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High-resolution pollen record from Efate Island, central Vanuatu: Highlighting climatic and human influences on Late Holocene vegetation dynamics

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Claire Combettes, Anne-Marie Sémah, Denis Wirmann. High-resolution pollen record from Efate Island, central Vanuatu: Highlighting climatic and human influences on Late Holocene vegetation dynamics. *Comptes Rendus. Palevol*, 2015, 14 (4), pp.251-261. 10.1016/j.crpv.2015.02.003 . hal-01170491

HAL Id: hal-01170491

<https://hal.sorbonne-universite.fr/hal-01170491v1>

Submitted on 13 Nov 2015

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1 Project: High-resolution pollen record from Efate Island, central Vanuatu:
2 Highlighting climatic and human influences on late Holocene vegetation
3 dynamics
4 Projet : Enregistrement pollinique à haute résolution de l'île d'Efate, Vanuatu
5 central : mise en évidence des influences climatique et humaine sur la
6 dynamique de végétation de l'Holocène récent

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20
21 ABSTRACT

22
23 Climate changes, sea-level variations, volcanism and human activity have influenced the environment
24 of the southwest Pacific Islands during the Holocene. The high-resolution palynological
25 analysis presented here concerns two specific levels (main lithological changes) of a well-dated
26 Holocene core, Tfer06, collected from Emaotfer Swamp, Efate Island (Vanuatu). Our aim is to
27 understand the role of climatic variability and human activities in shaping vegetation during these
28 changes. Between 3790-3600 cal yr BP, the development of vegetation marked by disturbance is a
29 marker of an increase in sustained El Niño events, also observed in many Asian-West Pacific areas.
30 Between 1500-900 cal yr BP, the increase in introduced taxa and in microcharcoal particles is
31 interpreted as human impact. In a forthcoming paper, the ongoing high-resolution palynological
32 analysis of the whole core will be compared and integrated into regional palaeoecological data.

33
34 Keywords: Pollen, Vegetation, Climate, Human settlement, Vanuatu, Holocene

35

36

37 RÉSUMÉ

38

39 Les changements climatiques, les variations du niveau de la mer, le volcanisme et les activités
40 humaines ont influencé l'environnement du sud-ouest Pacifique pendant l'Holocène. L'analyse
41 palynologique à haute résolution proposée dans ce papier se focalise sur deux niveaux spécifiques
42 (changements lithologiques) d'une carotte bien datée, Tfer06, prélevée dans le marais d'Emaotfer, sur
43 l'île d'Efate (Vanuatu). Le but est de comprendre le rôle des variations climatiques et des activités
44 humaines sur le développement de la végétation durant ces changements. Entre 3750-3600 ans cal BP,
45 l'essor d'une végétation secondaire est interprétée comme un marqueur d'une intensification des
46 phénomènes El Niño, observé aussi dans la région Asie-Pacifique. Entre 1500-990 ans cal BP,
47 l'augmentation des taxons introduits et des microcharbons est probablement un témoin des activités
48 humaines. Dans un prochain article, l'analyse palynologique de la carotte complète sera comparée aux
49 données paléoécologiques de la région.

50

51 Mots-clés : Pollen, Végétation, Peuplement humain, Climat, Vanuatu, Holocène

52

53

54

55 1. Introduction

56

57 During the Late Holocene, environmental conditions have principally been impacted by abrupt
58 climate changes, volcanic eruptions, tectonic uplift and/or human activities (Goudie, 2013; Wanner et
59 al., 2008). Palynology has the potential to be an effective tool to understand how the vegetation
60 responds to these events. Although the majority of palaeoenvironmental studies principally
61 concerns Europe and North America (Clement et al., 2001; Mackay et al., 2003), the amount of
62 palaeoecological research across the Pacific has continuously increased in the last decade (Cabioch et
63 al., 2008; Donders et al., 2007; Haberle et al., 2012; Rowe et al., 2013; Stevenson and Hope 2005;
64 Hope et al., 2009). The first humans (Lapita culture) settled Remote Oceania (southeast of the Solomon
65 Islands archipelago), ca. 3000 cal yr BP (Petchey et al., 2014; Sand, 2010, for a review). These human
66 groups have probably been affected by climate changes (Anderson et al., 2013; Brázdil et al., 2005;
67 Field and Lape, 2010), but have also certainly impacted the natural environment of pristine islands in
68 many ways (Anderson, 2009; Fall, 2005; Horrocks et al., 2009; Prebble and Wilmhurst, 2008;
69 Stevenson, 2004; Summerhayes et al., 2009).

