Late Holocene landscape reconstruction of the lower *'Ōpūnohu* Valley, *Mo'orea* Island (South Pacific, Society Islands) and its geoarchaeological implications

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Abstract

A multidisciplinary study was conducted in the high volcanic island of *Mo'orea* (South Pacific, French Polynesia) in order to reconstruct its long-term environmental evolution together with its history of human occupation over the last three millennia. The *'Ōpūnohu* Valley, in particular, records one of the longest and best documented human histories of the island dating from the first Polynesian (*Mā'oh*i) occupation, from roughly the 11th to the 18th Cent. CE. In order to reconstruct past landscape dynamics that include both the depositional history of the sediments and the shoreline mobility, we have studied six sedimentary profiles from the foothills and from the modern coastal floodplain. Laboratory work includes loss on ignition measurements, laser granulometry analyses and pollen/NPP identification. Chronostratigraphy was based on a series of five radiocarbon datings performed on charcoals, organic sediment, and coral debris. Palaeoenvironmental results reveal two major phases of detrital input related to deforestation (fires) and changes in land-use, first during the *Mā'ohi* period, and secondly at the onset of the European period. The substantial delivery of these fine-grained sediments into *'Ōpūnohu* Bay has contributed to the formation of a delta since the onset of the 2nd millennium CE. Our results bring to light the contribution of anthropogenic actions and external factors to explain the specific landscape evolution of the *'Ōpūnohu* coastal plain since the beginning of human settlement on the island. Finally, our work is of archaeological interest since it helps to determine primary settlement of the *Mā'ohi* people and associated structures in the context of a rapidly shifting shoreline.

Keywords: Stratigraphy; sedimentology; vegetation history; palaeoenvironments; Society Islands; shoreline mobility

1. Introduction

French Polynesia (South Pacific; Figure 1) is made up of 124 islands (Galzin and Meyer, 2024) divided between five archipelagos (namely the Austral, Gambier, Marquesas, Society, and Tuamotu Islands) located more than 5,000 km from any continent. French Polynesia represents one of the most recently settled environments on Earth, with people arriving approximately one millennium ago (Kahn, 2006; Wilmshurst et al., 2011; Montenegro et al., 2014; Hunt and Lipo, 2017). It is also an environment which has been highly impacted by anthropogenic activities since its early settlement, as demonstrated by palaeoenvironmental studies conducted, in particular, in the Society Islands since the early 1990s (Lepofsky et al., 1992 and 1996; Parkes, 1994 and 1997; Kahn et al., 2015; Stevenson et al., 2017). Indeed, the arrival of the first Polynesian people (*Te ta'ata Mā'ohi* in the Tahitian language) in the Society Islands, dated to around the onset of the 2nd millennium CE (Montenegro et al., 2014), left major evidence of drastic environmental changes caused by the introduction of many plants, useful mainly for food, medicine, ritual, sculpture or weaving purposes (Lepofsky, 2003; Lepofsky and Kahn, 2011; Whistler, 2009). The Society Islands, and in particular *Mo'orea* (Figure 1), were first settled around the 11th-13th Cent. CE (Kahn, 2011; Kahn and Sinoto, 2017), leading to a first phase of agricultural development that peaked during the 12th-17th centuries CE (Lepofsky et al., 1996; Lepofsky and Kahn, 2011). A phase of particularly intense development occurred in inland *Mo'orea*, while the coastal area seems to have been more sparsely settled from the 13th-15th Cent. CE (Stevenson et al., 2017). This situation can be attributed to the unique social organization of the valleys in the Windward Islands (Maric, 2016; Kahn and Lepofsky, 2022), where the social elite (*ari'i*) resided on coastal promontories, and the common people (*manahune*) lived in the valley interiors. The mid valleys and headwaters were therefore intensely occupied and exploited, and as a direct consequence, both the vegetation composition and the hillslopes were deeply impacted by human activities, with most of the food crops being grown in small home gardens, in expansive tree crop plantations, and in larger terraced and plot field systems of varied shape (Kahn et al., 2022). Ethnohistorical studies have given rise to considerable interest in better evaluating the complex human-environment relationships in both space and time, and at the scale of the catchment basin rather than at a within-site scale. Human impacts on the landscape included the clearing of primary forest on the hillslopes by burning and the subsequent establishment of open landscapes dominated by ferns (Lepofsky, 1994; Stevenson et al., 2017). During this period (13th-15th Cent. CE), agricultural terraces and barrages to retain sediments developed in the upper elevations (Lepofsky, 1994; Lepofksy and Kahn, 2011), testifying to heavy land-use in the upper/middle courses of the *'Ōpūnohu* catchment.

The second phase of major anthropogenic impact on landscape and vegetation coincides with the arrival of Europeans at the turn of the 19th century CE (Lepofsky et al., 1996). Contact with the Europeans and the staggering mortality brought about by their diseases forced the *Mā'ohi* people to abandon their agricultural structures. This opened the door to a new phase of agricultural development which was marked by the most significant burning activity since human settlement was first recorded on the island (Stevenson et al., 2017). New plants such as rice (Figure 2) were mainly cultivated on *Mo'orea* in the lowlands of the *'Ōpūnohu* Valley (Lepofsky et al., 1996) and in the coastal area.

Over the last three decades, several archaeological, ethnohistorical and palaeoecological studies have addressed the main human impacts on the terrestrial environments of *Mo'orea* since its early human occupation (Lepofsky et al., 1996; Lepofsky and Kahn, 2011; Kahn et al., 2015; Stevenson et al., 2017). Few of these studies, however, have focused on the long-term sedimentary dynamics and their impacts on either sediment transfers or on coastline mobility. In addition, studies that have aimed at reconstructing shoreline evolution in *Mo'orea* have exclusively covered the second half of the 20th Century CE and the first two decades of the 21st Century CE (Aubanel et al., 1999; Vieux et al., 2008; Benet, 2010; Madi Moussa et al., 2019). The aim of the present paper is thus to fill this gap concerning the coastal area of the lower *'Ōpūnohu* Valley and to reconstruct the shifting of the shoreline prior to and following the arrival of humans in *Mo'orea.* This enables to better evaluate the direct consequences of the accompanying anthropogenic activities, and the changes in land-use that they entailed, on the sedimentary and landscape dynamics over the last millennium. The geoarchaeological approach adopted here contributes significantly to improving understanding of landscape dynamics as influenced by human disturbances across time. This approach also permits better estimations of palaeoshoreline positions which, in turn, will encourage further archaeological surveys in pursuit of discovering the first human settlements in *Mo'orea*.

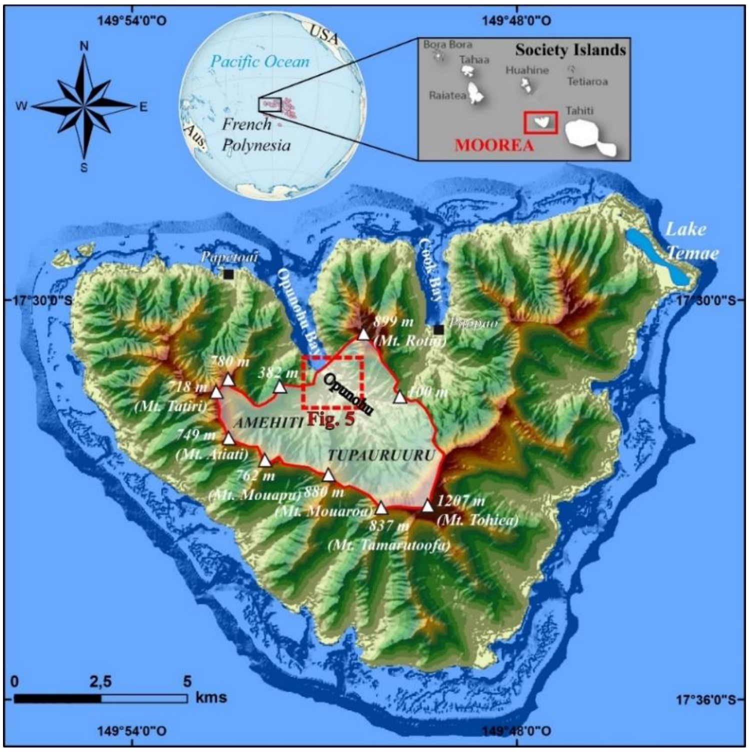

Figure 1 – Location map of the 'Ōpūnohu Valley (red line: full catchment basin) and of the stratigraphic profiles (red square with dashed lines). Elevation data are derived from LiDAR data (Shom-SAU-NSF, 2015; projection system : WGS 84).

