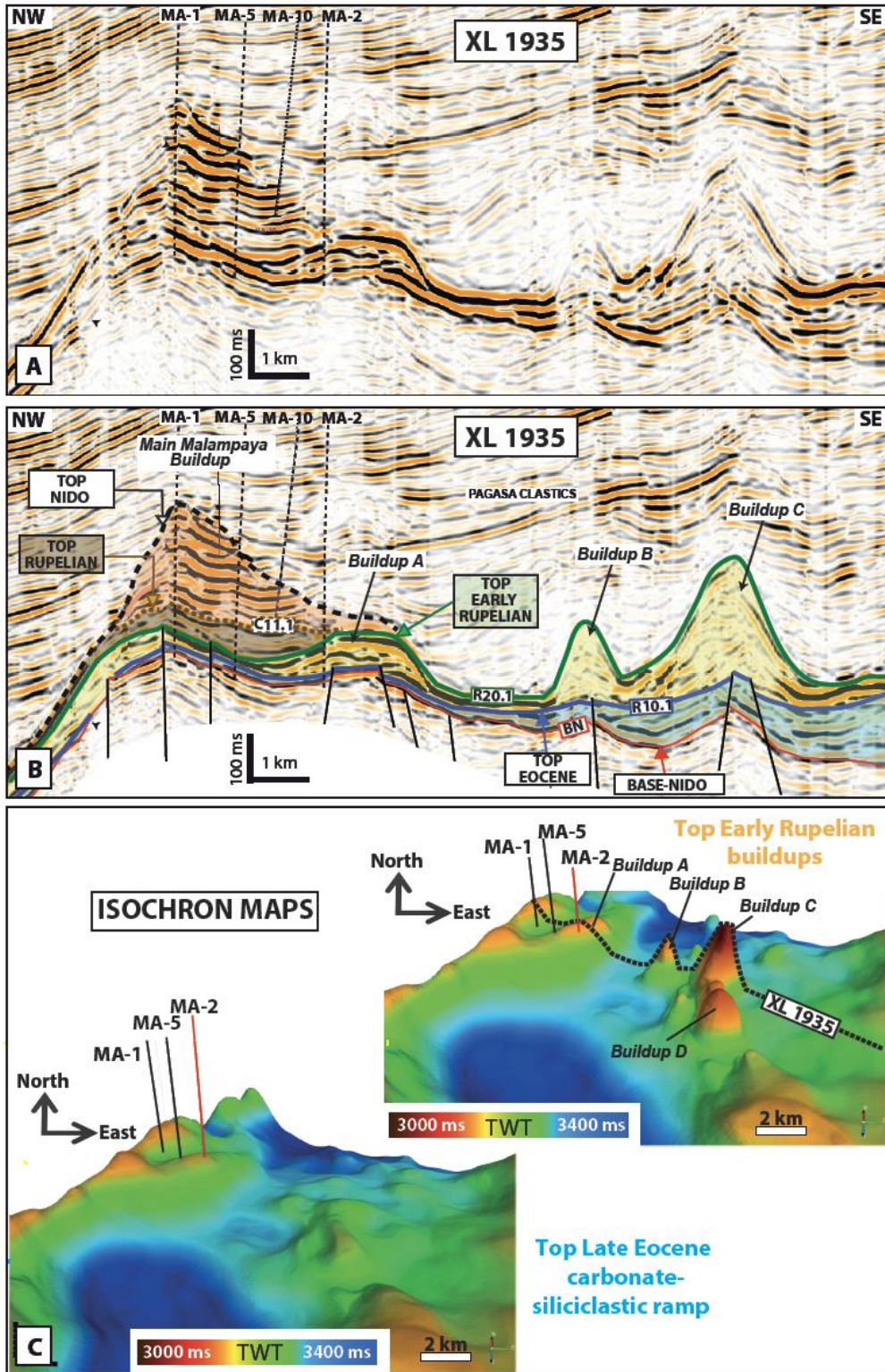


Figure 6: Uninterpreted (A) and interpreted (B) seismic profile (crossline XL1935); C) Two-way-time surface of Top Late Eocene (R10.1 reflector) and Top Early Rupelian buildups (R10.2 reflector) and location of crossline XL1935 (A-B).