70 Most research in the Vanuatu region has focused on submarine geology (Lecolle et al., 1990; Pineda
71 and Galipaud, 1998; Woodroffe and Horton, 2005), volcanology (Ash et al., 1978; Robin et al., 1993;
72 Witter and Self, 2007), archaeology (Bedford et al., 2006; Galipaud et al., 2014; Valentin et al., 2010)
73 and palaeoclimatic changes based on models and marine data (Asami et al., 2013; Corrège et al., 2000;
74 Donders et al., 2008). However, the relation between climate, vegetation and human activity still
75 remain unclear.

76 Wirrmann et al., (2011a) conducted one of the first terrestrial multi-proxy analyses of mid-
77 Holocene environmental changes in Vanuatu, based on the study of the core Tfer06 retrieved from
78 Emaotfer Swamp (Efate Island, central Vanuatu). The results indicate environmental changes,
79 correlated with climatic variations over the last 6670 cal yr BP. Three main vegetation groups were
80 observed, based on the preliminary pollen analysis. In order to understand the pattern of vegetation
81 change, our high-resolution palynological study covers specific sections of the core Tfer06, at
82 ca. 3790-3600 and 1500-900 cal yr BP, respectively. These sections, characterized by proxy variations
83 (lithology, microfauna-flora) indicate high environmental transformations. In this paper, our aim is to
84 distinguish the role of climatic changes from human activities in shaping vegetation during these
85 particular periods, to further compare our data with results obtained across the southwest Pacific
86 area.

87

88 2. Natural and archaeological settings

89

90 2.1. Natural settings

91 The Vanuatu Archipelago is located between the Australian and Pacific tectonic plates, at the east
92 margin of the Vanuatu Arc (Fig. 1). It comprises both subaerial and submarine volcanoes (Ash et al.,
93 1978), some of which are still active. These islands consist of lava formed by basalt volcanoes dating
94 from Late Miocene to Holocene. Efate Island, located in the central part of Vanuatu, consists mainly
95 of volcanic rocks levelled by erosion, and limestone terraces issued from tectonic uplifts. Emaotfer
96 Swamp, located on the south coast of Efate, lies on a Pleistocene limestone terrace (Ash et al., 1967-
97 1970). It is close to the Teouma Graben, on the left side of Teouma River. The water depth is currently
98 less than 1 m throughout the swamp. During the wettest season (December through April) the water
99 level rises and decreases during the drier season (July through September).

100 The oceanic context and the oceanic-atmosphere coupling (West Pacific Warm Pool, WPWP and
101 South Pacific Convergence Zone, SPCZ) mainly influence the subtropical climate of the archipelago
102 (Vincent, 1994). The location and the magnitude variability of WPWP and SPCZ control the
103 alternation of wet (summer) and relatively dry (winter) season, the wet season being often marked by
104 strong cyclones. Annual rainfall on Efate Island varies, on average, between 2400 mm on the west coast
105 and 3000 mm on the east coast (Cillaurren et al., 2001). The El Niño Southern Oscillation – ENSO –
106 (Wyrtki, 1975), the primary cause of long-term climate variability in the western Pacific (Kilbourne et
107 al., 2004; Moy et al., 2002), influences rainfall and sea surface temperatures (SSTs). The wind-driven
108 ocean currents move warm water in the ocean, eastward during the warm phase (El Niño) and
109 westward during the cool phase (La Niña). The strengthening of El Niño-like conditions causes the
110 northward shift of the SPCZ, consequently Vanuatu becomes relatively drier; conversely, under La
111 Niña-like conditions, the SPCZ is shifted southward and precipitation increases on Vanuatu. Palaeo-
112 ENSO records throughout the tropical Pacific region identify the onset of modern ENSO periodicities
113 after 5000 yr BP, with abrupt increases in ENSO magnitude around 3700 and 3300 yr BP (Brijker et al.,
114 2007; Donders et al., 2007, 2008; Gagan et al., 2004; Griffiths et al., 2010).

115 During late Quaternary, sea-level changes have occurred in relation to tectonic uplifts and eustatic
116 variations. In Vanuatu, the sea-level has risen by 120 m since the Last Glacial Maximum to 6 ka due
117 to eustatic variations, with a sudden acceleration after 11.3 ka (Cabiocch et al., 2003). Important forearc
118 tectonic effects vary with geographical position (Lecolle et al., 1990; Pineda and Galipaud, 1998): in
119 north Vanuatu, high uplift rates have been recorded (3.2 mm/yr on Malo), while they are weaker in
120 central Vanuatu. Estimations of the last interglacial uplift rate of 0.2-0.6 mm/yr, and 0.8-1 mm/yr are
121 reported on the northeast and southwest coast of Efate, respectively (Lecolle et al., 1990; Pineda and
122 Galipaud, 1998).