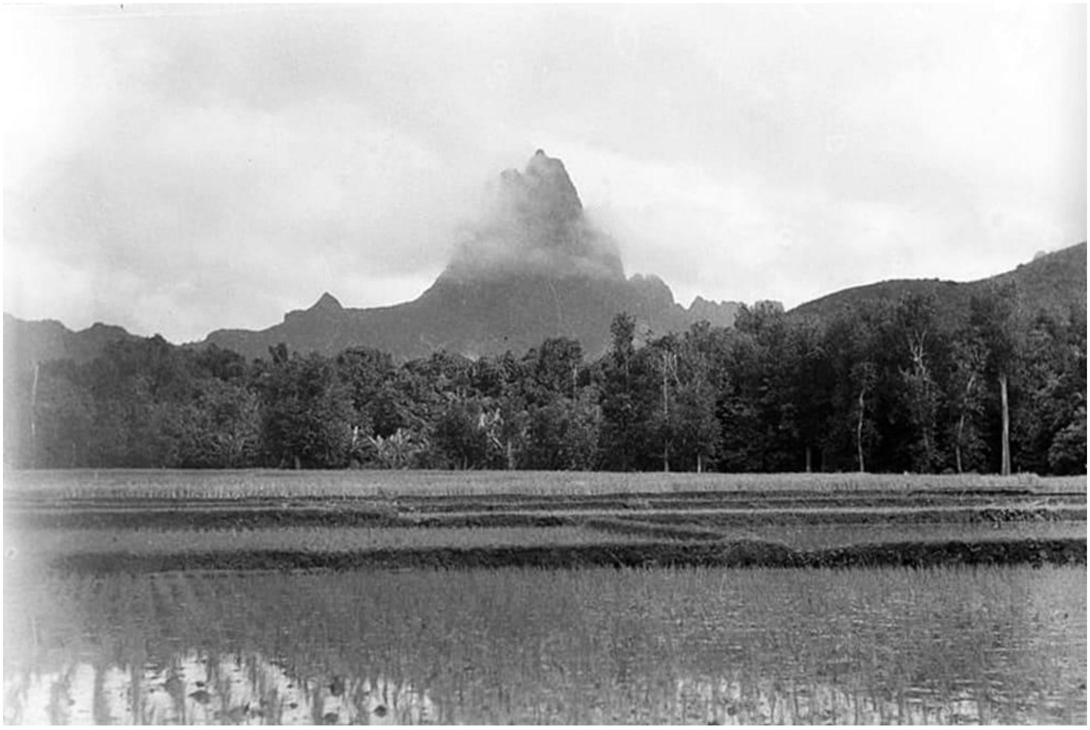

Figure 2 – Foreground: rice fields in the lower 'Ōpūnohu Valley in 1932 with Mt. Mou'aroa in the background. Credit: R. Parry

2. Study area

2.1. Topography, geology and hydrology

Mo'orea is a small (about 135 km²) high volcanic island (17°32'33''S, 149°49'50''W) located ca. 18 km to the north-west of Tahiti (Fig. 1), the main island of the Society Archipelago in French Polynesia. *Mo'orea* is characterized by a central volcano and a barrier reef protecting a lagoon of 49 km². The *'Ōpūnohu* catchment is the largest on the island and is situated in the north, covering a drainage basin of about 18 km² (Figure 1). It is bordered (Figure 1) to the north-east by Mt. *Rotui* (899 m), to the west by Mt. *Mouaro'a* (880 m) and to the south by Mt. *Tohi'e'a* (1207 m), the highest summit on the island. Steep slopes characterize the highest elevations, while the lower *'Ōpūnohu* River valley consists of a large floodplain covering ca. 1 km². From a geological point of view, the island consists of a shield volcano that emerged aerially between 1.72 and 1.52 million years ago (MYA; Le Dez et al., 1998; Figure 3). Immediately after the formation of the volcanic dome, a caldera began to form and a landslide of the north-central part of the island resulted in the current semicircular shape (Figure 2). Different cracks appeared in the shield volcano that were infilled by benmoreite in the region of *Papetō'a'ī* (Le Dez et al., 1998; Figure 3) from 1.53 to 1.47 MYA and by basalts around 1.52 MYA in the region of *Pa'opa'o-Paveo* (Le Dez et al., 1998; Figure 3). As a result, the *'Ōpūnohu* catchment encompasses the initial crater of the volcano at that time. This crater became a caldera 1.52 MYA, causing a translational displacement of Mt. *Rotui* to the north (Figure 3). *'Ōpūnohu* and Cook bays developed in the caldera where important subsidence is recorded (Le Dez et al., 1998). From a tectonic point of view, the Society Islands appear to be relatively stable (Camoin et al., 2012; Hallmann et al., 2020): subsidence rates are low and constant (Bard et al., 1996; Fadil et al., 2011), comprised between 0.25 mm per year on Tahiti (Hallmann et al., 2018) and 0.15 mm per year on Moorea (Pirazzoli and Montagionni, 1988). The Society Islands are characterized by a general low tidal amplitude of less than 0.15 m (Hallmann et al., 2018).

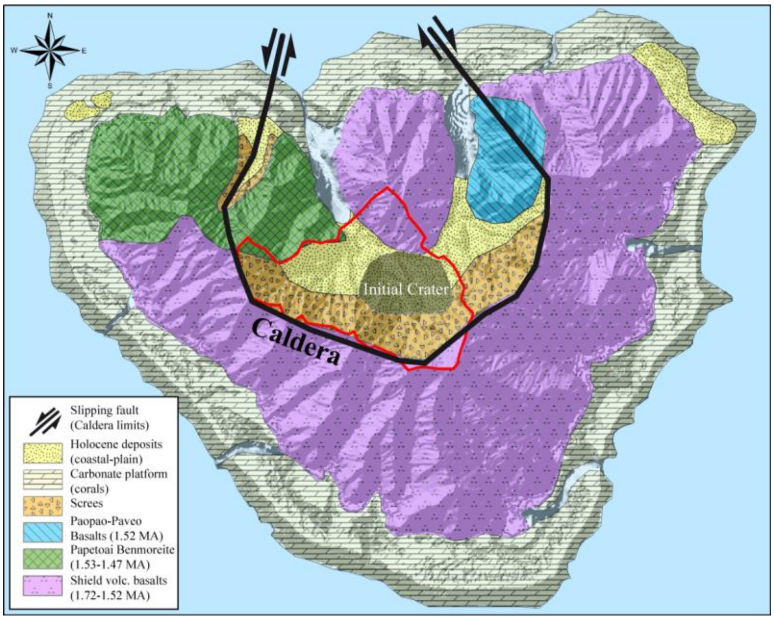

Figure 3 - Geological map of Mo'orea Island (adapted from Le Dez et al., 1998)

2.2. Present-day climate conditions and vegetation types

Mo'orea has a tropical oceanic climate with a relatively dry and cold season (May to October) alternating with a wet and warm season (November to April). Monthly air temperature ranges between 27.5°C in March and 24.4°C in August. Total precipitation ranges from 2600 (to the East, in the vicinity of Lake *Temae* at sea-level; Figure 4) to 3250-3500 mm per year (around *'Ōpūnohu* Bay and catchment; Figure 4) (Laurent and Maamaatuhaiahutapu, 2019).

