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

Claire Combettes, Anne-Marie Sémah, Denis Wirrmann

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Projet : Enregistrement pollinique à haute résolution de l'île d'Efate, Vanuatu central : mise en évidence des influences climatique et humaine sur la dynamique de végétation de l'Holocène récent

Claire Combettes, Département de Préhistoire (UMR7194)-MNHN Institut de PaléontologieHumaine, 1, rue René Panhard, 75013, PARIS ; IRD-Sorbonne Université (UPMC, UnivParis 06)-CNRS-MNHN,LOCEANLab.UMR7159, IRD France-Nord, 32,avenueHenriVaragnat,93143Bondycedex,France, 01.48.02.55.94., 01.48.02.55.54.claire.combettes@edu.mnhn.fr

Anne-Marie Sémah, IRD-Sorbonne Université (UPMC, Univ Paris 06)-CNRS-MNHN, LOCEAN Lab. UMR 7159, IRD France-Nord, 32, avenue Henri Varagnat, 93143 Bondy cedex, France ; Département de Préhistoire (UMR7194)-MNHN Institut de Paléontologie Humaine, 1, rue René Panhard, 75013, PARIS,01.48.02.55.94., 01.48.02.55.54.

Denis Wirrmann, IRD-Sorbonne Universités (UPMC, Univ Paris 06)-CNRS-MNHN, LOCEAN Lab. UMR 7159, IRD France-Nord, 32, avenue Henri Varagnat, 93143 Bondy cedex, France, 01.48.02.55.96., 01.48.02.55.54.

ABSTRACT

Climate changes, sea-level variations, volcanism and human activity haveinfluencedthe environment of the southwest Pacific Islands during the Holocene. Thehigh-resolution palynological analysispresented here concerns two specificlevels (main lithological changes) of a well-dated Holocene core, Tfer06, collected from Emaotfer Swamp, Efate Island (Vanuatu). Our aim is to understand the role of climatic variability and human activities in shaping vegetation during these changes. Between 3790-3600 cal yr BP, the development of vegetation marked by disturbance is a marker of an increase in sustained El Niño events, also observed in many Asian-West Pacific areas. Between 1500-900 calyr BP, the increase in introduced taxa and in microcharcoal particles is interpreted as human impact.In a forthcoming paper, the ongoing high-resolution palynological analysis of the whole core will be compared and integrated intoregional palaeoecological data.

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

RÉSUMÉ

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

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

1. Introduction

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

Mostresearch in the Vanuatu regionhas focused on submarine geology (Lecolle et al., 1990; Pineda and Galipaud, 1998; Woodroffea and Horton, 2005), volcanology (Ash et al., 1978; Robin et al., 1993; Witter and Self, 2007), archaeology (Bedford et al., 2006; Galipaud et al., 2014; Valentin et al., 2010) and palaeoclimatic changes based on models and marine data (Asami et al., 2013; Corrège et al., 2000; Donders et al., 2008). Howeverthe relation between climate, vegetation and human activity still remain unclear.

Wirrmann et al., (2011a) conducted one of the first terrestrial multi-proxy analyses of mid-Holocene environmental changes in Vanuatu, based on the study of the core Tfer06 retrieved from Emaotfer Swamp (Efate Island, central Vanuatu). The results indicateenvironmental changes, correlated with climatic variations over the last 6670 cal yr BP.Three main vegetation groupswere observed, based on the preliminary pollen analysis. In order to understand the pattern of vegetation change, our high-resolution palynological study covers specific sections of the core Tfer06, at *ca*.3790-3600 and 1500-900 cal yr BP, respectively. These sections, characterizedbyproxiesvariations (lithology, microfauna-flora)indicate highenvironmentaltransformations. In this paper, our aim isto distinguishthe role of climaticchangesfrom human activities in shaping vegetationduring these particular periods, tofurther comparing our data with results obtained across the southwest Pacific area.