123 This archipelago is quite young, and its flora is principally derived from Southeast Asia by winds,
124 sea and/or animals (Schmid, 1987).

125 Field trips conducted in September 2005 and October 2013 enabled us to characterize the present-
126 day vegetation around the Emaotfer Swamp. Its shores consist of wooded areas, rich in creepers, and
127 dominated by *Barringtonia edulis*, *Pandanus tectorius* and *Hibiscus tiliaceus*. Cyperaceae, Poaceae,

128 Nymphaeaceae and ferns cover the flooded zones of the swamp. The surrounding plateau is an
129 anthropogenic savannah, composed principally of Urticaceae, Moraceae, Burseraceae and
130 Flacourtiaceae, as a result of cattle grazing.

131

132 *2.2. Archaeological settings*

133 As on other South Pacific archipelagos, Vanuatu abounds in archaeological sites (Bedford, 2009;
134 Galipaud, 2004; Garanger, 1972; Shutler et al., 2002; Valentin et al., 2011). Bearers of the Lapita
135 culture began to settle Efate Island around 3000 cal yr BP, and one archaeological Lapita site has
136 been uncovered on Efate, on the west side of Emaotfer Swamp (Bedford et al., 2006): nearly 70 burials
137 features and remains of just over 100 individuals, some accompanied with pots, as well as a
138 contemporary midden constitute the Teouma cemetery. Burial use of the site continued for up to 200-
139 300 years, beginning *ca.* 3100-2900 cal yr BP or even slightly later *ca.* 2880-2800 cal yr BP (Petchey et
140 al., 2014). The Teouma cemetery is an outstanding Lapita archaeological site due to the significant
141 number of burials, which represents an early phase of Lapita migration into Remote Oceania (Bedford
142 et al., 2009). The settlement expanded across the cemetery area during the late Lapita-Erueti
143 transitional period (2700-2300 cal yr BP). But there are no traces of human occupation after 2300 cal
144 yr BP, until the development of a coconut plantation, about one century ago.

145 Languages, material cultures and social practices remained similar during Lapita period, whereas
146 the post-Lapita period was characterized by varied cultures, depending on time and geographic
147 positions (Bedford, 2009). Subsistence behaviour also changed in the southwest Pacific Islands: Lapita
148 people consumed a large range of food items, taken from the reef, inshore and terrestrial environment,
149 while post-Lapita people favoured lower trophic level terrestrial resources, suggesting the
150 intensification of horticulture (Field et al., 2009; Kinaston et al., 2013, 2014; Valentin et al., 2014).
151 However, to stimulate tuber growth of introduced plants (taro and yam), the settlers consistently cut
152 their flowers: hence, the paucity of these introduced taxa pollen may skew the palynological results.

153

154 *3. Methods*

155

156 *3.1. Site sampling and palynological analysis*

157 Four cores were retrieved from the southwest shore of Emaotfer Swamp (Wirmann and Sémah,
158 2006). The longest one, Tfer06, sliced into continuous 1 cm-width sections was sampled along its
159 longitudinal axis. Three lithological sequences were identified from the base to the top of the core:

160 - Unit I (from 480 to 431 cm) is composed of a homogenous clay-rich organic sediment, and has the
161 slowest sedimentation rate of 0.14 mm/yr.

162 - Unit II (from 431 to 151 cm) is composed of pinkish to red-brown or white patches in a compact
163 mud. Its sedimentation rate rose from 1.4 to 2.1 mm/yr.

164 - Unit III (from 151 cm to the top) corresponds to peat deposits, with a sedimentation rate of 1
165 mm/yr.

166 Hereafter, we present a detailed palynological study of 16 samples, 8 from each section 433-426 cm
167 and 151-108 cm.