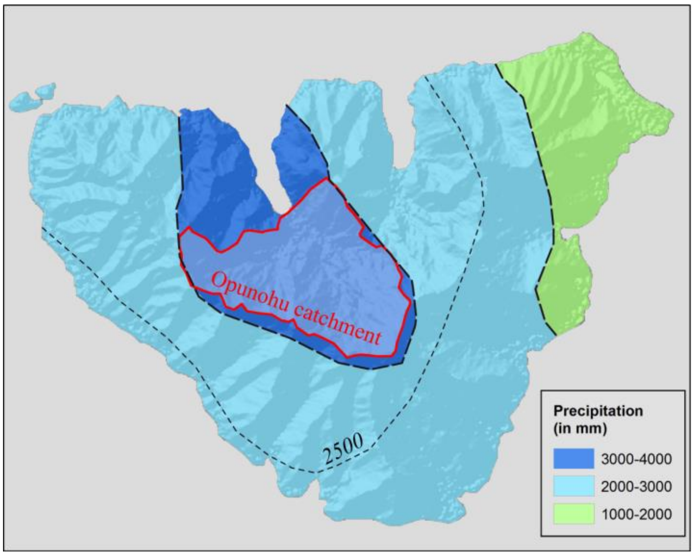

Figure 4 – Precipitation map of Mo'orea Island

Today, native primary forests cover only 6% (about 8 km²) of *Mo'orea* (Meyer et al., 2015), and are mainly situated on the highest summits of Mt *Tohi'e'a*, Mt *Rotui* and Mt *Mou'aputa*. Anthropogenic conversion due to urbanization, agriculture, and forestry plantations account for 32 % of the island (43 km²), principally in the coastal areas and flat lowlands. Highly invaded habitats cover 17 % of the island (23 km²). These include monotypic stands of several naturalized alien trees such as *Falcataria* (syn. *Albizia*) *moluccana* (Fabaceae), *Leucaena leucocephala* (Fabaceae), the African tulip *Spathodea campanulata* (Bignoniaceae), the Java plum *Syzygium cumini* (Myrtaceae), and the common *guava Psidium guajava* (Myrtaceae), as well as areas extensively planted with the Caribbean pine *Pinus caribaea* (Pinaceae). The remaining 45 % (60 km²) of the island is partially invaded with mixed native and non-native plant communities that can be called "hybrid habitats", including 25 % (ca. 34 km²) invaded by the small tree *Miconia calvescens* which forms dense stands in the subcanopy forest layer (Meyer et al., 2015).

The urbanized coastal areas reveal very few remains of the coastal strand, littoral and estuarine forests. Cultivated areas are situated in the lowlands and consist of mainly pineapple (*Ananas comosus)* and forestry plantations with Caribbean pine (*Pinus caribaea*), as well as some alien grasslands for cattle rearing. Regarding specifically the present-day vegetation composition of the *'Ōpūnohu* catchment, four main vegetation types are relatively preserved from human activities, and can be distinguished in the *'Ōpūnohu* Valley (Meyer et al., 2011) as follows:

i) low elevation wet forest or lowland rainforests (>100-400 m elev.) dominated by the native tree *Talipariti tiliaceum* (syn. *Hibiscus tiliaceus*), the native trees *Neonauclea forsteri*, *Crossostylis biflora*, *Rhus taitensis* and more rarely, presence of the small endemic tree *Pisonia tahitensis*. In the understory, presence of the endemic or native shrubs *Ixora mooreensis*, *Cyclophyllum barbatum*, the climbing liana *Freycinetia impavida,* and the large fern *Angiopteris evecta*;

ii) low elevation ridges mesic forest (>200-400 m) comprised of the native trees *Metrosideros collina, Pandanus tectorius, Wikstroemia coriacea, Tarenna sambucina*, *Commersonia bartramia*, more rarely the presence of endemic *Pittosporum taitense*, and in the understory, the ferns *Dicranopteris linearis, Davallia solida, Nephrolepis hirsutula*;

iii) exposed ridges and rocky slopes (> 400 m) with dominance of the native trees *Pandanus tectorius, Fagraea berteroana, Tarenna sambucina*. More rarely observable are the endemic tree *Meryta lanceolata* and the endangered *Santalum insulare* var. *raiateense*;

iv) mid elevation wet forest (> 400 m) made up of the endemic trees *Pterophylla* (syn. *Weinmannia*) *parviflora* var. *parviflora*, *Myrsine ovalis*, *Astronidium* sp., the native trees *Crossostylis biflora*, *Alstonia costata*, the endemic tree ferns *Cyathea affinis* (syn. *Alsophila tahitensis*) and *Cyathea societarum* (syn. *C. medullaris*), and in the understory, the rare endemic shrubs *Psychotria* sp., *Cyrtandra* spp. and native terrestrial orchids *Corymborkis veratrifolia*, *Calanthe* spp.

2.3. Archaeological background

The *'Ōpūnohu* Valley has been has been widely studied for archaeological purposes since the early 1960s (Green, 1961 and 1967). In particular, over the last three decades, the *'Ōpūnohu* catchment and *Amehiti*/*Tupauruuru* sub-drainage basins (Figure 1) were targeted for archaeological, ethnohistorical and palaeobotanical studies, revealing the existence of sites of human occupation, ritual practice, and agricultural structures such as terraces or dams for sediment retention (Lepofsky, 1994; Kahn ~~&~~ and Kirch, 2004; Hamilton ~~&~~ and Kahn, 2007; Kahn et al. 2015; Stevenson et al. 2017). All these studies have highlighted that anthropogenic disturbances on the environments and associated landscapes began with the arrival of the first Polynesians in the Society Islands and their settlement of both the coastal area and the interior of the catchment basin. Although still under debate~~d~~, initial colonization of the island is estimated at around 950 years BP, i.e. around the 11th century CE (Kahn, 2006 and 2011; Lepofsky et al. 1996; Kahn et al. 2015; Stevenson et al. 2017), with a possible earliest date of 700 CE (Lepofsky et al., 1992). The history of human occupation of the *'Ōpūnohu* Valley is probably the most documented of all valleys on the island and probably of all the French Polynesian islands. The lower *'Ōpūnohu* Valley and its coastal area was certainly considered to be ideal for multiple tropical crops (Stevenson et al., 2017) and in particular, for coconut plantations in the early period of initial human occupation of the palaeo-shore (Lepofsky et al., 1992; Lepofsky and Kahn, 2011). The choice of crops has evolved over time, with the lower river valley seeing a succession of agricultural activities, including coconut (*Cocos nucifera*) plantations, cattle rearing, sugar cane, coffee (*Coffea Arabica)*, vanilla (*Vanilla x tahitensis),* and finally pineapple (*Ananas comosus)* cultivation since the 19th century (Meyer et al., 2011).

Archaeological and ethnographical studies bear witness to the territory's occupation prior to European colonization, and suggest that the land in the *'Ōpūnohu* Valley may have been occupied by a much larger number of people at much higher altitudes than has been the case since the arrival of the Europeans (Hamilton and Kahn, 2007). The direct consequences of this long-term human occupation in terms of environmental changes have been addressed through a series of valuable geoarchaeological projects conducted from the 1990s to the 2010s which have included archaeological excavations as well as ethnohistorical and palaeoenvironmental reconstructions, all of which have pointed to the development of agriculture in the interior of the valley for agricultural purposes (Hamilton and Kahn, 2007; Kahn and Leposfky, 2022).

2.4. Previous sedimentological and palaeoenvironmental investigations

Over the past three decades, a series of palaeoenvironmental and geoarchaeological studies have been undertaken i) on the northern side of *Mo'orea*, mainly focusing on Lake *Temae* to the north-east (Stevenson et al., 2017; Figure 1), ii) to the north of the island along Cook's Bay (Kahn, 2012) and iii) in the upper reaches of the *'Ōpūnohu* River valley(Lepofsky, 1994; Lepofsky et al., 1996; Kahn, 2005;

Lepofsky and Kahn, 2011) and along the present-day shoreline (Hamilton and Kahn, 2007; Kahn et al., 2015). These previous studies have notably focused on charcoals, pollens, seeds and plant macroremains found in stratigraphic contexts of cores and in profiles during excavations. The main results of the palaeoenvironmental studies conducted on the northern side of *Mo'orea* have revealed major forest clearance brought about by the intense use of fire (Stevenson et al., 2017) shortly after the arrival of the *Mā'ohi* people. This has also been evidenced through the high concentration of charcoals found in sedimentary records documented in the lower *'Ōpūnohu* Valley by Lepofsky et al., 1996 (Fig. 5). The main stratigraphic results of the sections studied in the floodplain and on the lower hillslopes by Lepofsky et al., 1996 (Fig. 5) revealed two distinct phases of charcoal accumulations at depths of 1 and 2 m from the surface, respectively. However, both layers remain undated. General stratigraphy indicates a fine-grained deposition ca. 3 m thick overlying basal deposits formed by coarser sediments ranging from gravels to pebbles, and associated with fluvial-colluvial material.