Figure 07

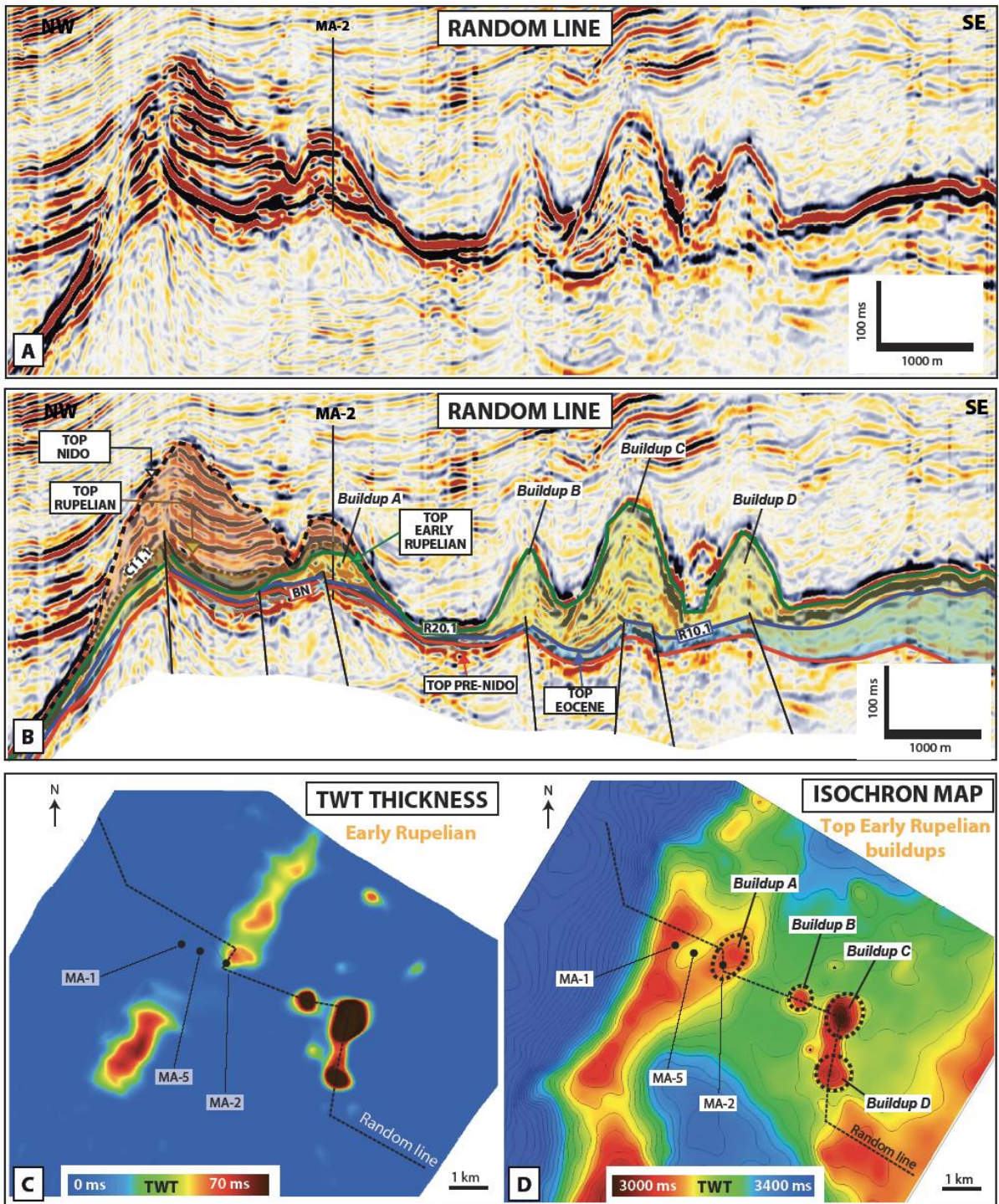


Figure 7: Uninterpreted (A) and interpreted (B) arbitrary line crossing buildups A, B, C, D and well Malampaya-2 (location on C and D); C) Two-way-time (TWT) thickness of early Rupelian unit SR1; D) Isochron map of Top Early Rupelian (R10.2 reflector).