168 Each sample of 1g was prepared by cleaning with KOH (this cleaning was repeated twice for rich
169 organic samples), and by elimination of the mineral phase, with a standard method using hot HF and
170 HCl (adapted from Sittler, 1955). The residue was then mixed with a known volume of glycerol, and
171 50 µl of this mixture was used to prepare pollen slides. On average 150-200 pollen grains and 30 taxa
172 were identified on each slide, except for the barren samples (<50 pollen grains counted). A total of
173 more than 100 taxa were identified. The diverse pollen flora was determined by comparison with the
174 collection of over 2000 slides held at the IRD (France), also with photographs and descriptions in
175 Bulalacao, (1997), Erdtman (1966), Ledru and Sémah, (1992) and with regional reference collections
176 currently held at the Department of Archaeology and Natural History of the Australian National
177 University (<http://apsa.anu.edu.au>). Charcoals, (black, opaque and angular particles $\geq 10 \mu\text{m}$), as fire
178 indicators (Whitlock and Larsen, 2001), were also counted. For each sample, the microcharcoal surface
179 was estimated according to the Clark method (1982). However, this method only indicates changes
180 in small microcharcoal particles abundance (<160 µm), and does not fully represent fire patterns, due to
181 the lack of coarser particles.

182

183 3.2. Dating

184 The chronology is based on AMS radiocarbon ages obtained on 18 samples: bulk disseminated
185 organic matter, vegetal remains, wood fragments and gastropod shells (Wirrmann et al., 2011a). The
186 samples were prepared in the LMC14 Laboratory (UMS 2572, CEA-CNRS-IRD-IRSN-MCC) at
187 Saclay (France), under the laboratory's routine quality control procedures (Cottureau et al., 2007). For
188 charcoal and wood, the classical acid - alkali - acid pretreatment was applied to remove any CaCO₃,
189 humic acid contaminants and to ensure the removal of the modern atmospheric CO₂.

190 Radiocarbon ages, including those taken from the literature, were calibrated using Oxcal 4.2.2 with
191 the Southern Hemisphere data set (Bronk, Ramsay and Lee, 2013; McCormac et al., 2004; Stuiver and
192 Pearson, 1993) and the two-sigma probability ranges, noted cal yr BP (Table 1). The ¹⁴C division
193 between the Northern and Southern Hemisphere is represented by the ITCZ (Inter-Tropical
194 Convergence Zone). Even if the SPCZ, which merges with the ITCZ, moves over Vanuatu half the year,
195 we chose to use the Southern Hemisphere calibration curve, in order to provide
196 comparable results between the whole core Tfer06 and palaeoenvironmental data from the southwest
197 Pacific area, especially New-Caledonia, located at 22°S. The curve of the age-depth model was
198 deduced by fitting a smoothed curve to the age by applying a Stineman function to the data (Fig. 2).
199 The curve of the age-depth model generated on the same dates by Bayesian statistics (P_sequence
200 model, Oxcal 4.2.2) matches the curve obtained from the smooth: that is why we kept the smooth

201 polynomial model to present the interpretation of the palaeoenvironmental data obtained on core
202 Tfer06.

203 The seven dates asterisked in Table 1 are considered as presenting sediment reworking (signs of
204 transportation and/or allochthonous material, mostly roots), and thus were not taken into account in the
205 age-depth model.

206

207 4. Results

208

209 The ecological interpretations are based on Backer and Bakhuizen van den Brink Jr., 1965; Munzinger
210 et al. (2011), Siméoni (2009), Smith (1979) and Wheatley (1992). As Chenopodiaceae (recently
211 included in Amaranthaceae family) reaches high percentages values in the pollen diagram, total pollen
212 sum does not count this taxon.

213 Pollen taxa are presented according to the five following ecological groups (Fig.3):

214 - Rainforest mainly consists of Araliaceae, Cunoniaceae, Menispermaceae, Myrtaceae (especially
215 *Syzygium*), *Peperomia*, *Podocarpus*, *Freycinetia*, *Dysoxylon*, *Ascarina*, *Ardisia*, *Nauclea* and
216 *Tapeinospermum*.

217 - Disturbed vegetation comprises Euphorbiaceae (*Acalypha*, *Mallotus/Macaranga*, *Homalanthus*)
218 Ulmaceae -except *Celtis*-, Malpighiaceae, Moraceae, Urticaceae, *Myrsine*, *Merremia*,
219 *Piper/Macropiper*.

220 - Mixed deciduous lowland forest is characterized by Fabaceae (including Mimosoideae),
221 Rutaceae, Burseraceae, Sapindaceae, Asteraceae, Poaceae, Chenopodiaceae, *Celtis*, *Maesa*,
222 and *Gardenia*. For convenience, we call it seasonal forest in this paper. This forest is found on the
223 leeward coasts of Vanuatu Islands, where the rainfall reduction during the dry season is amplified
224 compared to the windward coasts. Nevertheless, some of these taxa can be found in disturbed
225 vegetation. As the highest contents of disturbance indicators are not synchronous with the highest
226 contents of seasonal taxa in the pollen diagram (Fig.3), we considered that these groups have different
227 ecological meanings. We opted for separating disturbed vegetation from seasonal forest.