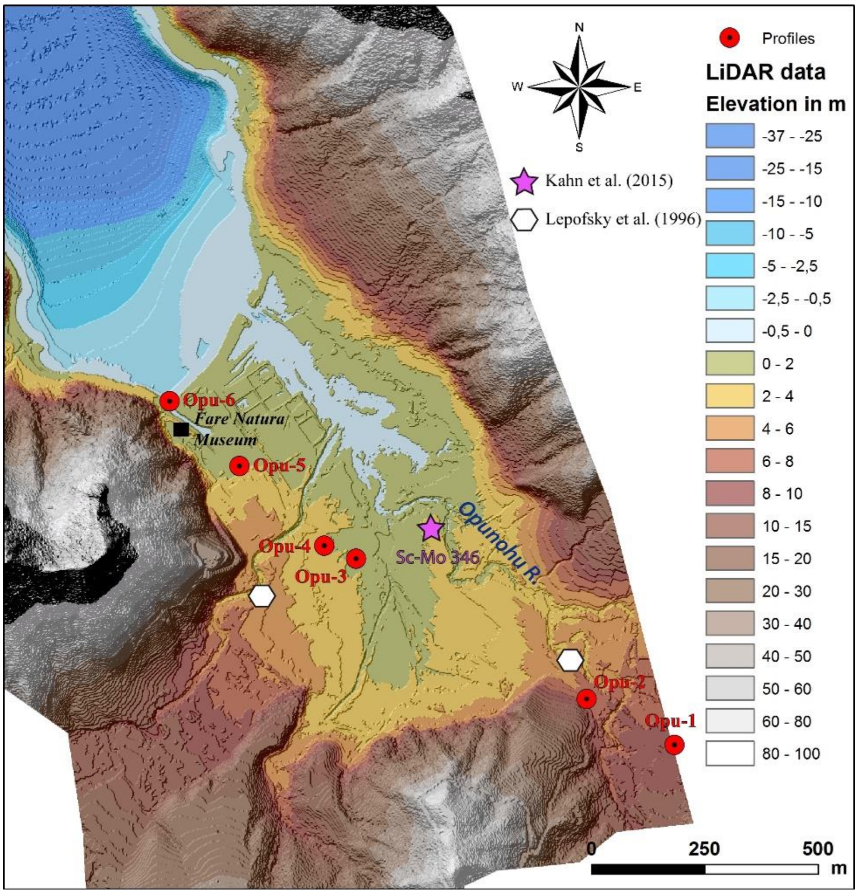

Figure 5 - Location map of the six sedimentary profiles (red circles, Table 1) and previous palaeoenvironmental studies (purple star and white polygons) located in the 'Ōpūnohu Valley floor. Digital Elevation model is derived from LiDAR data (Shom-SAU-NSF, 2015; projection system : WGS 84)

An important study was also conducted by Kahn et al. (2015) in the *'Ōpūnohu* Valley floor (Figure 5) in the same area that we investigate for the present paper : the profile referenced ScMo-346 (Kahn et al., 2015; Figure 5) reveals the depositional history through the first two meters from the surface and roughly confirms the stratigraphy obtained by Lepofsky et al. (1996). The stratigraphic results obtained can be summarized as follows, with three main units identified from the top (present day surface topography) to the bottom : i) from 0 to 60 cm deep: structureless reddish silty clay loams (colluvium), ii) From 60 to 130 cm deep : reddish to brown clayey silts (with less clay than the layer above), and iii) from 130 to 200 cm in depth : massive, structureless gleyed clays containing organic material in the lowermost part. The latter has been roughly dated between 280 and 0 cal BP (radiocarbon dating performed on an aerobically preserved *Persicaria* sp. seed) but most likely pre-dates European arrival (Kahn et al., 2015). This age is confirmed by the identification of many taxa probably related to Polynesian introductions (Prebble, 2008). The insect fauna is dominated by taxa probably introduced prehistorically, but includes smaller numbers of indigenous and/or endemic terrestrial and freshwater species (Kahn et al., 2015).

Studies conducted by Lepofksy et al. (1996) and more recently by Kahn et al. (2015) both provide valuable chronostratigraphical and palaeoecological information. Further to this, we have conducted new chronostratigraphic investigations so as to better evaluate the archaeological potentialities and elucidate the full Late Holocene morphological evolution of the *ʻŌpūnohu* coastal floodplain and in particular, the shifting of the adjacent shoreline.

3. Material and Methods

To enable reconstruction of the past landscape of the *ʻŌpūnohu* Valley floor including sediment geometry and palaeo-vegetation composition, six stratigraphic sections were excavated using a backhoe loader along a transect running from the foothills of Mt *Tohi'e'a* to the modern shoreline, following a general SE-NW direction (Figure 5; Table 1). Depending on the height of the water table, the soil pits ranged in depth from 150 to 220 cm. Each stratum was characterized for texture and colour, and the stratigraphic log of each section was generated. Elevation of each stratigraphic profile was derived from available LiDAR data (Shom-NAU-NSF, 2015) with vertical error of ± 0.1 m.

Table 1 - Stratigraphic profiles locations. Elevation is derived from LiDAR data (Shom-NAU-NSF, 2015) and processed using GIS software.

Profile	Length (in cm)	X (WGS 84)	Y (WGS 84)	Elevation amsl (in m, error : ± 0.1 m)
ʻŌpūnohu 1	160	-149.840672°	-17.525022°	+9,9
ʻŌpūnohu 2	200	-149.842484°	-17.524076°	+7,8
ʻŌpūnohu 3	150	-149.847228°	-17.521211°	+2,7
ʻŌpūnohu 4	165	-149.84788°	-17.52094°	+3,2
ʻŌpūnohu 5	145	-149.849616°	-17.519325°	+2,4
ʻŌpūnohu 6	220	-149.851048°	-17.518013°	+2,2

3.1. Organic matter/carbonate content

Loss-on-ignition (LOI) measurements were conducted at CEREGE following Dean (1974) and Bengtsson and Enell (1986). Sediment samples of approximately 10–20 g were taken at 10 cm intervals throughout the sequences derived from *'Ōpūnohu* 3 and 6 sections. After drying at 105°C to constant weight, the samples were heated to 550°C for 7 h to estimate the organic content. A second heating phase to 950°C for a further 7 h was undertaken to assess the proportion of carbonate.

3.2. Laser granulometry

Samples from *'Ōpūnohu* 3 and 6 sections were taken at 10 cm intervals. All the layers contained fine particles only (less than 2 mm), and laser diffraction grain-size analyses were then undertaken. The grain-size distribution was measured using a Beckman Coulter LS 13 320 laser granulometer at CEREGE following the protocol described in Ghilardi et al., 2012 and 2014.

3.3. Pollen and NPP identification

Pollen analysis was focused on 6 samples from Mo'orea Island. Samples were processed following standard methods (Goeury and Beaulieu, 1979; Girard and Renault-Miskovsky, 1969) using treatment with HCL, NaOH, flotation in dense Thoulet liquor, HF, and final mounting in glycerine. This first evaluation involved the analysis of one transect (line) for each sample using a Motic BA210E microscope fitted with ×10 oculars and ×40/60 objectives, in order to evaluate the potential interest of conducting palynological analyses on these sedimentary deposits in the context of future research.