2. Natural and archaeological settings

2.1. Natural settings

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

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

During late Quaternary, sea-level changes have occurred in relation to tectonic uplifts and eustatic variations. In Vanuatu, the sea-level has risen by 120 m since the Last Glacial Maximum to 6 ka due to eustatic variations, with a sudden acceleration after 11.3 ka (Cabioch et al., 2003). Important forearc tectonic effects vary with geographical position (Lecolle et al., 1990; Pineda and Galipaud, 1998): in north Vanuatu, high uplift rates have been recorded (3.2mm/yr on Malo), while they are weaker in central Vanuatu.Estimations of the last interglacial uplift rate of0.2-0.6mm/yr, and 0.8-1mm/yr are reported on the northeast and southwest coast of Efate, respectively(Lecolle et al., 1990; Pineda and Galipaud, 1998).

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

Field trips conducted in September 2005 and October 2013 enabled us to characterize the present-day vegetation around the Emaotfer Swamp.Its shores consist of wooded areas, rich in creepers, and dominated by *Barringtonia edulis*, *Pandanus tectorius* and *Hibiscus tiliaceus*. Cyperaceae, Poaceae, Nymphaeaceae and ferns cover the flooded zones of the swamp. The surrounding plateau is an anthropogenic savannah, composed principally of Urticaceae, Moraceae, Burseraceae and Flacourtiaceae,as a resultof cattle grazing.

2.2. Archaeological settings

As on other South Pacific archipelagos, Vanuatu abounds in archaeological sites (Bedford, 2009; Galipaud, 2004; Garanger, 1972; Shutler et al., 2002; Valentin et al., 2011). Bearers of the Lapita culture began to settle Efate Island around 3000cal yr BP, and one archaeological Lapita site have been uncoveredon Efate, on the west side of Emaotfer Swamp (Bedford et al., 2006): nearly 70 burials features and remains of just over100 individuals, some accompanied with pots, as well as a contemporary middernconstitute the Teoumacemetery. Burial use of the site continued for up to 200-300 years, beginning *ca.*3100-2900 cal yr BP or even slightly later*ca*. 2880-2800 calyr BP (Petchey et al., 2014). The Teouma cemeteryis an outstanding Lapita archaeological site due to the significant number of burials, which represents an early phase of Lapita migration into Remote Oceania (Bedford et al., 2009).The settlement expanded across the cemetery area during the late Lapita-Erueti transitional period (2700-2300 cal yrBP). But there are no traces of human occupation after 2300 cal yr BP, until the development of a coconut plantation, about one century ago.

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

3. Methods

3.1. Site sampling and palynological analysis

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

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

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

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

Hereafter, we present a detailed palynological study of 16 samples, 8 from eachsection433-426 cm and 151-108 cm.

Each sample of 1gwas prepared by cleaning with KOH (this cleaning was repeated twice for rich organic samples), and by elimination of the mineral phase, with a standard method using hot HF and HCl (adapted from Sittler,1955). The residue was then mixed with a known volume of glycerol, and 50 µl of this mixture was used to prepare pollen slides. On average150-200pollen grainsand 30 taxa were identified on each slide, except for thebarren samples (<50 pollen grains counted). A total of more than 100 taxa were identified. The diverse pollen flora was determined by comparison with the collection of over 2000 slides heldat the IRD (France), also with photographs and descriptions in Bulalacao, (1997), Erdtman (1966), Ledru and Sémah, (1992) and with regional reference collections currently held at the Department of Archaeology and Natural History of the Australian National University (http://apsa.anu.edu.au).Charcoals, (black, opaque and angular particles≥ 10 µm), as fire indicators (Whitlock and Larsen, 2001), were also counted.For each sample, the microcharcoal surface was estimated according to the Clark method (1982). However, this method only indicates changes insmall microcharcoal particles abundance (<160µm), anddoes not fully represent fire patterns, due to the lackof coarserparticles.

3.2. Dating

The chronology is based on AMS radiocarbon ages obtained on 18 samples: bulk disseminated organic matter, vegetal remains, wood fragments and gastropod shells (Wirrmann et al., 2011a). The samples were prepared in the LMC14 Laboratory (UMS 2572, CEA-CNRS-IRD-IRSN-MCC) at Saclay (France), under the laboratory's routine quality control procedures (Cottereau et al., 2007). For charcoal and wood, the classical acid - alkali – acid pretreatment was applied to remove any $CaCO_3$, humic acid contaminants and to ensure the removal of the modern atmospheric CO_2.