228 - Introduced taxa are constituted by: Musaceae and *Phyllanthus*.

229 - Swampy vegetation is composed of Elaeocarpaceae, Polygonaceae, Cyperaceae, Nymphaeaceae,
230 *Typha*.

231 - Mangrove and coastal vegetation consists of Rhizophoraceae, Sapotaceae, *Excoecaria*, *Aegiceras*,
232 *Sonneratia*, *Premna*, *Cocos*, *Pandanus*, *Argusia*, *Guettarda*, *Terminalia* and *Vitex*.

233

234 4.1. Period 3790-3600 cal yr BP (core section 433-426cm)

235 This sedimentary section is characterized by the occurrence of two consecutive pollen barren levels,
236 which defines two subzones (Fig.3, Table 2), from 3790 to 3760 and between 3680-3600 cal yr
237 BP. The lower subzone, characterized by the end of the unit I (clay-rich organic sediment), presents the

238 highest value for rainforest taxa (28-30%), dominated by Araliaceae, *Geissois*, *Ardisia* and *Nauclea*.
239 The rainforest also reaches its maximum diversity. *Rhizophora* and *Sonneratia* dominate
240 mangrove/littoral vegetation, also well represented (26%). Cyperaceae represent the only herbaceous
241 taxa. This zone shows moderate levels of ferns, and a low charcoal value. In the upper subzone, the unit
242 II replaces the unit I. The rainforest decrease (10-15%) is coeval with a markedly reduced diversity in
243 mangrove taxa (15%). These previous vegetation types are replaced by a vegetation marked by
244 disturbance (32 to 50%), dominated by *Mallotus/Macaranga* and a slight increase in herbaceous taxa
245 is showed by the onset of Poaceae (Fig.3).

246

247 4.2. Period 1500-990 cal yr BP (core section 151-108cm)

248 Between 1500-1450 cal yr BP (Fig. 3, Table 2), corresponding to the onset of peat deposit, the
249 vegetation remains relatively stable. Seasonal forest taxa reach maximum values (20 to 35%),
250 with dominant Mimosoideae and Fabaceae. However, the following slight changes occur: i)
251 Chenopodiaceae sometimes reach more than 50% of the total pollen sum; ii) Nymphaeaceae appear, and
252 herbaceous taxa (particularly Cyperaceae) increase; iii) fern spores show their higher content (50 to
253 70%), arboreal taxa the minimum content (4 to 10%). With the development of the peat unit, a
254 microcharcoal peak, coeval with a palynological richness peak, is noticed. Introduced taxa, dominated
255 by Musaceae, appear, and rise toward the end of the zone.

256 Due to this relative stability of the vegetation, we also studied two younger samples (1200 and 990
257 cal yr BP), from peat section (unit III– Fig.3, Table 2), to assess environmental changes. Around 1200
258 cal yr BP, an increase in rainforest taxa (15%), especially *Geissois*, *Weinmania* (Cunoniaceae) and
259 *Peperomia* is observed. A decrease in rainforest taxa occurs in the uppermost sample, while markers of
260 disturbance and introduced taxa, in particular, rise. Palynological richness declines and microcharcoal
261 particles are less prevalent.

262

263 5. Discussion: trends in vegetation, climate and human activity

264

265 The two sections show that rainforest dominated until 3700 cal yr BP, and was replaced afterwards
266 by disturbed vegetation. The decline of the large trees found in rainforest, favouring an increase in
267 runoff, and could explain the rise in sedimentation rate after this date. As disturbed vegetation is
268 principally composed of shrubs, the landscape opening allows larger water supply into the swamp.
269 Between 1500-1450 cal yr BP, seasonal forest dominated with highest diversity and values. Since 1200
270 cal yr BP, rainforest then introduced taxa replaced the seasonal forest.

271

272 5.1. Period 3790-3600 cal yr BP

273 A obvious change in the pollen record over this interval is observed. There was a rapid drop in the
274 rainforest and mangrove/coastal vegetation, which were replaced by indicators of disturbance. This

275 pollen signal, in conjunction with sedimentological and micro-faunal/floral studies (Wirrmann et al.,
276 2011a) suggests drier conditions at this time. The barren pollen zone, volcanic ash-free, is probably due
277 to the sediment oxidation from exposure of the substratum.