3.4. AMS Dating

The chronostratigraphy of the profiles was established using a series of 5 AMS radiocarbon samples performed on charcoals, plant remains, organic sediment and a fragment of coral (Table 2). The analyses were conducted in the Poznan (Poland) Radiocarbon Dating Laboratory. 14C ages were subsequently calibrated using Calib Software Version 8.2 (Stuiver and Reimer, 1993), the IntCal20 calibration curve for terrestrial samples (Reimer et al., 2020), and the Marine 20 calibration curve for the marine sample (Heaton, 2020). A regional correction for $\Delta R = -137 \pm 22$ was applied following Broecker et al., 1961 and Petchey et al., 2008.

Table 2 - Radiocarbon dating results

Section id	Depth (in m)	Elevation amsl (in m)	Material	BP	Error ±	Calibrated ages (2σ)	Lab. code
***'Ōpūnohu* 2**	0,64	+ 7,16	Charcoal	910	290	873-1319 CE	Poz-175546
***'Ōpūnohu* 3**	0,50	+ 1,7	Charcoal	335	30	1477-1683 CE	Poz-183502
***'Ōpūnohu* 6**	1,73	+ 0,47	Plant remains	85	30	1688-1924 CE	Poz-163101
	1,97	+ 0,23	Organic sediment	980	90	887-1230 CE	Poz-183866
	2,07	+ 0,13	Coral (fragment)	3185	35	1163-789 BCE	Poz-175865

4. Results

4.1. Biostratigraphy of the sedimentary profiles located in the foothills

Five Sedimentary Units can be identified, as follows (Figure 6) :

- Unit I is found only in the *'Ōpūnohu* 1 section and is a mixture of large rounded cobbles of black colour (basalt) embedded within a gravelly-sandy orange matrix.
- Unit II is encountered only in the *'Ōpūnohu* 2 section. It consists of a mixture of oxidized clays with inclusion of different beds of basaltic gravels (lowermost part of the unit) and large nodules of basalts (uppermost part of the unit).
- Unit III is found exclusively in the *'Ōpūnohu* 2 section and is comprised of layers of anoxic grey clays with thicknesses about 15 to 30 cm, with a dark grey sandy layer visible in its lowermost part.
- Unit IV is found in both profiles and is made up of a one-meter-thick stratum of oxidized orange clays. Radiocarbon dating was performed on a large piece of charcoal found in a rich, 10-cm-thick charcoal stratum, situated in the lowermost part of the unit (transition with Unit III), resulting in an age of 873-1319 cal. CE.
- Unit V is found in all profiles between the surface and depths of ca. 15-20 cm, and consists of a layer of humus (organic clays supporting the current soil; Fig. 3). This humus is brown in colour and supports the current root network.

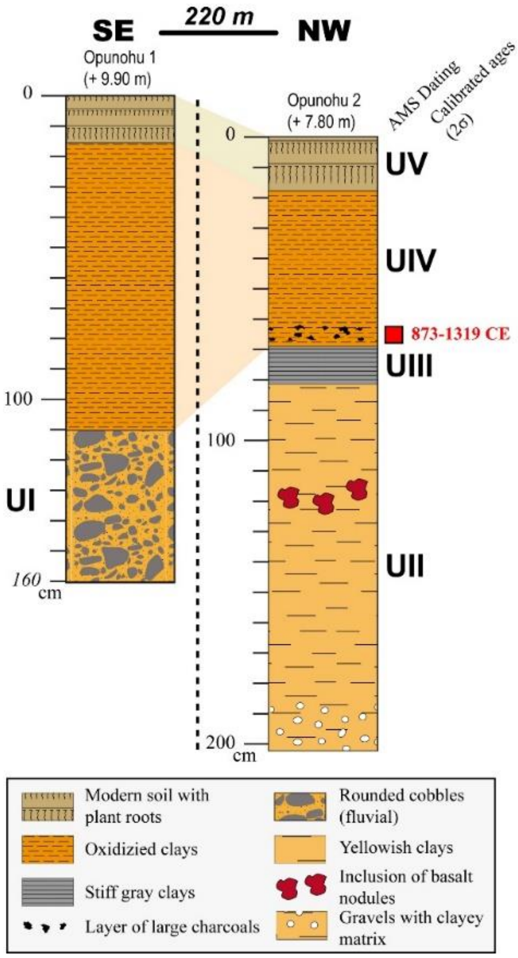

Figure 6 – Stratigraphic profiles 'Ōpūnohu 1 and 2 located in the foothills.

4.2. Biostratigraphy of the sedimentary profiles located in the valley floor/Estuary

Eight Sedimentary Units can be identified, as follows (Figure 7) :

- Unit 1 is found only in profile *'Ōpūnohu* 6, between 2.20 and 2 m deep, and is composed of a mixture of well-rounded basalt cobbles with coarse sands, coral debris and marine shell fragments: one full specimen of marine gastropod, *Conus* sp. has been identified. A large piece of branching coral found embedded within a sandy matrix between the large rounded basalt cobbles was radiocarbon dated, providing an age of 1219-856 cal. BCE. Unit 1 (sample at 2.07 m deep; Table 2) lacks pollen grains but does reveal rare occurrences of fungal spores. Unit 1 exhibits similar sediment texture as the basal unit identified by Lepofsky et al. (1996) at a similar depth. However, our work brings to light the novel presence of coral debris and marine molluscs embedded within this unit which is characterized by a high energy of deposition, thus indicating the direct influence of marine actions.
- Unit 2 is found exclusively in profile *'Ōpūnohu* 6, between 2 and 1.88 m below the surface, and comprises dark organic clays (mean grain-size is about 8 µm), with organic matter content of about 4%. Carbonate content is highest (4%) along the sequence in Unit 2. Optimal preservation of palynological remains and richness is observed for this layer (sample depth 1.97 m), revealing a good representation of Pteridophyte spores. Pollen grains of Ericaceae, Poaceae and *Persicaria* sp. (Polygonaceae) were also identified. The *Persicaria* species might be *Persicaria glabra* (syn. *Polygonum glabrum*), considered as a Polynesian introduction (Chevillotte et al., 2019), and currently known only from Tahiti and Ra'iatea in the Society Islands (Florence, 2004). Kahn et al. (2015; Figure 5) dated a *Persicaria* sp. seed from a depth of 2 m below the surface in a sedimentary profile obtained northwest of 'Ōpūnohu Bay, thus confirming the presence of this introduced species at a similar depth. The Ericaceae is probably *Vaccinium cereum* var. *cereum*, the only species of this family found in Mo'orea. The abundance of fungal spores also suggests a humid and organic environment associated with Unit 2. Radiocarbon dating performed on the lowermost part of Unit 2, where the *Persicaria* pollen grains were identified, indicates an age of 887-1230 cal. CE, while dating of the uppermost part of the unit remains imprecise.

