How agriculture, droughts and diseases shaped the island environments of Remote Oceania over the last Millennium

Working Paper

Author(s):
Camperio, Giorgia; Ladd, S. Nemiah; Prebble, Matiu; de Jonge, Cindy; Schneider, Tobias; Argiriadis, Elena; Lloren, Ronald; Nelson, Daniel; Delahaie, Amicie; Krentscher, Christiane; Dubois, Nathalie

Publication date:
2023-11-10

Permanent link:
https://doi.org/10.3929/ethz-b-000652388

Originally published in:
EarthArXiv, https://doi.org/10.31223/x5t106

How agriculture, droughts and diseases shaped the island environments of Remote Oceania over the last Millennium

Giorgia Camperio*[1,2], S. Nemiah Ladd[3], Matiu Prebble[4,5], Cindy de Jonge[2], Tobias Schneider[1], Elena Argiriadis[6,7], Ronald Lloren[1,2], Daniel B. Nelson[8], Amicie Delahaie[1,9], Christiane Krentscher[1], Nathalie Dubois[1,2]

*Corresponding author: giorgia.camperio@eawag.ch

Affiliations
[1]Department of Surface Waters Research & Management, Eawag, Dübendorf, 8600, Switzerland
[2]Geological Institute, Department of Earth Sciences, ETH Zürich, Zürich, 8092, Switzerland
[3]Department of Environmental Sciences, University of Basel, Basel, 4056, Switzerland;
[4]School of Earth and Environment, College of Science, University of Canterbury, Christchurch, 8041, New Zealand;
[5]Archaeology and Natural History, Culture History and Languages, The Australian National University, Canberra, ACT 2010, Australia;
[6]Institute of Polar Sciences, CNR-ISP, Venice, 30172, Italy;
[7]Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University, Venice, 30172, Italy.
[8]Department of Environmental Sciences – Botany, University of Basel, 4056, Basel, Switzerland;
[9]Laboratory of Geology, École Normale Supérieure, CNRS, PSL University, IPSL, Paris, France

E-mail addresses:
giorgia.camperio@eawag.ch
n.ladd@unibas.ch
matiu.prebble@canterbury.ac.nz
cindy.dejonge@erdw.ethz.ch
tobias.schneider@eawag.ch
elena.argi@unive.it
Ronald.lloren@eawag.ch
daniel.nelson@unibas.ch
amicie.delahaie@ens.fr
christiane.krentscher@gmail.com
nathalie.dubois@eawag.ch

Chapter

2

How agriculture, droughts and diseases shaped the island environments of Remote Oceania over the last Millennium

Giorgia Camperio[1,2], S. Nemiah Ladd[3], Matiu Prebble[4,5], Cindy de Jonge[2], Tobias Schneider[1], Elena Argiriadis[6,7], Ronald Lloren[1,2], Daniel B. Nelson[8], Amicie Delahaie[1,9], Christiane Krentscher[1], Nathalie Dubois[1,2]

[1]Department of Surface Waters Research & Management, Eawag, Dübendorf, 8600, Switzerland; [2]Geological Institute, Department of Earth Sciences, ETH Zürich, Zürich, 8092, Switzerland; [3]Department of Environmental Sciences, University of Basel, Basel, 4056, Switzerland; [4]School of Earth and Environment, College of Science, University of Canterbury, Christchurch,8041,New Zealand; [5]Archaeology and Natural History, Culture History and Languages, The Australian National University, Canberra, ACT 2010, Australia; [6]Institute of Polar Sciences, CNR-ISP, Venice, 30172, Italy; [7]Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University, Venice, 30172, Italy. [8]Department of Environmental Sciences – Botany, University of Basel, 4056, Basel, Switzerland; [9]Laboratory of Geology, École Normale Supérieure, CNRS, PSL University, IPSL, Paris, France

In preparation for submission to "*Quaternary Environments and Humans*"

Abstract

Over the past millennium, the Pacific Islands have experienced significant transformations, caused by different waves of human settlement and climatic variability. However, the paucity of archeological records coupled with the complex climatic setting of the tropical Pacific hinders our understanding of past environmental and societal changes. In this study, we employ a multi-proxy approach on sediment cores extracted from ponds on the west coast of Espiritu Santo, Vanuatu to investigate past human-climate dynamics. Through the analysis of human-associated proxies including fecal markers, palmitone — a specific lipid biomarker for taro — and charcoal, we reconstruct changes in human presence and activities. We reconstruct past climate from leaf wax hydrogen isotopes (δ^2H_{LW}) and branched glycerol dialkyl glycerol tetraethers (brGDGTs). Changes in pollen reveal major shifts in local and regional vegetation. In our record, the period from 1000 to 1300 CE is characterized by warm/wet conditions concomitant with demographic expansion inland. Around 1400 CE, δ^2H_{LW} data indicates a drier period. The coincident decrease in palmitone, despite high charcoal and fecal marker concentrations, suggests that drier conditions might have rapidly affected taro cultivation, but not the overall population, which declined more than a century later. We hypothesize that the establishment of one of the earliest European settlements in Oceania in 1606 CE further disrupted local demographics with the introduction of diseases. This study contributes to our understanding of the intricate relationship between human activities, climatic fluctuations, and landscape modifications in Remote Oceania over the past millennium.

Keywords

Paleoenvironment, Sediment, Biomarker, Tropical Pacific, Paleoclimate, Palynology

Introduction

The oceanic islands of the Pacific are some of the places last colonized by humans. Human activities have been a driving force in shaping island ecosystems since the arrival of first settlers (Nogué et al., 2021). However, climate shifts have exerted significant influence on past human settlement patterns and activities (Anderson et al., 2006, Allen, 2006, Montenegro et al., 2016). Furthermore, different waves of human settlement, including initial indigenous settlement, and later European colonization, have contributed differently to the pattern of environmental transformation. Understanding the dynamic interplay between different waves of human settlement and climate change is crucial in light of ongoing environmental crises as it can provide the knowledge guiding sustainable land-use strategies on island ecosystems (Nogué et al., 2017).

Remote Oceania encompasses islands and island nations known for their diverse cultures, languages, and landscapes (Green, 1991). These nations share common cultural and historical characteristics, making it a cohesive cultural region (Lawson, 2013). Vanuatu is known for its remarkable linguistic diversity, which attests to its cultural and historical complexity (François et al., 2015). Cultural changes over the last 1000 years contributed to the linguistic diversity observed today in the islands (Bedford and Spriggs, 2008) while land use practices, rooted in the culture of Vanuatu, have modified the landscape through activities like shifting cultivation and high intensity wetland cultivation. Taro, for example, is the main staple crop of the region and an integral part of Vanuatu's cultural landscapes. Evidence of its cultivation in irrigated gardens dates back to the last Millenium (Spriggs, 1997). However, the ways in which climatic factors influence both cultural changes and landscape transformations are complex and not well understood.

The complex climate patterns experienced in the Western Tropical Pacific have strong implications for understanding past human populations in the area. The South Pacific Convergence Zone (SPCZ), a band of rain and clouds which extends from the Intertropical Convergence Zone (ITCZ) over the southwest Pacific in a NW to SE direction, is the main seasonal hydroclimate driver in Vanuatu (Maes and Varillon, 2011). It retracts to the north of its mean position in midwinter and extends southward of its mean position in midsummer. Long term shifts in the position of the SPCZ can result in dramatic changes in precipitation, impacting small South Pacific island communities (Brown et al., 2020). In contrast, interannual climatic variability in the Tropical Pacific is dominated by the El Niño–Southern Oscillation (ENSO) (Kilbourne et al., 2004), while on decadal to multidecadal timescales, the Interdecadal Pacific Oscillation (IPO) modulates ENSO teleconnections within the SPCZ region, influencing precipitation patterns and extremes (Salinger, 2001). In Vanuatu, El Niño events bring warmer and drier conditions often leading to droughts, while La Niña brings wetter conditions and increased risk of flooding. An increase in storm frequency of approximately 40 % has been observed during ENSO events (Chand et al., 2016). The interaction between El Niño variability and other climatic features in the Tropical Pacific complicates our ability to understand the causes of past climatic change in this area, which exhibited substantial variability over the past millennium with sometimes large regional differences (Brown et al., 2020; Atwood et al., 2021). Reconstructing these climate variations is crucial to understand their potential influence on past human populations in the Pacific region.

Here, we use sedimentological records from two ponds located on the west coast of Espiritu Santo (hereafter referred to as Santo), the largest island in Vanuatu, to reconstruct landscape modifications and disentangle the human and climatic factor of changes over the last millennium (Figure 1). By studying changes in sediment composition, we can infer shifts in climate, vegetation, land use practices, and other environmental factors occurred in the catchment. We use fecal fossil molecules, namely coprostanol and its epimer, epicoprostanol, coupled with charcoal concentrations, as indicators of human presence and demographic changes (White et al., 2019; Keenan et al., 2021; Raposeiro et al., 2021). Charcoal concentrations and palmitone, a unique marker for the staple crop taro (*Colocasia esculenta* Schott) (Krentscher et al., 2019), are used to track horticulture practices. Branched glycerol dialkyl glycerol tetraether (brGDGTs) and the hydrogen isotopic composition of leaf waxes (δ^2H_{LW}) are used for climatic reconstructions (respectively for temperature and hydroclimate), and palynology is established to track vegetational changes. Finally, we reconstruct downcore changes in aquatic productivity and erosive events based on the total organic carbon content (TOC), carbon-to-nitrogen (C/N) ratio, biogenic silica and grain size distribution.

Environmental setting

Santo, the largest island of the archipelago, is geologically separated in two halves; the Sakao Peninsula in the East is made of terraced limestone from old coral reefs while the western side is dominated by the Cumberland Chain. This rapidly rising range of high volcanic mountains is oriented N-S and features steep slopes, ridges and deep valleys. Here Mount Tabwemasana is the highest peak of the archipelago, reaching 1879 m (Tzerikiantz, 2006; Pineda, 2011). The location of Santo close to the boundary of the Australian and the Pacific plates causes high levels of seismic activity, with the highest uplift rates (between 2 mm/yr and 6 mm/yr) observed in the west coast (Jouannic et al., 1980, Gaven et al., 1980, Taylor et al., 1992). Uplifted terraces can be found along many parts of the coastline. The west coast of Santo is characterized by a drier climate compared to the rest of the island (Terry, 2011), which results from an orographic effect on the eastern flank due to the prevailing south-east winds hitting the high mountain chain (Supplementary figure 1). Many rivers on the west coast are small and intermittent during the dry season (July-October). In these drier conditions, taro is cultivated in terraces and irrigated by channeling part of a stream. Taro is still cultivated extensively with traditional techniques, although coconut plantations are also widespread.

The west coast of Santo is characterized by three main primary forest vegetation types, described by Bouchet et al. (2011). *Agathis-Calophyllum* Kauri-Tāmanu forest, which is only found in the northern Cumberland Peninsula, above 600 m asl., in the few areas where it was not logged in the 19th and early 20th centuries. Medium-stature forest is much more widespread across west coast Santo. Many of the trees are tall and especially at lower elevations some deciduous species can be found such as *Pterocarpus indicus* (Fabaceae). The most characteristic element is *Castanospermum australe* (Fabaceae), one of the largest trees of this forest type. The subcanopy of medium stature forest includes species such as *Dendrocnide latifolia* and *Pipterus argenteus* (Urticaceae). At higher elevations (>500 m asl) the subcanopy changes to *Meryta neoebudica* (Araliaceae), *Myristica inutilis* (Myristicaceae) and *Ficus septica* (Moraceae). Where this forest type is disturbed, a number of secondary forest taxa become dominant including *Macaranga* spp. and *Rapanea* spp. (M. Prebble pers obs.) along with Arecaceae palms and *Pandanus* spp. Finally, montane cloud forest, now found above 800 m asl, is typically dominated by species belonging to several genera, including *Metrosideros* and *Syzygium* (Myrtaceae), *Weinmannia* and *Geissois* (Cunoniaceae), Quintinia (Quintiniaceae) and *Ascarina* (Chloranthaceae). Further to the secondary forest of medium stature forest, are the seasonal forest, scrub and grassland characteristic of many of the coastal lowland areas in close proximity to villages. In exceptionally dry areas that are frequently burnt, these forests are dominated by *Acacia spirorbis* (Fabaceae) and *Kleinhovia hospita* (Malvaceae). These areas were heavily exploited in the mid 19th century for the sandalwood trade (Shineberg, 1967), with *Santalum* spp. now rare in Santo.

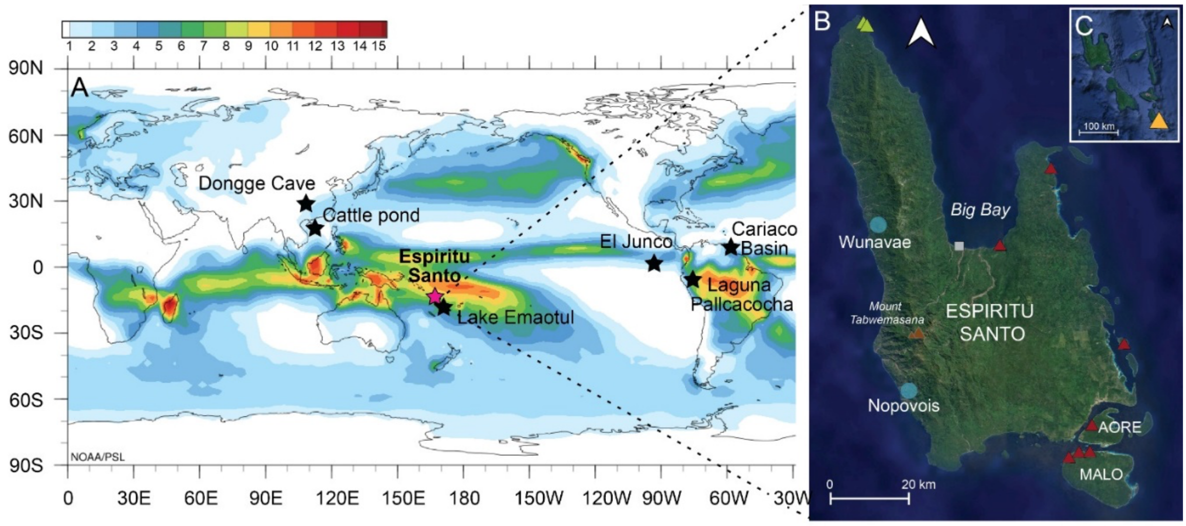


Figure 1. Coring sites on the island of Espiritu Santo A) Long term mean (1991 -2020) of surface monthly precipitation (mm/day) in the Tropical Pacific (Global Precipitation Climatology Project Monthly Analysis Product data provided by the NOAA PSL, Boulder, Colorado, USA, website at https://psl.noaa.gov). Color scale represents mm/day of precipitation. Stars indicate the location of the studies discussed in the text. B) The island of Espiritu Santo, coring sites (blue dots), Lapita archeological sites (red triangles), archeological excavations with possible indications of wet taro gardening 1000 BP (green triangles, Galipaud et al., 2004), European first landing location in Big Bay (grey square) are indicated. C) The position of Espiritu Santo with respect to Kuwae location (orange triangle).

Archaeological background and European contact

Archeological findings suggest that Santo was initially settled approximately 3000 yrs BP, particularly in the vicinity of Big Bay (Figure 1), where Lapita pottery shards associated with early settlements have been found (Bedford and Spriggs, 2008). From here, it has been hypothesized that people gradually spread across the small islands to the east and south of Santo (Galipaud, 2011). For instance, Malo, a small island to the south of Santo, provides evidence of initial settlement dating back around 2850 yrs BP (Galipaud, 1998). However, these early settlements appear to have been abandoned by around 2000 years BP, possibly in response to changing environmental conditions (Galipaud, 2011). The occupation of the west coast of Santo may have been later than in Big Bay or Malo. Excavations near Cape Cumberland on the northwest coast unveiled a date of 1000 years BP, revealing evidence of irrigated agriculture remains (Galipaud, 2004, Figure 1). Another excavation at the Malsosoba shelter, in the northwest of Santo, revealed pottery shards dating back 1000 years BP and a pig's molar dating back 300 years BP (Galipaud and Walter, 1997; Galipaud 2004; Tzerikiantz, 2006).