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

The seven dates asterisked inTable 1are considered as presenting sediment reworking (signs of transportation and/or allochthonous material, mostly roots),and thus were nottaken into account in the age-depth model.

4. Results

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

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

- Rainforestmainlyconsists ofAraliaceae, Cunoniaceae, Menispermaceae, Myrtaceae (especially *Syzygium*),*Peperomia*, *Podocarpus*, *Freycinetia*, *Dysoxylon*, *Ascarina*, *Ardisia*, *Nauclea* and *Tapeinospermum*.
- Disturbed vegetation comprisesEuphorbiaceae (*Acalypha*, *Mallotus*/*Macaranga*, *Homalanthus*) Ulmaceae -except *Celtis*-, Malpighiaceae, Moraceae, Urticaceae, *Myrsine*, *Merremia*, *Piper*/*Macropiper*.
- Mixed deciduous lowland forest is characterized byFabaceae (including Mimosoideae), Rutaceae,Burseraceae, Sapindaceae, Asteraceae, Poaceae,Chenopodiaceae, *Celtis*, *Maesa*, and*Gardenia*. For convenience, we call it seasonal forest in this paper.This forest is found on the leeward coasts of Vanuatu Islands, where the rainfall reduction during the dry season is amplified compared to the windward coasts.Nevertheless, some of these taxa can be found in disturbed vegetation.As the highest contents of disturbance indicators are not synchronous with the highest contents of seasonal taxa in the pollen diagram (Fig.3), we considered that these groups have different ecological meanings. We opted for separating disturbed vegetation from seasonal forest.
- Introduced taxa are constituted by: Musaceae and *Phyla*.
- Swampy vegetation is composed ofElaeocarpaceae, Polygonaceae, Cyperaceae, Nymphaeaceae, *Typha*.
- Mangrove and coastal vegetation consists of Rhizophoraceae, Sapotaceae, *Excoecaria*, *Aegiceras*, *Sonneratia*, *Premna*, *Cocos*, *Pandanus*, *Argusia*, *Guettarda*, *Terminalia* and *Vitex*.

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

This sedimentary section is characterized by the occurrence of two consecutivepollen barren levels, which defines two subzones (Fig.3, Table 2), from 3790 to 3760 and between 3680-3600 cal yr BP.The lower subzone, characterized by the end of the unit I (clay-rich organic sediment),presents the highest value for rainforest taxa (28-30%), dominated by Araliaceae, *Geissois*, *Ardsia*and *Nauclea*. The rainforest also reachesits maximum diversity. *Rhizophora* and *Sonneratia*dominate mangrove/littoral vegetation, also well represented (26%). Cyperaceae represent the only herbaceous taxa. This zone shows moderate levels of ferns, and a low charcoal value. In theuppersubzone, the unit II replaces the unit I.The rainforest decrease (10-15%) is coeval with a markedly reduced diversity in mangrove taxa (15%). These previous vegetationtypes are replaced by a vegetation marked by disturbance (32 to 50%), dominated by *Mallotus*/*Macaranga* and a slight increase in herbaceous taxa is showed by the onset of Poaceae (Fig.3).

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

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

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

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

Thetwo sections show thatrainforest dominated until 3700 cal yr BP, and was replaced afterwards bydisturbed vegetation.The decline of the large trees found in rainforest, favouring an increase in runoff,and could explain the rise in sedimentation rate after this date. As disturbed vegetation is principally composed of shrubs, the landscape opening allowslargerwater supply into the swamp. Between 1500-1450 cal yr BP, seasonal forest dominated with highest diversity and values. Since1200 cal yr BP, rainforestthenintroducedtaxareplaced the seasonal forest.

5.1. Period 3790-3600 cal yr BP

Anobvious change in the pollen record over this interval is observed. There was a rapid dropinthe rainforest and mangrove/coastalvegetation, which wererereplaced by indicators of disturbance. This pollen signal, in conjunction with sedimentological and micro-faunal/floral studies (Wirrmann et al., 2011a) suggests drier conditions at this time.The barren pollen zone, volcanic ash-free, is probably due to the sediment oxidation from exposure of the substratum.