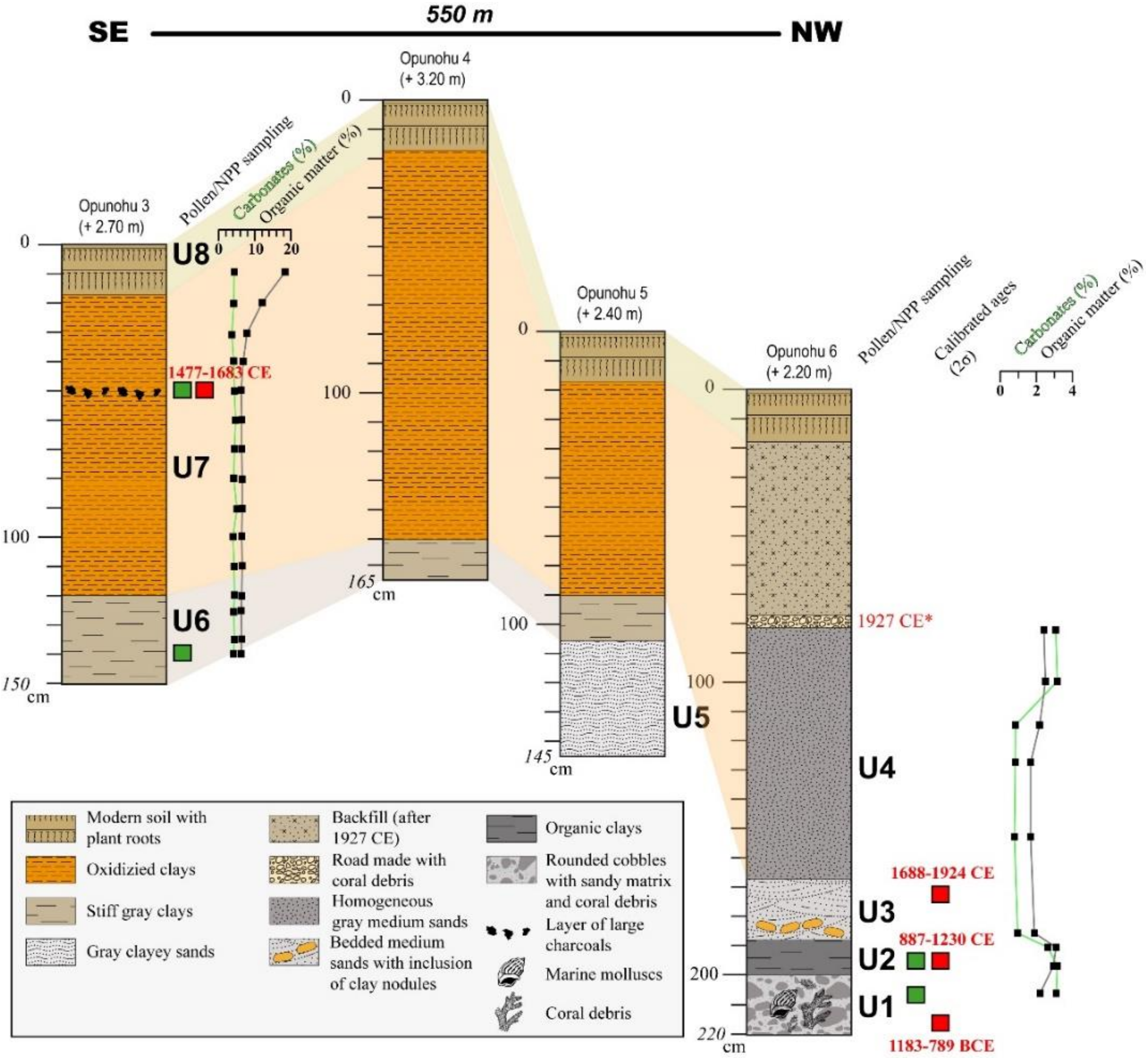

Figure 7 – Stratigraphic profiles 'Ōpūnohu 3, 4, 5 (located in the lower 'Ōpūnohu Valley) and 6 (River estuary). An asterisk* indicates that the age was provided by historical sources. Red square: position of 14C dating sample: green square : position of pollen sample used for identification

- Unit 3 is found only in the *'Ōpūnohu* 6 profile and consists of thin cross-bedded layers of homogeneous medium grey sands containing approximately 2% organic matter. Radiocarbon dating was performed on the uppermost part of Unit 3, providing an age of 1688-1924 cal. CE. It is noteworthy that the lowermost part of the unit is composed of medium grey sands (cross-bedded structure) with lenses of oxidized stiff clays.
- Unit 4 is found only in *'Ōpūnohu* 6 and is composed of homogeneous medium grey sands (with no sedimentary structure) containing 2 to 3% organic matter and around 2% carbonates. Mean grain-size is comprised between 180 and 250 µm. The age of Unit 4 is well constrained by radiocarbon dating for its lowermost part (1688-1924 cal. CE) while its uppermost part is modern, corresponding to a level rich in coral debris over which the island's circular coastal road was built in 1927 CE.
- Unit 5 is identified only for *'Ōpūnohu* 5 and comprises grey clayey sands showing thin bedded sections.

- Unit 6 is found in profiles *'Ōpūnohu* 3, 4 and 5 and is composed of stiff grey clays containing ca. 8 % organic matter and 6% carbonates. A sample at 135 cm from pit no. 3 shows good preservation and abundance of pollen and spores, with remarkably high concentrations of *Rivularia* (Rivulariaceae), a cyanobacterium related to shallow waters or humid soils and highly eutrophic conditions.
- Unit 7 is identified in all cores except *'Ōpūnohu* 6 section, and consists of oxidized (orange to brown colour) clays (mean grain-size: 2 µm) showing no sedimentary structure. Its thickness ranges from 0.70 to 1.20 m and it overlies Unit 6. Unit 7 is poor in pollen content, showing only the occurrence of fern spores (monoletes, Polypodiaceae ferns, *Dicranopteris linearis* and other triletes), as well as *Pseudoschizaea* (Figure 8). This palynological assemblage suggests dry conditions (probably seasonally desiccated wetlands or floodplain), affecting pollen preservation. A layer rich in charcoals was found at a depth of 0.50 m, roughly corresponding to the central part of Unit 7, and has been radiocarbon dated to 1477-1638 cal. CE. Unit 7 shows similar sedimentological features (oxidized structureless clays), with Unit IV identified in *'Ōpūnohu* 1 and 2 sections (Figure 6).
- Unit 8 is identified in all cores and is 20 cm thick, consisting of rich organic brown clays supporting the modern soils and the root network. Organic matter content is comprised between 13 and 18% while carbonate content is about 4%, remaining stable compared to Units 6 and 7.

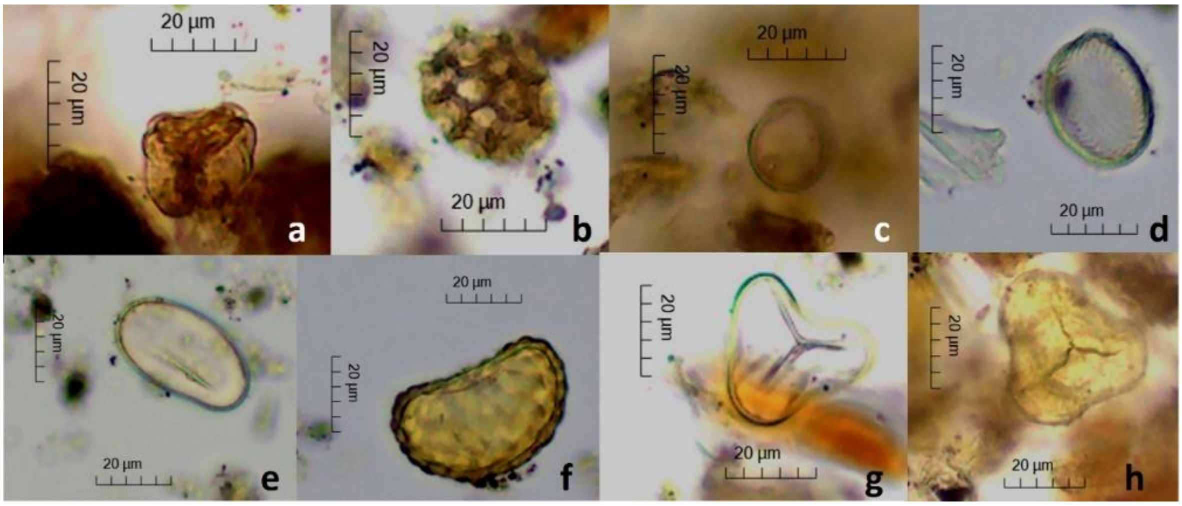

Figure 8 - Palynomorphs from 'Ōpūnohu 3 and 6 profiles: a) Ericaceae (Vaccinium cereum var. cereum); b) Persicaria sp.; c) Poaceae; d) Pseudoschizaea; e) monoletes Pteridophyta spores; f) Polypodiaceae; g) triletes Pteridophyta spores (Dicranopteris linearis, syn. Gleichenia linearis, Gleicheniaceae); and h) triletes Pteridophyta spores.