Santo was the first island of the Vanuatu archipelago to be contacted by Europeans when Portuguese explorer Pedro Fernandez de Queiros arrived in Big Bay in 1606 CE, naming the islands "Australia del Espiritu Santo" (Dickie, 1981; Figure 1). De Queiros and his crew settled in Big Bay for 40 days. This settlement represents one of the earliest European settlements in Remote Oceania (Berrocal and Sand, 2021). In his accounts De Queiros reports a well-populated region, with cultivations and inhabitants engaged in pottery-making, however the accuracy of his reporting is questionable (Jolly, 2003). The contact with the local population was brief and conflictual and it is probable that diseases were introduced having a detrimental impact on local people (Marshall, 1937).

Material and Methods

Study site

The coring campaign was conducted in July 2017 CE using a percussion corer (UWITEC, Mondsee, Austria) equipped with a 63 mm diameter PVC tube. Two sediment cores were retrieved from the center of two ponds (Richardson et al., 2022) located on the west coast of Santo (Figure 1): Nopovois, also known as Lac Soulematsi (15°29'49.14"S 166°44'8.30"E, 121 cm long), and Wunavae (15° 6'42.33"S 166°39'39.60"E, 83 cm long) following the toponymy assigned by local inhabitants in absence of official names. Nopovois is located 370 m above sea level (asl), has a perimeter of 500 m at the maximum height of water level, and a 59.4 ha catchment. Maximum depth at coring time was 2.8 m, surface temperature varied from 24.3 °C in the morning to 26.7 °C in the afternoon. Conductivity was stable at 96.7 µS/cm, while dissolved oxygen went from 5.39 mg/l to 8.61 mg/l and pH from 6.9 to 7.4, between the morning and the afternoon. Near bottom waters (2.6 m water depth) had a temperature of 23.5 °C, conductivity of 108 µS/cm, dissolved oxygen between 0.01-0.02 mg/l, and a pH of 6.6 at both times of the day. Nopovois is located 300 m from a village which, at the time of coring, was composed of ca. 10 traditional houses. Coconut plantations, taro and peanuts were the main crops cultivated in the catchment. Wunavae is located 490 m asl and has a catchment of 4.95 ha and a perimeter of 300 m. Maximum depth at the time of coring was 2.8 m. The near surface water (0.2 m w.d.) had a temperature of 22.7 °C, conductivity of 233 µS/cm, dissolved oxygen of 0.1 mg/l, and a pH of 6.3. Temperature decreased to 21 °C near the bottom (2.5 m w.d.), while conductivity increased to 334 µS/cm, dissolved oxygen decreased to 0.02 mg/l, and pH increased to 6.7. Wunavae was almost entirely covered with aquatic plants, and surrounded by a high canopy seasonal semi-deciduous forest reflecting the typical vegetation of this part of the island (Bouchet et al., 2013). The direct surroundings of lake Wunavae were uninhabited, the closest village being located on the coast. Cores were sectioned on-site at 1 cm intervals and stored in Whirl Paks at –20 °C. Samples were then freeze-dried and macrofossils separated from the sediment matrix.

Chronology

High-resolution chronologies from radiocarbon-dated terrestrial macrofossils were previously described for these cores (Camperio et al., in prep). Bayesian age depth models provide a bottom age of 943 - 1042 CE for Wunavae and 813 - 1041 CE for Nopovois. The high-resolution chronology from 1000 to 1960 CE provides strong chronological constraints for both cores. The core section from 42 - 121 cm in Wunavae is based on 35 radiocarbon-dated macrofossils, while 35 radiocarbon-dated macrofossils constrain the age model in the core section 42 - 83.5 cm of Nopovois. The frequent plateaus in the calibration curve between 1600 and 1800 CE coupled with high accumulation rates in the upper part of the cores (after 1960 CE) increase the uncertainties in this time window for lake Nopovois. The low sedimentation rate could potentially indicate a hiatus between 1600 - 1900 CE. The upper 40 cm of the cores, which correspond to the last century, were presented in detail in a previous study (Camperio et al., in prep.) and are therefore not discussed in further details here.

Bulk geochemistry

The number of samples reported in this section refers to the period of interest, namely section 42 - 121 cm for Wunavae and section 42 - 83.5 cm for lake Nopovois. Bulk geochemical analyses were carried out in the Sedimentology laboratories at Eawag, Dübendorf. Downcore total carbon (TC) and total nitrogen (TN) content of 40 samples for Wunavae and 25 for Nopovois were measured with an EURO Elemental Analyser (EA) 3000 (HEKAtech GmbH, Wegberg, Germany). Total inorganic carbon (TIC) was measured with a titration Coulometer (CM5015, UIC Inc., Joliet, USA). Total organic carbon (TOC) was calculated using the equation TOC = TC - TIC. The atomic ratio between TOC and TN was calculated in the section of interest. 40 samples from Wunavae and 25 from Nopovois were measured for biogenic silica (BiSi) concentrations following the method by Ohlendorf and Sturm (2008). Standards for aluminum (Fluka analytical, Lot Nr. 1404169), silicon (J.T. Baker, Lot Nr. N081093), and sodium (J.T. Baker, Lot Nr. N082168) were used for BiSi quantification. Grain size measurements were performed at 2 cm resolution for both cores. Sediment samples were dispersed in $NaPO_4$ and placed overnight in an overhead shaker prior to being measured with a Beckman Coulter LS 13 320 (laser diffraction particle analyzer).

Biomarkers

Lipid extraction, purification and quantification were performed in the Sedimentology laboratories at Eawag, Dübendorf. All glassware used with biomarker samples was thermally cleaned at 450 °C for 5 hours. A recovery standard composed by 5a-androstane, 1-nonadecanol, heneicosanoic acid and 3-eicosanone was quantitatively added to the freeze-dried, homogenized sediment. Lipids were extracted from 40 samples of the Wunavae core (section 41 - 121 cm) and 20 samples of the Nopovois core (section 41 - 83.5) evenly distributed along the core length. A mixture of DCM/MeOH (9:1, v/v) was used for the extraction with a Dionex ASE 350 (Thermo Scientific). If available, a maximum of 3 g of sediment was processed, otherwise, smaller quantities were used. The total lipid extracts were dried under a gentle stream of nitrogen before saponification with 3 mL of 1 N KOH in MeOH and 2 mL of solvent-extracted Milli-Q water at 70 °C for 3–16 h. The neutral fraction was separated from the aqueous phase using 2 mL hexane three times. The remaining aqueous phase was acidified to pH <2 with 4 N HCl, and the protonated fatty acids were recovered using liquid-liquid extraction with 4ml hexane 3 to 4 times. Exchangeable hydrogen atoms on fatty acids were replaced with hydrogen of known isotopic composition via methylation by adding 7 mL of MeOH:HCl (95:5) solution to each fatty acid sample and heating to 70°C for 12h. After cooling, 7mL of deionized water was added to the samples and fatty acid methyl esters (FAMEs) were recovered using 4 ml hexane 3 to 4 times. For samples in which n-C_{28} FAMEs were abundant enough for gas chromatography-isotope ratio mass spectrometry (GC-IRMS), $AgNO_3$-Silica Gel (~10 wt. % loading) was used to purify FAMEs for hydrogen isotope ratio (δ^2H) measurements (detailed below).

Pre-packed 500 mg/6 mL Silica gel columns (Biotage, Uppsala, Sweden) were used to separate the neutral fraction into 4 subsequent fractions: 1) hydrocarbons and *n*-alkane (4 mL of hexane), 2) ketones and aldehydes (4 mL of hexane/DCM, 2:1, v/v), 3) sterols and other alcohols (4 mL of DCM/MeOH, 19:1, v/v), 4) more polar compounds (4 mL of MeOH). The third fraction compounds were converted into trimethylsilyl derivatives prior to analysis by adding 25 µL each of N,O-bis-(trimethylsilyl)trifluoroacetamide (BSTFA) and pyridine and heating to 60 °C for one hour. Compounds were identified and quantified by gas chromatography–mass spectrometry (GC–MS). The GC–MS analyses were performed on an Agilent 7890B gas chromatograph with an Agilent HP-5MS column (30 m x 0.25 mm x 0.25 mm film thickness) coupled with an Agilent 5977B mass spectrometer (MS) and a flame ionization detector (FID) (Agilent Technologies, Santa Clara, USA). Ketones and the derivatized sterols were run with a Selected Ion Monitoring method targeting m/z 215 (quantified), 355, 370 for coprostanol and epicoprostanol and 71, 239, 255 (quantified) for palmitone. External standards with the targeted compounds were added for identification and quantification via external calibration curve (abcr GmbH, 16-Hentriacontanone; lot 1398514 for palmitone, Sigma-Aldrich CAS 360-68-9 Lot 0000188007 for coprostanol, and Sigma-Aldrich CAS 516-92-7 Lot 127M4099V for epicoprostanol). Fatty acids and alkanes were run in Total Ion Scan mode and quantified with the internal standards (5a-androstane for alkanes and heneicosanoic acid for the fatty acids) and normalized to gr TOC. Agilent Mass Hunter was used for identification and peak integration.

The Paq ratio was used to account for differences in *n*-alkanes chain lengths that can inform on the contribution of aquatic plants and is calculated according to Ficken et al., (2000):

$$Paq = \frac{C_{23} + C_{25}}{C_{23} + C_{25} + C_{29} + C_{31}} \qquad \text{(Eq. 1)}$$

This ratio is based on the assumption that C_{23} and C_{25} are mainly produced by macrophytes and is used as a proxy for emergent aquatic plants (0.4 - 0.6), submerged aquatic plants (> 0.6), and terrestrial plants (0.02 - 0.25) (Ficken et al., 2000; Sikes et al., 2009). The TAR is calculated following (Tenzer et al., 1999; Fang et al., 2014):

$$TAR = \frac{C_{24} + C_{26} + C_{28}}{C_{12} + C_{14} + C_{16}} \qquad \text{(Eq. 2)}$$

The ratio is interpreted as source contribution of either terrigenous (TAR > 4) or aquatic (< 2) origin (Tenzer et al., 1999; Fang et al., 2014). *n*-Alkanes average chain length (ACL_{23-33}) were calculated including shorter chains (Poynter and Eglinton, 1990):

$$ACL_{23-33} = \frac{23 \cdot C_{23} + 25 \cdot C_{25} + 27 \cdot C_{27} + 29 \cdot C_{29} + 31 \cdot C_{31} + 33 \cdot C_{33}}{C_{23} + C_{25} + C_{27} + C_{29} + C_{31} + C_{33}} \qquad \text{(Eq. 3)}$$

Fatty acid ACL_{22-30} was calculated following Eglinton and Hamilton (1967):

$$ACL_{22-30} = \frac{22 \cdot C_{22} + 24 \cdot C_{24} + 26 \cdot C_{26} + 28 \cdot C_{28} + 30 \cdot C_{30}}{C_{22} + C_{24} + C_{26} + C_{28} + C_{30}} \qquad \text{(Eq. 4)}$$

An underivatized aliquot (10 %) of fractions F3 and F4 were recombined for brGDGTs analysis. Samples were filtered using a 0.45 µm PTFE filter prior to analysis using high-performance liquid chromatography–atmospheric pressure chemical ionization–mass spectrometry (HPLC-APCI–MS), as described by Hopmans et al. (2016), with a modified column temperature (40 °C). Detection was achieved in selected ion monitoring mode for *m/z* 1050, 1048, 1046, 1036, 1034, 1032, 1022, 1020 and 1018 for brGDGTs. Agilent Chemstation software was used to integrate peak areas. Branched GDGTs analysis was conducted at the Biogeoscience laboratory at ETH Zurich. Mean annual temperature reconstruction based on brGDGTs was obtained following Zhao et al. (2023) tropical calibration regression, since the composition assessment based on a ternary diagram revealed that this calibration fits the largest variation of the dataset (Supplementary Figure 2).

The δ^2H_{LW} analyses were performed in the Biogeochemistry Laboratory at Eawag's Center for Ecology, Evolution, and Biogeochemistry in Kastanienbaum. The samples were analyzed on a Trace GC Ultra gas chromatograph (GC) coupled to a Thermo Delta V Plus isotope ratio mass spectrometer (IRMS) via a GC Isolink operated in pyrolysis mode and ConFlo IV interface (Thermo Fisher Scientific, Bremen, Germany). The measured values were normalized to the VSMOW/SLAP scale using hydrogen isotope standards purchased from Arndt Schimmelmann at Indiana University. Measurement accuracy and precision were assessed from a quality control standard, a hydrocarbon fraction from oak leaves that were originally collected in Berkeley, California.

Pollen and charcoal

Palynomorph analyses (including pollen and spores) were conducted at a 5 cm resolution downcore. Each 1 cm^3 sample was processed using standard procedures (10 % HCl, hot 10 % KOH, and acetolysis) (Moore et al., 1991). Samples were spiked with exotic *Lycopodium clavatum* L. tablets to allow the palynomorph and charcoal concentrations to be calculated. Counts continued until reaching at least 100 terrestrial palynomorphs. The vegetation types (primary, secondary, dryland herbs, etc.) were determined from a regional synthesis of Pacific Island plant ecology (Mueller-Dombois and Fosberg, 1998). Charcoal particle data presented here is < 125 microns, recorded from pollen preparations.

Table 1. Interpretation of proxies in west Santo. More detailed explanation can be found in the supplementary material.

Proxy	Interpretation	References
Human Traces		
Microcharcoal concentration	Burning	Kershaw et al., 1997
Fecal molecules	Omnivores feces (presence of humans, pigs)	Bethell, 1994; Bull et al., 2003
Palmitone	Taro cultivation - horticulture	Krentscher et al., 2019
Terrestrial and Aquatic Ecosystem Changes		
Total Organic Carbon (TOC%)	Changes in erosion and productivity	Meyers and Teranes, 2001
C/N values	Submerged/emerged/terrestrial vegetation	Meyers, 1994; Xia et al. 2014; Gong et al. 2018
BiSi	Diatoms – lake productivity and water level	Conley and Schelske, 2001
Sand	Erosion (+)	Håkanson and Jansson, 1983
Clay	Tephra layers (++)	Lowe and Nelson, 1983; Cashman and Rust, 2016
Pollen	Vegetation	Mueller-Dombois and Fosberg, 1998
Paq	Aquatic vegetation	Ficken et al., 2000
TAR	Relative sources of short and long chain fatty acids	Tenzer et al. 1999; Fang et al. 2014
ACL	Terrestrial vegetation – grass (+)	Eglinton and Hamilton, 1967; Poynter & Eglinton, 1990
Climatic Proxies		
δ^2H of longer-chain fatty acids	Precipitation and hydroclimate	Ladd et al., 2021
MBT'5ME	temperature based on brGDGT distribution	De Jonge et al., 2014
MAAT brGDGTs	Mean Annual Air Temperatures	Zhao et al., 2023

Results

Most proxies follow similar downcore trends in Wunavae and Nopovois (Figure 2, Supplementary Figure 3). However, given the lower sampling resolution in Nopovois, we focus our interpretation on Lake Wunawe, using Lake Nopovois as a support. Unless specified, the results described and discussed below refer to Lake Wunavae. The results provided hereafter are based on median calibrated ages. The age ranges are available in (Camperio et al., in prep). Interpretation guidelines for the proxies below is provided in Table 1.