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

However, the mangrove forest decrease illustrates a drop in sea level rather than a climatic change. The relative sea level-change across the Pacific can be summarized as apost glacial eustatic riseuntil6000-4000yrBP (Cabioch et al., 2003), followed by a late Holocene hydro-isostatic drawdown (Dickinson, 2001). In Vanuatuco-seismic uplift, due to the subduction of the D'Entrecasteaux Ridge, has also to be taken into account (Neef and Veeh, 1977, Lecolle et al., 1990). Around 3700 yr BP, the end of the eustatic rise was coeval with tectonic uplift rate close to 1mm/yr in the south of Efate which in turn induced a sea-level decrease, marked by the loss of mangrove forest. The occurrence of former rolled-coral in several archaeological sites (Bedford et al., 2007; Dickinson, 2001; Pineda and Galipaud, 1998) confirms that the sea level was higher than today when the first settlers arrived.

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

5.2. Period 1500-990 cal yr BP

Except increases in Cyperaceae, Chenopodiaceae, fern spores and microcharcoal particles, there arelittle significant variations in the pollen record between 1500 and 1450 cal yr BP. The vegetation remainedbroadly stable, while Wirrmann et al.(2011a) show lithological, micro-faunal and -flora changes during this period: peat replaced poor-organic sediments and acidophilus diatom speciesreplaced species of high conductivity water.The occurrence of these deposits, associated with an increase of fern spores and Cyperaceae, may correspond to a hydroseral succession.Adapted plants invade open water, reducing water flow, trapping sediment and contributing to the invasion by emergent vegetation. As peat accumulates, made up of the remains of this vegetation, the water body becomes progressively shallower.The high percentage of Chenopodiaceae pollen grains, often foundin clumps, indicates close proximity of this vegetation type, and shows a decrease in water level, in agreement with the peat development.An increase in vegetation cover could prevent important runoff, resulting in a decline of sedimentation rate. However, the decrease in diatom species characteristic of saline conditions is inconsistent with shallower water (Van Dam et al., 1994). It could be explained by an increase in humic compounds,due to higher-levelvegetation decomposition.

The peak in microcharcoal particles shows an increase in fire intensity and/or quantity.This was possibly because of further sustained El Niño events, from 2000 to 1400 yr BP, peaking at 1500 yr BP, associated with a period of IASM rainfall minimum(Denniston et al., 2013, 2014 Gagan et al., 2004).ButCyperaceae, Chenopodiaceae and fern variations more certainlymarklocal environmental change, likely variations in water level,than a climate event.Hence, ENSO and IASM rainfall variations seem to have a low impacton the vegetation. We propose that human populationstook advantage of theselocal drier conditions, or even favoured thembysetting fires too,tocultivate different Musaceae, including bananas. The occurrence of *Phyla* is an additional evidence of human influence on vegetation: this planthas presumably been cultivated for ornamental and medicinal use,and is now considered as a weed (Smith, 1979).

A significant change in the pollen record is observed around 1200 cal yr BP. There is a sharp decline of seasonal forest taxa, coeval with an increase in rainforest taxa, suggestingrelatively wetter conditions, as observedat the same time in New-Caledonia (Wirrmann et al., 2011b). This could be linked to the decline in El Niño eventsafter1500 yr BP (Denniston et al.,2013, 2014; Gagan et al., 2004; Moy et al., 2002). But rainforest taxa values increased only250 years after the onset of decline in El Niño events. One could explain this fact bya rapid growth and reproduction of light-tolerant species(disturbed vegetation) compared to rainforest species (Chave, 1999, Prévost, 1983).Moreover, the increase in taxa such as *Geissois* and *Weinmania*, characteristic of higher altitudes, suggestslower regional temperatures compared to 3790 cal yr BP. At 990 cal yr BP, the significant rise in introduced taxa, coeval with a decrease in rainforest taxa,is interpreted as human impact; which suggests a more permanent settlement in this area, perhaps longer than during the Lapita period, in this area.

6. Conclusions

Our high-resolution palynological studyshows:

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

- Between1500-990 cal yr BP, climatic variationshad less influence on vegetation. Intensive agriculture could have prevented a return of the primary rainforest after 1200 cal yr BP, even if conditions became wetter.

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

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

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

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

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

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

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

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

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

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

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 calculésissus 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	$\partial^{13}C$ (‰)	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	Thiarideae 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

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