Figure 08

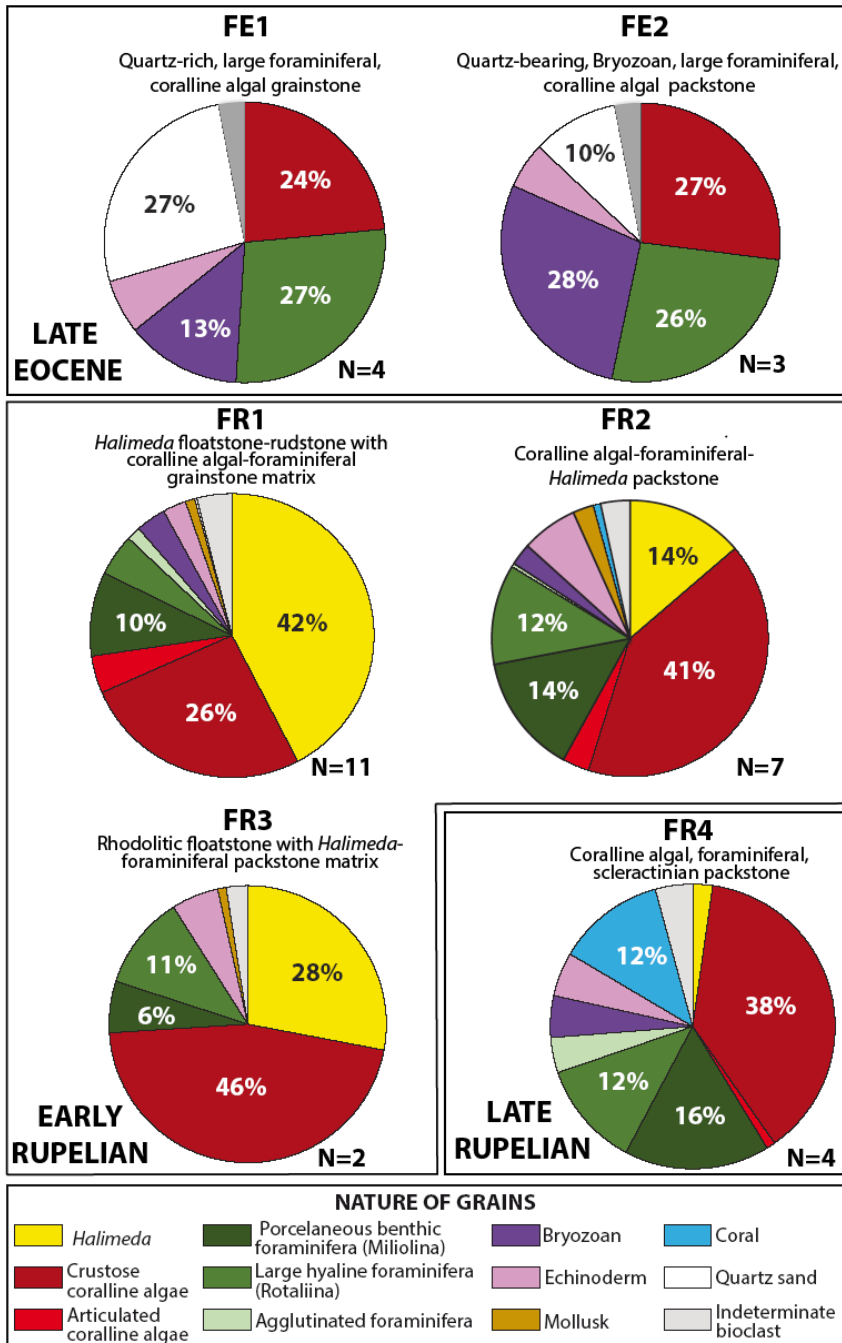


Figure 8: Average grain composition of Upper Eocene (FE1, FE2), Lower Rupelian (FR1, FR2 and FR3) and Upper Rupelian (FR4) facies.