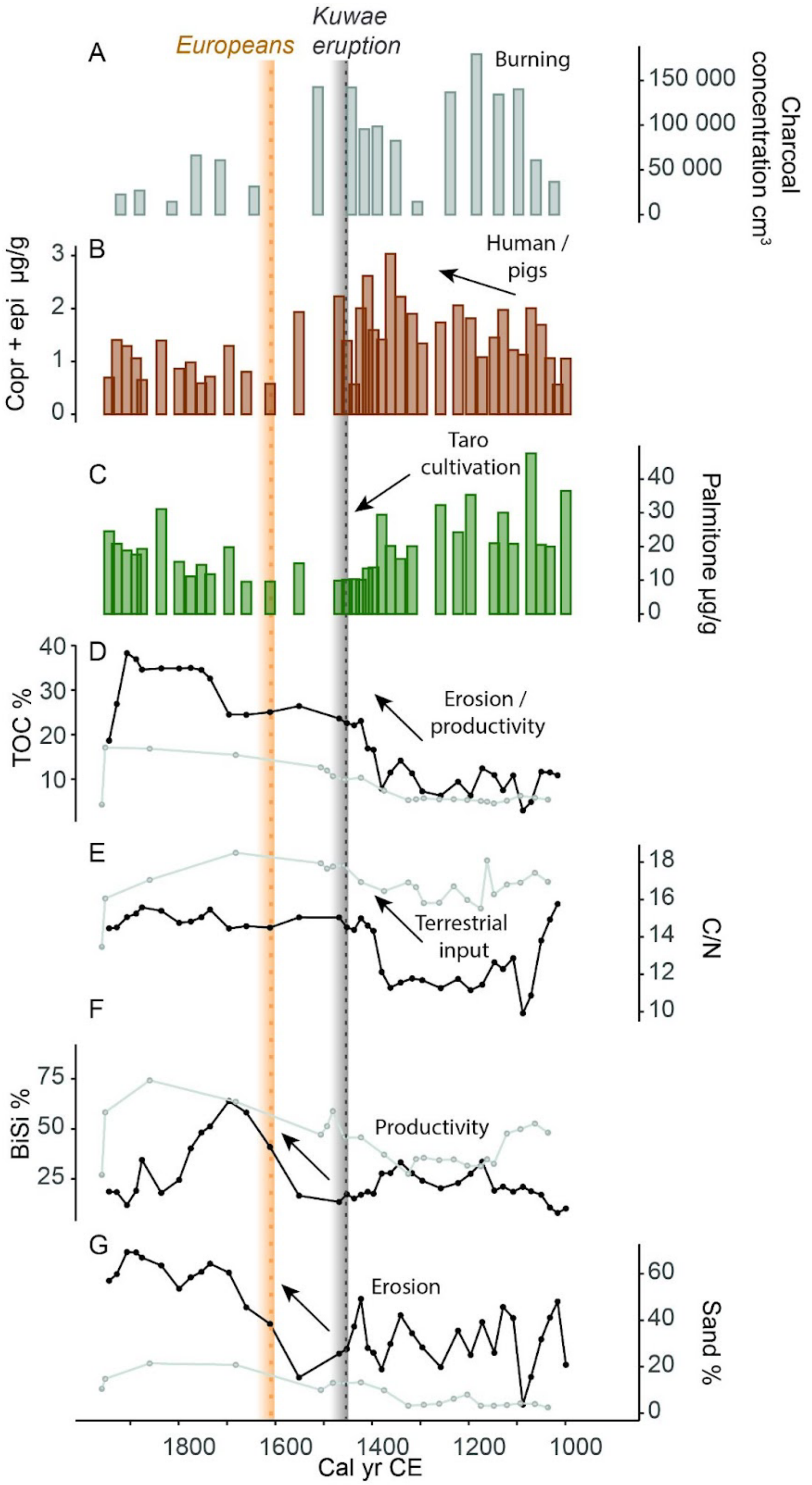


Figure 2. Proxies for human presence and activities, and environmental changes from Lake Wunavae and Lake Nopovois, west Santo. (A) Charcoal concentration (grains/cm^3), (A) fecal markers (brown) and (B)

palmitone (green) concentrations (μg/g TOC) from Wunavae. (D) TOC (%), (E) C/N, (F) BiSi (%) and (G) sand (%) from Wunavae (black lines) and Nopovois (light grey).

1000 - 1300 CE

Charcoal particles are present at the bottom of both cores, and increase to a maximum of 180,000 grains/cm^3 around 1200 CE (Figure 2A). Fecal sterols, despite some minor fluctuations, are stable at 1.5 $\pm$ 0.1 μg/g for Wunavae and 1.6 $\pm$ 0.1 μg/g for Nopovois (Figure 2B and Supplementary Figure 3). Palmitone is most abundant at the bottom of the core in Wunavae with the highest peak around 1100 CE with 48 μg/g, while it maintains sustained concentration (29 $\pm$ 3μg/g) in Nopovois (Figure 2C). Minor fluctuations between 8.2 and 9.8 % characterize TOC content of Wunavae in this period (Figure 2D). In Nopovois, TOC is stable around 5 $\pm$ 0.8 %. This low TOC is consistent with a peak in clay (Supplementary Figure 4) which indicates the presence of a microtephra also observed during pollen analysis in both cores. C/N decreased from 16 – the highest value – at the bottom of the Wunavae core to a minimum of 9 around 1100 CE (Figure 2E). In Nopovois, C/N maintains stable values between 11.6 and 12.4. Biogenic silica is stable in Wunavae during this interval, with an average of 20 $\pm$ 2 % and only one small peak around 1100 CE possibly linked to the tephra layer (Figure 2F). Sand fluctuates greatly between 45 and 20 % in Wunavae, while it only fluctuates between 3 and 7% in Nopovois (Figure 2G). In Wunavae, the landscape is dominated by secondary forest (Figure 3), with notable abundance of ferns and dryland herbs. Conversely, in Nopovois, grassland prevails as the primary vegetation type, followed by secondary forest, wetland herbs, and ferns. δ^2H values of n-C_{28} increase from -182 $\pm$ 3 ‰ 1000 years BP to -136 $\pm$ 1 ‰ around 1250 CE; n-C_{30} and n-C_{26} follow the same trend (Figure 4A). The Paq ratio ranges between 0 and 2 (Figure 4B), ACL_{23-33} follows a decreasing trend from an average of 29 to 28 (Figure 4C). The TAR ratio is stable around 4 (Figure 4D) while ACL_{22-30} starts decreasing slightly from 27 around 1000 CE to 26 around 1300 CE (Figure 4E). brGDGTs reconstructed mean annual air temperature (MAAT) fluctuates with a decreasing trend from 24 °C around 1000 CE to a minimum of 21 °C around 1200 CE (Figure 4F).

1300 - 1500 CE

During this time interval, changes were observed across several proxy indicators. In Wunavae, charcoal concentrations reached 140,000 cm^3, while fecal sterols reached their highest concentration of 3 μg/g in 1362 CE. In contrast, the concentration of palmitone experienced a sharp decline, maintaining a minimum concentration for this period at 10 ± 0.1 ug/g from ca. 1400 to 1450 CE. This sharp palmitone decline was not consistently observed in Nopovois. Both TOC% and the C/N ratio show a step-like increase in Wunavae around 1400 CE, reaching a maximum TOC of 23 % around 1420 CE. Subsequently, a sudden decrease was recorded in charcoal, fecal sterols, and palmitone around 1500 CE in Wunavae. Meanwhile BiSi% remained relatively stable, around 22 ± 2 %. Sand content exhibited substantial variability, with alternating peaks between 50 % and lows of 20 %. In Nopovois, TOC%, C/N, BiSi%, Sand% all show a slight increase.

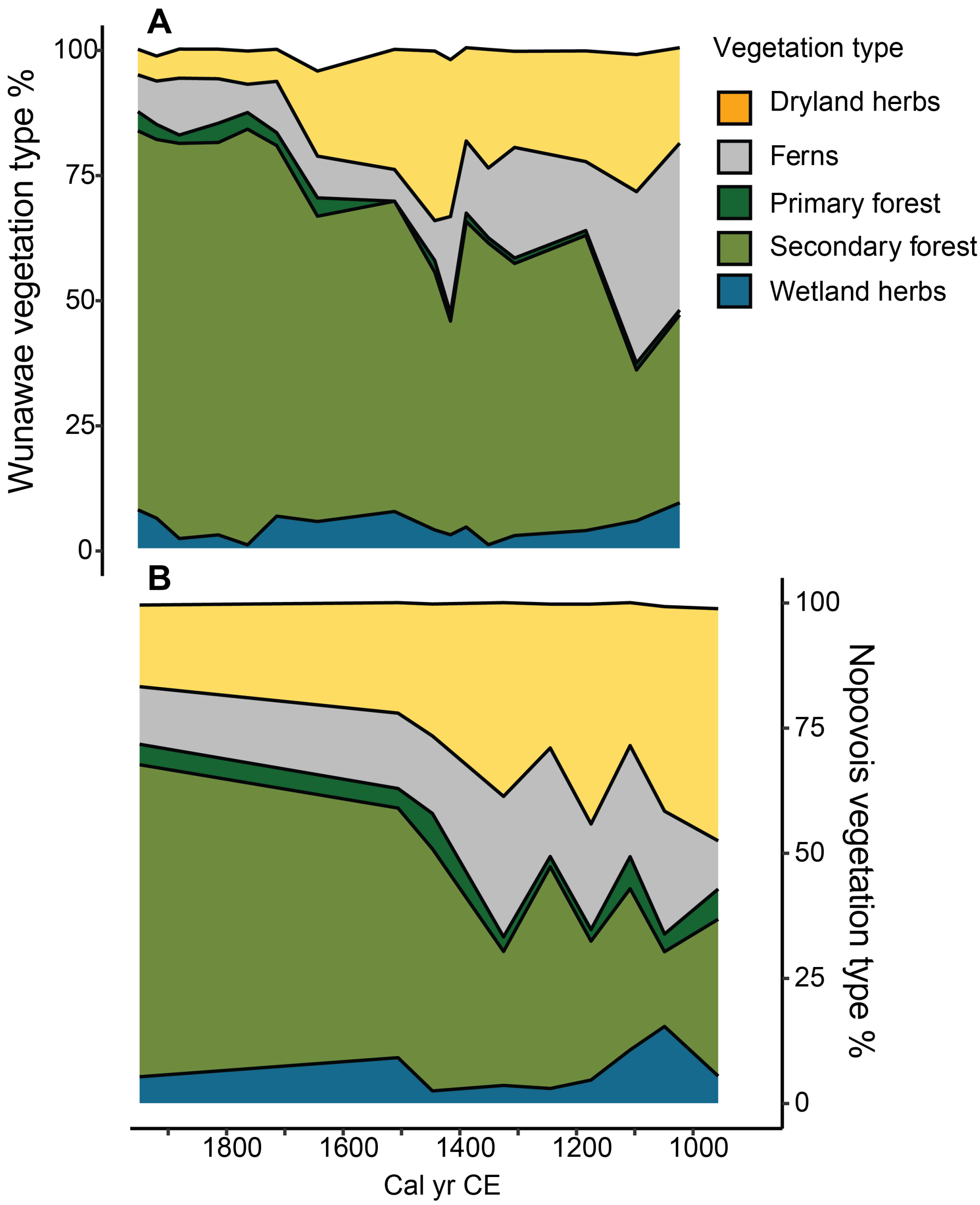


Figure 3. Regional vegetation changes in west Santo. Vegetation type (%) for Wunavae (A) and Nopovois (B), with wetland herbs in blue, secondary forest in light green, primary forest in dark green, ferns in grey, and dryland herbs in orange.

In Wunavae, dryland herbs reach their maximum around 1450 CE (Figure 3). The n-C_{28} δ^2H values reached their highest value of -112 ± 2 ‰ around 1400 CE (Figure 4). Both Paq and TAR record significantly more elevated values between 1400 and 1500 CE, with Paq reaching its maximum of 0.8 and TAR its maximum value of 12 in 1400 CE. Meanwhile, ACL_{23-33} records lower values in the interval 1300-1400 CE, followed by higher values in the interval 1400-1500 CE, while ACL_{22-30} shows the opposite pattern with higher values from 1300 to 1400 CE, and lower values from 1400 to 1500 CE. Finally, MAAT maintains minimum values around 21 °C from 1200 to 1400 CE, followed by a slight increase to 22 °C around 1500 CE.

1500 - 1800 CE

During this timeframe, charcoal concentrations (50,000 ± 15,000 cm^3), fecal markers (1 ± 0.1 µg/g), and palmitone concentrations (17 ± 2 µg/g) all reached their lowest values. However, there is a notable step increase in TOC% around the year 1700 CE, while C/N values remain predominantly stable throughout this period. BiSi% experiences a long and significant peak between 1550 and 1800 CE, reaching its highest value in 1700 CE. The sand content steadily increases, with a peak of 64% in 1700 CE.

Dryland herbs decline in both cores, with a sharp decrease in Poaceae noted in Wunavae in 1700 CE (Supplementary Figure 5). Secondary forest vegetation becomes prevalent in the landscape during this period, accompanied by an increase in *Macaranga* observed in both ponds. In Wunavae, there is also notable growth of *Phyllanthus* and *Pandanus* (Supplementary Figure 5). Additionally, *Botryococcus* makes its appearance in both lakes (Supplementary Figures 5-8).

The n-C_{28} δ^2H values exhibit a continuous decline, reaching their minimum of 179 ± 3 ‰ around 1750 CE (Figure 4). Both Paq and TAR values decline relatively steadily following their peak. While ACL_{23-33} increases throughout this interval, reaching its maximum level in the youngest layers, ACL_{22-30} first increases until 1600 - 1700 CE and then decreases steadily. MAAT shows an increase, with a peak in 1700 CE, following a similar trend as BiSi.

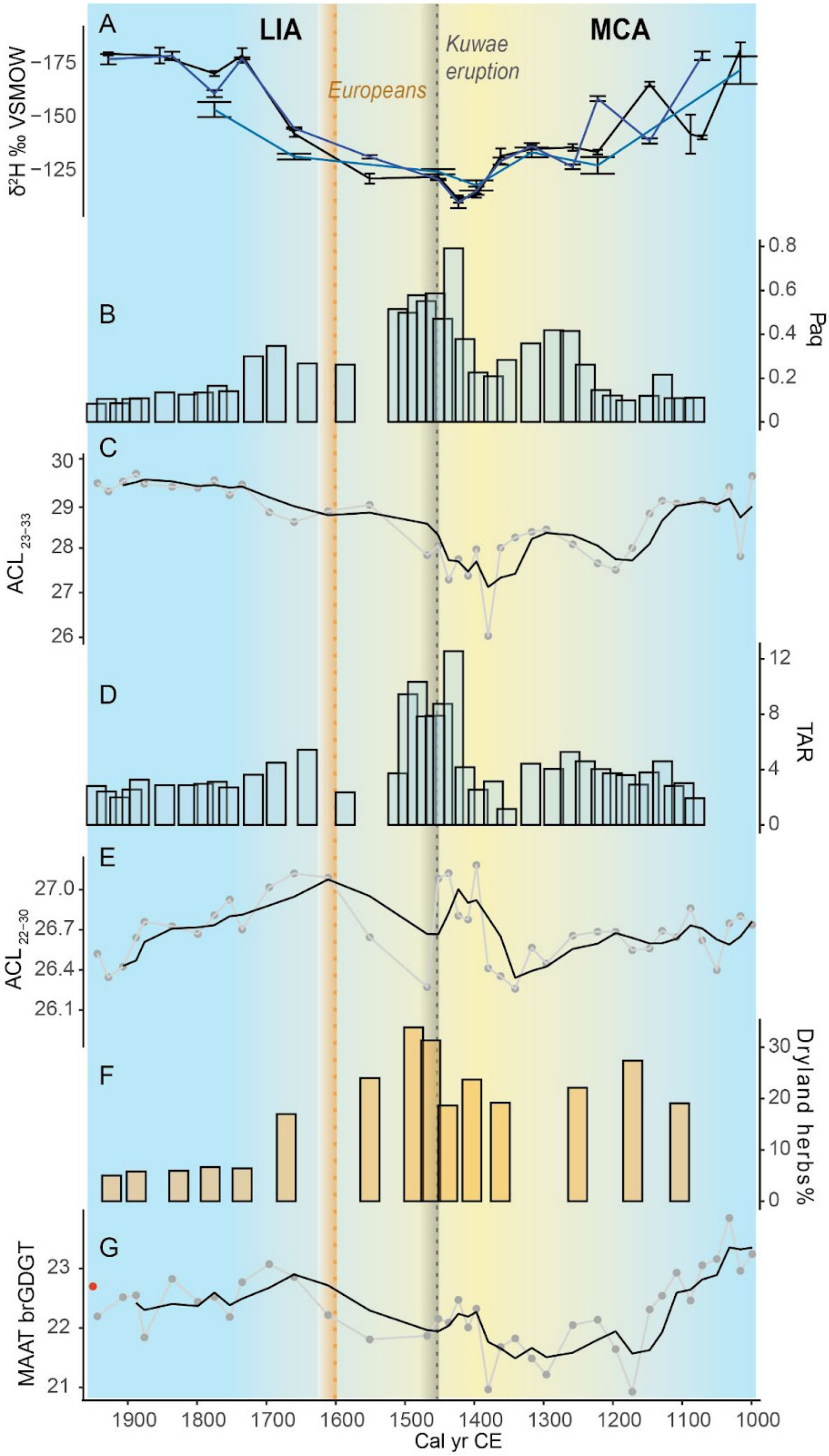


Figure 4. Last millennium climatic signal from Wunavae, west Santo. (A) δ^2H values of n-C_{26} (green), n-C_{28} (black), n-C_{30} (blue), (B) Paq, (C) $ACL_{23\text{-}33}$, (D) TAR, (E) $ACL_{22\text{-}30}$, (F) MAAT brGDGT using the calibration by Zhao et al. (2023). Black lines represent the 3 point running mean. Blue shadings represent wetter intervals while yellow shading indicates the drought period. The grey dotted line shows the timing of the Kuwae eruption (1452 CE). The yellow dotted line marks the European arrival in 1606 CE. The red dot indicates the lake surface temperature in 2017.