5. Discussion

5.1. General landscape evolution (from the foothills to the shoreline) related to Mā'ohi settlement of the island

The stratigraphic profiles obtained for the lower *'Ōpūnohu* River enable to partially sketch in its palaeoenvironmental evolution over approximately the last three millennia (Figure 9), and to define it more robustly from the onset of the anthropization of *Mo'orea* one millennium ago, onward. When the first Polynesians arrived on the northern shore of *Mo'orea* ca. 950 years ago, the present-day coastal floodplain did not yet exist. In its place was most probably a shallow marine protected bay that extended ca. 1 km southward from the present-day shoreline (Figure 9). At that time, sea level was near the present height and the last 1000 years can be characterized by robust sea level stability (Hallmann et al., 2018). The palaeobay probably covered an area of approximately 0.5 km², according to the combination of the sedimentary profile chronostratigraphies. The seafloor was characterized by the presence of well-rounded basalt cobbles originating from the surrounding slopes of *Ōpūnohu* palaeobay, found mixed with marine sands rich in marine fauna. The presence of these rounded basalt cobbles is well attested in the foothills, where profile *'Ōpūnohu 1* (Unit I; Figure 6) shows them embedded with a clayey matrix of orange colour. Additional, deeper coring is required, in particular 200 m S/SW of *'Ōpūnohu* 3 profile (Figure 9), in order to elucidate more precisely the maximal extent of this ancient marine bay.

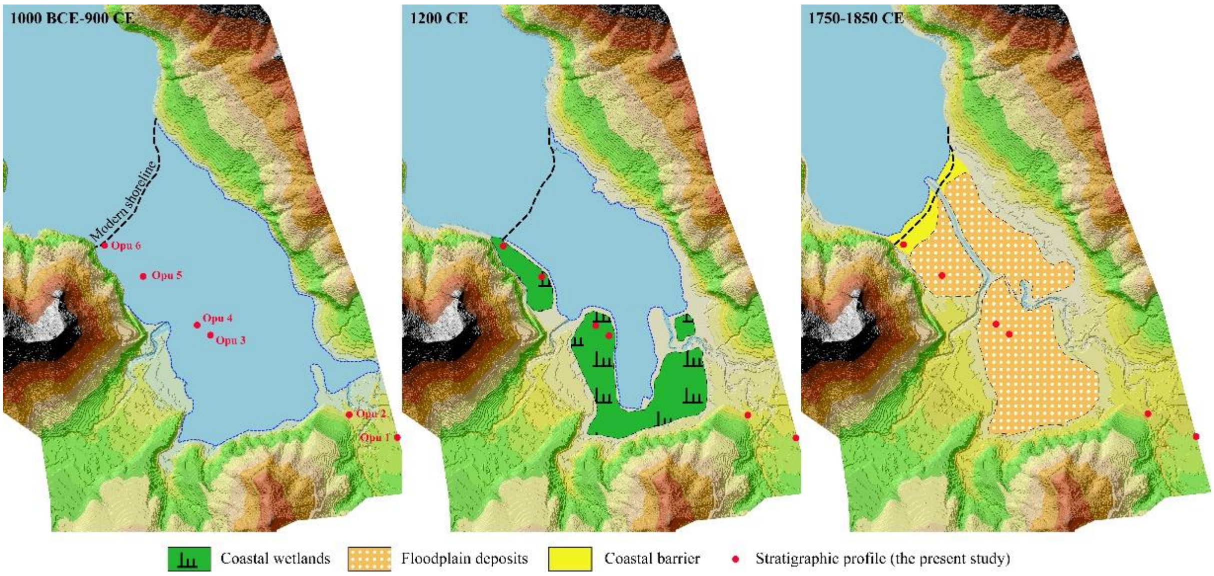

Figure 9 – Palaeogeographic reconstruction of the lower 'Ōpūnohu River for the last 3 000 years.

Around the onset of the 2nd millennium CE and the arrival of the *Mā'ohi* people, important regional deforestation occurred. This is evidenced by pollen results derived from Lake *Temae* (Stevenson et al., 2017) which indicate the burning of the vegetation cover on the foothill slopes, and is corroborated in the present study through the presence of a charcoal layer dated ca. 1050 CE in sedimentary profile

‘Ōpūnohu 2 (Figure 6), located on the foothill. At the same time, upslope establishment of *Dicranopteris linearis* fernlands is attested (Lepofsky ~~&~~ and Kahn, 2011). The burning activity, characterized by abundant pieces of charcoals embedded within the sediment, has previously been identified in the lower *‘Ōpūnohu* Valley by Lepofsky et al. (1996; Figure 5). Direct consequences of this forest clearance on the lower valley slopes included the erosion of sediments and their deposition into the ancient marine bay with substantial detrital input of oxidized clays on the foothill slopes, as revealed by sedimentary profiles *‘Ōpūnohu* 1 and 2. *‘Ōpūnohu* 6 profile shows that at around the onset of the 2^{nd} millennium CE, a clear shift in sedimentary dynamics occurred, from high energetic marine conditions (coarse sediments) to calm conditions of deposition, with the development of coastal swamps related to a general context of fluvio-deltaic progradation. Our chronostratigraphic data also confirm previous stratigraphic studies (Lepofsky et al., 1996) that revealed a massive detrital input following a period of charcoal accumulation in the lowlands. Finally, we also bring to light for the first time a precise radiocarbon dating age of this first human disturbance on the terrestrial ecosystems of the *‘Ōpūnohu* catchment.

In *‘Ōpūnohu* 6, one pollen grain of the introduced plant *Persicaria* was identified at 1.97 m (Figure 8), confirming ancient evidence of this wetland plant on the island of *Mo’orea* (Prebble, 2008; Kahn et al., 2015). The age obtained for the layer containing this pollen grain ranges from the 9^{th} to the 13^{th} Cent. CE. Considered as a Polynesian introduction, this plant is found only in wetlands and its presence is thought to predate the arrival of Europeans in the valley (Kahn et al., 2015). This latter finding clearly reveals the extensive presence of wetlands in the coastal plain prior to the arrival of the Europeans and immediately following the arrival of the *Mā’ohi* people. The existence of these swamplands is clearly associated with fluvio-deltaic dynamics. *Vaccinium cereum* pollen was also discovered in *‘Ōpūnohu* 6 (same layer containing *Persicaria* pollen grains): this small shrub is rare in Mo’orea today and is only found at high elevation (observed on the summit of Mt *Fairurani* at about 700 m and on Mt *Tohiea* between 1,000 and 1,200 m elevation). Its discovery in *‘Ōpūnohu* 6 indicates that the reconstruction of the palaeoenvironment can provide new biogeographical information such as the existence of *Vaccinium cereum* at a lower altitude than today. Further investigation is needed to link the newly discovered species to their carbon-14 datings with certainty, and thus resolve various ongoing controversies concerning the origin of certain plants in the valley.

5.2. Landscape changes linked to the Mā’ohi /European civilizations: a second major deltaic advance

Evidence exists for burning on the lower hillslopes, contemporary with the *Mā’ohi* people’s arrival but also persisting throughout the peak of maximum occupation, around the 15^{th}-17^{th} Cent. CE. This is evidenced by the presence of a thick layer of charcoal accumulation on profile *‘Ōpūnohu* 3 (Unit 7, Figure 7), making it clear that severe anthropogenic actions persisted for the duration of the *Mā’ohi* period until the final stages of *Mā’ohi* occupation of the catchment basin. Indeed, at ca. 550 BP, there is substantial archaeological evidence for well-developed communities in interior valleys such as the *ʻŌpūnohu* Valley (Kahn et al., 2015 and references therein). Our work indicates that the vegetation of the lower hill slopes during the *Mā'ohi* period was characterized by ferns (degraded vegetation), which agrees well with previous pollen investigations conducted on Lake *Temae* (Stevenson et al., 2017). In addition, our findings confirm previous sedimentological results obtained in the nearby area by Lepofsky et al., 1996 (Figure 5), demonstrating the presence of two layers exhibiting high charcoal concentration: the first at ca. 1 m deep, and the second 2 m below the surface. Both layers remain imprecisely dated but there is evidence to believe that the first layer may date from the 15th-17th Cent. CE, while the deeper one corresponds to the initial period of burning of primary forest at the onset of the 1st millennium CE.