Figure 09

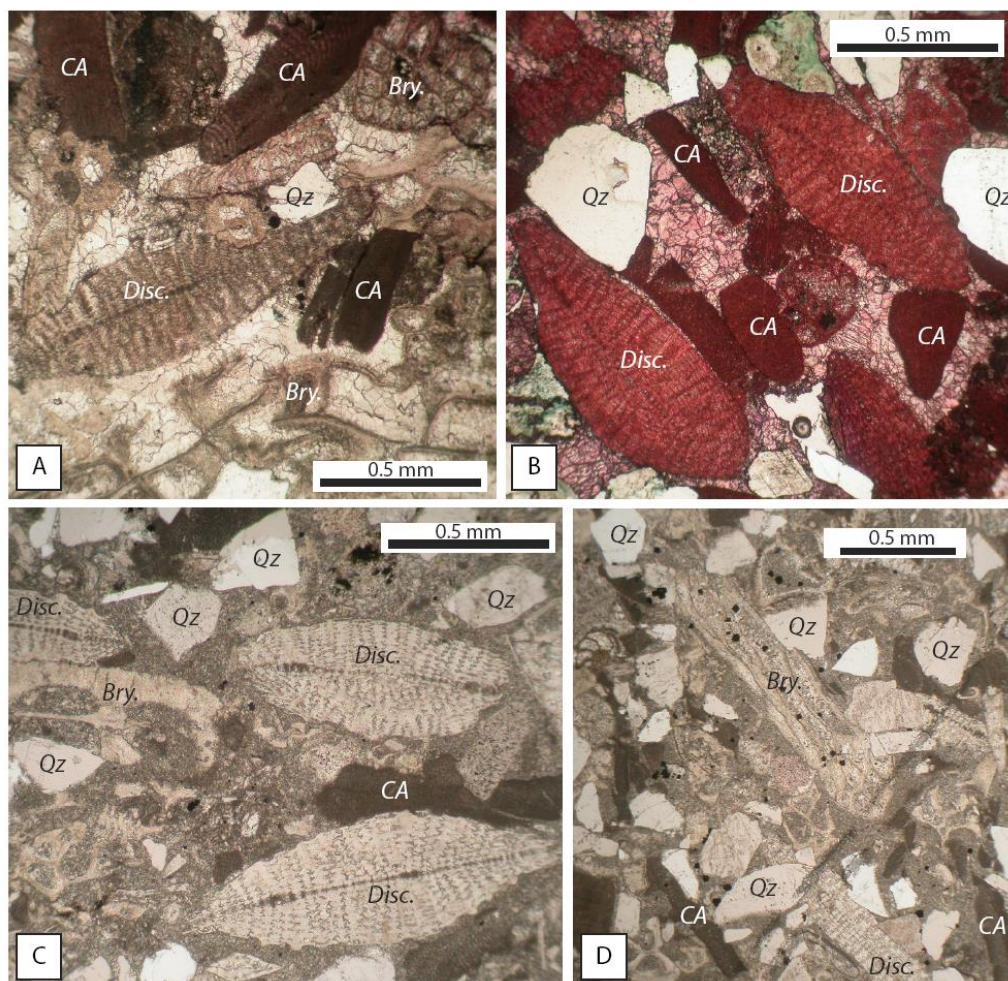


Figure 9: Thin section microphotograph of Late Eocene microfacies: A-B) Quartz-rich, foraminiferal-coralline algal grainstone (Facies FE1); C-D) Quartz-bearing, bryozoan, foraminiferal, coralline algal packstone. Disc.: Discocyclusina; Bry.: bryozoan; CA: coralline algae; Qz: quartz grains (Qz).