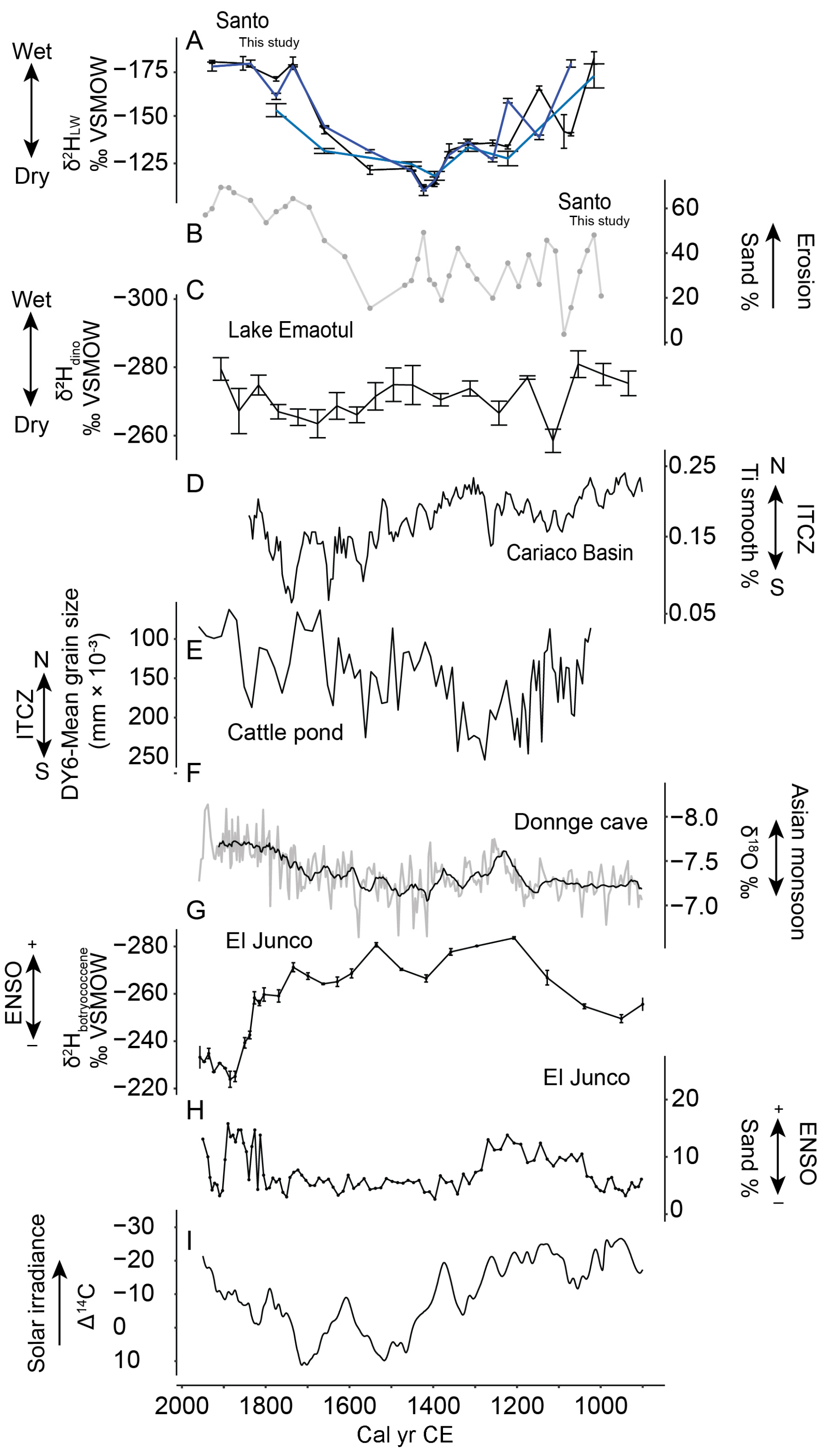


Figure 5. Climatic reconstructions for the period 900 - 2000 CE across the Pacific. (A) n-alkanoic acids δ^2H_{LW} in west Santo, (B) Sand fraction in west Santo, (C) Lake Emaotul (Efate, Vanuatu) $\delta^2H_{dinosterol}$ (Sear et al., 2020), (D) Cariaco Basin Ti% (Haug et al., 2001), (E) Cattle Pond (Dongdao Island, South China Sea) mean grain size (Yan et al., 2011), (F) $\delta^{18}O$ stalagmite from Dongge Cave with 10 pt running mean (Wang et al., 2005), (G) Galápagos El Junco Lake $\delta^2H_{botryococcene}$ (Sachs et al., 2009), (H) Galápagos El Junco Lake sand fraction (Conroy et al., 2008), (I) Solar Irradiance (Hogg et al., 2020).

Discussion

We produced records of climate and human activities from sediment cores from two ponds on the west coast of Espiritu Santo, Vanuatu. The multi-proxy records reveal three different hydroclimatic phases over the last millennium and two contrasting intervals of human-related activities. Charcoal, palmitone and fecal markers are present from the beginning of the record 1000 years BP, and decrease significantly by 1400 CE, when TOC and the C/N ratio reveal a large step-like increase, and the pollen starts to record an increase in secondary forest. In the following discussion we place these results in the broader climatic context, and consider the possible effects that the hydroclimatic changes had on the inhabitants.

Warmer and wetter conditions 1000 years BP favored the establishment of inland settlements and taro gardens in west Santo

Within the last millennium, linguistic variations became more marked in Vanuatu (Tryon, 1996), pottery decorations diversified (Bedford & Spriggs, 2018; Spriggs, 1997) and, as elsewhere in tropical Pacific Islands during the period (Nunn and Britton, 2001; Nunn, 2003), interior settlement probably became common (Galipaud, 2011). Archeological findings suggest that humans first ventured to west Santo around 1000 years BP (Galipaud, 2004). The presence of charcoal at the bottom of both cores and the very similar age of their oldest layer suggests that these lakes may be man-made reservoirs. As observed in other islands in the Pacific, initial settlement required land modifications, in particular forest clearance that increased the water yield and supplied sediment to impede drainage (Hope et al., 1999). This is further confirmed by the bottom age of a third pond in the area which dates to 1000 years BP and has charcoal at the bottom (Krentscher et al., 2019). The simultaneous creation of these water reservoirs 1000 years BP supports the inland expansion of people with water management strategies. Archeological evidence for taro gardens dating to 1000 years BP has been found in the northwest of Santo (Galipaud, 2004). Taro is a crop that prefers wet conditions, for which Melanesians (and Polynesians) developed specific cultivation techniques and terraced gardens. Extensive taro irrigated gardens are still present in the area today.

There are no other archeological findings indicating the presence of humans in west Santo until a site in northwest Santo that is dated to 1700 CE (Wirrman et al., 2011), leaving a gap of 700 years without any indication of human presence or activities. In contrast to the patchy archeological record, the sedimentary archives we retrieved from Lake Wunavae and Lake Nopovois attest to the stable presence of people in the region from 1000 to approximately 1500 CE, with activities like burning (charcoal) and planting (palmitone) (Figure 2). The minimal changes in erosion during this period suggests a relatively stable environment. These findings would be in line with the demographic increase observed along agricultural expansion 1000 years BP on the island of Efate, located further south in Vanuatu (Combettes, 2015; Bedford et al., 2018). The n-C_{28} δ^2H record from Lake Wunavae coupled with brGDGT-reconstructed temperature suggest wetter and warmer conditions during this interval (Figure 4, Supplementary figure 9), providing the ideal setting for the expansion of agriculture.

Melanesian resilience to prolonged drought

Following this wet and warm period which favored inland expansion of agriculture, we observed a decline in palmitone starting around 1300 CE. This interval is marked by a shift towards drier conditions recorded by the highest n-C_{28} δ^2H values. The change in environmental conditions towards sustained drought is confirmed by an increase in dryland herbs at 1300 CE, while secondary forest taxa increase around 1400 CE. The orographic effect of the Cumberland Chain (Supplementary Figure 1) exacerbates the dryness in west Santo, where reservoirs might have dried out leading to a direct impact on both human populations and ecosystems. Droughts can lead to the depletion of freshwater resources, to land degradation, and increased sedimentation in water bodies. Indeed, the TOC, C/N, TAR (terrigenous vs aquatic) and Paq indicate an ecosystem shift in 1400 CE, led by a decrease in water level. The lower water levels led to an expansion of the littoral zone and likely promoted the growth of macrophytes, suggested by high Paq values (Figure 4B). These macrophytes may have outcompeted microalgae in the lake, which would account for the reduced TAR values we see during this interval (Figure 4D). Contrary to the usual interpretation of the TAR, in this context it indicated a disproportionate contribution of longer chains in the range of macrophytes in these settings.

Prolonged drought can have devastating effects on crops and food production, leading to food shortages and potential famine (Annamalai et al., 2015; Iese et al., 2021), which can be especially severe for communities relying heavily on horticulture, such as in

Melanesia. This can, in turn, impact traditional practices, gardening, hunting, and spiritual beliefs associated with the land and its resources (Mortreux and Barnett, 2009; Smith, 2013), and trigger population movements (Sear et al., 2020). However, the abrupt decline in palmitone is not mirrored in charcoal concentrations, which remained high until ca. 1500 CE, nor by fecal markers concentrations, which reached a maximum between 1350-1500 CE (Figure 2). These contrasting records suggest that while the taro crops suffered from the dry conditions or were moved elsewhere, burning continued, indicating that people were still present despite the drier conditions. This could indicate that the drying trend had a negligible impact on local inhabitants. This prolonged drought is marked by the large-scale Kuwae eruption (Gao et al., 2006) in 1452 CE, which is associated with major ecosystem shifts in the lake of Emaotul, in the island of Efate (Strandberg et al., 2023). However, the absence of tephra in our sediment cores suggests that the eruption did not have a direct impact on west Santo. The population living in the former Kuwae island sought refuge on other islands, especially on Efate, with which they had long standing connections (Garanger, 1972; Robin et al., 1994). Whether people relocated to Santo or there were societal changes related to the eruption remains speculative. Furthermore, the decrease in dryland herbs we observe in Santo after the eruption and the increase in secondary forest would be in contrast with the increase in grass described in Efate (Strandberg et al. 2023). Regional differences and winds might explain the different observations.

The arrival of Europeans and return to wetter/warmer conditions

Wunavae is located in the proximity of Big Bay, where the first Europeans landed in 1606 CE (Figure 1). From historical accounts, we know that the encounter between Europeans and local inhabitants was conflictual and rather short, lasting only a couple of months (Markham, 1904; Kelly, 1966). The impact of European contact on Pacific Island populations was previously characterized by a substantial decline and, in some cases, near-collapse of these populations (Kirch & Rallu, 2007; Spriggs, 1997; Scarr, 1967). According to Markham (1904), most of the crew arriving at Big Bay showed signs of illness. Therefore, the contact with Europeans in Santo could explain the drop in fecal marker and charcoal we observe between 1550-1600 CE, or at least it would have exacerbated the consequences of the prolonged drought (ca. 1400 CE) on humans with the spread of diseases that would have hindered population recovery. However, internal demographic fluctuations could also have played a role especially in these harsh conditions with absence of water. Various internal migrations took place from inland to the coast in the last two centuries (Pascal, 2020), thus we cannot exclude that in such a long time span (1500-1800 CE) societal changes influenced settlement locations.

After the abrupt decline in human traces (fecal sterols, palmitone, charcoal), favorable wetter/warmer conditions characterize the period around 1700 CE. These are signaled by a decrease in n-C_{28} δ^2H values and an increase in MAAT. An increase in precipitation is further evident by an increase in sand content which indicates an increase in erosion further supported by an increase in TOC (Figure 2). The decrease in macrophytes as recorded in the Paq coupled with an increase in BiSi would indicate another ecosystem shift possibly driven by higher water levels. The vegetation changes around 1550 CE, with a decline in dryland herbs and an increase in secondary forest, could be indicative of environmental changes linked with a period of increased precipitation but could also be the result of land abandonment. Wetter conditions in Santo would be favorable to the reestablishment of agriculture and settlements, however we do not observe any increase in human traces in this period.

West Santo and the broader climatic context

The settlement of west Santo took place in the context of two distinct climatic periods that have been observed globally (PAGES 2k Consortium, 2013; Masson-Delmotte et al., 2013): the Medieval Climate Anomaly (MCA, ~950-1250 CE) and the Little Ice Age (LIA, ~1450-1850). The n-C_{28} δ^2H record from Lake Wunavae coupled with brGDGT-reconstructed temperature suggest wetter and warmer conditions during the MCA (Figure 4, Supplementary figure 9), providing the ideal setting for the expansion of agriculture. However, these local trends do not clearly fit into a coherent regional picture, and the nature of hydroclimate change in the tropical Pacific during the last millennium is still controversial (Atwood et al., 2021). Recent basin-wide syntheses of paleoproxy data reveal spatial heterogeneities in precipitation patterns, signaling complex mechanisms of precipitation variability and potential unknown biases in certain paleohydrological reconstructions (Sear et al., 2020; Atwood et al., 2021; Maloney et al., 2022). Most records of climate change of the past millennium from the tropical Pacific are from sites located around the margins of the basin (e.g. Haug et al., 2001; Moy et al., 2002), with relatively few records available within the core of the Pacific ITCZ and SPCZ.

Some of these records show consistent dissimilarities, similar to the heterogeneity of precipitation trends in the regions within the brief time covered by the instrumental record (Salinger et al., 2013). Recent runoff records and $\delta^2H_{dinosterol}$ from three SPCZ sites, Uvea (Wallis and Futuna), Upolu (Samoa) and Efate (Vanuatu, Figure 5C) reveal a dry MCA (Maloney et al., 2022), which is not what we observe in west Santo. However, the precipitation change signal is minor in these records, and there is no coherent signal among these sites during the following LIA (Maloney et al., 2022). Overall, *n*-C_{28} δ^2H record from west Santo would be consistent with the records suggesting a southward position of the ITCZ during the MCA, such as the Cariaco Basin Ti% (Haug et al., 2001; Figure 5D), the Cattle Pond (Dongdao Island, South China Sea) mean grain size (Yan et al., 2011; Figure 5F), the weaker Asian monsoon observed in Dongge Cave (Wang et al., 2005, Figure 5G), and Galápagos El Junco Lake $\delta^2H_{botryococcene}$ (Sachs et al., 2009; Figure 5E). Nowadays, Santo receives highest precipitation between January and March, when the SPCZ is well developed and the ITCZ is in its southernmost position. We therefore suggest that a southward shift or more permanent southern position of the ITCZ would lead to a well-developed SPCZ and hence wetter conditions in west Santo.

ENSO variability during these climate intervals is also a matter of debate, with either persistently weak ENSO variability evidenced during the MCA (Cobb et al., 2013; Rein et al., 2005), or strong ENSO variability during this time (Ledru et al., 2013; Moy et al., 2002; Rustic et al., 2015; Tan et al., 2019; Toth et al., 2015). Lake sediment records from El Junco in Galápagos Islands and Laguna Pallcacocha in southern Ecuador indicate intensified El Niño activity and more frequent ENSO events in the late MCA (Moy et al., 2002; Conroy et al., 2008; Figure 5H-I). El Niño events bring droughts to Vanuatu, but here west Santo records wetter conditions - with a drying trend - over this interval, which could be linked to different El Niño flavor (Karamperidou et al., 2015). Subsequent precipitation records were produced in El Junco using the δ^2H of lipid biomarkers (Sachs et al., 2009; Atwood and Sachs, 2014). Atwood and Sachs (2014) interpreted $\delta^2H_{dinosterol}$ as a proxy for long term rainfall whereas $\delta^2H_{botryococcene}$ (Figure 5E) was interpreted as a proxy for changes in rainfall associated with moderate to strong El Niño. Despite several coherent features between the El Junco sand record (Conroy et al., 2008) and the El Niño Rainfall Index ($\delta^2H_{botryococcene}$) (Atwood and Sachs, 2014), both records disagree for the interval 1250–1850 CE, with the sand record suggesting that the intensity of rainfall was similar to, or lower than, modern conditions, while the El Niño Rainfall Index suggests that El

Niño-related rainfall was higher. Overall, the El Niño Rainfall Index based on $\delta^2H_{botryococcene}$ agrees better with our west Santo n-C_{28} δ^2H record than the sand record, with more intense El Niño rainfall in the Galápagos from 1200 to 1700 CE corresponding to the prolonged drought in west Santo (Figure 5). This prolonged drought extends from the end of the MCA well into the LIA. This dry interval suggesting that west Santo was south of the SPCZ fits with the climatic records that indicate a northward ITCZ during this time, such as the Ti% in the Cariaco Basin (Haug et al., 2001) and the smaller grain sizes in Cattle Pond (Figure 5) (Yan et al., 2011). Similarly, nearly all CMIP5/PMIP3 models and all CESM ensemble members simulate dry conditions along the southwestern edge of the SPCZ during the LIA relative to the MCA (Atwood et al., 2021), which is supported by our n-C_{28} δ^2H records.