278 The palynological variations correlate with ENSO variability documented by previous works
279 (Donders et al., 2008; Gagan et al., 2004; Moy et al., 2002). The replacement of rainforest by seasonal
280 forest in 80 years could be linked to a peak in sustained El Niño dated from 3700 yr BP (Brieker et al.,
281 2007). The rainforest supported the first notable El Niño events until 3700 yr BP and then decreased.
282 The Indonesian-Australian summer monsoon (IASM) decline from 4200 yr BP (Denniston et al.,
283 2013, 2014), could also favour drier conditions in the area. A similar paleoenvironmental pattern is
284 observed in many Asian-West Pacific areas (Cabioch et al., 2008; Ellison, 1994; Haberle and Ledru,
285 2001; Haberle et al., 2001; Sémah and Sémah, 2012; Shulmeister and Lees, 1995; Wirrmann et al.,
286 2011b), although in some tropical Pacific islands, changes in the pollen record, coeval with increase in
287 charcoal values, are observed only after 3000 yr BP, and are interpreted as signs of the onset of
288 human impact (Hope et al., 1999; Hope et al., 2009; Stevenson, 2004).

289 However, the mangrove forest decrease illustrates a drop in sea level rather than a climatic change.
290 The relative sea level change across the Pacific can be summarized as a post-glacial eustatic
291 rise until 6000-4000 yr BP (Cabioch et al., 2003), followed by a late Holocene hydro-isostatic drawdown
292 (Dickinson, 2001). In Vanuatu, seismic uplift, due to the subduction of the D'Entrecasteaux Ridge,
293 has also to be taken into account (Neef and Veeh, 1977; Lecolle et al., 1990). Around 3700 yr BP, the
294 end of the eustatic rise was coeval with tectonic uplift rate close to 1 mm/yr in the south of Efate which
295 in turn induced a sea-level decrease, marked by the loss of mangrove forest. The occurrence of former
296 rolled coral in several archaeological sites (Bedford et al., 2007; Dickinson, 2001; Pineda and
297 Galipaud, 1998) confirms that the sea level was higher than today when the first settlers arrived.

298 The emergence of the Lapita culture on Mussau (Papua New Guinea) is dated around 3400 cal yr
299 BP (Denham et al., 2012). The dispersal of Lapita people occurred after the onset of regional drier
300 conditions. Moreover, during El Niño phase, the easterly winds decline, facilitating the sail-powered
301 transport from New Guinea to the eastern islands (Anderson et al., 2006). If the precise causes of this
302 eastward migration remain unclear, yet El Niño events have to be taken into account in the settlement
303 of Remote Oceania.

304

305 *5.2. Period 1500-990 cal yr BP*

306 Except increases in Cyperaceae, Chenopodiaceae, fern spores and microcharcoal particles, there
307 are little significant variations in the pollen record between 1500 and 1450 cal yr BP. The vegetation
308 remained broadly stable, while Wirrmann et al. (2011a) show lithological, micro-faunal and -flora
309 changes during this period: peat replaced poor-organic sediments and acidophilous diatom
310 species replaced species of high conductivity water. The occurrence of these deposits, associated with
311 an increase of fern spores and Cyperaceae, may correspond to a hydrosere succession. Adapted plants

312 invade open water, reducing water flow, trapping sediment and contributing to the invasion by
313 emergent vegetation. As peat accumulates, made up of the remains of this vegetation, the water body
314 becomes progressively shallower. The high percentage of Chenopodiaceae pollen grains, often found in
315 clumps, indicates close proximity of this vegetation type, and shows a decrease in water level, in
316 agreement with the peat development. An increase in vegetation cover could prevent important runoff,
317 resulting in a decline of sedimentation rate. However, the decrease in diatom species characteristic of
318 saline conditions is inconsistent with shallower water (Van Dam et al., 1994). It could be explained by
319 an increase in humic compounds, due to higher-level vegetation decomposition.

320 The peak in microcharcoal particles shows an increase in fire intensity and/or quantity. This was
321 possibly because of further sustained El Niño events, from 2000 to 1400 yr BP, peaking at 1500 yr BP,
322 associated with a period of IASM rainfall minimum (Denniston et al., 2013, 2014; Gagan et al.,
323 2004). But Cyperaceae, Chenopodiaceae and fern variations more certainly mark local environmental
324 change, likely variations in water level, than a climate event. Hence, ENSO and IASM rainfall
325 variations seem to have a low impact on the vegetation. We propose that human populations took
326 advantage of these local drier conditions, or even favoured them by setting fires too, to cultivate different
327 Musaceae, including bananas. The occurrence of *Phyllanthus* is an additional evidence of human influence
328 on vegetation: this plant has presumably been cultivated for ornamental and medicinal use, and is now
329 considered as a weed (Smith, 1979).