Figure 10

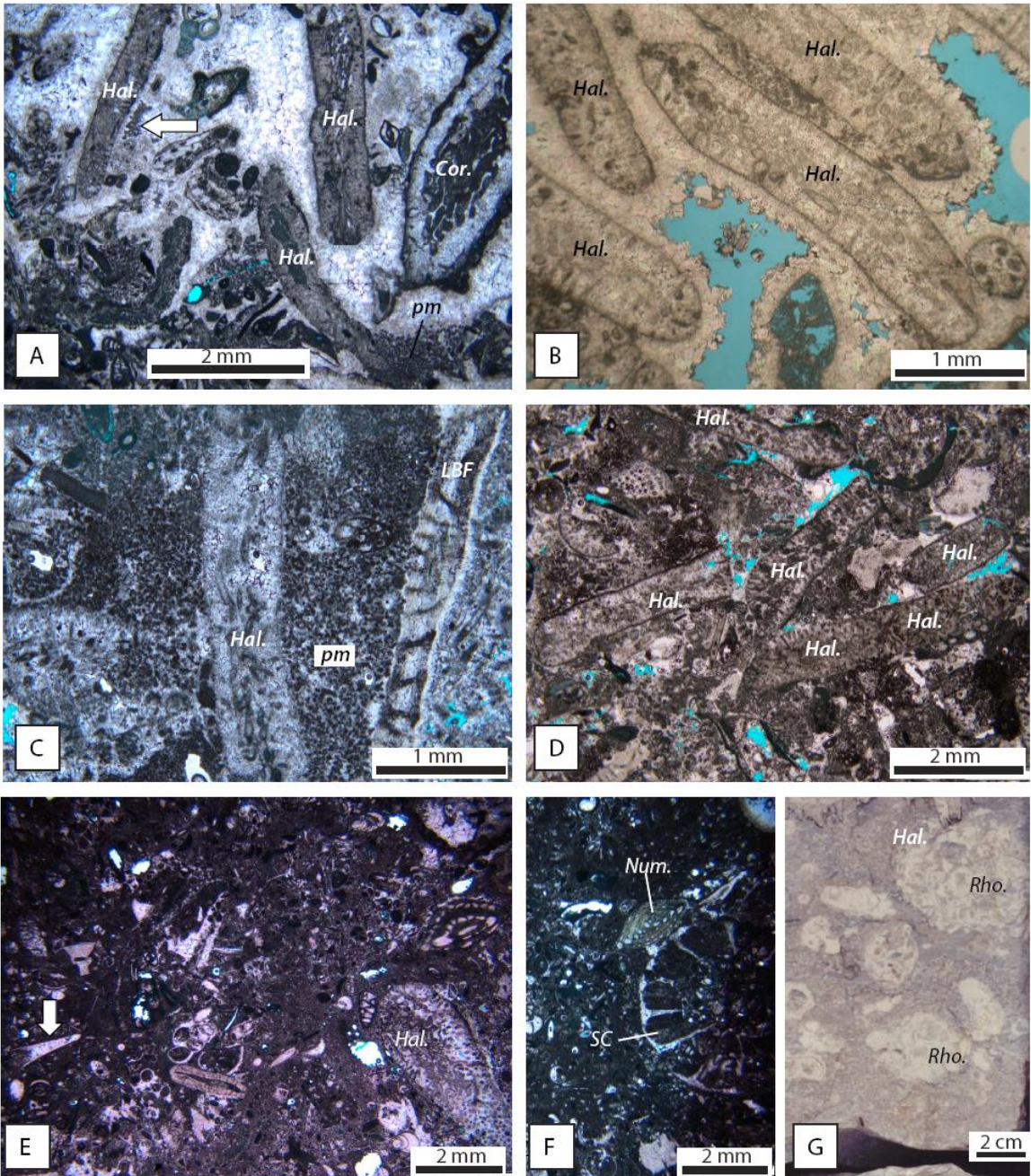


Figure 10: **A-B-C-D)** Thin section microphotograph of early Rupelian microfacies (Facies FR1): *Halimeda*-rudstone showing random or vertically-oriented *Halimeda* segments (Hal.), scarce coral branches (Cor.), flat-shaped large benthic foraminifers (LBF), geopetal peloidal matrix infills (pm) and homogeneous micrite infill postdating isopacheous bladed calcite cements (black arrow); **E-F)** Thin section microphotograph of early Rupelian microfacies FR2: Coralline algal-foraminiferal-*Halimeda* packstone (FR2) with sparse pteropod (white arrow), *Nummulites* (Num.) and solitary coral (SC); **G)** Core photograph of macrofacies FR3: Rhodolithic floatstone (Rho.: rhodolith).