Conclusion

The limited space on small islands amplifies the dynamics between humans and climate. In ancient Melanesia, where climatic extremes such as cyclones, droughts, and abrupt climatic shifts are common, the reliance of societies on the surrounding ecosystems for their livelihoods must have required strategic adaptations to cope with sudden changes. Our records reveal the complex interplay of climate and humans in shaping melanesian landscapes. Although climatic shifts are evident in the sediment records, these are not reflected in changes in demography which rather align with the first contact with Europeans. This provides a further line of evidence on the resilience of local populations before European contact. A sustained population is evident from our record prior European arrival. Demographic increase characterizes the period around 1000 CE when people started moving inland and expanding agriculture. The possible anthropogenic origin of the inland reservoirs of Wunavae and Nopovois could be evidence of the water management strategies practiced at the time. A warm and wet interval as the one observed in the core provides the ideal setting for the expansion of agriculture. The drier period around 1400 CE is associated with a prolonged drought which affected the production of taro. However, it is not until 1600 CE that human traces are at a minimum. An increase in precipitation in this period would have favored agriculture and the growth of taro. However, this period coincided with the first European contact, during which new diseases could have been transmitted to the local population. Given the evidence of European impact on other islands in Vanuatu it is likely that this first contact drove the abrupt demographic decrease observed in our record. Our results reveal an unknown history of Melanesia, which emphasize the importance of understanding societal resilience to climate change, particularly in vulnerable environments like island ecosystems.

Acknowledgments

We would like to thank the west Santo communities for allowing us on their territory and providing guidance in the field, specifically chief Aram and his brother Jonah from Kerepua who guided us through the whole expedition in the west Coast. Jack Alick, Alison, Jethro, Jemis assisted us during coring in Wunavae, Richard in Tasmate, Oliver, Malkam, Pereae, Vepei, Josaia, Marinoel, Keven, Tomsen, and chief Borouwono Metio from Tanekoro assisted during coring in Nopovois. We thank Richard Shing and Henline Mala from the Vanuatu Cultural Center and Reedly Tari, Donna Kalfatak and Primrose Malosu from DEPC for their guidance in the permit process. The research permit was approved by the Vanuatu National Cultural Council and the Department of Environmental Protection and Conservation (DEPC). We thank Irene Brunner, Pascal Rünzi, Silvia Bollhader, Christiane Krentscher for their technical support, Danny Nef for his assistance in the field. We thank Nannan Li, Ronald Lloren, Marteen Blaauw, Irka Hajdas and Luckas Wacker for providing feedback and discussion.

References

Allen, M. S. (2006). New Ideas about Late Holocene Climate Variability in the Central Pacific. Current Anthropology, 47(3), 521–535.

Anderson, A., Chappell, J., Gagan, M., & Grove, R. (2006). Prehistoric maritime migration in the Pacific islands: An hypothesis of ENSO forcing. The Holocene, 16(1), 1–6.

Annamalai H, Keener V, Widlansky MJ, & Hafner J (2015) El Niño strengthens in the Pacific: preparing for the impacts of drought. Asia Pacific Issues, (122).

Atwood, A. R., Battisti, D. S., Wu, E., Frierson, D. M. W. & Sachs, J. P. Data-Model Comparisons of Tropical Hydroclimate Changes Over the Common Era. Paleoceanography and Paleoclimatology 36, e2020PA003934 (2021).

Atwood, A.R., Sachs J. P. (2014) Separating ITCZ- and ENSO-related rainfall changes in the Galápagos over the last 3 kyr using D/H ratios of multiple lipid biomarkers, Earth and Planetary Science Letters, Volume 404, Pages 408-419,

Bedford, S., Siméoni, P., & Lebot, V. (2018). The anthropogenic transformation of an island landscape: Evidence for agricultural development revealed by LiDAR on the island of Efate, Central Vanuatu, South-West Pacific. Archaeology in Oceania, 53(1), 1–14.

Bedford, S., & Spriggs, M. (2018). The Archaeology of Vanuatu: 3,000 Years of History across Islands of Ash and Coral. In E. E. Cochrane & T. L. Hunt (Eds.), The Oxford Handbook of Prehistoric Oceania, Oxford University Press.

Bedford, S. & M. Spriggs, 2008. Northern Vanuatu as a Pacific crossroads: The archaeology of discovery, interaction, and the emergence of the “ethnographic present”. Asian Perspectives 47.1: 95-120.

Cruz Berrocal, M., & Sand, C. (2021). A question of impact: Did we underestimate the consequences of the sixteenth and seventeenth centuries period of early European exploration in the Pacific?. The Journal of Island and Coastal Archaeology, 16(2-4), 231-260.

Bethell, P.H., Goad, L.J., Evershed, R.P., 1994. The study of molecular markers of human activity: the use of coprostanol in the soil as an indicator of human faecal material. J. Archaeol. Sci.

Bouchet, P., Le Guyader, H., Pascal, O. (2013) The Natural History of Santo, French Natl Museum Natl History, 569p.

Brown, J. R., Lengaigne, M., Lintner, B. R., Widlansky, M. J., van Der Wiel, K., Dutheil, C., ... & Renwick, J. (2020). South Pacific Convergence Zone dynamics, variability and impacts in a changing climate. Nature Reviews Earth & Environment, 1(10), 530-543.

Bull, I.D., Elhmmali, M.M., Roberts, D.J., Evershed, R.P., 2003. The application of steroidal biomarkers to track the abandonment of a Roman wastewater course at the Agora (Athens, Greece). Archaeometry 45 (1), 149e161.

Camperio, C., Ladd, S. N., Prebble, M., Welte, C., Kumar Kotra, K., Dubois, N. (in preparation for Radiocarbon) Bomb pulse dating in Vanuatu tracks past extreme events in areas lacking instrumental records

Cashman, K., & Rust, A. (2016). Introduction: Part 2: Volcanic Ash: Generation and Spatial Variations. In Volcanic Ash: Hazard Observation (pp. 5-22). Elsevier Inc..

Chand, S. S., Tory, K. J., Ye, H., & Walsh, K. J. E. (2016). Projected increase in El Niño-driven tropical cyclone frequency in the Pacific. Nature Climate Change, 7, 123. URL:

Cobb, K. M., Westphal, N., Sayani, H. R., Watson, J. T., Di Lorenzo, E., Cheng, H., Edwards, R. L., & Charles, C. D. (2013). Highly Variable El Niño–Southern Oscillation Throughout the Holocene. Science, 339(6115), 67–70.

Combettes, C., Sémah, A.-M., & Wirrmann, D. (2015). High-resolution pollen record from Efate Island, central Vanuatu: Highlighting climatic and human influences on Late Holocene vegetation dynamics. Comptes Rendus Palevol, 14(4), 251–261.

Conley D.J., and Schelske, J.L. 2001. Biogenic silica, p. 281–293.InJ. P. Smol, H. J. B. Birks, and W. M. Last [eds.], Tracking environmental changes in lake sediments. V. 3: Terrestrial, al-gal, and siliceous indicators. Kluwer

Conroy, J. L., Overpeck, J. T., Cole, J. E., Shanahan, T. M., & Steinitz-Kannan, M. (2008). Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. Quaternary Science Reviews, 27(11–12), 1166–1180.

De Jonge, C., Hopmans, E. C., Zell, C. I., Kim, J. H., Schouten, S., & Damsté, J. S. S. (2014). Occurrence and abundance of 6-methyl branched glycerol dialkyl glycerol tetraethers in soils: Implications for palaeoclimate reconstruction. Geochimica et Cosmochimica Acta, 141, 97-112.

Dickie, E.R., 1981. A note on the naming of Malo Island, Vanuatu. Journal of the Polynesian Society, 90.1: 111-6

Eglinton, G., & Hamilton, R. J. (1967). Leaf Epicuticular Waxes: The waxy outer surfaces of most plants display a wide diversity of fine structure and chemical constituents. Science, 156(3780), 1322-1335.

Fang, J., Wu, F., Xiong, Y., Li, F., Du, X., An, D., & Wang, L. (2014). Source characterization of sedimentary organic matter using molecular and stable carbon isotopic composition of n-alkanes and fatty acids in sediment core from Lake Dianchi, China. Science of the Total Environment, 473, 410-421.

Ficken, K. J., Li, B., Swain, D. L., & Eglinton, G. (2000). An n-alkane proxy for the sedimentary input of submerged/floating freshwater aquatic macrophytes. Organic geochemistry, 31(7-8), 745-749.

François, A., Franjieh, M., Lacrampe, S., Schnell, S. (2015). The exceptional linguistic density of Vanuatu. in: The Languages of Vanuatu: Unity and Diversity — ed. by A. François, S. Lacrampe, M. Franjieh & S. Schnell (pp.1–21), Chapter: 1, Publisher: Asia–Pacific Linguistics

Galipaud, J.-C. (2004). Settlement history and landscape use in Santo, Vanuatu. In A Pacific Odyssey: Archaeology and Anthropology in the Western Pacific. Papers in Honour of Jim Specht. Records of the Australian Museum, Supplement, 29, 59–64.

Galipaud, field report 1998 Galipaud, J.C., 1998. The Lapita Site of Atanoasao Malo, Vanuatu. Field Report No 8. Port Vila: ORSTOM

Galipaud, J-C. & A. Walter, 1997. Forêts Insulaires. Rapport intermédiaire du programme: Se Nourrir à Santo. Port Vila: ORSTOM/APFT.

Galipaud, J.C., 2004. Settlement history and landscape use in Santo, Vanuatu. Records of the Australian Museum, Supplement 29: 59-64.

Galipaud, J.C., 2011. The prehistory of Santo. In: Bouchet et al.: 469-75.

Gao, C., Robock, A., Self, S., Witter, J. B., Steffenson, J. P., Clausen, H. B., Siggaard-Andersen, M.-L., Johnsen, S., Mayewski, P. A., & Ammann, C. (2006). The 1452 or 1453 A.D. Kuwae eruption signal derived from multiple ice core records: Greatest volcanic sulfate event of the past 700 years. Journal of Geophysical Research, 111(D12), D12107.

Garanger, J. (1972). Arch eologie des Nouvelles H ebrides: Contribution a la connaissance des ıles du Centre. Publications de La Société Des Océanistes, 30.

Gaven, C., M. Bernat, C. Jouannic & F. Taylor, 1980. Mouvements verticaux des Nouvelles-Hébrides pendant les derniers 120 000 ans. Datation de coraux par la méthode Io-U. Comptes-Rendus de l'Académie des Sciences 290(D): 175–178.

Gong, X., Xu, Z., Lu, W., Tian, Y., Liu, Y., Wang, Z., ... & Li, Z. (2018). Spatial patterns of leaf carbon, nitrogen, and phosphorus stoichiometry of aquatic macrophytes in the arid zone of northwestern China. Frontiers in Plant Science, 9, 1398.

Green, R.C. (1991) Near and Remote Oceania: Disestablishing 'Melanesia' in culture history in: A. Pawley (Ed.), Man and a Half: Essays in Pacific anthropology and ethnobiology in honour of Ralph Bulmer, The Polynesian Society, pp. 491-502

Håkanson, L and M. Jansson (1983) Principles of Lake Sedimentology Springer, Berlin, 316 pp.

Haug, G. H., Hughen, K. A., Sigman, D. M., Peterson, L. C., & Röhl, U. (2001). Southward Migration of the Intertropical Convergence Zone Through the Holocene. Science, 293(5533), 1304–1308.

Hope G., O'Dea D., Southern W. (1999). Holocene vegetation histories in the Western Pacific : alternative records of human impact. In : Galipaud Jean-Christophe (ed.), Lilley I. (ed.). Le Pacifique de 5000 à 2000 avant le présent : suppléments à l'histoire d'une colonisation = The Pacific from 5000 to 2000 BP : colonisation and transformations. Paris : IRD, p. 387-404. (Colloques et Séminaires). Conférence Lapita : Le Pacifique de 5000 à 2000 avant le Présent : Suppléments à l'Histoire d'une Colonisation, 3., Port Vila (VAN), 1996/06/31.

Hopmans, E. C., Schouten, S., & Sinninghe Damsté, J. S. (2016). The effect of improved chromatography on GDGT-based palaeoproxies. Organic Geochemistry, 93, 1–6.

Iese V, Kiem AS, Mariner A, Malsale P, Tofaeono T, Kirono DGC, Round V, Heady C, Tigona R, Veisa F, Posanau K, Aiono F, Haruhiru A, Daphne A, Vainikolo V, Iona N (2021) Historical and future drought impacts in the Pacific islands and atolls. Clim Change 166(1–2):1–24.

Jolly, M., 2009. The Sediment of Voyages: Re-membering Quirós, Bougainville and Cook in Vanuatu. In M. Jolly, S. Tcherkézoff & D. Tryon (Eds.), Oceanic Encounters : Exchange, Desire, Violence. Canberra: ANU Press: 57-112

Jouannic, C., F.W. Taylor, A.L. Bloom & M. Bernat, 1980. Late quaternary uplift history from emerged reef terraces on Santo and Malekula Islands, central New Hebrides Island arc. CCOP Sopac Technical Bulletin (3): 91–108.

Karamperidou, C., Di Nezio, P. N., Timmermann, A., Jin, F. F., & Cobb, K. M. (2015). The response of ENSO flavors to mid-Holocene climate: implications for proxy interpretation. Paleoceanography, 30(5), 527-547.

Keenan, B., Imfeld, A., Johnston, K., Breckenridge, A., Gélinas, Y., & Douglas, P. M. (2021). Molecular evidence for human population change associated with climate events in the Maya lowlands. Quaternary Science Reviews, 258, 106904.

Kelly, C. (Ed.). (1966). La Austrialia del Espíritu Santo: The journal of Fray Martín de Munilla O.F.M. and other documents relating to the voyage of Pedro Fernández de Quirós to the South Sea (1605–1606) and the Franciscan Missionary Plan (1617–1627) (Vol. 2). The Hakluyt Society: Cambridge

Kershaw, A.P., Bush, M.B., Hope, G.S., Weiss, KF., Goldammer, J.G., Sanford, R. (1997). The contribution of humans to past biomass burning in the tropics. In: Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B. (eds) Sediment Records of Biomass Burning and Global Change. NATO ASI Series, vol 51. Springer, Berlin, Heidelberg.

Kilbourne, K. H., Quinn, T. M., Taylor, F. W., Delcroix, T., & Gouriou, Y. (2004). El Niño-Southern Oscillation-related salinity variations recorded in the skeletal geochemistry of a Porites coral from Espiritu Santo, Vanuatu: coral record of salinity variations. Paleoceanography, 19(4), n/a-n/a.

Kirch, P. V., & Rallu, J.-L. (Eds.). (2007). The growth and collapse of Pacific island societies: Archaeological and demographic perspectives. University of Hawai'i Press.

Krentscher, C., Dubois, N., Camperio, G., Prebble, M., & Ladd, S. N. (2019). Palmitone as a potential species-specific biomarker for the crop plant taro (Colocasia esculenta Schott) on remote Pacific islands. Organic Geochemistry, 132, 1–10.

Ladd, S. N., Maloney, A. E., Nelson, D. B., Prebble, M., Camperio, G., Sear, D. A., Hassall, J. D., Langdon, P. G., Sachs, J. P., & Dubois, N. (2021). Leaf Wax Hydrogen Isotopes as a Hydroclimate Proxy in the Tropical Pacific. Journal of Geophysical Research: Biogeosciences, 126(3), e2020JG005891.

Lawson, S. (2013) Melanesia': The History and Politics of an Idea, The Journal of Pacific History, Vol. 48, No. 1, pp. 1-22.

Ledru, M.-P., Jomelli, V., Samaniego, P., Vuille, M., Hidalgo, S., Herrera, M., & Ceron, C. (2013). The Medieval Climate Anomaly and the Little Ice Age in the eastern Ecuadorian Andes. Climate of the Past, 9(1), 307–321.