When Europeans later settled the island during the second half of the 18th Cent. CE (contact with the *Mā'ohi* is dated 1767 CE; Kahn et al., 2015), a new phase of great disturbance in terms of land-use strategies occurred, inducing transformations which can be compared to those of the *Mā'ohi* phase of occupation (Lepofsky and Kahn, 2011) in terms of landscape changes. Indeed, archaeological excavations highlight the abandonment of the middle/upper slopes and a more specific agricultural development in the lowlands and on the coastal strip, areas favoured by the Europeans. The abandonment of the higher land at the arrival of Europeans may be indicative of a drastic decrease of the *Mā'ohi* population due to the introduction of various diseases (Hamilton and Kahn, 2007). As a direct consequence, the middle to upper slopes of the *ʻŌpūnohu* catchment underwent depopulation, which subsequently led to the abandonment of agricultural terraces and barrages in the upper/middle elevations during the 19th Cent. CE. The collapse of these structures at the transition between the *Mā'ohi* and European phases of occupation provoked a mobilization of colluvial deposits by the *ʻŌpūnohu* River in the context of a regional high precipitation regime (3000 to 4000 mm per year; Figure 4), and the sediments hitherto trapped during the half millennium of intense land-use by the *Mā'ohi* people were inevitably delivered into the river bed as a result. The consequences of this on the sedimentary dynamics are visible in the chronostratigraphic results obtained for profile *ʻŌpūnohu* 6: there is a thick (1 m) and homogeneous stratum composed of well sorted medium to coarse sands, roughly dated to the 19th to early 20th Cent. CE (Figure 6), which may correspond to the input of colluvial material/floodplain deposits into the shallow coastland wetlands. Indeed, the presence of cyanobacteria *Rivularia* attests to high eutrophication in agreement with the initial phase of deltaic progradation. During the European period of occupation (duration 1 to 2 centuries), major deltaic advancement occurred and the shoreline probably extended further into the sea in what is today *ʻŌpūnohu* Bay (Figure 9). However, the exact position of the palaeoshoreline during the 19th Century remains difficult to determine due to the important coastal erosion that has occurred over the last decades (Benet, 2020; Taiarui et al., 2017) and requires a further coring campaign.

5.3. A combination of natural and anthropogenic parameters to explain the landscape evolution

As demonstrated above, the *'Ōpūnohu* coastal/deltaic plain formed over the last millennium due to anthropogenic factors that strongly influenced sedimentary deposition into what was a protected marine bay when the first inhabitants settled the island. The main consequences of long-term land use within the catchment basin resulted first from the clearing of native species-rich forests, followed by a significant mobilization of colluvial material (oxidized clays) from the upper and lower hillslopes into the main river. This massive detrital input occurred over approximately one millennium with almost no discontinuity and led to the formation of a large coastal plain that can be defined as a delta formation. The timing and specific conditions required for the edification of deltas worldwide has been broadly studied, including for example in the Mediterranean Sea (Stanley and Warne, 1994; Bruckner et al., 2005). Indeed, in addition to sediment delivery into the sea, different external factors must be taken into account to explain the timing of these newly created pieces of land during the Holocene. Among these, we can cite the slowdown in sea level rise observed ca. 6000 years ago in the Mediterranean, for example (Vacchi et al., 2018), but also favourable tectonic activities such as regional and local subsidence. Regarding the Holocene sea level oscillations in French Polynesia, studies conducted over the last four decades (Pirazzoli et al., 1985 and 1988; Pirazzoli and Montagionni, 1986; Bernier et al., 1990; Bard et al., 1996; Hallmann et al., 2018 and 2020) globally show a period of sea level highstand of less than a metre above present-day sea level in the Society Islands between 4.1 and 3.4 kyr BP (Hallmann et al., 2018 and 2020). At *Mo'orea*, this sea level highstand is placed at +0.50 m amsl at the Mid-Holocene, with a peak between 3.9 and 3.6 kyr BP (Pirazzoli et al., 1988; Bernier et al., 1990). Following this period, relative stability can be observed followed by a marked RSL drop over the last 1200 years to reach the present-day position (Pirazzoli et al., 1985; 1988; Hallmann et al., 2018). Chronostratigraphic evidence obtained on the *'Ōpūnohu* coastal area for the present study reveals a marine level that was radiocarbon dated to between 1219 and 856 cal. BCE (3.17-2.81 kyr BP) at a relative elevation of + 0.13 m amsl. The sea level curve established first by Pirazzoli et al. (1985) and later by Hallmann et al. (2018) indicates a position of + 0.5 to 0.6 m amsl for the period ranging from ca. 3.2 to 2.8 kyr BP. Our palaeoenvironmental record acquired in the distal part of the deltaic plain supports a higher sea level position at around the onset of the 1st millennium BCE, suggesting a difference of a full 30 to 40 cm below the curve established by Hallmann et al., 2018. The combination of sea level rise deceleration (or slowdown for the Mediterranean, for example) together with a massive deposition of terrestrial sediments into a shallow seafloor are the main drivers of delta creation worldwide, and can likewise explain the formation of the *'Ōpūnohu* deltaic plain. Possible effects of local subsidence must also be taken into account to explain the difference of -30 to -40 cm with the curve established by Hallmann et al. 2018. Indeed, the *'Ōpūnohu* catchment is situated above the caldera and so may be influenced by continuous local land subsidence, a phenomenon which is, however, much more challenging to measure precisely. Regional studies conducted to evaluate the subsidence rates in the French Polynesian islands indicate values comprised between 0.15 mm per year at *Mo'orea* (Pirazzoli et al., 1985 and 1988) and 0.25 mm per year at Tahiti (Thomas et al., 2012). In the present study we show that the delta formation revealed for the first time herein resulted from a combination of natural and anthropogenic parameters, as has also been observed elsewhere around the world, as in the Mediterranean Sea, for example.

6. Conclusions

Based on a multiproxy palaeoenvironmental approach, our study offers for the first time elements concerning the diachronic morphological evolution of the floodplain of the *'Ōpūnohu* Valley, situated on the northern side of *Mo'orea* Island. A transect combining chronostratigraphic sections was established from the present-day shoreline to the foothills, thus helping to estimate the main rhythms of fluvio-deltaic progradation of the *'Ōpūnohu* River in a general context of sea level drop over the last millennium. The main results obtained for the present study are as follows :

1) Two main phases of shoreline advance have been identified corresponding to i) the initial phase of human occupation by the *Mā'ohi* civilization one millennium ago, when almost all the catchment basin was reclaimed for agricultural purposes, and ii) the onset of European colonization, certainly due to the abandonment of the upper/mid lands and to major changes in terms of land-use that resulted in the breakdown of ancient agricultural structures such as terraces or barrages that had previously served to retain sediments and prevent slope erosion.

2) The present study confirms the dating of the initial settlement of Mo'orea by the *Mā'ohi* people as obtained by previous archaeological and ethnohistorical studies: an age from the Mid to Late 11th Cent. CE has been confirmed based on the dating of a substantial charcoal layer situated at the base of a thick colluvial sedimentary unit in the foothills. This date corresponds to a drastic change in terms of landscape dynamics, when local conditions shifted from natural to highly anthropized environments.

3) The initial fluvio-deltaic formation of the *'Ōpūnohu* River is dated from the 11th Cent. CE and can be related to a massive detrital input following the primary deforestation (burning) of the hillslopes within the catchment. In this context, vegetation is characterized by the replacement of the pristine forest by ferns on the foothills.

4) Our study confirms a sea level highstand at 3-2.8 kyr BP, as previously observed regionally. However, local subsidence probably minimized the precise vertical position by a value 0.3 to 0.4 m below the sea level curves established for the area at that time.

The identification of the palaeoshoreline position at the arrival of the *Mā'ohi* people is a subject of considerable archaeological interest and calls for further chronostratigraphic investigations based on additional, deeper boreholes. Furthermore, there is a need for new palaeoecological proxies, such as more complete pollen sequences. This would enable to bridge the phase prior to human arrival with the periods of *Mā'ohi* occupation and European colonization in order to fully reconstruct the human-environments interactions over the last millennium in the French Polynesian islands.

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