Figure 11

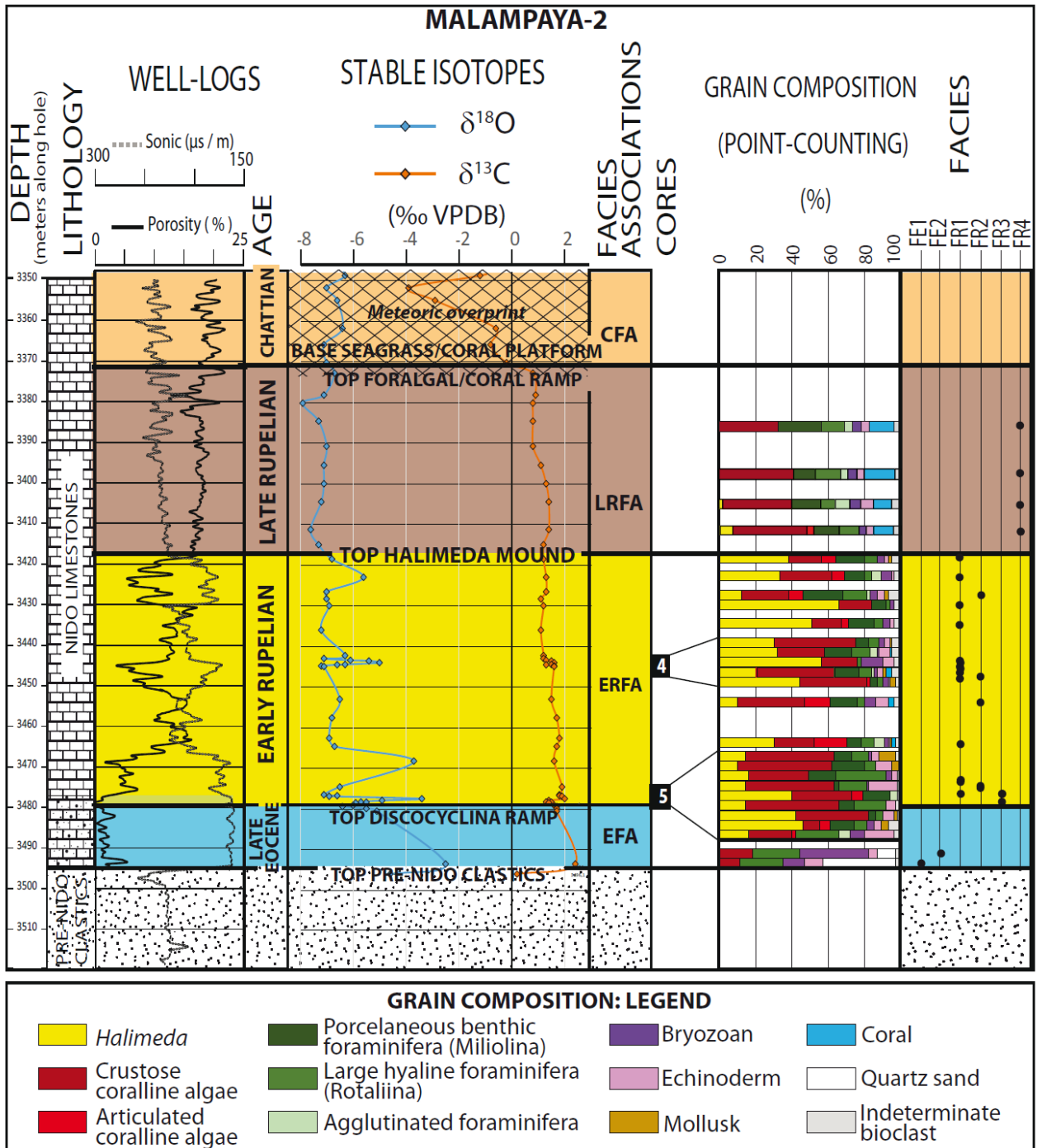


Figure 11: Malampaya-2 well : well-logs, vertical facies distribution, grain composition (point-counting) and facies associations.