Lowe, D.J. and Nelson, C.S. 1983. Guide to the nature and methods of analysis of the clay fraction of. Tephras from the South Auckland region, New Zealand. Occasional Report No. 11, University of Waikato, Department of Earth Sciences. 69p.

Maes, C., & Varillon, D. (2011). Climatic and Oceanic Conditions around Santo (pp. 57–61).

Maloney, A.E. Richey, J. N., Nelson, D. B., Hing, S. N., Sear, D. A., Hassall, J. D., Langdon, P. G., Sichrowsky,U., Schabetsberger, R., Malau, A., Meyer, J.-Y., Croudace, I. W., Sachs, J. P. (2022) Contrasting Common Era climate and hydrology sensitivities from paired lake sediment dinosterol hydrogen isotope records in the South Pacific Convergence Zone, Quaternary Science Reviews, Volume 281, 107421.

Markham, C. (Ed.). (1904). The voyages of Pedro Fernandez de Quirós, 1595 to 1606 (Vol. 2). Cambridge: The Hakluyt Society.

Marshall, A.J., 1937. The Black Musketeers. London: Heinemann

Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, A., Gonzalez Rouco, J., Jansen, E., Lambeck, K., Luterbacher, J., Naish, T., Osborn, T., Otto-Bliesner, B., Quinn, T., Ramesh, Rojas, M., Shao, X., Timmermann, A., 2013. In-formation from paleoclimate archives. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgely, P.M. (Eds.), Climate Change 2013 - the Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernnmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 383e464.

Meyers, P. A. (1994). Preservation of elemental and isotopic source identification of sedimentary organic matter. Chemical geology, 114(3-4), 289-302.

Meyers, P. A., & Teranes, J. L. (2001). Sediment Organic Matter. In W. Last, & J. P. Smol (Eds.), Tracking Environmental Change Using Lake Sediments (pp. 240-267). Dordrecht: Kluwer Academic Publishers.

Montenegro, Á., Callaghan, R. T., & Fitzpatrick, S. M. (2016). Using seafaring simulations and shortest-hop trajectories to model the prehistoric colonization of Remote Oceania. Proceedings of the National Academy of Sciences, 113(45), 12685–12690.

Moore, P. D., Webb, J. A., & Collison, M. E. (1991). Pollen analysis. Blackwell scientific publications.

Mortreux, C., and J. Barnett (2009). Climate change, migration and adaptation in Funafuti, Tuvalu. Global Environmental Change, vol. 19, pp. 105-112.

Moy, C. M., Seltzer, G. O., Rodbell, D. T., & Anderson, D. M. (2002). Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. Nature, 420(6912), Article 6912.

Mueller-Dombois, D., Fosberg, F. R. (1998) Vegetation of the Tropical Pacific Islands, Series Ecological Studies 132, Springer-Verlag New York, Inc.

Nogué, S., de Nascimento, L., Froyd, C. A., Wilmshurst, J. M., de Boer, E. J., Coffey, E. E. D., Whittaker, R. J., Fernández-Palacios, J. M., & Willis, K. J. (2017). Island biodiversity conservation needs palaeoecology. Nature Ecology & Evolution, 1(7), Article 7.

Nogué, S., Santos, A. M., Birks, H. J. B., Björck, S., Castilla-Beltrán, A., Connor, S., ... & Steinbauer, M. J. (2021). The human dimension of biodiversity changes on islands. Science, 372(6541), 488-491.

Nunn, P. D. (2003). Revising ideas about environmental determinism: Human-environment relations in the Pacific Islands. Asia Pacific Viewpoint, 44(1), 63–72.

Nunn, P. D., & Britton, J. M. R. (2001). Human-Environment Relationships in the Pacific Islands around A.D. 1300. Environment and History, 7(1), 3–22.

Ohlendorf, C., & Sturm, M. (2008). A modified method for biogenic silica determination. Journal of Paleolimnology, 39(1), 137–142.

PAGES 2k Consortium (2013). Continental-scale temperature variability during the past two millennia. Nature Geoscience, 6, 339–346.

Pascal, E. M. 2020 The Potters of Espiritu Santo, A socio-historical study of survival and loss of tradition. PhD thesis. The University of Waikato

Pineda, R. 2011. Vanuatu REDD + Demonstration Activities: Participatory pilot site demarcation and description. Report for SPC/GIZ Regional Project "Climate Protection through Forest Conservation in Pacific Countries". Fiji: SPC Land Resources Division.

Poynter, J.G., Eglinton, G., 1990. Molecular composition of three sediments from hole 717c: The Bengal fan. Proc. Ocean Drill. Program, Sci. Results 116, 155–161.

Raposeiro, P. M., Hernández, A., Pla-Rabes, S., Gonçalves, V., Bao, R., Sáez, A., ... & Giralt, S. (2021). Climate change facilitated the early colonization of the Azores Archipelago during medieval times. Proceedings of the National Academy of Sciences, 118(41), e2108236118.

Rein, B., Lückge, A., Reinhardt, L., Sirocko, F., Wolf, A., & Dullo, W.-C. (2005). El Niño variability off Peru during the last 20,000 years. Paleoceanography, 20(4).

Richardson, D. C., Holgerson, M. A., Farragher, M. J., Hoffman, K. K., King, K. B., Alfonso, M. B., ... & Sweetman, J. N. (2022). A functional definition to distinguish ponds from lakes and wetlands. Scientific reports, 12(1), 10472.

Robin, C., Australian Geological Survey Organisation, & IAVCEI General Assembly. (1993). The Geology, volcanology, petrology-geochemistry, and tectonic evolution of the New Hebrides Island Arc, Vanuatu: IAVCEI, Canberra 1993 : excursion guide. Australian Geological Survey Organisation.

Rustic, G. T., Koutavas, A., Marchitto, T. M., & Linsley, B. K. (2015). Dynamical excitation of the tropical Pacific Ocean and ENSO variability by Little Ice Age cooling. Science, 350(6267), 1537–1541.

Sachs, J. P., Sachse, D., Smittenberg, R. H., Zhang, Z., Battisti, D. S., & Golubic, S. (2009). Southward movement of the Pacific intertropical convergence zone AD 1400–1850. Nature Geoscience, 2(7), Article 7.

Salinger, M. & Renwick, James & Mullan, Brett. (2001). Interdecadal Pacific Oscillation and South Pacific Climate. International Journal of Climatology. 21. 1705 - 1721. 10.1002/joc.691.

Salinger, M.J., McGree, S., Beucher, F. et al. A new index for variations in the position of the South Pacific convergence zone 1910/11–2011/2012. Clim Dyn 43, 881–892 (2014).

Scarr, D. (1967). Recruits and recruiters: A portrait of the Pacific Islands labour trade. The Journal of Pacific History, 2(1), 5-24.

Sear, D.A., Allen, M.S., Hassall, J.D., Maloney, A.E., Langdon, P.G., Morrison, A.E., Henderson, A.C.G., Mackay, H., Croudace, I.W., Clarke, C., Sachs, J.P., Macdonald, G., Chiverrell, R.C., Leng, M.J., Cisneros-Dozal, L.M., Fonville, T., 2020. Human settlement of East Polynesia earlier, incremental, and coincident with prolonged South Pacific drought. Proc. Natl. Acad. Sci. Unit. States Am. 117, 8813e8819.

Shineberg, D., 1967. They came for sandalwood: a study of the sandalwood trade in the South West Pacific, 1830-1865. Melbourne University Press, Melbourne.

Sikes, E. L., Uhle, M. E., Nodder, S. D., & Howard, M. E. (2009). Sources of organic matter in a coastal marine environment: evidence from n-alkanes and their δ13C distributions in the Hauraki Gulf, New Zealand. Marine Chemistry, 113(3-4), 149-163.

Smith, R. (2013). Should they stay or should they go? A discourse analysis of factors influencing relocation decisions among the outer islands of Tuvalu and Kiribati. Journal of New Zealand and Pacific Studies, vol. 1, No. 1, pp. 22-39.

Spriggs, M. (1997). The Island Melanesians. Oxford: Blackwell.

Spriggs, M. (1997). Landscape catastrophe and landscape enhancement: Are either or both true in the Pacific. Historical ecology in the Pacific Islands: prehistoric environmental and landscape change, 80-104.

Spriggs, M., 1997. The Island Melanesians. Oxford: Blackwell.

Strandberg, N. A., Sear, D. A., Langdon, P. G., Cronin, S. J., Langdon, C. T., Maloney, A. E., Bateman, S. L., Bishop, T., Croudace, I. W., Leng, M. J., Sachs, J. P., Prebble, M., Gosling, W. D., Edwards, M., & Nogué, S. (2023).

Island ecosystem responses to the Kuwae eruption and precipitation change over the last 1600 years, Efate, Vanuatu. Frontiers in Ecology and Evolution, 11.

Tan, L., Shen, C.-C., Löwemark, L., Chawchai, S., Edwards, R. L., Cai, Y., Breitenbach, S. F. M., Cheng, H., Chou, Y.-C., Duerrast, H., Partin, J. W., Cai, W., Chabangborn, A., Gao, Y., Kwiecien, O., Wu, C.-C., Shi, Z., Hsu, H.-H., & Wohlfarth, B. (2019). Rainfall variations in central Indo-Pacific over the past 2,700 y. Proceedings of the National Academy of Sciences, 116(35), 17201–17206.

Taylor, F. W. (1992). Quaternary Vertical Tectonics of the Central New Hebrides Island Arc. Proc. Ocean Drill. Program Initial Rep, 134, 33–42.).

Tenzer, G. E., Meyers, P. A., Robbins, J. A., Eadie, B. J., Morehead, N. R., & Lansing, M. B. (1999). Sedimentary organic matter record of recent environmental changes in the St. Marys River ecosystem, Michigan–Ontario border. Organic Geochemistry, 30(2-3), 133-146.

Terry, J.P., 2011. Drainage, hydrology and fluvial geomorphology. In: Bouchet et al: 46-51.

Toth, L. T., Aronson, R. B., Cheng, H., & Edwards, R. L. (2015). Holocene variability in the intensity of wind-gap upwelling in the tropical eastern Pacific. Paleoceanography, 30(8), 1113-1131.

Tryon, D. T. (1996). Mae-Morae and the languages of Epi (Vanuatu). In Oceanic studies: Proceedings of the First International Conference on Oceanic Linguistics. Pacific Linguistics.

Tzerikiantz, F, 2006. Ples blong mi wea? (Où est ma terre ?) Pratiques et discours contemporains autour de la mobilité à l'Ouest de Santo, Vanuatu. Universite Aix-Marseille I ED 355 Espaces, Cultures, Sociétés Laboratoire d'accueil: CREDO-UMR 6574 (Centre de Recherche et de Documentation sur l'Océanie) Maison Asie Pacifique, Université de Provence, Marseille. Thèse de Doctorat

Wang, Y., Cheng, H., Edwards, R. L., He, Y., Kong, X., An, Z., Wu, J., Kelly, M. J., Dykoski, C. A., & Li, X. (2005). The Holocene Asian Monsoon: Links to Solar Changes and North Atlantic Climate. Science, 308(5723), 854–857.

White, A. J., Stevens, L. R., Lorenzi, V., Munoz, S. E., Schroeder, S., Cao, A., & Bogdanovich, T. (2019). Fecal stanols show simultaneous flooding and seasonal precipitation change correlate with Cahokia's population decline. Proceedings of the National Academy of Sciences, 116(12), 5461-5466.

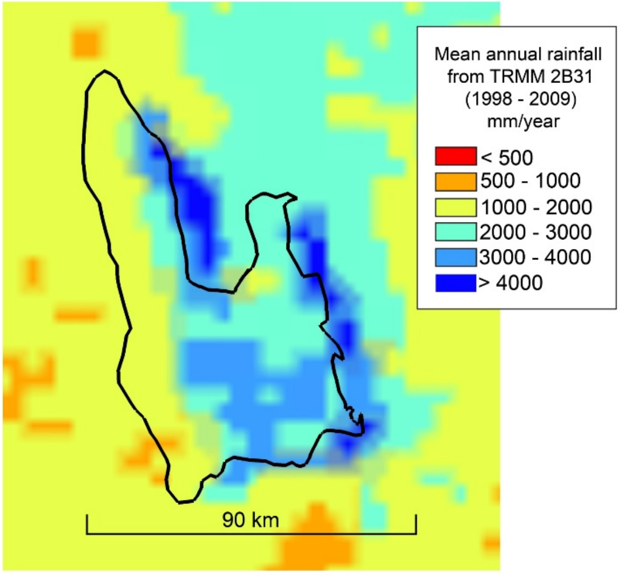
Wirrmann, D., J-C. Galipaud, A-M. Sémah & T. Alcover, 2011. Caves as archives. In: Bouchet et al.: 278-83.

Xia, C., Yu, D., Wang, Z., & Xie, D. (2014). Stoichiometry patterns of leaf carbon, nitrogen and phosphorous in aquatic macrophytes in eastern China. Ecological Engineering, 70, 406-413.

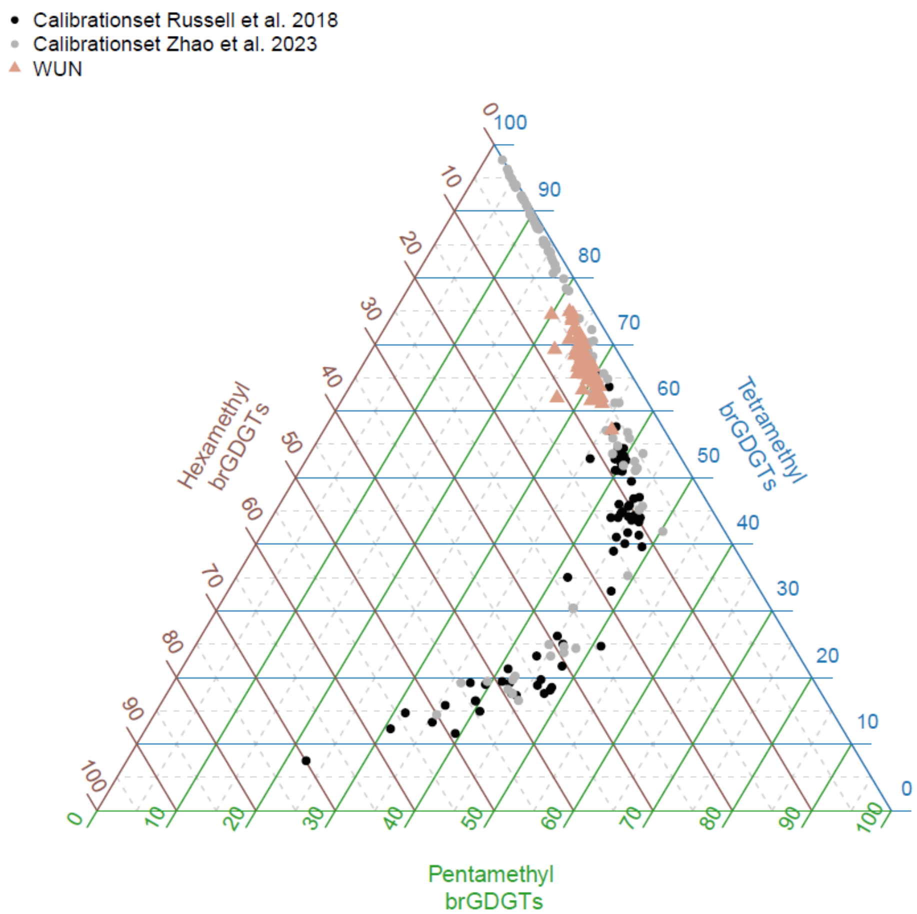
Yan, H., Sun, L., Oppo, D. W., Wang, Y., Liu, Z., Xie, Z., ... & Cheng, W. (2011). South China Sea hydrological changes and Pacific Walker Circulation variations over the last millennium. Nature communications, 2(1), 293.

Zhao, B., Russell, J. M., Tsai, V. C., Blaus, A., Parish, M. C., Liang, J., ... & Bush, M. B. (2023). Evaluating global temperature calibrations for lacustrine branched GDGTs: Seasonal variability, paleoclimate implications, and future directions. Quaternary Science Reviews, 310, 108124.