330 A significant change in the pollen record is observed around 1200 cal yr BP. There is a sharp
331 decline of seasonal forest taxa, coeval with an increase in rainforest taxa, suggesting relatively wetter
332 conditions, as observed at the same time in New-Caledonia (Wirrmann et al., 2011b). This could be
333 linked to the decline in El Niño events after 1500 yr BP (Denniston et al., 2013, 2014; Gagan et al.,
334 2004; Moy et al., 2002). But rainforest taxa values increased only 250 years after the onset of decline
335 in El Niño events. One could explain this fact by a rapid growth and reproduction of light-tolerant
336 species (disturbed vegetation) compared to rainforest species (Chave, 1999; Prévost, 1983). Moreover,
337 the increase in taxa such as *Geissois* and *Weinmannia*, characteristic of higher altitudes, suggests lower
338 regional temperatures compared to 3790 cal yr BP. At 990 cal yr BP, the significant rise in introduced
339 taxa, coeval with a decrease in rainforest taxa, is interpreted as human impact; which suggests a more
340 permanent settlement in this area, perhaps longer than during the Lapita period, in this area.

341

342

343 6. Conclusions

344

345 Our high-resolution palynological study shows:

346 - Between 3790-3600 cal yr BP, the vegetation change presents a good covariance with sea-level
347 change and ENSO phenomenon. These natural events certainly affected the mangrove forest and the
348 rainforest, respectively.

349 - Between 1500-990 cal yr BP, climatic variations had less influence on vegetation. Intensive
350 agriculture could have prevented a return of the primary rainforest after 1200 cal yr BP, even if
351 conditions became wetter.

352 - Furthermore, human influence on vegetation has been demonstrated for the first time in Efate.

353 In summary, the vegetation dynamics details the timing of environmental changes already
354 published. However, discriminating with certitude the climatic impact from the hydrologic, ecological
355 and human activities on the vegetation is complex, these factors could occur at the same time.

356 The whole analysis of the core Tfer06, which covers the last 5 millennia, will allow us to study
357 vegetation dynamics before and after the Lapita colonization. These results will be compared with other
358 palaeoecological data obtained across the southwest Pacific, to expand our knowledge of the relation
359 between climate changes, human activities and vegetation dynamics during the Late Holocene.

360

361 Acknowledgments

362

363 We would like to thank the team of the Herbarium of Vanuatu (Port Vila) and especially Chanel Sam
364 for the helpful discussions, during our stay in Vanuatu and by mail afterward. We acknowledge the
365 landowners for the facilities provided during the fieldwork, and the Ni Vanuatu population for the
366 hospitality and availability. We are grateful to Mariama Barry and the anonymous reviewers for their
367 review of the manuscript and suggestions that led to the improvement of the earliest version.

368 The reference collection for Vanuatu is carried out, for the most part, thanks to the IRD herbarium
369 (NOU), Nouméa. This work was supported by the Research Unit Biogéochimie-Traceurs-Paléoclimats
370 (BTP LOCEAN, UMR 7159, CNRS-IRD-UPMC-MNHN, France) and by the Department of
371 Prehistory (UMR 7194, MNHN, France). Carbon dating was conducted at the IRD through UMS 2572
372 LMC14 (CEA-CNRS-IRD-IRSN-MCC, France). This study was financially supported by a grant from
373 the Région Ile-de-France (ref. 12016503).

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598 Fig.1: A) The Vanuatu Archipelago with the three geological ridges, their ages of formation (after Ash
599 et al., 1978; Witter and Self, 2007), and the locations of archaeological sites (after Bedford et al.,
600 2006). B) Location of Emaotfer Swamp (red rectangle) on the left bank of Teouma River (after Hema
601 Maps Vanuatu, 3rd edition, 1999). C) Topographic sketch of the area close to the swamp and location
602 of the archaeological and coring sites (after Hema Maps Vanuatu, 3rd edition, 1999).

603 Fig.1 : A) L'archipel du Vanuatu, avec ses trois chaînes géologiques, leur âge de formation (d'après
604 Ash et al., 1978; Witter and Self, 2007), et les positions des sites archéologiques (d'après Bedford et
605 al., 2006). B) Localisation du marais d'Emaotfer (rectangle rouge) sur la rive droite de la rivière
606 Teouma (d'après Hema Maps Vanuatu, 3^{ème} édition, 1999). C) Carte topographique de la zone autour
607 du marais, et localisation du site archéologique et du site de carottage (d'après Hema Maps Vanuatu,
608 3^{ème} édition, 1999).