Figure 12

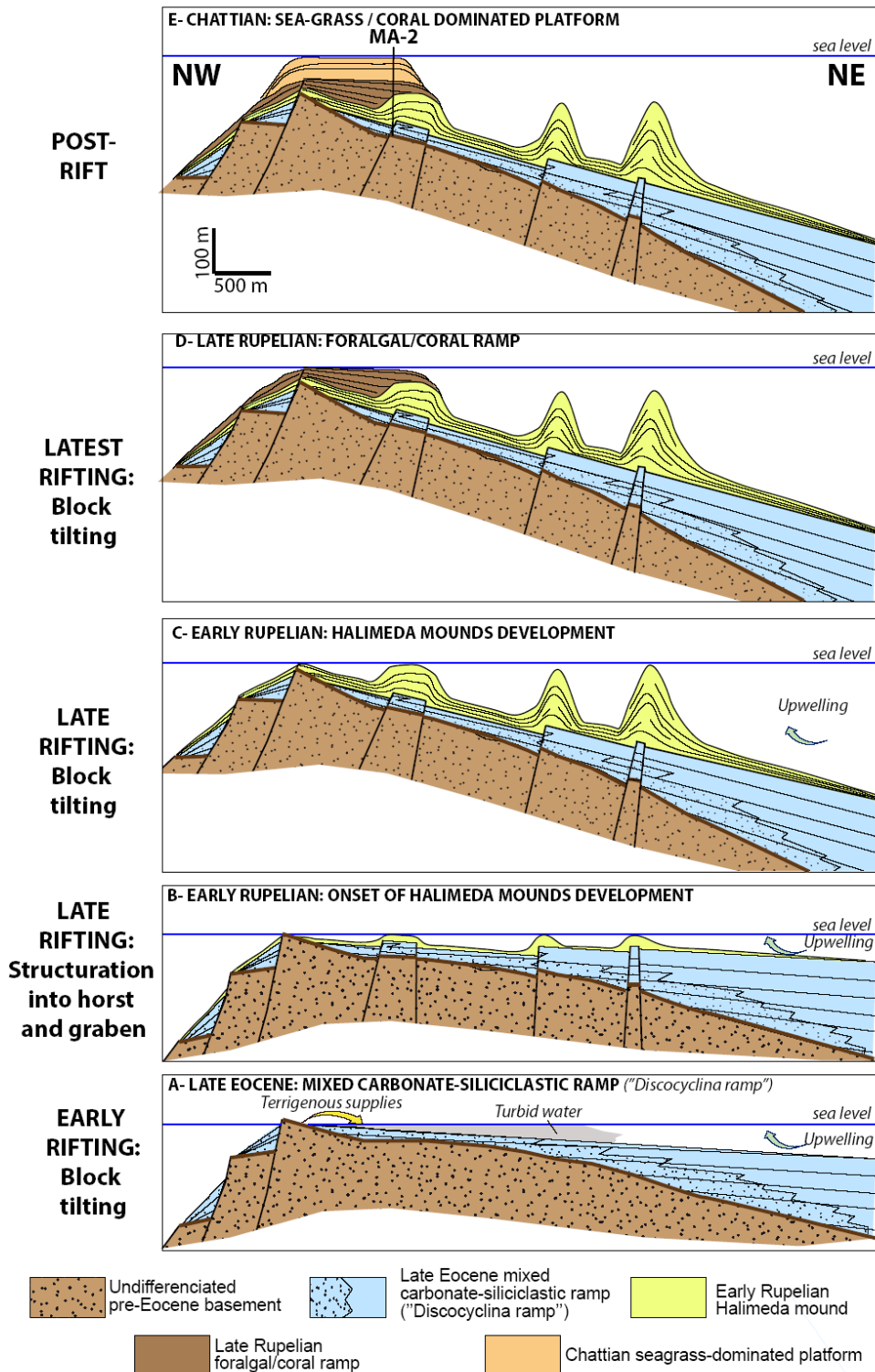


Figure 12: Growth pattern of the carbonate buildups of Malampaya from the late Eocene to the early Miocene in relation to tectonic evolution and paleoceanographic changes.

Table 1

	Maximum TWT thickness (ms)	Estimated maximum thickness (m)	Buildup diameter at base (m)	Dip angle of buildup flanks (top buildup surface)
Buildup A	50	125	1100	21°
Buildup B	150	380	850	42°
Buildup C	220	580	1300	40°
Buildup D	130	330	800	39°

Table 1 : Morphologic features of buildups A, B, C and D.

Supplementary Material S1

Sedimentary unit	Surface	Seismic Marker	Seismic TWT (ms)	Depth at well (meters, TVDSS)	Interval Velocity (m/s)	
					From well-to-seismic tie	From integration of sonic log
	Top early <u>Rupelian</u>	R20.1	3125	3402		
Early <u>Rupelian</u> (SR2)	-	-	-	-	5040	5070
	Top Eocene	R10.1	3150	3465		
Late Eocene (SR1)					-	6333
	Base <u>Nido</u>	BN	3170	3480		
<u>Pre-Nido</u> clastics					-	4234

Supplementary Material S1: : MA-2 well: well-to seismic tie and interval velocities.