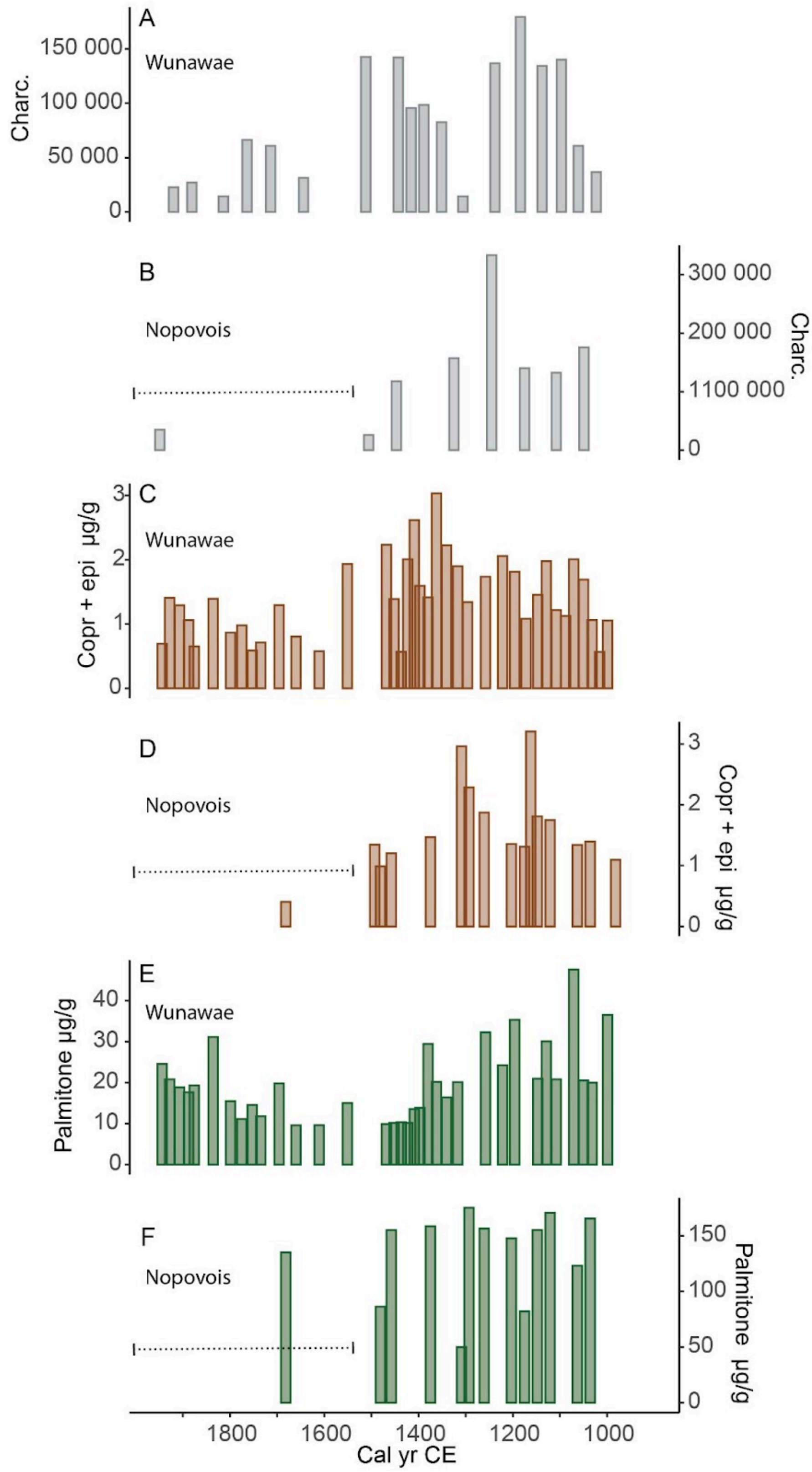
Supplementary material



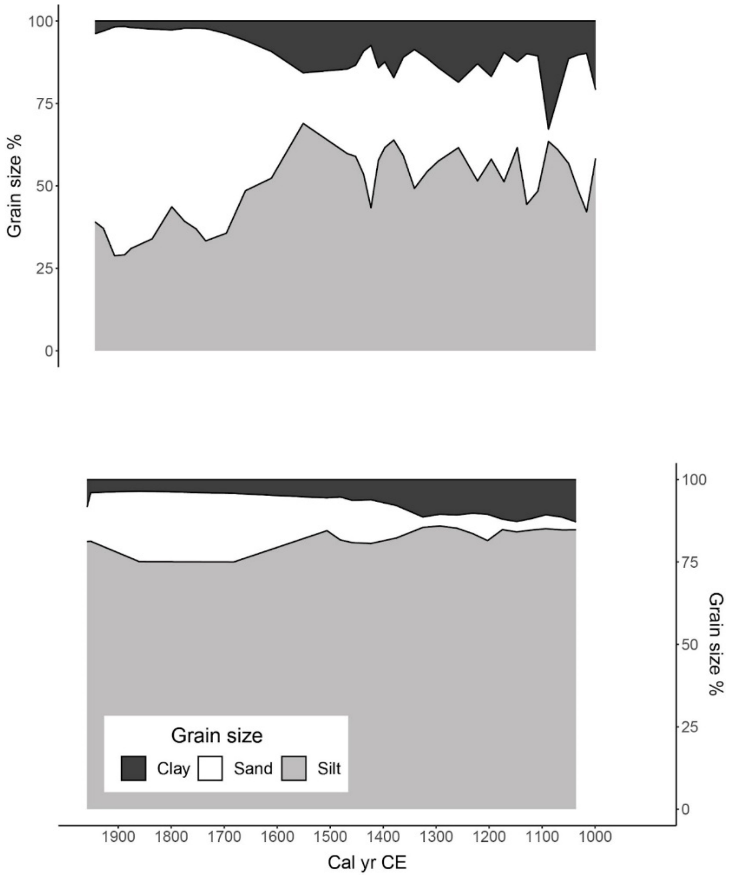
Supplementary Figure 1. Orographic effect on Santo. Color shading according to mean annual rainfall (Bookhagen, 2010). Mean annual rainfall derived from calibrated TRMM 2B31 data.



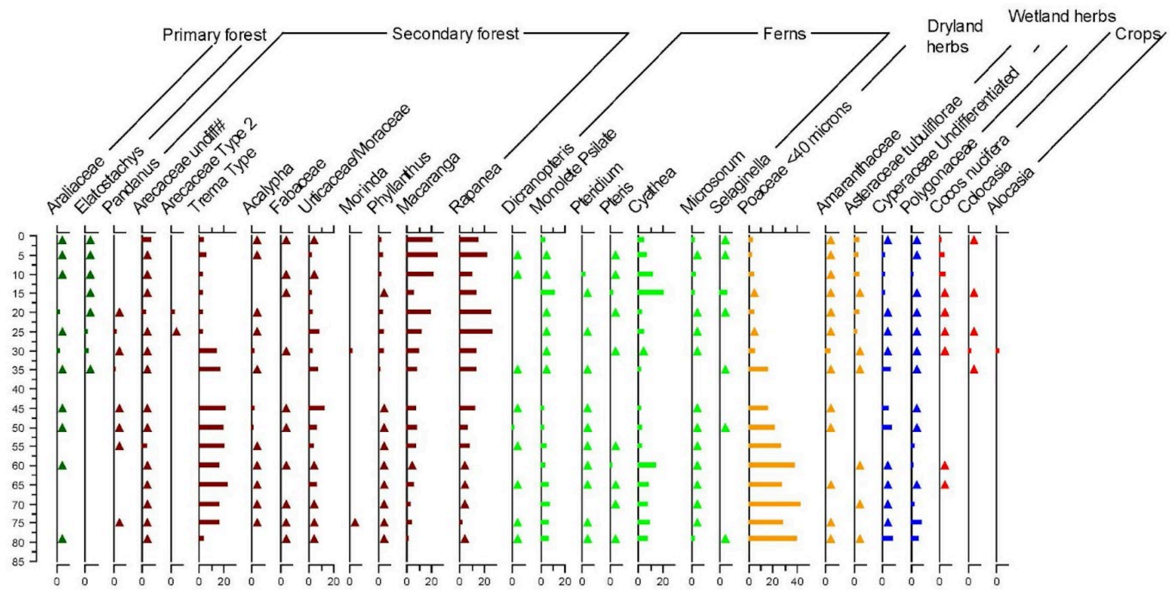
Supplementary Figure 2. Ternary diagram of brGDGT distributions in tropical lake sediments. The brGDGT distributions from Wunavae pond (triangles) fits best the Zhao et al. (2023) calibration rather than the Russell et al. (2018).



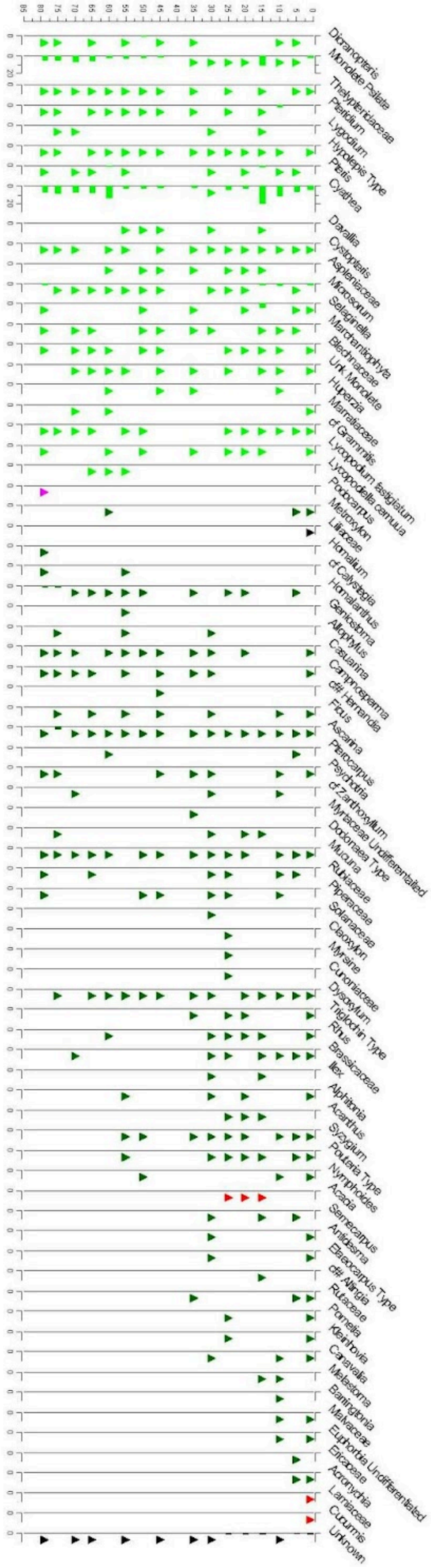
Supplementary Figure 3. Human traces in the west coast of Santo. Charcoal concentration (grey in charcoal grains per cm³) for Wunavae (A) and Nopovois (B), fecal markers concentration (brown) for Wunavae (C) and Nopovois (D), and palmitone (green) for Wunavae (E) and Nopovois (F). Black dotted line represents the slow sediment accumulation rate in Nopovois.



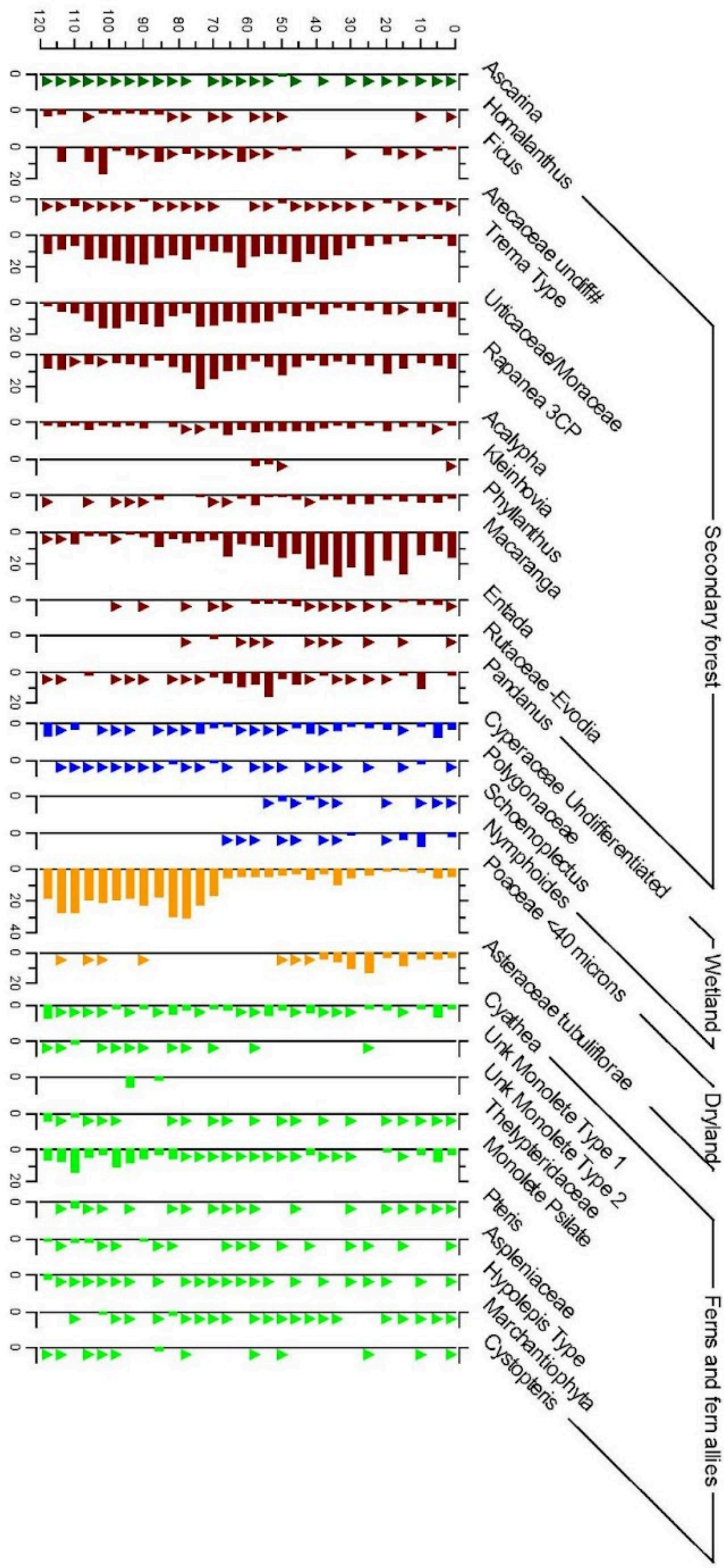
Supplementary Figure 4. Downcore grainsize distribution for Wunavae (top) and Nopovois (bottom). The clay peak in Wunavae at 1100 CE corresponds to a microtephra.



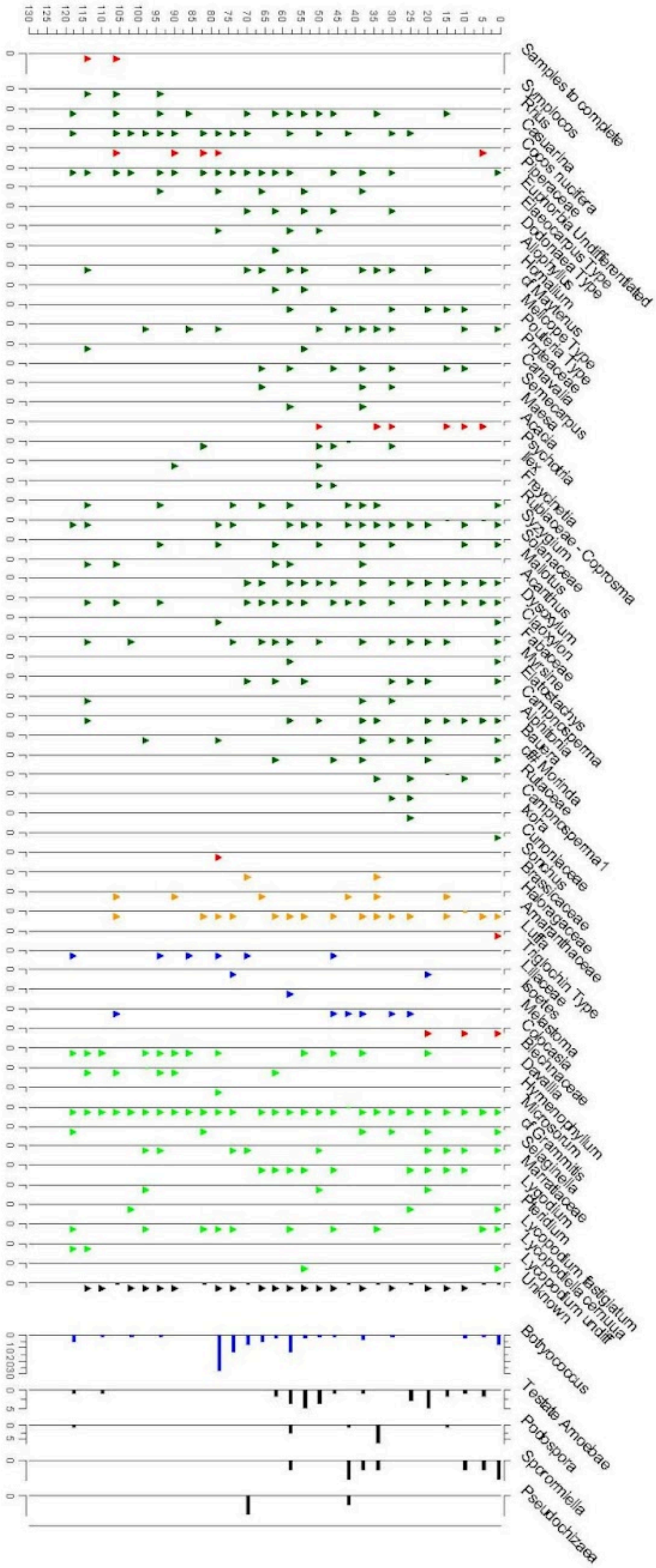
Supplementary Figure 5. Palynological diagram for Wunavae. Major taxa are grouped from left to right as major (taxa with > 5% of total sum for any sample). Taxa are sorted within these groups in stratigraphic succession using the sort function in C2 Data Analysis. Taxa are color coded according to their respective vegetation type; dark green primary forest; maroon secondary forest; light green - pteridophytes; orange - dryland grasses and herbs; blue - sedges, rushes and aquatic plants; and red - exotics (including plant cultigens).