609

610 Fig.2: Lithology and chronology of the core Tfer06. The age-depth model is undertaken by fitting a
611 polynomial smoothed curve through the calibrated ages, without the dates asterisked (see Table 1 and
612 text § 3.2 for explanation). The Zones A and B correspond to the studied samples.

613 Fig. 2 : Lithologie et chronologie de la carotte Tfer06. Le modèle d'âge-profondeur est réalisé en
614 ajustant les dates calibrées par une courbe lissée polynômiale, sans prendre en compte les dates avec
615 astérisques (voir Table 1 et texte § 3.2). Les zones A et B correspondent aux échantillons présentés
616 dans ce papier.

617

618 Fig. 3: Pollen diagram from sedimentary sequences A and B of core Tfer06. Non arboreal pollen taxa
619 are noted NAP, other taxa correspond to arboreal pollen or AP.

620 Fig. 3 : Diagramme pollinique issu de la séquence sédimentaire de la carotte Tfer06. Les grains de
621 pollen non arborés sont notés NAP. Les autres taxa correspondent aux grains de pollen arborés ou AP.

622

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624

625 Table 1: Radiocarbon ages (LMC14 UMS 2572, CEA-CNRS-IRD-IRSN-MCC, France), obtained on
626 core Tfer06 calibrated applying Oxcal 4.2.2 (Bronk Ramsey and Lee, 2013; <https://c14.arch.ox.ac.uk>),
627 and the calibration curve ShCal 13. The asterisks indicate samples excluded from the age-depth model
628 (see the text § 3.2).

629 Tableau 1 : Ages radiocarbones (LMC14 UMS 2572, CEA-CNRS-IRD-IRSN-MCC, France), obtenus
630 sur la carotte Tfer06, calibrés selon Oxcal 4.2.2 (Bronk Ramsey and Lee, 2013 ;
631 <https://c14.arch.ox.ac.uk>) et la courbe de calibration ShCal 13. Les astérisques indiquent les
632 échantillons qui ne sont pas considérés dans le modèle d'âge-profondeur (voir le texte § 3.2).

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Table 2: Computed ages for each studied sample, according to the age-depth model (see the text § 3.2 and Fig. 3).

Tableau 2 : Ages calculés issus du modèle d'âge-profondeur, pour chaque échantillon présenté dans ce papier (voir le texte et la Fig.3).

LMC 14 N°	Samples (cm)	Dated material	$\delta^{13}\text{C}$ (‰)	Conventional radiocarbon age	2-sigma calibration (cal yr BP)
SacA 8798	90-91	Peat	-26.6	940 +/-30	736-905
SacA 8799	141-142	Peat	-21.4	1630 +/-30	1382-1543
SacA 8800*	159-160	Wood	-23.6	1295 +/-30	1074-1269
SacA 8801*	173-174	Thiaridae shell	-0.8	2985 +/-30	2973-3210
SacA 8802	173-174	Vegetal	-23.9	1800 +/-30	1585-1740
SacA 10686*	192-195	Vegetal	-25.6	1365 +/-30	1184-1296
SacA 11603*	253-254	Bulk disseminated organic matter	-14.9	2620 +/-30	2500-2766
SacA 8803*	264-265	Vegetal	-29.3	1280 +/-30	1069-1266
SacA 7992	301-302	Vegetal	-27.4	2250 +/-30	2151-2331
SacA 7993	301-302	Gastropod shell	-7.7	2225 +/-30	2096-2316
SacA7994	348-350	Wood	-27.2	2425 +/-45	2329-2701
SacA 7995	376-377	Vegetal	-28.1	2605 +/-30	2497-2759
SacA 27953*	420-421	Bulk disseminated organic matter	-11.4	3900 +/-30	4156-4413
SacA 11604*	432-433	Bulk disseminated organic matter	-19	3550 +/-30	3650-3883
SacA 7996	441-442	Wood	-28.2	3025 +/-30	3006-3326
SacA 27954	450-451	Bulk disseminated organic matter	-23.5	3925 +/-30	4161-4421
SacA 8804	461-462	Bulk disseminated organic matter	-18.3	4025 +/-30	4296-4527
SacA 4819	478-479	Bulk disseminated organic matter	-23.65	5900 +/-60	6496-6845

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Core section	Depth (cm)	Calibrated ages (cal yr BP) computed by age-depth model	
B	108	990	
	128	1200	
	146	1450	
	147	1462	
	148	1473	
	149	1482	
	150	1492	
	151	1500	
A	425	3600	
	426	3630	
	427	3653	
	428	3680	
	Barren pollen zone	429	3705
		430	3730
		431	3760
		432	3790