Supplementary Material S2

Well	depth (meters along hole)		Halimeda	Encrusting RA	Articulated RA	Porcelaneous F.	Rotaliina	Textulariina	Bryozoan	Echinoderm	mollusks	coral	Qz	indet.
MA-1	3492	FE1	0	27	0	0	35	0	10	5	0	0	20	3
MA-1	3491	FE1	0	32	0	0	28	0	15	4	0	0	18	3
MA-1	3486	FE1	0	24	0	0	23	0	16	6	0	0	28	3
MA-1	3477	FE2	0	28	0	0	29	0	27	5	0	0	8	3
MA-1	3470	FE2	0	35	0	0	24	0	20	6	0	0	12	3
MA-2	3478,45	FR3	42	40	0	4	4	0	0	6	2	0	0	2
MA-2	3477,88	FR3	14	52	0	8	18	0	0	5	0	0	0	3
MA-2	3477,46	FR1	40	33	6	15	0	4	0	0	0	0	0	2
MA-2	3476,85	FR2	14	49	0	3	15	0	1	16	0	0	0	2
MA-2	3476,7	FR2	16	33	0	15	28	0	3	3	0	0	0	2
MA-2	3476,47	FR2	10	52	0	18	6	0	0	9	4	0	0	1
MA-2	3475	FR2	14	49	0	10	9	0	2	4	9	0	0	3
MA-2	3463	FR1	30	22	18	8	7	6	2	1	1	2	0	3
MA-2	3453	FR2	10	37	14	15	4	0	6	7	0	3	0	4
MA-2	3447,3	FR1	44	37	2	4	3	0	3	1	3	0	0	3
MA-2	3445	FR2	20	42	0	15	7	1	2	3	2	3	0	5
MA-2	3444,62	FR1	56	20	0	0	2	0	12	6	0	0	0	4
MA-2	3443,9	FR1	32	26	0	15	10	4	1	6	0	1	0	5
MA-2	3442	FR1	30	45	0	7	6	0	3	3	1	0	0	5
MA-2	3436,5	FR1	51	16	4	14	5	0	4	2	0	0	0	4
MA-2	3430	FR1	66	18	0	8	2	0	2	0	0	0	0	4
MA-2	3428,5	FR2	12	26	8	22	13	2	4	4	2	0	0	7
MA-2	3423,5	FR1	33	29	7	11	4	5	6	1	0	0	0	4
MA-2	3415,5	FR1	38	18	8	16	7	0	4	2	2	0	0	5
MA-2	3411,5	FR4	7	41	4	14	11	0	4	4	0	11	0	4
MA-2	3405	FR4	2	38	0	16	8	8	6	7	0	10	0	5
MA-2	3397	FR4	0	41	0	12	14	4	5	4	0	17	0	3
MA-2	3385	FR4	0	32	0	24	15	4	4	5	0	11	0	5

Supplementary Material S2: Grain composition from point-counting on thin-sections.

Supplementary Material S3

<u>Modern Halimeda bioherms</u>	<u>Reference</u>	<u>water- depth (at top)</u>	<u>Thickness</u>	<u>diameter at base</u>	<u>slope angle</u>	<u>Biota</u>	<u>Texture</u>
Miskito Channel, Nicaraguan Rise, SW Caribbean Sea	Hine et al., 1988	40-50m	up to 140 m	up to 750 m	10-25°	Unbroken <u>Halimeda</u> segment, mollusks, echinoderms, <u>rhodoliths</u>	Packstone-grainstone
<u>Kalukalukuang Bank</u> , eastern Java Sea (Indonesia)	Roberts et al, 1987; Phipps and Roberts, 1988	20-40m	20-50m	~100-200m	10-30°	Disarticulated <u>Halimeda</u> plates, foraminifers	Rudstone- <u>floatstone</u>
Big Bank Shoals, Timor Sea, Australia	Heyward et al., 1997	28-45m					
Northern Great Barrier Reef, Australia	<u>Orme</u> et al., 1978; Davies and Marshall, 1985; Drew and Abel, 1988; Marshall and Davies, 1988; <u>Mc Neil</u> et al., 2016, 2020, 2022)	20-40m	5-20m		10-15°	<u>Halimeda</u> segments (>60%), benthic foraminifers (<u>soritids</u> , <u>alveolinids</u>)	Unconsolidated packstone to <u>floatstone</u> -rudstone
Southern Great Barrier Reef, Australia	Searle and Flood (1988)	20-30m	up to 14m				

Supplementary Material S3: : Summary of published modern *Halimeda* bioherms and their geomorphologic and sedimentologic features.

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