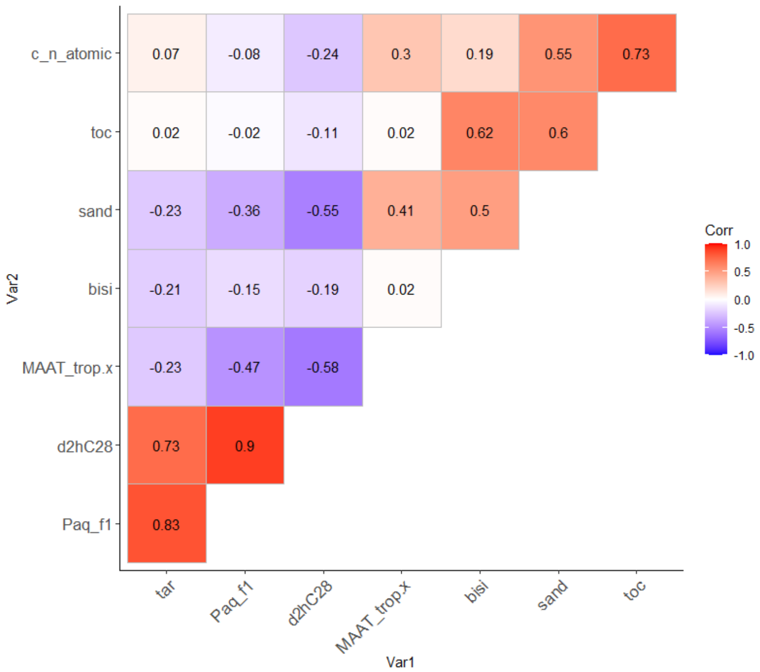
Supplementary Figure 6. Palynological diagram for Wunavae. Major taxa are grouped from left to right as major (taxa with > 5% of total sum for any sample). Taxa are sorted within these groups in stratigraphic succession using the sort function in C2 Data Analysis. Taxa are color coded according to their respective vegetation type; dark green primary forest; maroon secondary forest; light green - pteridophytes; orange - dryland grasses and herbs; blue - sedges, rushes and aquatic plants; and red - exotics (including plant cultigens).



Supplementary Figure 7. Palynological diagram for Nopovois. Taxa are presented as for Figure S5.



Supplementary Figure 8. Palynological diagram for Nopovois. Taxa are presented as for Figure S6.



Supplementary Figure 9. Correlation plot between the biomarkers and bulk geochemical proxies. Warmer colors (red) indicate higher positive correlation between two proxies whereas colder colors (blue) indicate negative correlation.

S1. Proxy interpretation as referred to in Table 1.

Human traces

Microcharcoal concentration (grains/cm^3) is interpreted as a proxy for burning and in this context mostly associated with anthropogenic activities. Although natural fires are not infrequent in the region, shifting cultivation is a practice most likely employed during the initial settlement of the Pacific Islands Pacific (Roos et al., 2023). Fecal molecules have been previously applied in sedimentary context to trace human presence and demography (D'Anjou et al., 2012; White et al., 2019; Sear et al., 2020; Shillito et al., 2020; Keenan et al., 2021; Raposeiro et al., 2021). Coprostanol and epicoprostanol are not unique to humans, as they are produced by pigs and other omnivores (Prost et al., 2017), however such animals were introduced to the Remote Pacific islands by humans (Larson et al., 2007), strengthening the potential of these molecules to reflect human presence in this setting. We used palmitone, a unique marker for taro (*Colocasia esculenta Schott*) which is the main staple crop of the region (Krentscher et al., 2019), to track horticulture. The cultivation of taro requires preventing the plants from flowering to promote the development of larger edible tubers. This practice can limit the production of pollen by taro plants, making it challenging to identify taro cultivation in sediment records using traditional palynological analysis. Thus, palmitone holds high potential as a tracer of taro and early horticulture (Krentscher et al., 2019).

Terrestrial and aquatic ecosystems changes

TOC% reflects changes in erosion and productivity (Meyers and Teranes, 2001) C/N values can be interpreted with higher values (>20) corresponding to an increase in terrestrial input, however in our record C/N never reach those values and is rather indicating changes between submerged vascular or non-vascular plants (lower values) and floating plants (Meyers, 1994, Xia et al. 2014, Gong et al., 2018). BSi is a proxy for the presence of diatoms. Although we cannot distinguish between species, this proxy correlates with other proxies such as C/N, pollen, Paq and TAR, giving indications related to productivity, water levels, and ecosystems shifts. Increase in sand is associated with an increase in erosion, while sharp peaks in clay are associated with tephra layers. Pollen provides indication on changes in vegetation, where secondary forest indicates a landscape that has been disturbed, dryland herbs could be a consequence of land clearing and/or drier periods and wetlands herbs can give indication on the aquatic ecosystems. Paq provides an indication on aquatic vegetation where higher values indicate higher presence of C_{23} and C_{25}, disproportionately represented by macrophytes (Ficken et al., 2000). TAR indicates the changes in contribution between short and long chain fatty acids where C14, C16 and C18 are mainly associated with algae (Tenzer et al., 1999; Fang et al., 2014), thus TAR is similar to Paq and other aquatic proxies. ACL gives indication on changes in vegetation type with higher values usually interpreted as reflecting higher grass contribution.

Climatic proxies

The hydrogen isotopic composition (δ^2H) of fatty acids was measured to identify past changes in precipitation. Long chain n-alkanoic acids are the main constituents of leaf waxes (Meyers and Ishiwatari, 1993) and their δ^2H reflects variations in the isotopic composition of the source of water uptaken by plants and it can be used to reconstruct past hydroclimate in the tropical Pacific (Ladd et al., 2021). Besides changes in precipitation, δ^2H values can be affected by evapotranspiration that enhances isotopic values in dry conditions (enrichment), by changing vegetation that can lead to different isotope fractionations (Garcin et al., 2022), and by changes in the source and transport pathways of the rain/clouds (Risi et al., 2012; Kurita, 2013; Aggarwal et al., 2016). Nevertheless the "amount effect" and evaporative enrichment work in the same direction, thus δ^2H values can still be used to detect overall wetter/drier conditions, without quantitative inference. δ^2H of longer chain n-alkanoic acids (n-C_{26}, n-C_{28}, n-C_{30}) covary. For the interpretation of hydroclimatic variations, we decided to rely on the δ^2H n-C_{28} values given the higher number of measurements available.

A calibration model is used to interpret changes in brGDGTs distribution as quantitative, but relative changes in temperature. The variation in the number of methyl groups (summarized as the MBT'_{5ME}, the Methylation of Branched Tetraethers Index), within different brGDGTs is generally indicative of temperature variations on a global scale. This ratio was at the basis of initial temperature calibrations between soil brGDGTs and mean annual air temperature (MAAT) (De Jonge et al., 2014). Also brGDGT calibration methods for lakes primarily rely on empirical relationships established between the relative abundance of different brGDGTs in surface sediments and either mean annual temperatures or warm-season temperatures (Zhao et al., 2023). Calibrations that include tropical lakes brGDGTs shows a consistent response of brGDGTs to mean annual air temperatures across tropical regions, despite the diverse environmental and geological conditions present in these areas (Zhao et al., 2023).

References

Aggarwal, P. K., Romatschke, U., Araguas-Araguas, L., Belachew, D., Longstaffe, F. J., Berg, P., ... & Funk, A. (2016). Proportions of convective and stratiform precipitation revealed in water isotope ratios. Nature Geoscience, 9(8), 624-629.

Bookhagen, B. 2010, High resolution spatiotemporal distribution of rainfall seasonality and extreme events based on a 12-year TRMM time series, Geophysical Research Letters.

D'Anjou RM, Bradley RS, Balascio NL, Finkelstein DB. Climate impacts on human settlement and agricultural activities in northern Norway revealed through sediment biogeochemistry. Proc Natl Acad Sci U S A. 2012 Dec 11;109(50):20332-7.

De Jonge, C., Hopmans, E. C., Zell, C. I., Kim, J. H., Schouten, S., & Damsté, J. S. S. (2014). Occurrence and abundance of 6-methyl branched glycerol dialkyl glycerol tetraethers in soils: Implications for palaeoclimate reconstruction. Geochimica et Cosmochimica Acta, 141, 97-112.

Fang, J., Wu, F., Xiong, Y., Li, F., Du, X., An, D., & Wang, L. (2014). Source characterization of sedimentary organic matter using molecular and stable carbon isotopic composition of n-alkanes and fatty acids in sediment core from Lake Dianchi, China. Science of the Total Environment, 473, 410-421.

Ficken, K. J., Li, B., Swain, D. L., & Eglinton, G. (2000). An n-alkane proxy for the sedimentary input of submerged/floating freshwater aquatic macrophytes. Organic geochemistry, 31(7-8), 745-749.

Garcin, Y., Schefuß, E., Dargie, G. C., Hawthorne, D., Lawson, I. T., Sebag, D., ... & Lewis, S. L. (2022). Hydroclimatic vulnerability of peat carbon in the central Congo Basin. Nature, 612(7939), 277-282.

Gong, X., Xu, Z., Lu, W., Tian, Y., Liu, Y., Wang, Z., ... & Li, Z. (2018). Spatial patterns of leaf carbon, nitrogen, and phosphorus stoichiometry of aquatic macrophytes in the arid zone of northwestern China. Frontiers in Plant Science, 9, 1398.

Keenan, B., Imfeld, A., Johnston, K., Breckenridge, A., Gélinas, Y., Douglas, P.M.J. (2021) Molecular evidence for human population change associated with climate events in the Maya lowlands, Quaternary Science Reviews, Volume 258, 106904.

Krentscher, C., Dubois, N., Camperio, G., Prebble, M., & Ladd, S. N. (2019). Palmitone as a potential species-specific biomarker for the crop plant taro (Colocasia esculenta Schott) on remote Pacific islands. *Organic Geochemistry*, *132*, 1–10.

Kurita, N. (2013). Water isotopic variability in response to mesoscale convective system over the tropical ocean. Journal of Geophysical Research: Atmospheres, 118(18), 10-376.

Ladd, S. N., Maloney, A. E., Nelson, D. B., Prebble, M., Camperio, G., Sear, D. A., Hassall, J. D., Langdon, P. G., Sachs, J. P., & Dubois, N. (2021). Leaf Wax Hydrogen Isotopes as a Hydroclimate Proxy in the Tropical Pacific. Journal of Geophysical Research: Biogeosciences, 126(3), e2020JG005891.

Larson, G., Cucchi, T., Fujita, M., Matisoo-Smith, E., Robins, J., Anderson, A., ... & Dobney, K. (2007). Phylogeny and ancient DNA of Sus provides insights into neolithic expansion in Island Southeast Asia and Oceania. Proceedings of the National Academy of Sciences, 104(12), 4834-4839.

Meyers, P. A. & R. Ishiwatari, 1993. Lacustrine organic geochemistry — an overview of indicators of organic matter sources and diagenesis in lake sediments. Org. Geochem. 20: 867–900

Meyers, P. A., 1994. Preservation of source identification of sedimentary organic matter during and after deposition. Chem. Geol. 144: 289–302.

Meyers, P. A., & Teranes, J. L. (2001). Sediment Organic Matter. In W. Last, & J. P. Smol (Eds.), Tracking Environmental Change Using Lake Sediments (pp. 240-267). Dordrecht: Kluwer Academic Publishers.

Prost, K., Birk, J. J., Lehndorff, E., Gerlach, R., & Amelung, W. (2017). Steroid biomarkers revisited–Improved source identification of faecal remains in archaeological soil material. PloS one, 12(1), e0164882.

Raposeiro, P. M., Hernández, A., Pla-Rabes, S., Gonçalves, V., Bao, R., Sáez, A., Shanahan, T., Benavente, M., de Boer, E. J., Richter, N., Gordon, V., Marques, H., Sousa, P. M., Souto, M., Matias, M. G., Aguiar, N., Pereira, C., Ritter, C., Rubio, M. J., … Giralt, S. (2021). Climate change facilitated the early colonization of the Azores Archipelago during medieval times. *Proceedings of the National Academy of Sciences*, *118*(41), e2108236118.

Risi, C., Noone, D., Worden, J., Frankenberg, C., Stiller, G., Kiefer, M., ... & Sturm, C. (2012). Process-evaluation of tropospheric humidity simulated by general circulation models using water vapor isotopic observations: 2. Using isotopic diagnostics to understand the mid and upper tropospheric moist bias in the tropics and subtropics. Journal of Geophysical Research: Atmospheres, 117(D5).

Russell, J. M., Hopmans, E. C., Loomis, S. E., Liang, J., & Damsté, J. S. S. (2018). Distributions of 5-and 6-methyl branched glycerol dialkyl glycerol tetraethers (brGDGTs) in East African lake sediment: Effects of temperature, pH, and new lacustrine paleotemperature calibrations. Organic Geochemistry, 117, 56-69.

Sear, D.A., Allen, M.S., Hassall, J.D., Maloney, A.E., Langdon, P.G., Morrison, A.E., Henderson, A.C.G., Mackay, H., Croudace, I.W., Clarke, C., Sachs, J.P., Macdonald, G., Chiverrell, R.C., Leng, M.J., Cisneros-Dozal, L.M., Fonville, T., 2020. Human settlement of East Polynesia earlier, incremental, and coincident with prolonged South Pacific drought. Proc. Natl. Acad. Sci. Unit. States Am. 117, 8813e8819.

Shillito, L. M., Blong, J. C., Green, E. J., & van Asperen, E. N. (2020). The what, how and why of archaeological coprolite analysis. Earth-Science Reviews, 207, 103196.

Roos, C. I., Field, J. S., & Dudgeon, J. V. (2023). Fire activity and deforestation in Remote Oceanian islands caused by anthropogenic and climate interactions. *Nature Ecology & Evolution*, 1–9.

Tenzer, G. E., Meyers, P. A., Robbins, J. A., Eadie, B. J., Morehead, N. R., & Lansing, M. B. (1999). Sedimentary organic matter record of recent environmental changes in the St. Marys River ecosystem, Michigan–Ontario border. Organic Geochemistry, 30(2-3), 133-146.

White, A. J., Stevens, L. R., Lorenzi, V., Munoz, S. E., Schroeder, S., Cao, A., & Bogdanovich, T. (2019). Fecal stanols show simultaneous flooding and seasonal precipitation change correlate with Cahokia's population decline. Proceedings of the National Academy of Sciences, 116(12), 5461-5466.

Xia, C., Yu, D., Wang, Z., & Xie, D. (2014). Stoichiometry patterns of leaf carbon, nitrogen and phosphorous in aquatic macrophytes in eastern China. Ecological Engineering, 70, 406-413.

Zhao, B., Russell, J. M., Tsai, V. C., Blaus, A., Parish, M. C., Liang, J., ... & Bush, M. B. (2023). Evaluating global temperature calibrations for lacustrine branched GDGTs: Seasonal variability, paleoclimate implications, and future directions. Quaternary Science Reviews, 310, 108124